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Fowler, Ashley M.; Jørgensen, A.M.; Coolen, Joop W. P.; Jones, Daniel O. B.; Svendsen, Jon Christian; Brabant, Robin; Rumes, B.; Degraer, Steven

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Quo Vadimus

The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it

A. M. Fowler [1,2]*, A.-M. Jørgensen[3], J. W. P. Coolen [4,5], D. O. B. Jones[6], J. C. Svendsen[7], R. Brabant [8], B. Rumes[8], and S. Degraer[8]

[1]*Fish Ecology Laboratory, School of Life Sciences, University of Technology Sydney, NSW 2007, Australia*
[2]*School of Life and Environmental Sciences, Deakin University, Burwood, VIC 3125, Australia*
[3]*Eco-Effective Strategies, Galileiplantsoen 14, 1098 NA Amsterdam, The Netherlands*
[4]*Wageningen Marine Research (Formerly IMARES), PO Box 57, 1780 AB Den Helder, The Netherlands*
[5]*Aquatic Ecology and Water Quality Management Group, Wageningen University, Droevendaalsesteeg 3a, 6708 PD Wageningen, The Netherlands*
[6]*National Oceanography Centre, European Way, Southampton SO14 3ZH, UK*
[7]*National Institute of Aquatic Resources (DTU Aqua), Technical University of Denmark, Building 201, 2800 Kgs. Lyngby, Denmark*
[8]*Royal Belgian Institute of Natural Sciences (RBINS), Operational Directorate Natural Environment (ODNature), Marine Ecology and Management (MARECO), Vautierstraat 29, 1000 Brussels, Belgium*

**Corresponding author: tel: +61 9 435 4652; e-mail: ashley.fowler@uts.edu.au.*

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As decommissioning of oil and gas (O&G) installations intensifies in the North Sea, and worldwide, debate rages regarding the fate of these novel habitats and their associated biota—a debate that has important implications for future decommissioning of offshore wind farms (OWFs). Calls to relax complete removal requirements in some circumstances and allow part of an O&G installation to be left in the marine environment are increasing. Yet knowledge regarding the biological communities that develop on these structures and their ecological role in the North Sea is currently insufficient to inform such decommissioning decisions. To focus debate regarding decommissioning policy and guide ecological research, we review environmental policy objectives in the region, summarize existing knowledge regarding ecological aspects of decommissioning for both O&G and OWF installations, and identify approaches to address knowledge gaps through science–industry collaboration. We find that in some cases complete removal will conflict with other policies regarding protection and restoration of reefs, as well as the conservation of species within the region. Key ecological considerations that are rarely considered during decommissioning decisions are: (i) provision of reef habitat, (ii) productivity of offshore ecosystems, (iii) enhancement of biodiversity, (iv) protection of the seabed from trawling, and (v) enhancement of connectivity. Knowledge gaps within these areas will best be addressed using industry infrastructure and vessels for scientific investigations, re-analysis of historical data held by industry, scientific training of industry personnel, joint research funding opportunities, and trial decommissioning projects.

Keywords: artificial reefs, biodiversity, conservation, decommissioning, ecosystem, marine policy, North Sea, offshore infrastructure, platform, sustainability, wind farm

Introduction

Ageing offshore oil and gas (O&G) fields in the North Sea and elsewhere, as well as decommissioning of the first offshore wind farms (OWFs; Yttre Stengrund and Utgrunden in Sweden, and Vindeby in Denmark), have prompted debate about how offshore energy infrastructure can best be decommissioned in a way that minimizes costs and long-term liabilities and maximizes environmental and other societal benefits. Under current regulations, it is estimated that in the coming 30–40 years some €90 billion or more will have to be spent on decommissioning of 1350 offshore O&G installations across the North Sea (Climate and Pollution Agency, 2011; NexStep, 2018; Oil and Gas Authority, 2018). Decommissioning costs for OWFs are still largely uncertain, but for the United Kingdom it has been estimated that the costs of decommissioning the 37 OWFs now operating or in pre-construction lie between £1.28 and £3.64 billion (Department of Business, Energy and Industrial Strategy, 2018a). Although O&G installations will have to be decommissioned as a result of reservoirs reaching the end of their operational life, wind turbines within OWFs will have to be removed and/or repowered every 20–30 years, owing to equipment degradation and permit expiry (Smyth *et al.*, 2015). Most of the costs will be covered either by taxpayers through tax concessions, shareholder participation by the state, or renewable energy subsidies (Climate and Pollution Agency, 2011; Department of Business, Energy and Industrial Strategy, 2018a; NexStep, 2018; Oil and Gas Authority, 2018).

Next to being costly, decommissioning can have substantial impacts on marine ecosystems and the wider environment. Impacts that are traditionally assessed in comparative analyses completed by offshore energy companies relate to energy use, emissions to air, seabed disturbance, risk of pollutant leakage during and after decommissioning, and impacts associated with waste handling onshore (Ekins *et al.*, 2006; Fowler *et al.*, 2014). Equally important, however, but rarely assessed in decommissioning environmental impact assessments (EIAs), are the impacts of loss of hard substrate, loss of biological communities that have developed on the infrastructure, and removal of no-fishing zones around offshore structures (Macreadie *et al.*, 2011). Recent research suggests the choice of decommissioning option may have a much wider impact on marine ecosystems than first thought (Claisse *et al.*, 2014; Fowler *et al.*, 2018; Henry *et al.*, 2018). Environmental researchers and stakeholders are increasingly calling for revision of decommissioning policy, both globally and in the North Sea, to expand the range of allowable decommissioning options and the environmental considerations on which the decisions are based (Ekins *et al.*, 2006; Jørgensen, 2012; Fowler *et al.*, 2014, 2018).

Expanding the range of allowable options and environmental considerations will help optimize decommissioning outcomes for North Sea ecosystems, but will also increase the complexity and data requirements of the decision. Choosing between alternative options entails complex environmental trade-offs among different types of impact (e.g. energy use vs. emissions saved by recycling vs. value of ecosystems negatively affected by removal) occurring in numerous environments (i.e. offshore vs. onshore) over a range of scales (i.e. localized short-term through to regional long-term). Comparative analyses, including multi-criteria decision analysis, have been identified as a way forward for optimizing decommissioning decisions, because they structure the decision problem, force explicit consideration of all decision components, and are capable of balancing competing environmental considerations (Ekins *et al.*, 2006; Fowler *et al.*, 2014; Kerkvliet and Polatidis, 2016; Burdon *et al.*, 2018; Willsteed *et al.*, 2018). The range of environmental considerations for offshore infrastructure decommissioning and comparative analyses that can be used to compare them were recently reviewed by Sommer *et al.* (2019). However, knowledge regarding many environmental considerations, including ecological considerations recently identified as high priority (Fowler *et al.*, 2018), is currently insufficient to facilitate comparisons of performance among decommissioning options in the North Sea. We simply lack the ecological data necessary to populate the comparative frameworks and generate robust decisions. Without further progress on the baseline ecology of decommissioning, holistic and informed decisions regarding the fate of North Sea infrastructure cannot be made and the environmental outcomes of decommissioning in the region may not be maximized.

To focus debate regarding decommissioning policy and guide ecological research that supports holistic decommissioning decisions in the North Sea, we: (i) outline the context of decommissioning in the region, including the environmental policy objectives and ecosystem components potentially affected by decommissioning activity, (ii) outline the need for and summarize current knowledge of the key ecological considerations for decommissioning, including the relative impacts that different decommissioning options may have, (3) identify approaches for efficiently addressing knowledge gaps through science-stakeholder cooperation, and (4) identify potential legislative and operational barriers to partial decommissioning.

Decommissioning context

The North Sea is a shallow arm of the northeast Atlantic Ocean bounded by the United Kingdom and mainland Europe (Figure 1). Oceanography in the region is dominated by tidal flow, entering via the English Channel to the south and between Scotland and Norway to the north (Otto *et al.*, 1990). Together with wind-driven currents, tidal residuals establish a dominant anticlockwise circulation (Sündermann and Pohlmann, 2011). Water depth increases from south to north, ranging between an average of 20 m near Denmark and Germany to >800 m near Norway (Figure 1). Benthic habitats consist primarily of sandy and muddy sediments, punctuated by areas of coarse substrate such as gravel and rocks, mostly present in the coastal waters surrounding the United Kingdom and Norway, with some smaller patches offshore (Figure 1c).

At present, 1350 O&G installations are operating in the OSPAR maritime area, most of which are in the North Sea (OSPAR Commission, 2018; Figure 1a), and some 4000 wind turbines (WindEurope, 2018; Figure 1b). OSPAR is an international convention among 15 national governments that aims to prevent and eliminate marine pollution and achieve sustainable management of the maritime area within the Northeast Atlantic. In the United Kingdom alone, there are 674 O&G installations, 139 in The Netherlands, 452 in Norway, 16 in Denmark, and 2 in Germany. O&G installations are present in two large clusters; in the south in shallow English, Dutch and Danish waters, and in the north in deep Scottish and Norwegian waters (Figure 1a). These structures are located in water depths ranging from 2 m (Mittelplate in Germany) to more than 800 m (Ormen Lange in Norway). Approximately 190 installations are located in <30 m water depth, with 510 installations between 30 and 100 m, and some 640 installations in waters deeper than 100 m (OSPAR Commission, 2018; Figure 1a). Most installations are located in areas with a seabed consisting of sand, gravel, or mud, but a few Norwegian and United Kingdom installations are located in areas with rocky reefs and cold-water corals (Figure 1c). OWFs have mostly been established in shallow southern coastal waters in England, Belgium, The Netherlands, Germany, and Denmark

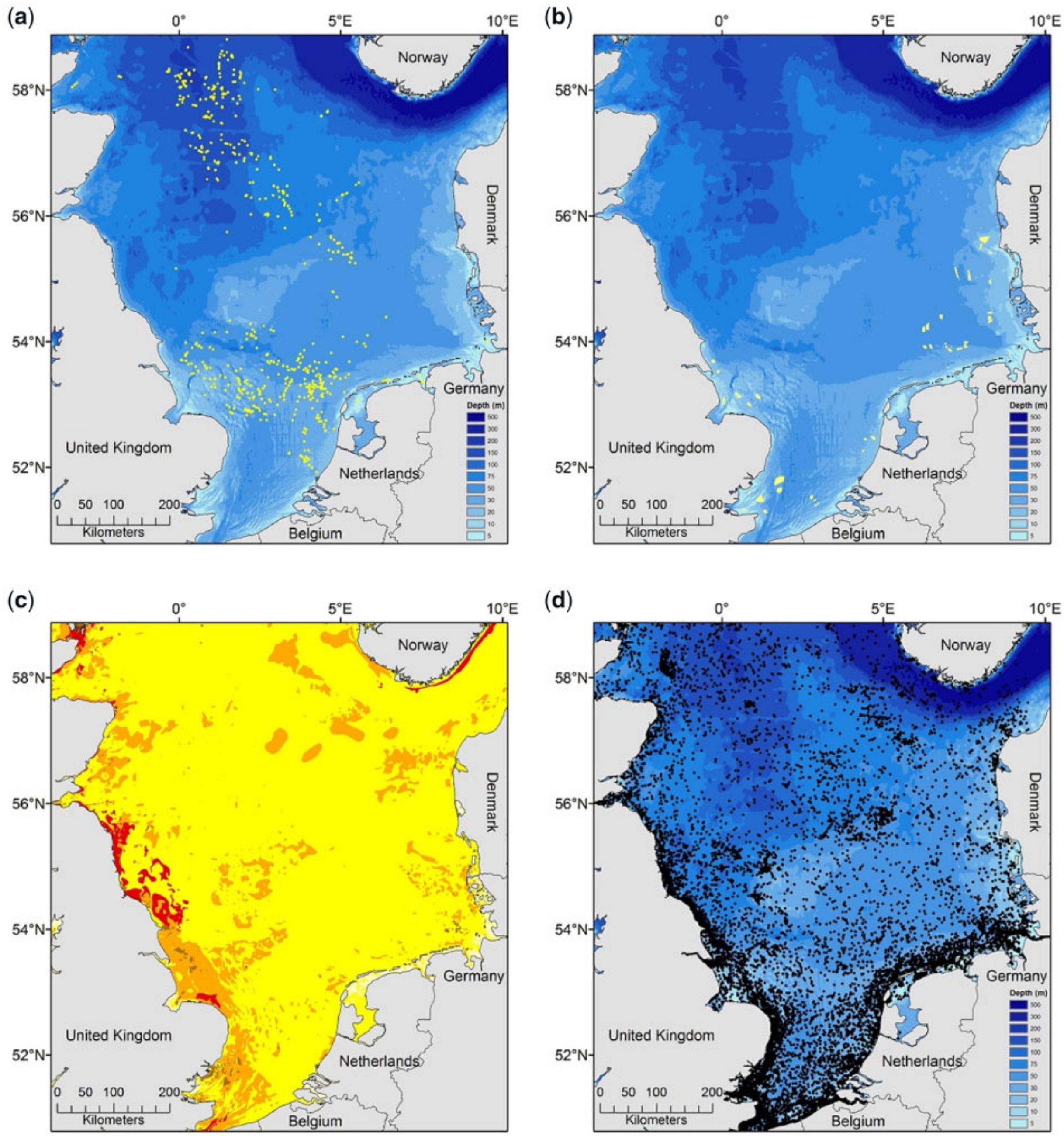

Figure 1. Locations of (a) O&G installations (OSPAR Commission, 2015), (b) OWFs, (c) benthic habitats (EMODnet, 2015), and (d) shipwrecks (Lettens, 2015) in the North Sea. Benthic habitats are sand and mud (lightest shade), mixed (intermediate dark shade), coarse sediment including gravel (intermediate light shade), and rocky reef (darkest shade). Wind turbine data were compiled by J. T. van der Wal (July 2016) from the WindSpeed project, OSPAR Commission, 4COffshore, and the national authorities of Norway, Denmark, Germany, Belgium, the United Kingdom, and the Netherlands.

(Figure 1b). Furthermore, ∼27 000 shipwrecks are present throughout the North Sea (Coolen *et al.*, 2018a; Figure 1d).

Most O&G installations and many wind turbines will have to be decommissioned in the next 20–30 years. As a result of the OSPAR Decision 98/3 and national "clean seabed" policies, they will predominantly have to be removed from the marine environment. This process has already begun and a significant proportion of these structures are now entering or fast approaching decommissioning. In the North Sea region, OSPAR Decision 98/3 and national decommissioning regulations seek to ensure safe access to and use of the seabed for all users, limit the risks of offshore chemical pollution during and after decommissioning, and minimize long-term liabilities for the state (polluter-pays principle). At the same time, OSPAR and the EU work at a much wider scale to achieve a range of policy objectives related to conservation and rehabilitation of marine ecosystems. These include:

(i) Protection, conservation, and restoration of ecosystems and the biological diversity of the maritime area, including species-engineered habitats such as Ross worm reefs (*Sabellaria spinulosa*; OSPAR Commission, 1992);

(ii) Conservation of key natural species and habitats, including sandbank habitats, reef habitats, and various reef-related species, such as deep-water coral (*Desmophyllum pertusum*, formerly *Lophelia pertusa*), horse mussels (*Modiolus modiolus*), and flat oysters (*Ostrea edulis*; The Council of the European Communities, 1992);

(iii) Establishment of Marine Protected Areas (MPAs) to protect specific areas from some or all human activities. In 2012, almost 18% of the Greater North Sea was protected either as a nationally-designated area (Common Database on Designated Areas) or as a Natura2000 area under either the EU Habitats Directive or the Birds Directive (European Environment Agency, 2015). The designation of MPAs does not necessarily mean that the area is effectively protected from damaging fishing practices. In particular, the EU Common Fisheries Policy has often been criticized for being inconsistent with conservation goals (Qiu and Jones, 2013);

(iv) Achievement of a "good environmental status," defined as "The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive..." (The European Parliament and Council of the European Communities, 2008) under the EU Marine Strategy Framework Directive. The environmental status is defined by 11 qualitative descriptors that include maintenance of biodiversity and populations of commercial species within safe biological limits, no adverse alteration of ecosystems by non-indigenous species, and maintenance of seabed integrity at a level that safeguards the structure and functions of ecosystems.

In recent years, the European Commission and national policy makers have increasingly stimulated active restoration of habitats. For example, EU member states are obliged to "take appropriate conservation measures to maintain and restore the habitats and species for which [a Natura2000 site] has been designated to a favourable conservation status" (European Commission, 2018). Also, experience and research have shown that protection alone often is not enough, and not the most cost-effective action, for a degenerated habitat to recover (e.g. Saunders *et al.*, 2017). For example, in 2012 larvae had to be imported from Norway in order to restore a Swedish *Desmophyllum* reef (Dahl *et al.*, 2012), whereas Denmark is importing rocks from Norway to restore local stone reef habitats (Mikkelsen *et al.*, 2013). Restoration of the stone reef habitat is required, because at least 42 km^2 of the historic stone reefs have been removed by anthropogenic activities, which has led to protection and active restoration of stone reefs in numerous locations in Denmark under Natura2000 (Kristensen *et al.*, 2017). Importantly, removed historic stone reefs cannot recover without active restoration. Similarly, European flat oysters (*O. edulis*) were recently imported from Norway to restore extinct offshore flat oyster reefs in the Netherlands (WWF, 2018). Flat oyster reefs were present in an area spanning many thousands of km^2 but have disappeared since the onset of the industrial fishery (Berghahn and Ruth, 2005). Restoration efforts are taking place within Natura2000 areas, designated for reef habitat, but also elsewhere, e.g. in offshore wind farm areas (e.g. Van Oord, 2019).

Species present on offshore energy structures include those that are also observed regularly on protected (reef) habitats (Coolen *et al.*, 2018a), species of conservation interest because of their reef-building capacities, e.g. *D. pertusum* (Bell and Smith, 1999) and *S. spinulosa* (Leonhard *et al.*, 2006), as well as non-native species (Coolen *et al.*, 2018a). Meanwhile, the value of ecosystems that have developed on and around offshore energy structures and their potential regional importance to biological populations does not play a significant role in decisions on how disused energy structures should be decommissioned. Nor do regional and national nature protection policies include strategies for how such structures could be developed and managed in such a way that they support important natural ecosystems. This situation may lead to conflicts between policies/objectives regarding habitat protection and those of infrastructure removal. For example, although natural *D. pertusum* reefs are protected (OSPAR Commission, 2008) and may benefit from the supply of larvae from colonies living on O&G installations (Henry *et al.*, 2018), the response to a question in the Murchison decommissioning process was that "JNCC [Joint Nature Conservation Committee] advise that as *L. pertusa* would not have occurred without the presence of the platform, mortality as a result of decommissioning operations would not be considered as an issue of significant concern for the EIA" (CNR International, 2013). As a consequence, the operator of the Murchison installation may not be required to include *D. pertusum* in an EIA to assess the ecological consequences of removing the installation from the marine environment. A similar scenario occurred during 2017 in relation to the Ninian North platform, which is only ~1 km away from a natural *D. pertusum* reef (OSPAR Commission, 2015; Fortune and Paterson, 2018). Similarly, the OWF Vindeby in Denmark was decommissioned and removed in 2017, although it was surrounded by eight Natura2000 areas with stone reef habitat (1170) listed as protected in line with EU guidelines (European Commission Directorate-General for Environment, 2013). The EIA for Vindeby decommissioning and removal indicated that local fisheries for Atlantic cod (*Gadus morhua*) could decline as a result of decommissioning and the associated loss of OWF reef habitat in Denmark (Nicolaisen *et al.*, 2016). Additional OWFs surrounded by protected reef habitat in Denmark are facing decommissioning and are likely to be removed in the near future (e.g. the Tunø Knob OWF). Whatever approach is taken to protect natural biogenic reefs, the presence of these reefs on and around artificial structures at sea should not be ignored.

In the North Sea, harbour porpoise (*Phocoena phocoena*), grey seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*) are protected within some Natura2000 areas and a large Special Area of Conservation located in the United Kingdom sector (Ministry of the Environment, 2013; Kommune *et al.*, 2017). Marine mammals are also present around offshore installations, as shown for harbour porpoise and other cetaceans (Todd *et al.*, 2016). Seals have been shown to actively seek out structures such as OWF foundations and pipelines, most likely to forage (Russell *et al.*, 2014). Offshore installations may also play a role in survival of other mobile species under pressure (e.g. cod, sharks; Robinson *et al.*, 2013), yet the exact nature of the role and the implications for population maintenance are currently unknown (Lindeboom *et al.*, 2011).

Decommissioning options and ecological considerations

Alternatives to complete removal (partial removal)

According to current regulations (OSPAR Decision 98/3 and national regulations), all disused offshore installations should be fully removed and transported to shore for reuse, recycling, or final disposal. Derogations from this rule are allowed only for "[the footings of] steel installations weighing more than ten thousand tonnes in air; gravity-based concrete installations; floating concrete installations; and any concrete anchor-base which results, or is likely to result, in interference with other legitimate uses of the sea." (OSPAR Decision 98/3 Annex 1). Also a permit may be issued for "any other disused offshore installation to be dumped or left wholly or partly in place, when exceptional and unforeseen circumstances resulting from structural damage or deterioration, or from some other cause presenting equivalent difficulties, can be demonstrated" (OSPAR Decision 98/3, art. 3). Competent (i.e. national) authorities may issue a permit for derogation only after consultation with the other Contracting Parties, following the specific procedure described in Annex 3 of OSPAR Decision 98/3. The scope for derogations is reviewed at regular intervals "in order to reduce the scope of possible derogations" (OSPAR Decision 98/3, art. 4 and 7).

Unlike platforms, the removal of pipelines is not mandated by OSPAR Decision 98/3. Policies regarding their decommissioning vary among nations and decommissioning options are considered on a case-by-case basis (Rouse *et al.*, 2018). Also, decommissioning policies for wind turbines differ between North Sea countries and some legal experts have indicated that OSPAR Decision 98/3 may not apply to wind turbines, as these are not covered by the definition of offshore installations within the OSPAR Convention (van Beuge, 2016). In the United Kingdom, where wind farm operators are obliged to present a decommissioning plan as part of the permit procedure, the general rule is that structures must be removed to shore except for scouring protection and concrete foundations, which may be left in place (Topham and McMillan, 2017). In Denmark, Belgium, the Netherlands, and Germany, wind farm operators are legally obliged to restore the site to its original state (i.e. remove all structures to shore), unless otherwise agreed by the Minister in consultation with the proper officials. The removal of the OWF Vindeby included power cables to shore and all foundation elements. The objective of this policy is that the seabed should be restored to its "original" pre-installation state and material from installations reused or recycled, although the original state of the seabed may not be known. After removal, the area is opened up to other users again, including trawl fishing. With the recent focus on combining nature restoration with OWFs (e.g. the Netherlands), over time decommissioning policies for wind farms in many North Sea countries may follow the United Kingdom example and develop to also allow for leaving in place scouring protection and concrete foundations.

Despite the current policy preference for complete removal of disused installations in the North Sea, a range of alternative methods exist, including numerous partial removal options where some sections of the structure are left in the marine environment while the remainder is transported to shore for reuse, recycling, or scrap (Ekins *et al.*, 2006; Fowler *et al.*, 2014; Scarborough Bull and Love, 2019; Sommer *et al.*, 2019). These options differ primarily in the extent of material left, the location of that material (either *in situ* or redeployed elsewhere), and the fate of material brought to shore. In other regions with significant offshore infrastructure, such as the US Gulf of Mexico, which has over 6000 offshore structures (National Oceanic and Atmospheric Association, 2018), the legislative regime often allows for alternatives to complete removal (Scarborough Bull and Love, 2019). In the Gulf of Mexico, a "rigs-to-reefs" programme has been implemented for O&G platforms, which allows them to be turned into artificial reefs for attracting marine life. Over 530 platforms have already been reefed to date (Bureau of Safety and Environmental Enforcement, 2018). Potential alternatives to complete removal for offshore installations in the North Sea, including rigs-to-reefs, have typically been discussed at a high level, for example, partial removal as compared with full removal (e.g. Smyth *et al.*, 2015), or have been considered with respect to the range of technical methods by which a limited number of true alternatives could be achieved (e.g. Kerkvliet and Polatidis, 2016). Smyth *et al.* (2015) suggested a "renewables-to-reefs" programme may be viable for decommissioning of offshore wind turbines in the North Sea. Fowler *et al.* (2018) identified nine potential alternatives to complete removal for offshore installations in the North Sea, with expert opinion identifying numerous alternatives that have likely similar, or even better, environmental outcomes than complete removal.

Based on the preferences of environmental experts recently expressed in Fowler *et al.* (2018) and experiences elsewhere in the world, the most relevant alternative (but now largely illegal) decommissioning options to consider for O&G structures and wind turbines in the North Sea are: (i) partial removal, leaving >25 m free draught, and transport of the top sections to shore for reuse or recycling (Figure 2a); (ii) "topping," leaving >25 m free draught, and placing the top section on the seabed next to the installation base (Figure 2b); (iii) toppling the structure in place (Figure 2c), and (iv) partial removal and relocation of cleaned sections to a designated reefing area (Figure 2d). In all cases, topsides and other emergent sections would be removed at least to a level where they would not pose a safety risk, unless an installation could be reused for new (economic) functions for which the topside is essential. An example of an oil platform that has been reused without removal of the topside is the Sipadan Seaventures Dive Resort in Malaysia, but for the North Sea, we do not consider this type of solution viable in most cases. Although the BEIS Guidance Note explicitly mentions 55 m free draught, referring to the International Maritime Organization (IMO), we use a minimum of 25 m free draught here, because the IMO has accepted this for designated reef areas elsewhere in the world (e.g. Gulf of Mexico), and because of the fact that no ships entering the North Sea via the Dover Strait have a draught of more than 22.6 m (United Kingdom Hydrographic Office, 2015). The exact method used for each decommissioning option would likely vary on a case-by-case basis, depending on numerous factors, including the engineering considerations specific to each installation and the local environment. Ecological outcomes of partial removal options may differ considerably between O&G installations and wind turbines, owing to the structural differences between these installation types and resulting potential differences in associated biological communities. Environmental trade-offs among decommissioning alternatives, including energy consumption, emissions, and recycling, are also likely to differ to some extent between the two installation types. Such differences may render some decommissioning options suitable for one installation type, but not the other.

Ecological considerations

Although EIAs for decommissioning in the North Sea address numerous potential environmental impacts, they rarely consider the value of marine ecosystems that have developed on and around

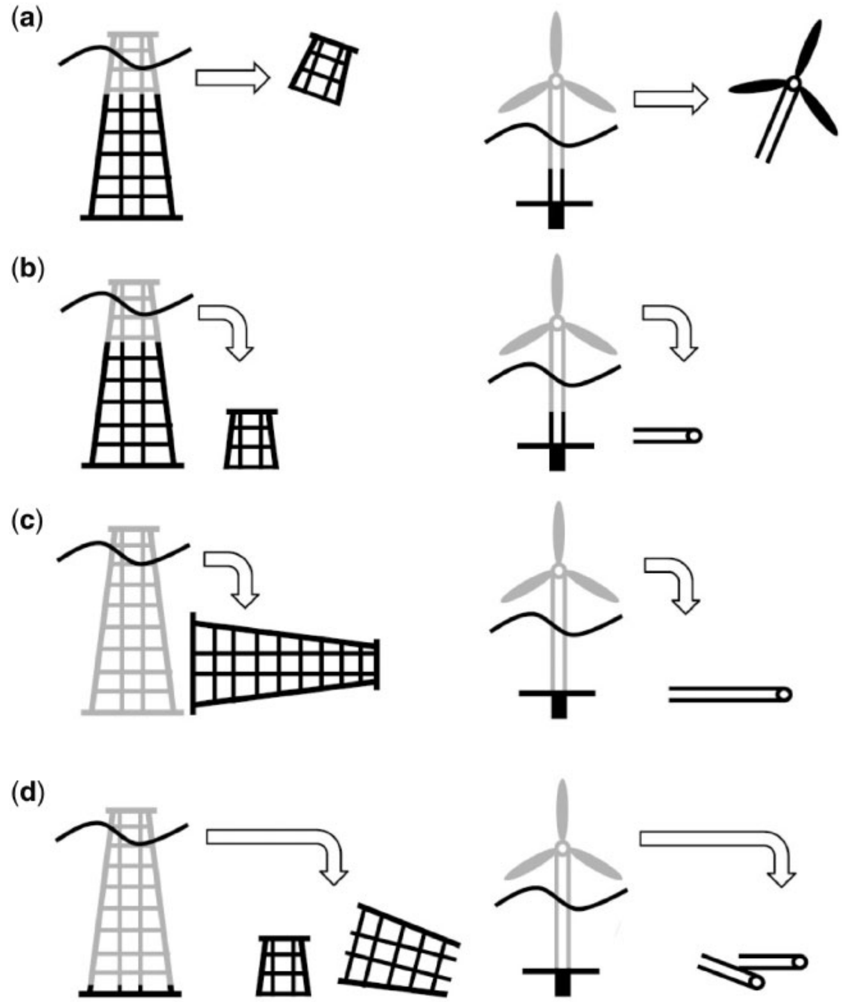

Figure 2. Schematic representation of potential alternatives to complete removal for decommissioning of O&G installations (left) and wind turbines (right) in the North Sea: (a) partial removal, where the base is left *in situ* and the top sections are removed and transported to shore for recycling, reuse, or scrap; (b) "topping," where the top section of the structure is removed and deployed *in situ* beside the base; (c) toppling the whole structure *in situ*, (d) partially removing the structure and redeploying the top section in a designated reefing area. Greyed sections represent the original position of structures prior to decommissioning. NB: options that retain structure above the seabed would be restricted to depths >25 m, given the IMO free draught requirement of 25 m applied to artificial reefs in other regions of the world.

infrastructure, or the interactions between these ecosystems and other (natural) ecosystems in the surrounding region. Regulatory guidance on decommissioning indicates the need to consider species of conservation significance, specifically habitat-forming *D. pertusum* (formerly *L. pertusa*) and *S. spinulosa*, yet does not provide guidance on other ecosystem components (Department of Business, Energy and Industrial Strategy, 2018b). Nor does it suggest that the presence of species of conservation significance on the structure that is to be decommissioned could or should form an argument for leaving the structure (partially) in place. In addition to the way EIA guidelines have been formulated by the European Commission and translated into national guidelines, this situation has resulted from a historical focus, e.g. in the London Convention and the OSPAR Convention, on preventing chemical pollution of marine ecosystems, and from a limited understanding of the potential importance of infrastructure ecosystems in the North Sea relative to other regions (e.g. California, Helvey, 2002). However, the scale of future decommissioning activity has generated a recent increase in decommissioning research, including investigations into the biological communities associated with offshore infrastructure (Coolen *et al.*, 2018a, b; Gormley *et al.*, 2018; Todd *et al.*, 2018) and the connectivity between these communities and natural ecosystems throughout the North Sea (Henry *et al.*, 2018; van der Molen *et al.*, 2018).

Given the rapid increase in decommissioning activity, the growing recognition that complete removal may not always provide the best environmental outcomes (Burdon *et al.*, 2018; Fortune and Paterson, 2018; Fowler *et al.*, 2018), and therefore the urgent need to investigate the broader suite of potential impacts of decommissioning alternatives, we summarize current knowledge regarding the key ecological considerations for decommissioning in the North Sea. We also explore potential differences in these considerations among the decommissioning alternatives identified in the previous section, where information is available. Our shortlist of ecological considerations was developed from research priorities identified in a recent survey of environmental experts from ten nations in the North Sea area (Fowler *et al.*, 2018), as well as those considerations that have been identified as important in other regions, mainly the well-studied regions of California and the Gulf of Mexico. The full list of ecological considerations in Fowler *et al.* (2018) represents an amalgamation from numerous sources.

Provision of reef habitat

Partial removal options will maintain more of the existing artificial reef and associated biological communities in the North Sea, whereas complete removal will clearly result in their loss (Ekins *et al.*, 2006; Smyth *et al.*, 2015). With partial removal, shallow offshore reef habitat could be removed while leaving deep habitat in place, thereby minimizing disturbance of the seabed as the footings remain untouched (Figure 2a and b). Fowler *et al.* (2018) identified partial removal as the preferred decommissioning option in the region and one of the reasons for this was that the species composition on the deeper sections of offshore structures (near the seabed) is more similar to natural rocky reefs (Coolen *et al.*, 2018a), whereas the shallow sections hold species such as mussel beds (*Mytilus edulis*) and associated fauna that do not occur naturally in the offshore environment. For example, recent research investigating the sessile organisms inhabiting platforms and wind turbines in the North Sea found the proportion of non-indigenous species was greater in the shallower sections near the water surface (Coolen *et al.*, 2018a). Other partial removal options that do not retain the lower structural sections *in situ* will have greater impacts on the reef habitat provided. For example, the option of "toppling" *in situ* will disturb the existing benthic reef habitat and associated biota (Figure 2c), which in time is likely to be replaced by a deeper reef community (Rezek *et al.*, 2018), e.g. replacement of shallow mussel- or kelp-dominated communities by anemone- or coral- dominated communities, as commonly observed in the North Sea (e.g. Coolen *et al.*, 2018a).

Although partial removal options would retain more of the artificial reef habitat present in the North Sea, they do not reverse the initial loss of soft-sediment ecosystems that occurred during installation. In addition, offshore structures may continue to impact surrounding soft-sediment ecosystems through interactions between reef-associated and soft-sediment organisms, for example the "halo" effect of grazing and predation observed around other artificial structures in the marine environment (Posey and Ambrose, 1994). However, despite the potential for negative ecological interactions, impacts appear restricted to the close vicinity of artificial structures (Reeds *et al.*, 2018), and there is limited evidence that offshore installations negatively impact surrounding fish assemblages (Stenberg *et al.*, 2015). For example, van Deurs *et al.* (2012) examined short- and long-term effects of an OWF on three species of sandeel (*Ammodytes marinus*, *Ammodytes tobianus*, and *Hyperoplus lanceolatus*) in the vicinity of wind turbines. Within 1 year after construction, the densities of juveniles and adults of the three species were positively affected (van Deurs *et al.*, 2012). Within a longer term period (7 years after construction), neither a positive or negative effect was detected (van Deurs *et al.*, 2012). At Block Island Wind Farm, off Rhode Island (USA), a study of seven flatfish species found neither a reef effect nor negative impacts (i.e. overall neutral effect) of offshore installations (Wilber *et al.*, 2018). Any effects of retained offshore infrastructure on surrounding soft-sediment ecosystems may be minimal on a regional scale, given the small amount of affected soft-sediment habitat relative to natural soft-sediment habitats in the North Sea (Stenberg *et al.*, 2015; Hyder *et al.*, 2017).

Despite the relatively small amount of reef habitat provided by offshore installations, their removal may still have regional impacts in the North Sea owing to the biological connectivity between offshore installations and natural reefs (see "Enhancement of connectivity" section; Henry *et al.*, 2018). This connectivity may take time to develop, as reef organisms may be initially impacted by construction and may take several years to colonize new structures (Henry *et al.*, 2018). The spatial distribution of infrastructure habitat within the broader network of reef habitat in the region may require consideration in decommissioning decisions (van der Molen *et al.*, 2018), particularly given that O&G infrastructure is mainly located in areas that have minimal natural hard substrate (Figure 1a). To function as "stepping stones" between otherwise isolated biological populations, infrastructure should be close enough to source populations, but also close to destination populations e.g. following the framework suggested by Roberts *et al.* (2003) for selection of marine reserves. Like other regions (e.g. California, Claisse *et al.*, 2014), infrastructure reefs in the North Sea may also be more productive for some taxa than natural reefs, further emphasizing the need to look beyond a simple comparison of habitat amount when attempting to understand the ecological impacts of removing offshore installations in the region.

Importantly, the artificial habitat provided by installations may resemble protected natural habitats and even host species of conservation interest in the North Sea. Scour protection associated with wind turbines, pipelines, and other seafloor infrastructure may resemble protected rocky reef habitats (Reubens *et al.*, 2013a, 2014) that may require active restoration after impact to meet habitat requirements of the EU Habitats Directive and Habitat Regulation Assessments (Kristensen *et al.*, 2017). Should scour protection or other installation foundations represent similar natural values as natural reefs (which is not always the case, Coolen *et al.*, 2018a), they may help ensure that regions meet required standards for protection and restoration of marine habitats, provided that installations are present in areas where the habitat is listed. Thus, there are potential synergies between offshore installations and restoration of historical reefs. Currently, permits for new OWFs (e.g. in the Netherlands, but not in Belgium, Denmark, or the United Kingdom) require coordination of such dual efforts, requiring the addition of "nature-inclusive" measures designed to enhance "policy relevant" species, such as *O. edulis* (Lengkeek *et al.*, 2017).

Biogenic reefs are home to many—often rare—species and offer great value with regards to ecosystem functioning (e.g. locally-increased productivity and reproductivity; Kent *et al.*, 2017; Fariñas-Franco *et al.*, 2018). Biogenic reefs hence are considered a top priority for conservation and restoration in many (inter)national regulations (e.g. EU Habitats Directive). Several North Sea reef-building species such as *D. pertusum* (previously *L. pertusa*), *S. spinulosa*, and *O. edulis* are found on O&G installations and wind turbine foundations (Leonhard *et al.*, 2006; Kerckhof *et al.*, 2018a). The former, particularly in the deeper waters of the North Sea (Gass and Roberts, 2006) but also in other regions, such as the Gulf of Mexico (Macreadie *et al.*, 2018). This is why sometimes a non- or partial removal option for offshore infrastructure is advocated (e.g. Fowler *et al.*, 2018). *Desmophyllum pertusum* is listed under CITES Appendix II, meaning that the United Nations Environmental Programme recognizes that this species may become threatened with extinction in the future. It however remains unclear whether scleractinian corals are included on the CITES list because the species may become threatened, or because the habitat they create may become threatened. The OSPAR Commission, for the protection of the marine environment of the Northeast Atlantic, has recognized endogenic *D. pertusum* reefs as a threatened habitat in need of protection.

Although offshore structures indeed contribute to species' population size, extent, and connectivity (Henry *et al.*, 2018), they only protect the reef habitat created by these species when it falls within the fishing restriction zone surrounding offshore structures (Roberts, 2002). Given that not the species itself, but rather its biogenically-created habitat (i.e. biogenic reef) is currently at risk, it could be argued that the mere presence of individuals or clusters of individuals of reef-building species like *D. pertusum* and *Ostrea* sp. on offshore structures alone should not be used to justify their non- or partial removal. However, such biogenic reefs could develop on structures given sufficient time. In this event, guidelines regarding the minimum size of biogenic habitat that warrants preservation would assist decisions regarding appropriate decommissioning options. In Denmark, biogenic reefs down to 10×10 m are mapped and protected via the EU Habitat Directive (Dahl and Petersen, 2018). The potential for offshore structures to aid the connectivity of potentially fragmented natural populations of vulnerable reef-building species should also be considered (e.g. Henry *et al.*, 2018). However, vulnerable reef habitats in the North Sea will need proper conservation and management, in addition to and independent of the decision-making process for decommissioning.

Productivity of offshore ecosystems

Although direct measures of ecosystem productivity are lacking for offshore infrastructure in the North Sea, indirect evidence of their productivity is mounting. Studies are increasingly reporting abundances and movements of fish and crustacean species associated with offshore installations in the North Sea and in the transitional waters towards the Baltic Sea. Much of the scientific literature suggests that installations provide similar functions for marine organisms as reefs (Petersen and Malm, 2006; Lindeboom *et al.*, 2011; Reubens *et al.*, 2013a, b, 2014; van Hal *et al.*, 2017). The installations function as reefs by providing habitat, food, and sheltering opportunities, leading to aggregation of individuals around the installations (Lindeboom *et al.*, 2011). For example, Soldal *et al.* (2002) investigated fish associated with a North Sea platform and documented the presence of large aggregations of Atlantic cod (*Gadus morhua*) and saithe (*Pollachius virens*) in proximity to the structure. Løkkeborg *et al.* (2002) reported that densities of both species declined rapidly ∼100–300 m from installations. Similar aggregations of gadoids are known from areas in the North Sea where natural stone reefs prevail (Wieland *et al.*, 2009). Despite the mobility of these species, they may remain within the vicinity of offshore installations for extended periods, or "home" to installations. For example, an investigation of fish residency around an O&G platform in the Norwegian sector of the North Sea revealed that 50% of acoustically-tagged Atlantic cod remained within the vicinity of a platform over a 3-month period, with numerous fish leaving the array and returning throughout the study period (Jørgensen *et al.*, 2002). Similar findings of residency have been reported for Atlantic cod living near OWFs (Reubens *et al.*, 2013b).

Elevated fish abundances near installations may be partly explained by increased food availability (Leonhard *et al.*, 2006; Reubens *et al.*, 2013b). Fujii (2016) investigated stomach contents of fish associated with O&G installations in the North Sea and reported that spatio-temporal variability in the diet of the most dominant fish species, saithe, was partly explained by proximity to the infrastructure, indicating that foraging depended on food availability near the structure. It was suggested that the physical presence of infrastructure attracts populations of euphausiids, which in turn affect the distribution and feeding habits of saithe populations (Fujii, 2016). These may in turn provide food for foraging cetaceans and pinnipeds (Todd *et al.*, 2016). Offshore installations may yield similar benefits for marine birds, with attraction of some species to OWFs likely linked to greater availability of reef-associated prey relative to surrounding areas (Dierschke *et al.*, 2016). Such "reef effects" of offshore installations may also be enhanced by fishing exclusion zones inside OWFs (Reubens *et al.*, 2013a) and the exclusion radius of 500 m surrounding O&G installations (Todd *et al.*, 2018), given these zones prevent the removal of fish biomass associated with the structures.

Evidence for reproduction of organisms associated with offshore installations in the North Sea also exists. A recent study of assemblages associated with an O&G complex near the Dogger Bank suggests that these structures may function as spawning sites for associated fish and invertebrates, and hence contribute to additional production of these taxa (Todd *et al.*, 2018). The authors found that lumpsucker fish (*Cyclopterus lumpus*), Atlantic cod (*G. morhua*) and the whelk (*Buccinum undatum*) may use offshore installations for various stages of reproduction. Similarly, studies have observed pregnant two-spotted gobies (*Gobiusculus flavescens*) and higher abundances of several size classes associated with OWFs, indicating that the reef habitats associated with installations facilitate reproduction and contribute to enhanced production (Andersson and Öhman, 2010; van Hal *et al.*, 2017). Indeed, Krone *et al.* (2017) used similar findings to conclude that offshore installations increase the production rate of edible crab (*Cancer pagurus*).

Enhancement of biodiversity

The installation of infrastructure in a soft-sediment environment results in a localized increase in species richness and diversity through colonization by reef-associated taxa. Fouling communities can include up to 95 species per structure, of which up to 90% can be absent in the surrounding soft sediment (Coolen *et al.*, 2018a). Fish species with a hard substrate preference such as goldsinny wrasse (*Ctenolabrus rupestris*; van der Stap *et al.*, 2016; van Hal *et al.*, 2017), leopard spotted goby (*Thorogobius ephippiatus*; van Moorsel and Coolen, 2017), and Ballan wrasse (*Labrus bergylta*; Kerckhof *et al.*, 2018b) can be observed on offshore structures despite being extremely rare on the surrounding seabed. Complete installation removal will eliminate the large complex three-dimensional habitat that supports or attracts these species and, in time, the species will likely disappear from the local environment. Alternative removal options that preserve some of the artificial substrate could retain part of this increased local diversity, conserving the biodiversity "hotspot." However, the importance of this localized diversity to the species' population and ecosystems in a larger North Sea context is unclear, because many of these species are present at other structures and natural reefs, potentially reducing the significance of retaining those individuals associated with a single installation (Hyder *et al.*, 2017).

Biodiversity associated with offshore structures is "artificial" in two senses. First, it is less likely to have occurred naturally at the installation location and second, the biological community on vertical surfaces often does not resemble that associated with natural rocky reefs (Coolen *et al.*, 2018a). Species composition differs between natural and artificial reefs in the North Sea, depending on depth, location, orientation, age, and material of the artificial reef (Petersen and Malm, 2006; Coolen *et al.*, 2018a). In the intertidal zone of artificial reefs, for example, species composition is strongly different from that on natural rocky reefs. Dominant species such as *M. edulis*, green algae, and other associated shallow-water species are almost completely absent from natural reefs in waters of similar depth without water surface contact (Coolen *et al.*, 2018a). Furthermore, non-native species are more abundant in the intertidal zone on offshore structures (Coolen *et al.*, 2018a). Although these species increase local species richness, this is often not considered an added value.

Perspectives differ among stakeholder groups regarding the relative value of artificial vs. natural biodiversity. Although some groups strongly oppose alternatives to complete removal, others suggest that we now live in the Anthropocene, where all habitats are impacted by human activities and purely natural habitats are not available anymore (Lindeboom *et al.*, 2011). The latter is particularly true of the North Sea, which has been substantially impacted by multiple human-induced stressors for centuries, including overfishing and, more recently, climate change (Halpern *et al.*, 2008). Diversity associated with artificial structures, including offshore installations, is typically considered in regard to taxonomic composition. However, functional diversity and associated ecosystem services may be a more relevant consideration regarding the potential ecological value of offshore infrastructure (Cadotte *et al.*, 2011).

Protection of the seabed from trawling

Safety zones in and around OWFs and O&G installations are creating areas where in most cases trawling is prohibited. Maintaining a 0.5 km safety distance around each O&G installation is mandatory, resulting in a 0.79 km^2 no-trawling zone per installation. The ~1350 O&G installations in the North Sea therefore only have a limited contribution to fishing exclusion areas, protecting <1100 km^2 of seabed, depending on the extent to which the safety zones around the installations overlap (Rouse *et al.*, 2018). This represents ~0.1% of the North Sea area. Installations are also located mainly in deeper waters in relatively homogenous soft-sediment habitats where the pressure of trawling can be lower compared with shallower areas. The presence of no-trawling zones around OWFs however may be more spatially important. By 2030, almost 48 GW of installed capacity is anticipated in the North Sea, taking up large parts of the maritime zones of Germany, the Netherlands, Denmark, the United Kingdom, and Belgium (WindEurope, 2018). Bottom trawling will most likely be excluded in most OWFs, which will then substantially contribute to non-trawled surface area in the North Sea. In Belgium alone for example, 14% of the Belgian part of the North Sea (~420 km^2) will be closed for trawling when all currently planned OWFs have been constructed. Under the above-mentioned scenario, for the entire North Sea, the combined surface area of all OWFs would exceed 6000 km^2, assuming 1 km^2 per wind turbine and 6000 turbines of 8 MW each, totalling to 48 GW (WindEurope, 2018). Note that the exclusion of bottom trawling fishery in OWFs does not imply that the seabed remains entirely undisturbed for the operational phase (20–25 years) of the OWF, as maintenance works (cable repair or reburial, renewal of scour protection) will result in disturbance of—albeit relatively small—parts of the seabed.

Partial removal of offshore structures (e.g. topsides of wind turbines) provides protection from trawling but displaces fishing effort, potentially concentrating it in other areas (Piet *et al.*, 2018). Vandendriessche *et al.* (2013) showed that the closure of Belgian OWFs resulted in a redistribution of fishing activities in the area, with vessel monitoring data showing an increase of fishing effort in the areas surrounding the OWFs. Rouse *et al.* (2018) showed a modest aggregation of fishing around O&G pipelines, potentially aiming to benefit from local artificial reef effects. These kinds of interactions of commercial fisheries and the energy industry at sea should be given greater consideration when comparatively assessing decommissioning options, including the decommissioning of pipelines. On the other hand, reopening areas to fishing after complete decommissioning of offshore structures has a substantial effect and the ecosystem will, in the absence of legislation to prevent fishing in these areas, return to a prior state reflecting the effects of fishing pressure.

Enhancement of connectivity

Leaving sections of installations in place will sustain the role structures play in connecting isolated populations of species through the "stepping-stone" effect (Macreadie *et al.*, 2011; Adams *et al.*, 2014), which can be of importance for native as well as non-native species (Coolen *et al.*, 2016; Henry *et al.*, 2018). Larval dispersal modelling has shown that installations may play a role in the regional dispersal of native benthic species (Coolen, 2017; Dannheim *et al.*, 2018; Henry *et al.*, 2018; van der Molen *et al.*, 2018). Adams *et al.* (2014) showed that this is of particular importance for structures placed near the border of distribution limits of species. Native and non-native species able to colonize structures near the edges of their distributional range could then distribute to regions that would be out of reach without the presence of artificial structures or other vectors, potentially accelerating the rate by which species are able to colonize new regions (Adams *et al.*, 2014). Populations of native blue mussels (*M. edulis*) were present on offshore installations in the North Sea up to 181 km offshore, whereas larval dispersal models predicted *M. edulis* larvae to travel only up to 85 km in a single generation, showing that some artificial vector likely facilitated the dispersal process (Coolen *et al.*, 2018b).

Numerous vectors for distribution extension exist in addition to energy installations, such as ballast water exchange, hull fouling on commercial and recreational vessels, and flotsam, reducing the potential impact of increased connectivity for both non-native and native species (Coolen, 2017). Species may also use the 27 000 wrecks and thousands of navigational buoys present in the North Sea, as well as 100 000 km^2 of patchy coarse sediment to distribute, reducing the likely impact of platforms and wind turbines on connectivity (Mineur *et al.*, 2012; Coolen *et al.*, 2016). Hence, the impact of the loss of connectivity resulting from complete removal of offshore infrastructure would likely depend on the uniqueness of the habitat they provide for individual species and their geographical position relative to other habitats and vectors.

Other environmental considerations

Although the energy industry in the North Sea has substantial knowledge and experience regarding typical environmental considerations during exploration and production phases (e.g. seabed disturbance, contamination, emissions), considerably less is known about potential impacts occurring during the decommissioning phase. There has also, by regulatory requirement, been a focus on the potential effects of infrastructure removal on seabed habitats and species, and approaches to mitigate these impacts. Knowledge regarding both the relative impacts of alternative decommissioning options and impacts of non-traditional environmental issues are therefore extremely limited.

The consumption of natural resources and energy associated with decommissioning activities, reuse or recycling is explicitly mentioned in OSPAR Decision 98/3 Annex 2 as a factor that should be considered, and much of the region's environmental policies are directed at increasing energy and resource efficiency through a "circular economy." Although decommissioning activities are highly energy intensive, recycling of the recovered steel—which is often more than 95%—saves large amounts of energy as compared with the production of virgin steel (Ekins *et al.*, 2006).

Emissions to air and other environments (leaching to groundwater, discharges to surface fresh water, and effects on soil), and chemical and physical pollution are also explicitly mentioned in OSPAR 98/3 Annex 2. Key emissions to air (CO_2 and NO_x) primarily arise from diesel-powered vessel activities related to decommissioning and will tend to be lower for partial decommissioning options than for full removal (Ekins *et al.*, 2006), unless the avoided emissions related to steel recycling exceed the additional vessel emissions associated with full removal to shore. When making such comparisons, the true yield of recycled materials from offshore structures must be considered, given some proportion of materials will be degraded by the marine environment and therefore not suitable for recycling. The impacts relating to onshore disposal (i.e. landfill) of unrecyclable materials must also be factored into comparative assessment between decommissioning options.

Chemical and physical pollution may arise from leakage from polluted structures (e.g. storage tanks or cells) during the decommissioning process, or over a longer time frame if these structures are left offshore. Pollution could also arise from disturbance of drill cutting piles beneath and around the footings of the jacket, whereby chemical contaminants already present in the sediment are resuspended (Henry *et al.*, 2017). This risk often forms an argument for partial removal, as disturbance especially takes place when the footings have to be excavated from the seabed, and from trawling once the structure has been removed and the area returned to other users of the sea. Partial removal options that cover and protect drill cutting piles from further disturbance may reduce the spread of benthic pollutants relative to decommissioning options that disturb such areas.

Addressing knowledge gaps through stakeholder cooperation

Effective and environmentally-sound decommissioning decisions in the North Sea will require a much broader base of ecological information than is currently available. This information must be obtained rapidly to guide decommissioning decisions for the many O&G installations approaching obsolescence in the region. However, research in the offshore environment is often logistically challenging and expensive, limiting both the breadth and quality of information that can be obtained, particularly for independent researchers (Gates *et al.*, 2017; Macreadie *et al.*, 2018). Given the time constraints involved, independent research alone is unlikely to provide the level of ecological knowledge required to guide environmentally-sound decommissioning decisions.

Various other stakeholders, particularly O&G companies, collect data as part of routine operations to inform engineering decisions, environmental management, or in collaboration with external bodies (Jones, 2009; Gates *et al.*, 2017; Macreadie *et al.*, 2018). Although such data can often provide valuable information on infrastructure ecosystems, far beyond the initial purpose of collection, it can be challenging for external parties to access (Murray *et al.*, 2018). Yet this need not be the case, as much of this environmental information is not of a sensitive nature and is non-confidential (Macreadie *et al.*, 2018). Multi-stakeholder collaboration, including companies, regulators, scientists, and NGOs, can help to access and synthesize environmental information held by specific groups, such as that which occurs through the INSITE projects (see below, Bakke *et al.*, 2018). In practice, this collaboration may be complicated, with different stakeholders having differing, even competing, interests. This has led to mistrust and scepticism among stakeholder groups regarding decommissioning decisions in the past and potentially explains the regional divergence in decommissioning policy (Jørgensen, 2012). Part of the data required for decommissioning decisions actually involves the preferences of those stakeholders involved, to prioritize particular input to the decision and prioritize research in a limited time frame (Fowler *et al.*, 2014). By evaluating the critical information required for decision-making, key research gaps can be identified and addressed within the narrow time frames available.

Although stakeholder consultation was beyond the scope of the current study, we used the information in the preceding sections to generate a list of research questions designed to fill critical gaps in our ecological knowledge of offshore decommissioning in the North Sea (Table 1). These questions provide a starting-point for discussions among stakeholders willing to pursue collaborative ecological research and can be expanded to include additional research questions that arise during such discussions. Below, we outline methods of potential research collaboration between two key stakeholder groups—independent researchers and the offshore energy industry—that are likely to maximize efficiency by drawing on the relative strengths of each group. While focusing on these two groups, which are essential for addressing any knowledge gaps in this area, it is important to also involve other groups, especially environmental NGOs, nature conservation consultees, and fishery organizations, in the process of formulating questions and assigning relative weights to different ecological and environmental criteria for subsequent decision-making (Fowler *et al.*, 2014). Involvement of all groups will improve transparency of the research and decision-making process. Without maximum involvement and transparency, these groups are very likely to dismiss the outcomes of research and decisions where industry is involved, because of their fundamental distrust of the O&G industry and their perception of partial removal or reefing as "dumping" (Jørgensen, 2013), which was recently reconfirmed through the responses of several green NGOs to the Brent Decommissioning Plan (Walmsley, 2017).

Table 1. Key ecological considerations and research questions for decommissioning of offshore infrastructure in the North Sea.

1. Provision of reef habitat
What types of reef habitat do offshore installations provide and how do these compare to natural reefs?
Although generally low in total volume relative to natural reef, does offshore infrastructure provide a substantial fraction of specific habitat types, e.g. deep reef?
How does the habitat provided by offshore infrastructure compare to other artificial reef, e.g. shipwrecks?
How will various decommissioning alternatives change the regional availability of infrastructure habitat types?
What are the physical and ecological impacts of infrastructure habitat on surrounding soft-sediment ecosystems?
Does offshore infrastructure provide significant habitat for ecologically- or commercially-important species?
Does offshore infrastructure provide significant habitat for rare or protected species?
Does offshore infrastructure provide significant habitat for exotic or invasive species?
2. Productivity of offshore ecosystems
What biomass of sessile invertebrates currently inhabits offshore infrastructure?
Which mobile fauna are more abundant within the exclusion zone than in surrounding habitats?
How does the biomass of reef-associated mobile species compare to other reef habitat, both natural and artificial?
Are fishery-important species resident or transient on offshore installations?
What is the growth rate of invertebrates and fish associated with offshore infrastructure and how does this compare to natural habitats?
Do offshore installations provide recruitment sites or nursery habitat for ecologically- or commercially-important species?
What is the total productivity of offshore installations in the region for fishery-important species?
3. Enhancement of biodiversity
How does community structure and function vary with location, design, materials, and environmental factors?
Are biological communities that develop on offshore infrastructure structurally and functionally diverse relative to natural reefs?
How do environmental factors like temperature, depth, and currents influence biodiversity on offshore infrastructure?
Does the biodiversity of infrastructure ecosystems vary among regions in the North Sea?
Does biodiversity differ between O&G installations and wind turbines?
What are the relative impacts of different decommissioning options on local biodiversity (e.g. "topping" vs. "toppling")
How do soft-sediment ecosystems recover after full removal of an offshore installation?
Does local biodiversity on offshore infrastructure contribute to regional diversity through movement of mobile organisms or larval dispersal?
What are the biodiversity trade-offs between infrastructure ecosystems and the soft-sediment ecosystems they replace?
What ecosystem services are provided by biological communities associated with offshore installations?
4. Protection of the seabed from trawling
Do benthic ecosystems differ between the exclusion zone surrounding offshore infrastructure and non-protected areas?
What are the structural and functional differences of benthic communities between protected and non-protected seabed?
What is the biomass of ecologically-important species currently protected by exclusion zones?
What is the biomass of commercially-important species currently protected by exclusion zones?
How will mass removal of offshore infrastructure affect regional patterns and extent of trawling?
Is trawling effort greater near the boundaries of exclusion zones?
Are catches of commercially-important species greater near exclusion zones?
How will mass removal of offshore infrastructure affect regional patterns and extent of trawling?
How does trawling over drill cutting piles and other polluted seabed after full removal of offshore installations impact associated fauna?
5. Enhancement of connectivity
What is the extent of larval dispersal and connectivity among offshore installations and natural habitats?
How do offshore installations influence the movement of mobile organisms?
Do offshore installations enhance connectivity of commercially- or ecologically-important species in the region?
Do offshore installations increase the spread of exotic or invasive species in the region?
How will the mass removal of infrastructure affect regional connectivity among biological populations?
What impacts will partial removal have on the connectivity of different taxonomic and functional groups?

Ecosystem observation and monitoring using infrastructure and vessels of opportunity

To increase knowledge of infrastructure ecosystems, observational data on numerous ecosystem components, beyond those already included in standard EIAs, are required. The infrastructure and vessels operated by industry have considerable value for scientific investigation of offshore environments and are potentially available for research purposes when not required for industry operations (e.g. Jones, 2009; Gates *et al.*, 2017). This "standby time" can be accessed by researchers for minimal additional cost to industry. In return, researchers can provide data and analysis for industry to use in EIAs and to meet corporate social responsibility requirements. For example, to study epifouling communities on offshore structures, which include many small or cryptic species, remote techniques such as video obtained by remotely operated vehicles (ROVs) may not provide sufficient details (van der Stap *et al.*, 2016). Therefore *in situ* samples are often required to "ground-truth" taxonomic identifications made using video. These may be obtained, for example, by ROV using scrapers and dredge pump equipment (Ashtead Technology, 2018), although sampling by scuba or surface-supplied divers is applied in most field studies (Coolen *et al.*, 2018a). Some analyses may be possible without ground-truthing in well-researched areas, and these may benefit from autonomous approaches for image acquisition and analysis (Gormley *et al.*, 2018). In return for the use of industry resources, researchers provide collection assistance and experience with taxonomic identifications to better report on infrastructure fouling. Some studies have utilized offshore industry infrastructure such as dive support vessels to investigate fouling macrofauna diversity on structures during inspection repair and maintenance work (IRM) performed by divers (e.g. Coolen *et al.*, 2016, 2018a, b). Marine biologists certified for offshore commercial diving were allowed to dive with the IRM teams, resulting in cost-effective investigations for both researchers and industry partners. Other investigations have used similar approaches, or acquired access permits from industry, to obtain data on the associations of seals and porpoises with infrastructure (Russell *et al.*, 2014; Todd *et al.*, 2016).

Analysis of archived underwater videos and images held by the industry

Installations in the North Sea are inspected by operators on a regular basis, commonly making use of ROVs equipped with camera systems to examine the structural integrity of the installation. All inspections are recorded on video and summarized in reports. These videos and associated still images provide an opportunity for independent researchers to investigate a broad range of questions regarding infrastructure ecosystems, including the composition and diversity of associated faunal communities, abundance patterns of larger fouling species and mobile organisms, ecological interactions between reef-associated and soft-sediment communities, species depth ranges and descriptions of species new to science (Gates *et al.*, 2017; Macreadie *et al.*, 2018; Murray *et al.*, 2018). Video resolution is often lowered and compressed to reduce storage space, and images can have poor clarity owing to turbid conditions during inspection, preventing the detection and identification of small and cryptic species. However, dominant species can still typically be observed and large-scale patterns can often be discerned (van der Stap *et al.*, 2016; Coolen *et al.*, 2018b). Studies have already been performed in the North Sea using industry images and have provided insights into community differences across spatial gradients (van der Stap *et al.*, 2016; Coolen *et al.*, 2018b) and through time (Whomersley and Picken, 2003). Because operators inspect installations every 2–3 years and tend to store videos over long periods of time, for example some companies still store VHS tapes (JWPC, pers. obs.), many hours of inspection video are potentially available for research, providing rare opportunities to build long-term datasets on offshore ecosystems (Macreadie *et al.*, 2018). Recent developments in automated species recognition may make new data available at relatively low cost (Gormley *et al.*, 2018). However, issues associated with the transfer of video data from older media types (e.g. VHS tape) to contemporary digital video formats may limit the extent of longer term datasets available from archived collections. The challenge of storing the high-definition (HD) video increasingly being used by industry may also limit the extent of future datasets. Lastly, defined processes of quality assurance and control (QA/QC) are required to ensure collection of valid data from video archives.

Training of industry personnel by scientists to collect basic data

Once collaborative associations are established, further efficiencies can be gained through engagement and training of industry personnel in basic data collection methods. Industry personnel are often interested in the biology and ecology of the offshore environment and can be engaged to participate in scientific investigations while working offshore (Gates *et al.*, 2017). This can occur during working hours, if industry has committed personnel to assist with independent research, or during personal time outside of working hours, provided the activity has been adequately risk-assessed and follows ethical and safety standards. For example, ROV pilots can be trained in underwater survey techniques, which will improve standardization of video data and the repeatability of environmental surveys through time. Personnel can also be trained in the deployment and retrieval of sampling equipment, including push cores and faunal traps. The operations can provide personnel with learning experiences that can be reapplied to industry operations, for example, sampling using push corers can provide less experienced ROV operators with additional training in delicate underwater tasks that can then be applied to similar industry operations. In some cases, training of industry personnel in basic data collection can negate the need for independent researchers to visit industry infrastructure, reducing associated costs and health and safety risks for the operator. For example, industry personnel trained in basic species identification are able to note unusual sightings, obtain video recordings, and relay these remotely to researchers (Gates *et al.*, 2017).

Joint-funding opportunities

Joint funding opportunities for scientists and industry primarily arise when industry is able to provide shiptime, equipment, or personnel to collect data around offshore infrastructure. Ships of opportunity may be accepted by funding agencies as co-financing to meet requirements of co-funding by industry. This has, for example, been applied by Coolen *et al.* (2016, 2018a, b), who sampled offshore installations using dive crews and dive support vessels made available by Neptune Energy, a Dutch O&G operator. This in-kind support, combined with cash contributions by industry was used to fund a PhD project (Coolen, 2017), as well as additional post-doctoral and laboratory analyst positions. The international SERPENT project was created to provide scientists with an opportunity to use offshore equipment at times when industry had no need for it to be operational (Gates *et al.*, 2017), and the Australian branch of this organization (SEA-SERPENT) was initially funded through an industry linkage grant between local O&G companies and university researchers. Working-class ROVs were provided to sample deep habitats, which may have been too costly to investigate otherwise (Jones, 2009). Joint industry projects such as the INSITE programme (INfluence of man-made Structures In The Ecosystem, https://www.insitenorthsea.org/), funded by a group of O&G operators from the United Kingdom, yet managed by an independent science secretariat, have provided researchers with an opportunity to investigate population connectivity and environmental effects of offshore infrastructure in the North Sea (Bakke *et al.*, 2018).

Pilot decommissioning projects involving industry and independent researchers

Trial projects that enact decommissioning alternatives, including partial removal, and monitor the ecological changes that occur before and after decommissioning will be essential, where legally possible, for understanding potential impacts of large-scale decommissioning on North Sea ecosystems. They provide an opportunity to examine the ecological risks of decommissioning options while also facilitating dialogue and fostering working relationships among stakeholders who will be involved in the decommissioning process. Such projects will likely uncover hidden logistic and regulatory challenges that can be used to refine collaborations on decommissioning science in the future.

A recent example of pilot project development in the North Sea is that of ENGIE E&P Nederland BV (later Neptune Energy). Between 2015 and 2017, the company explored the possibility of a pilot decommissioning project in the Dutch sector of the North Sea. A plan was developed for the partial decommissioning of O&G platforms L-10C, L-10D, and L10-G on the Dutch CS, resulting in a proposal for a 15-year pilot study, in which the ecological impacts of partial removal would be compared with those of full removal and an experimental zone would be created around one of the partially removed structures. Inside the experimental zone, various types of marine habitat restoration were to be undertaken. A wide range of stakeholders—fishers, environmental NGOs, scientists, and government—were involved in the process of developing the pilot project, most of them being supportive. Eventually, the operator decided to discontinue the project because of uncertainties regarding the regulatory process associated with repurposing the offshore installation into an experimental reef and the liabilities during the pilot period (15 years; letter to stakeholders from ENGIE and EBN, 31 January 2018). This experience shows both the potential for such pilot projects to engage wide groups of stakeholders in a positive manner and the importance of governments being willing to develop flexible regulatory solutions for pilot projects, especially in relation to liabilities, and taking shared responsibility for maximizing opportunities provided by disused offshore installations to help achieve marine conservation goals. A way to reduce the legal complexities associated with repurposing an offshore energy installation into an artificial reef might be to develop ecological pilots around installations that would, in the first place, be reused for other purposes, e.g. CO_2 storage, and around the few structures that are applicable for derogation from the full removal obligation, where these structures are not already undergoing decommissioning consent processes.

Pilot decommissioning projects, especially for installations applicable for derogation, could also be used to develop joint decommissioning assessment and decision frameworks that address the objectives of all stakeholders. Prior to commencing a decommissioning project, stakeholder workshops can be used to identify stakeholder objectives, identify environmental considerations relating to those objectives (e.g. clear seabed for trawling, reef habitat for threatened species), weight the relative importance of environmental impacts, and develop a decommissioning decision model (Fowler *et al.*, 2014; Smyth *et al.*, 2015; Burdon *et al.*, 2018). This type of stakeholder-driven approach has recently been used by Shell UK to model the best decommissioning option for the storage cell contents associated with gravity-based structures of the Brent Field (Shell U.K., 2017), but has not succeeded in avoiding a negative response from green NGOs. Burdon *et al.* (2018) have also use stakeholder feedback to refine their decommissioning decision model for use within MPAs.

Case studies of stakeholder cooperation to address ecological knowledge gaps

INSITE

To expand the scientific knowledge base on the role of O&G infrastructure in the North Sea ecosystem, a group of UK-based energy companies funded the INSITE programme. The first phase of this programme was operational between 2015 and 2017 and aimed to: "(1) Investigate the magnitude of the effects of man-made structures compared with the spatial and temporal variability of the North Sea ecosystem, considered on different time and space scales; and (2) Investigate to what extent, if any, do the man-made structures in the North Sea represent a large inter-connected hard substrate system" (Bakke *et al.*, 2018). After establishing the aims of the project, the funding was allocated to an independent scientific advisory board, which published a call for proposals. To ensure independence, the O&G companies involved in the funding were informed on progress but were not directly involved with the research. In total, nine projects were awarded. Research efforts varied from modelling population connectivity using oceanographic and particle tracking models (e.g. Hyder *et al.*, 2017; Coolen *et al.*, 2018b; Dannheim *et al.*, 2018; Henry *et al.*, 2018; van der Molen *et al.*, 2018), to biodiversity analysis using industry-provided ROV footage (Coolen *et al.*, 2018b), sampling fauna on and around offshore installations (Coolen *et al.*, 2018a, b), meta-analysis of existing datasets (Dannheim *et al.*, 2018), development of decision support models (Burdon *et al.*, 2018), and data workshops (Murray *et al.*, 2018). INSITE provides a useful model for large-scale research collaborations between independent researchers and offshore energy companies that could be mediated by regulators and independent advisory boards to ensure objectivity and transparency. This has led to a second round of industry and research council funding.

OWF developments in Denmark and the Netherlands

Construction of OWFs in Denmark commenced in the 1990s and resulted in the development of a knowledge base concerned with the environmental effects of OWFs on birds, marine mammals, benthic invertebrates, and fish (DONG Energy *et al.*, 2006; Fox *et al.*, 2006), as well as life cycle analyses of the materials used for the wind turbines (Schleisner, 2000). The work involved a diverse range of stakeholders and partners, covering industry, governmental and private research agencies, universities, NGOs, and local residents (Sovacool *et al.*, 2008). The approach developed a positive dialogue among stakeholders and yielded in-depth environmental monitoring to support the adjustment of mitigation activities in a flexible and adaptable manner (Magagna *et al.*, 2012). Broad collaboration and inclusion of stakeholders helped address knowledge gaps, especially during the early constructions of OWFs. For example, the NGO Danish Ornithological Society provided baseline bird data prior to the construction of OWFs (Noer *et al.*, 2000). The successful involvement of diverse stakeholders to address knowledge gaps in relation to the implementation of OWFs in Denmark suggests that involving stakeholders to improve decommissioning of offshore installations is likely to be a feasible and useful approach.

In the Netherlands, a number of pilot projects are now being developed in which OWFs (Borssele I–V, Gemini and Luchterduinen) are combined with ecosystem enhancement, especially focused on restoration of flat oyster (*O. edulis*) banks that covered large parts of the southern North Sea in the 19th century. These projects are developed by OWF operators in collaboration with research institutes, environmental NGOs, and offshore contractors. In addition, a Joint Industry Project (JIP HaSPro) is assessing possibilities for nature-inclusive design of scour and cable protections for OWFs (T. Raaijmakers, presentation at Blue Week 2018). The interest in nature-inclusive design of OWFs clearly has arisen since the Dutch government included "nature-inclusive design" in their tender procedure for Borssele V. Until now, it was unclear whether the ecosystems that develop within OWFs as a result of deliberate measures would also have to be removed with decommissioning of the turbines.

Legislative and operational barriers to partial decommissioning

There are several barriers to partial decommissioning of O&G infrastructure and wind turbines in the North Sea that will hinder implementation of the practice, despite any potential ecological benefits that may arise. These barriers continue to be considered during discussions among stakeholders and development of research programmes to avoid misconceptions regarding currently-achievable options. Such discussions will also flag changes to current policy and practice that would be required to enact any decommissioning alternatives in the future.

First, in article 2.1(a) of the Convention for the Protection of the Marine Environment of the Northeast Atlantic, 1992 ("OSPAR Convention"), Contracting Parties agree to take all possible steps to prevent and eliminate pollution and to take the necessary measures to protect the maritime area against adverse effects of human activities, so as to safeguard human health and to conserve marine ecosystems and, when practicable, restore marine areas, that have been adversely affected. In some national legislation (e.g. Belgian MMM-law), this latter point has been interpreted as an obligation for the offshore energy industry to restore marine areas, as far as possible, to their condition prior to the start of activities. Operators of OWFs are legally obliged to set aside funds for the removal of turbines, foundations, cables, scour protection, and other support infrastructure (Ministerial Decree for every Belgian OWF). Second, when *in situ*, turbine foundations and scour protection seal off the seabed, negatively impacting seabed integrity, which is one of the qualitative descriptors for determining "good environmental status" (GES) under the Marine Strategy Framework Directive (MSFD). Third, any large structures that project above the seabed following decommissioning may pose a risk to bottom trawling fisheries where safety zones are removed, as snagging of gear may lead to capsize of the vessel. Leaving such structures projecting from the seabed will also permanently reduce clearance for vessels, posing the primary risk for large vessels that have drifted outside navigational routes (MARIN, 2013). Such safety concerns are likely to outweigh ecosystem benefits where remaining structures would prevent minimal clearance of large vessels.

Finally, the so-called "residual liability" (liability for plugged and abandoned wells, and for any material left offshore) has become a strong driver of industry decisions regarding which decommissioning strategy to pursue. North Sea countries have taken somewhat different approaches in regulating liability for disused offshore installations, but only Norway facilitates transfer of liability from the operator to the state. With the possible exception of Norway, current liability regimes provide a strong disincentive for consideration of decommissioning options where structures are (partially) left offshore. Until processes for relieving residual liability for companies are developed, it is likely that derogations will only be sought in extreme cases where removal of all infrastructures is simply not possible, or the cost is prohibitive. Decommissioning decisions will therefore likely remain limited by financial and reputational risk, even if partial removal options become permissible (Cripps and Aabel, 2002). Involvement of non-corporate entities (e.g. energy regulators) is therefore required to facilitate change towards a system that is driven more wholly by optimization of environmental outcomes. In situations where some operator liability is retained, monitoring of market activity may be required to ensure that sales of assets near the end of operational life are not enacted to offload this residual liability (Hamzah, 2003).

Summary and conclusions

Optimizing the environmental outcomes of decommissioning O&G installations and OWFs in the North Sea will likely require a shift away from blanket removal policy towards a more flexible system that allows alternatives to complete removal on a case-by-case basis, following consideration of a broad range of ecological and other environmental impacts. Although derogations from complete removal are allowed in some circumstances, most infrastructure (O&G jackets and wind turbines) will have to be completely removed from the North Sea under current policies and regulations. A more flexible case-by-case system would adhere to the adaptive management approach to protection of the marine environment articulated within OSPAR's Northeast Atlantic Environment Strategy (OSPAR Agreement 2010-03):

> "Adaptive management requires the application of the precautionary principle so that measures are taken when cause–effect relationships are not yet fully established scientifically, and modified when more knowledge becomes available."

For decommissioning, the most precautionary approach would be to temporarily suspend the obligatory removal of offshore infrastructure to facilitate research into the potential impacts of large-scale removal on North Sea ecosystems. Temporary suspension presents minimal environmental risk, at least in the short-term, because structures approaching decommissioning have already remained in place for decades. The suspension would also allow for research into the relative impacts of alternative decommissioning methods, including key partial removal options:

(1) Leaving the lower jacket *in situ* and transporting the top sections to shore;
(2) "Topping" and placing the top section on the seabed next to the installation base;
(3) Toppling the structure in place;
(4) Partial removal and relocation of cleaned sections to a designated reefing area.

To focus decommissioning research in the North Sea, we summarized current knowledge regarding five ecological considerations that are not typically considered when making decommissioning decisions, but are likely pivotal to a successful outcome for marine ecosystems:

(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.

Empirical research on these considerations for offshore installations has been limited to date and we propose a series of research questions to address major knowledge gaps relating to each consideration (Table 1). Given the inherent challenges and costs associated with ecological research in the offshore environment, knowledge gaps are unlikely to be addressed by independent researchers within a timely manner, particularly for O&G installations. Cooperation between the offshore energy industry and independent researchers is necessary to fill most knowledge gaps and could involve the use of industry vessels for scientific investigations, re-analysis of historical industry data, basic scientific training of industry personnel, pursuit of joint research funding opportunities, and pilot decommissioning projects. Some of these approaches have already been successfully implemented on a small-scale within the North Sea, supporting their pursuit on a region-wide scale. Environmentally optimal decommissioning will only be achieved within the North Sea if stakeholders can pool their resources, knowledge, and experience to further scientific understanding of these novel marine ecosystems.

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