Ecosystem Services 78 (2026) 101811

Contents lists available at ScienceDirect

Ecosystem Services

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

Review Paper

Understanding the role of offshore energy structures in ecosystem service delivery: Applying global findings to the North Sea

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ARTICLE INFO

Keywords:
Ecosystem services
Energy transition
Biodiversity
Decommissioning
Societal benefits
DAPSI(W)R(M)
Offshore structures

ABSTRACT

The marine environment provides a wealth of ecosystem services, which can deliver human benefit when combined with built, human or social capital. Through the expansion of offshore energy infrastructure, human intervention has reshaped marine ecosystems on a global scale. Yet, the changes that these structures induce in the environment and the knock-on effects on ecosystem services remains poorly understood. This study aims to first provide a comprehensive review on the role of offshore energy structures in ecosystem service delivery, synthesising findings from 18 countries over a 42-year period. These findings are then structured under the DAPSI(W)R(M) framework, to draw links between human activity, environmental effects and ecosystem services. The findings are discussed in the context of UK energy transitions in the North Sea.

The life stage of the structure and the specific marine environment were the biggest driving forces behind how a structure affected ecosystem services. The initial construction stage created many pressures within the environment, which in turn negatively affected how people engaged with the marine environment through the displacement of commercial fishing, local tourism and visual enjoyment of the seascape. Conversely, structures in place for several years fostered reef-like habitats, leading to enhanced tourism, increased fish stocks and improved nutrient cycling by benthic species.

Existing research has focused primarily on the construction and operation periods, with limited research available which addresses how different decommissioning approaches will affect associated communities and ecosystem services. By improving knowledge around the role that offshore structures have in the delivery of ecosystem services and the tools used to assess a structures value, such findings could support informed decision-making for decommissioning on a global scale.

1. Introduction

Over the past 60 years, global energy demand has risen sharply due to population growth and technological advancement, driving increased reliance on energy development (Coyle and Simmons, 2014). Traditional, non-renewable resources dominated the energy industry until the early 21st Century, when the environmental effect of greenhouse gas production gained public attention (Higgins and Foley, 2014). This led to a shift towards renewable energy, with £190 billion invested globally in renewable resources in 2012 (Balcioglu, 2017). In 2015, 196 countries pledged to reduce global temperature rises, marking the first multilateral agreement to address climate change (Paris Agreement, 2015). This led to the formation of the Net Zero Emissions by 2050 strategy, which pushed for decarbonisation of the global energy sector (Net Zero Strategy, 2021).

The movement towards a greener future has prompted the gradual phase-out of hydrocarbon energy resources in many regions, including offshore oil and gas infrastructure (Burdon et al., 2018). On a global

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https://doi.org/10.1016/j.ecoser.2025.101811
Received 16 July 2025; Received in revised form 4 November 2025; Accepted 23 December 2025
Available online 10 February 2026

scale, 2000 oil and gas platforms in marine spaces are due to be decommissioned by 2040 (Hem, Redman and Serscikov, 2016). International agreements, such as the United Nations Convention for the Law of the Sea (1994), the Oslo-Paris agreement (OSPAR 98/3) and the London Protocol (1996), call for full removal of all structures and associated pipelines during decommissioning in many areas. However, the environmental effect or physical practicalities of this practice are not fully understood, leading several countries to explore alternative approaches, such as leaving the platform foundations in situ (e.g. derogation under OSPAR 98/3) or repurposing them as artificial reefs in other locations (Van Elden et al., 2019). Additionally, the policy landscape is constantly changing, leaving the door open for alternative decommissioning approaches to become acceptable on a global scale in the future. As marine legislation is highly complex and variable between jurisdictions, this review will first address global policy around decommissioning, before placing this in the context of a UK policy landscape (Boyes and Elliott, 2014).

A substantial proportion of offshore renewable energy development is in the North Sea, with approximately 30 wind farms, in addition to 260 oil and gas platforms currently operational in the UK's exclusive economic zone (EEZ) (Fig. 1; Riddick et al., 2019; The Crown Estate, 2025). The UK plans to install an additional 65GW of offshore wind energy by 2030 to meet net zero emission goals, contributing to the increased urbanisation of this basin (Peschko et al., 2024). However, the transition from oil and gas to wind energy comes at a cost, as the UK is estimated to spend £40 billion on decommissioning in the next 40 years, with £24 billion being spent by 2032 (National Sea Transition Authority, 2023). Over half of the decommissioning cost is for well plugging and abandonment, which is required regardless of the decommissioning approach used (North Sea Transition Authority, 2025). It is vital that the development of wind farms and subsequent decommissioning of oil and gas is well-informed by scientific research, to ensure the environmental, economic and social consequences of the energy transition are fully understood and managed. The application of global research to a North Sea context draws on the wealth of information already available and provides valuable insight into the role that offshore structures play, both in society and the natural environment. Broadening current knowledge on the ecological value of North Sea structures could inform more holistic practices, that centre decision-making during decommissioning around the preservation of natural resources.

The simultaneous proliferation of offshore wind farms and the decommissioning of oil and gas platforms pose a challenge to biodiversity on a global scale. The marine environment performs many environmental processes and functions that can be utilised for human

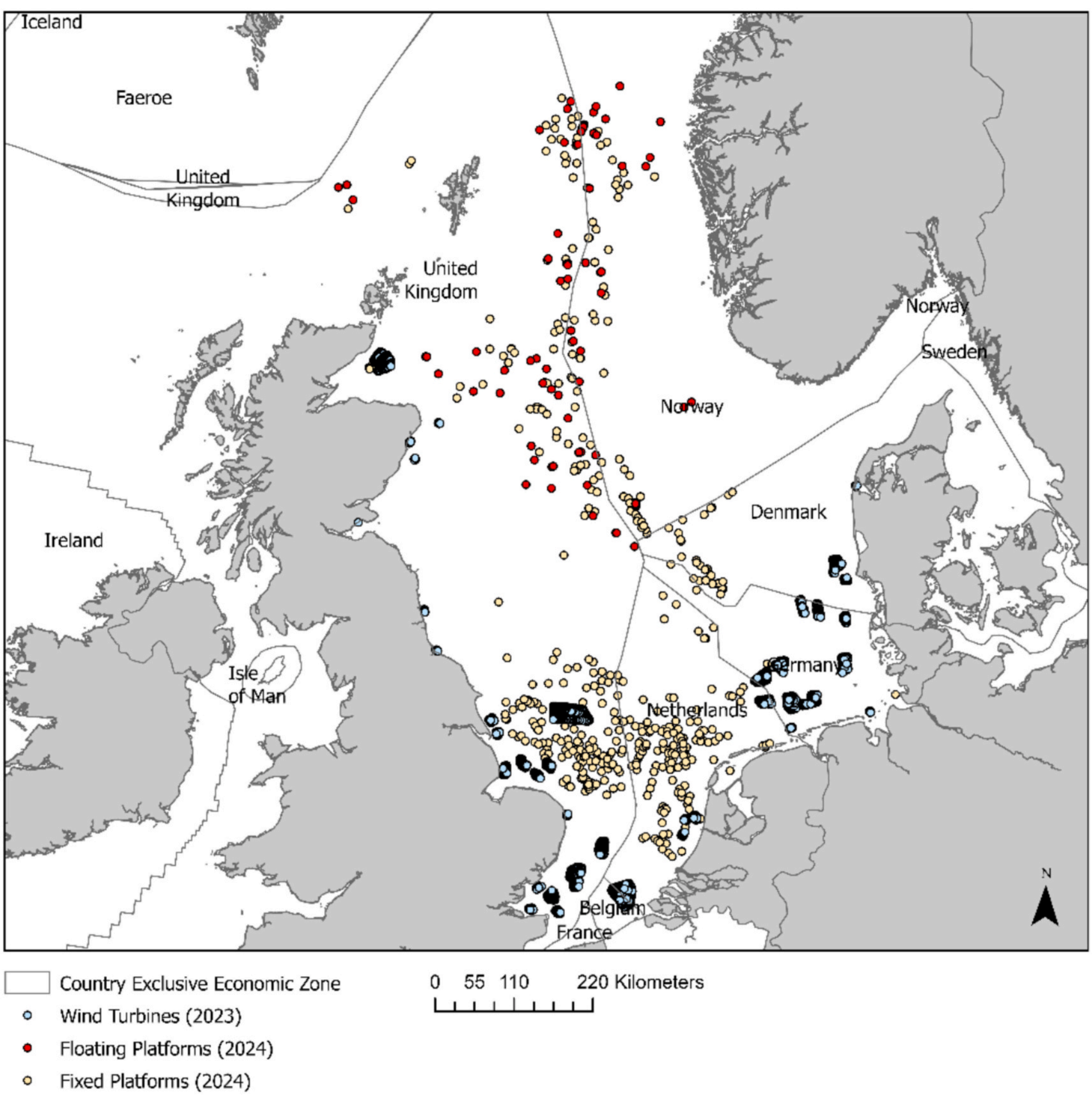

Fig. 1. The number of wind turbines andfloating or fixed oil and gas platforms in the North Sea, with lines showing each bordering countries exclusive economic zone.

benefit, known as ecosystem services (Mace, Norris and Fitter, 2012). When combined with built, human, or social capital, such as the installation of wind turbines, ecosystem services, such as the flow of wind, can result in a benefit to society, for example renewable energy provisions (Burdon et al., 2024a). As the full provision of ecosystem services is reliant on a functioning and healthy ecosystem, any changes to the ecosystem will result in a change to the service (Cardinale et al., 2012).

Investigating how renewable and non-renewable energy structures influence the value of natural resources (natural capital) and the services they provide helps us better understand their collective effect on environmental and social wellbeing (Burdon et al., 2024b). As this review focuses on ecosystem services, any "effects" discussed relate only to those that influence ecosystem services, as opposed to "general" environmental effects (e.g. disturbance of deep-water sponge communities (Vad et al., 2018)).

Many frameworks exist to identify and quantify ecosystem services, with some being wide ranging in their ecosystem scope (e.g. TEEB, CICES, UKNEA), and others being specific to a given ecosystem such as the marine environment (e.g. UKNEAFO)(Table 1). There are three types of ecosystem services associated with the natural environment, which can provide societal benefits to humans. Provisioning services relate to any tangible products that can be directly extracted from the environment (e.g. commercial fish), cultural services are any societal benefits derived during human interaction with the natural environment (e.g. recreational diving) and regulating services are natural processes or functions that provide an indirect benefit to human life (e.g. coastal protection).

Decommissioning is a complex challenge in the marine environment, and therefore the DAPSI(W)R(M) project structuring method is valuable in simplifying some of the complexity (Burdon et al., 2018). The Drivers, Activities, Pressures, State change, Impacts (on Welfare), Responses (as Measures) framework (known as DAPSI(W)R(M)) is a problem structuring framework which helps us to understand complex problems (Elliott et al., 2017). This framework identifies the Drivers of basic human needs (such as the need for energy) which require Activities (such as offshore wind developments), which lead to Pressures on the system (such as noise disturbance), which are the mechanisms of State changes in the natural system (such as the displacement of seabirds from feeding grounds) which then leads to Impacts (on human Welfare) (such as tourism and nature watching). Addressing such changes in the natural and human system requires Responses (as Measures), such as the preservation of alternative foraging grounds nearby. Within the DAPSI(W)R(M) framework, natural capital and ecosystem services are represented by the State changes (in the natural environment) whereas societal benefits are represented by the Impacts (on Welfare) (in the human domain).

At present, several reviews have been published which address the environmental effect of offshore wind farms (Degraer et al., 2020; Hooper et al., 2017; Mangi, 2013; Watson et al., 2024) and offshore oil and gas platforms (Bravo et al., 2023; Richard et al., 2024; Van Elden et al., 2019) on ecosystem services. However, only one review included comparison of different offshore structure types when discussing how structures effect ecosystem services (Papathanasopoulou et al., 2015). Papathanasopoulou et al (2015) provides a synthesis of current knowledge on the effect that offshore wind farms, oil and gas platforms and

Table 1
The ecosystem service classification frameworks, including DAPSI(W)R(M), which is employed in this review.

Framework	Year	Ecosystem service categories	Key features	Strengths	Weaknesses	References
Millenium Ecosystem Assessment (MEA)	2003	Provisioning, regulating, Cultural, Supporting	First framework to categorise ecosystem services	- Introduced ecosystem services framework - Can be applied to any habitat	- Categorises natural processes and functions as supporting services - Does not separate the ecosystem service from the societal benefit, results in double-counting	MEA, 2003; Beaumont et al., 2007; Burdon et al., 2024b
The Economics of Ecosystems and Biodiversity (TEEB)	2007	Provisioning, Regulating, Cultural, Habitat services	Valuation of natural resources, emphasises global cost of biodiversity loss	- Standardised structure for valuating natural processes and ecosystem services - Integration of values into decision-making on all levels	- Categorises select processes and functions as "habitat services" (e.g. Genetic diversity)	De Groot et al., 2012; Hedden-Dunkhorst et al., 2015
UK National Ecosystem Assessment (UKNEA)	2011	Provisioning, Regulating, Cultural, Supporting	Employs MEA framework to link natural processes to human wellbeing	- First attempt to categorise the benefits from UK's natural environment	- Underpinned by MEA categories, includes supporting service category - Categorises ecosystem processes as "intermediate services", resulting in double-counting of services	UK NEA, 2011
Common International Classification of Ecosystem Services (CICES)	2012	Provisioning, Regulating, Cultural	Classification of services, includes links to other frameworks	- Bridged a gap between existing classification frameworks - Aids in ecological accounting of services - States the biophysical aspects of the service that can be managed - Focuses only on final services that link to societal benefits	- Categories are not applicable to offshore energy structures	Haines-Young and Potschin-Young, 2018
UK National Ecosystem Assessment Follow-On (UKNEAFO)	2014	Provisioning, Regulating, Cultural	Expansion of UKNEA to marine and freshwater habitats	- Development of Natural - Capital Asset Check, to link environmental change to economic impact - Wider application to marine habitats	- Underpinned by MEA categories, includes supporting service category - Categorises ecosystem processes as "intermediate services", resulting in double-counting of services	Turner et al., 2015; UNEP, 2014

nuclear installations have on ecosystem services, using the Millenium Ecosystem Assessment framework to categorise services.

Here, the DAPSI(W)R(M) framework is employed, to draw clear links between human activities and the delivery of ecosystem services. Additionally, this review separates effects by structure life stage (see supplementary Fig. S1), to determine how the structure's role in the environment changes over time. The aim of this review is to firstly undertake a general global review, before discussing these findings in a UK North Sea context and identify gaps for future research.

2. Methods

2.1. Literature selection

A literature review was undertaken to build a comprehensive list of the ecosystem services and their associated societal benefits which are supported or directly provided by marine energy structures. The term "marine energy structures" in this study refer to seabed fixed oil and gas and fixed monopile wind structures on shelf seas, as this is where most offshore structures are located. As information on floating wind technology is still at the research phase, published papers only hypothesise their effects on the environment (e.g. Causon and Gill, 2018; Bravo et al., 2023; Watson et al., 2024).

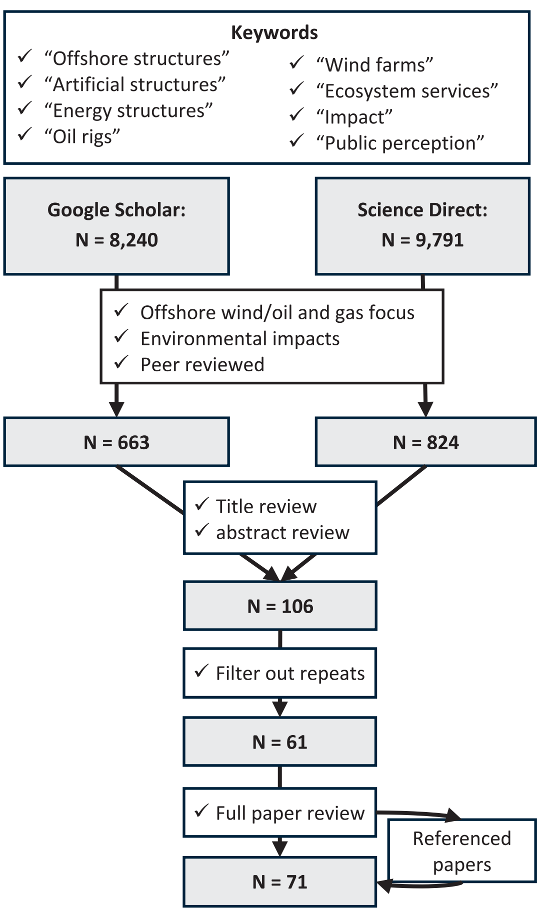

Fig. 2. Methodology used for literature selection.

The search engines ScienceDirect and Google Scholar were used to collate peer-reviewed research papers that described at least one effect that offshore structures had on the marine environment. The review aimed to capture all papers related to environmental effects, so a specified time period was not included in the search. Within each search engine, keywords were used to return papers around this topic, with each keyword relating to a structure combined with "public perception", "ecosystem services", "environmental impact" and searched individually (Fig. 2). To expand upon the review conducted by Papathanasopoulou et al. (2015), which reviewed literature from only ScienceDirect and Web of Science, this review adopted a"snowball approach" (Wohlin et al., 2022), by including relevant literature that was referenced by the papers found on ScienceDirect and Google Scholar (Fig. 2).

The literature includes unique research, conceptual and systematic review papers. Due to the plethora of literature available for this topic, only those which were peer-reviewed were accepted. For each paper, the following information was recorded: lead author, year published, focus (e.g. conceptual, review), methodology, study location, funder, structure(s) of focus and number of effects and/or services identified.

2.2. Categorisation of ecosystem services under DAPSI(W)R(M)

All effects to ecosystem services reported within the literature were categorised according to the DAPSI(W)R(M) framework (Table 2; Fig. 3). Each effect was only recorded once; a column was included within the framework which indicated how many times that change was reported within the literature to ensure no double-counting occurred (Supplementary data spreadsheet). The drivers of human activities responsible for each environmental pressures and the resulting state change were informed by the literature. The ecosystem service categories outlined by the UK NEAFO framework were used to categorise the effect of each pressure on human welfare (Turner et al., 2015). As DAPSI(W)R(M) is not a dedicated ecosystem services framework, the UK NEAFO framework was applied to provide a standardised typology of ecosystem services affected by each pressure (Supplementary data spreadsheet).

3. Results

3.1. Scope of the literature: oil and gas platforms and offshore wind farms

The review included 71 peer-reviewed papers, with those focusing solely on the effects of oil and gas (49 papers) and offshore wind (19) being the most abundant and comparison studies that included both structure types less so (3 papers). The literature reviewed covers a 42-year period, with most papers published in the last 20 years (Fig. 4).

Literature on oil and gas platforms is present throughout the 42-year period, with an increase in the frequency of publications towards the

Table 2
Example categorisation of environmental effects under the DAPSI(W)R(M) framework, showing the added column "Ecosystem service affected".

Driver	Activity	Pressure	State change	Ecosystem service affected	Impact (on human Welfare)	Responses (as Measures)
Energy demand	Operation of Oil platform (Drilling)	Noise disturbance from drilling activity	Displacement of marine mammals from known breeding and foraging grounds	Places and seascapes	Tourism and nature watching	Preservation of alternative breeding / foraging grounds
Decommissioning obligation	Full removal of offshore Oil platform	Disposal of marine growth in landfill	Greenhouse gas emissions during decomposition	Climate regulation	Healthy climate	Removal of marine growth in situ
Renewable energy targets	Construction of offshore Wind Farm	Physical disturbance of seabed	Smothering of fish eggs on seabed	Fish and Shellfish	Food (wild fish stocks)	Movement of fishing to other areas

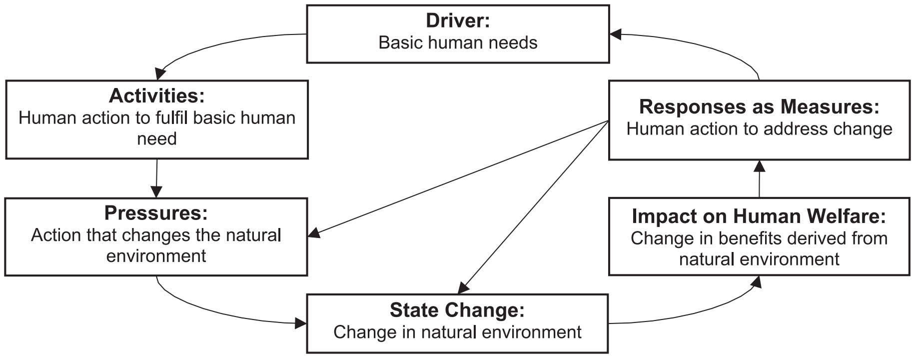

Fig. 3. The DAPSI(W)R(M) framework, showing the links between each category (Adapted from Atkins et al., 2011).

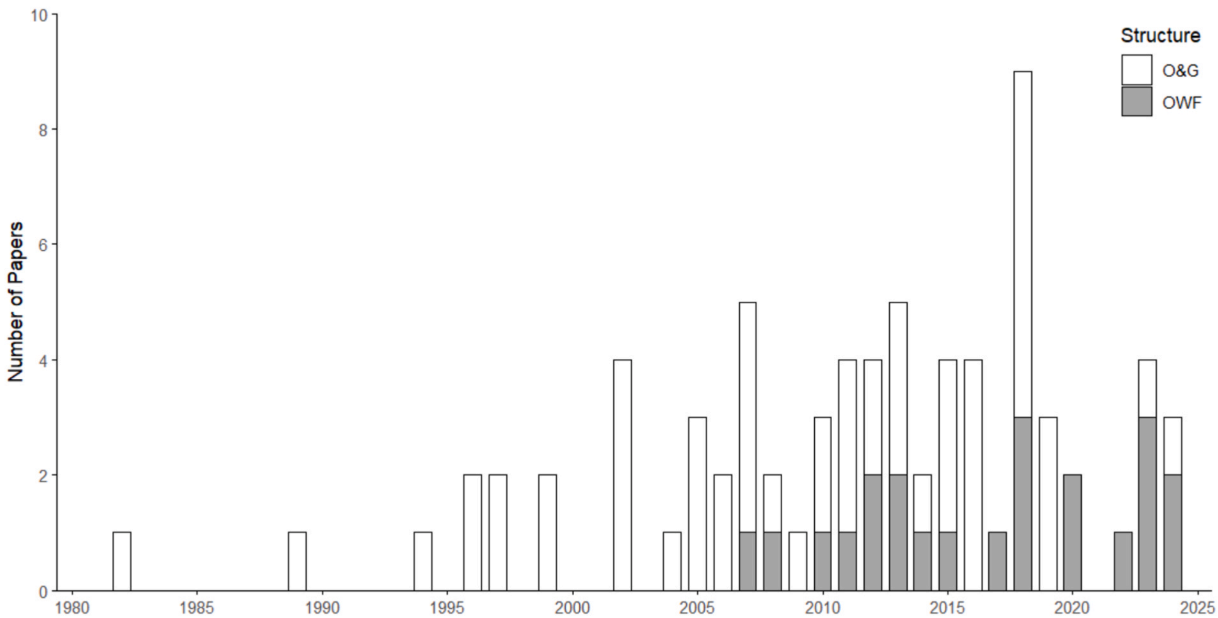

Fig. 4. The number of papers published per year from 1980 to 2025, for the subset of literature reviewed with a focus on the effect of offshore wind farms (OWF) and oil and gas (O&G) platforms.

early 21st Century. Offshore wind farms did not become a focal point in this subset of papers until 2007, with publications increasing over time, reaching a peak in 2018.

3.2. Global distribution of research

Research was produced across five different continents, with lead authors from Europe (n = 39) accounting for the greatest number of publications (Fig. 5). However, literature published by authors residing in North America (n = 24), Australia (n = 5), South America (n = 2) and Africa (n = 1) also contributed to the review.

For publications with a focus on offshore oil and gas platforms, Europe (n = 22) and North America (n = 21) accounted for the majority, with fewer papers being published in Australia (n = 4), South America (n = 1) and Africa (n = 1) (Fig. 5b). The most frequently studied locations for oil and gas papers were the North Sea (n = 11), Santa Barbara Channel (n = 10), Gulf of Mexico (n = 5), Beaufort Sea (n = 4) and Adriatic Sea (n = 3). Similarly to the oil and gas literature, Europe (n = 16) dominated publications on offshore wind farms, with North America (n = 2) and South America (n = 1) contributing to the literature to a lesser degree (Fig. 5a). Studies in European waters predominantly took place in the North Sea (n = 9), with others also conducted in the English Channel (n = 1), Baltic Sea (n = 1), Cape Cod (n = 1) and Bay of Saint-Brieuc (n = 1).

3.3. Nature of research

Unique research articles (49) contributed the most information to this research topic, although review articles (17) and methodology papers (5) were also identified. Within the research articles, data collection predominantly took place following the construction of the energy structure, with only two articles drawing comparisons between pre- and post-construction data.

Four research articles used alternative methodologies to hypothesise how future developments will influence the delivery of ecosystem services, using surveys to capture perceived social effects within a community and ecosystem modelling methods to predict future environmental effects. The review also contained one lab-based study, which tested the effect that exposure to oil spill sheens had on seabird feathers in a laboratory setting as opposed to in the field, due to the ethical implications of the methodology.

3.4. Ecosystem services of focus

The following results were produced using a modified UK NEAFO framework to structure the findings in the context of the flow between natural capital, ecosystem services and societal benefits (Fig. 6; Turner et al., 2015). All terms in black were identified within the literature, whereas all terms in grey represent categories that exist within the UK

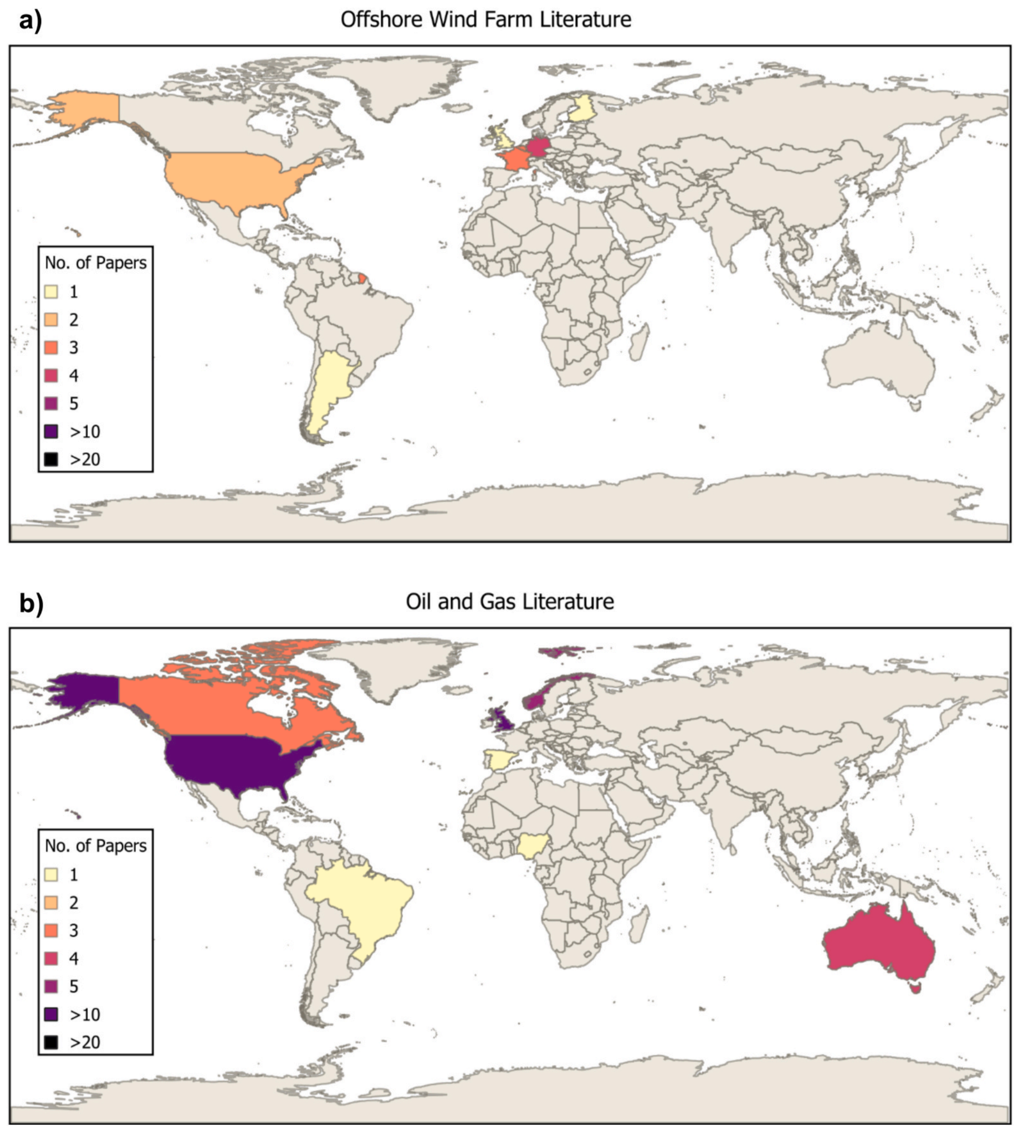

Fig. 5. Total number of papers per country, with a) offshore wind farms and b) oil and gas platforms as their primary focus.

NEAFO framework, but were not addressed by the research reviewed. For a complete overview of the ecosystem services identified within this review, please see the supplementary data spreadsheets provided.

3.5. Ecosystem services by life stage

3.5.1. Oil and gas platforms

The literature review covered every stage of a platform's life cycle, from construction through to decommissioning (Supplementary data spreadsheet). Although the operational stage was the primary focus in 83% of studies, one third also reported on the effects of other life stages. Furthermore, some papers separated the operational stage into multiple phases, with pressures from drilling activities (e.g. accumulation of drilling muds) and oil spills (e.g. mortality of fouling species) separated from those produced merely by the continued presence of the platform (e.g. nursery grounds for juvenile fish).

The stage of an oil and gas platform's life which introduced the greatest number of pressures was the operational stage, with changes to provisioning, cultural, and regulating services reported (Fig. 7). However, effects on services were reported across the three categories for all life stages, with the least reported during the construction phase and the most during the operational stage. Within the construction phase, 75% of effects to ecosystem services were negative, compared to 57% during the operation phase (Fig. 7). Additionally, the three decommissioning options varied significantly in their effect on ecosystem services, with the conversion of platforms into "reefs" sustaining more services than the full or partial removal of platforms.

3.5.2. Offshore wind farms

The literature on offshore wind farms was constrained to the construction and operation phase, with the operation phase the focus in 93% of studies. Thus, reported pressures on ecosystem services were largely constrained to the operation phase, with changes to provisioning, cultural, and regulating services reported (Fig. 8). Provisioning ($n = 22$ services) and cultural ($n = 19$) were the most widely reported services to be affected, however, regulating services ($n = 13$) were also frequently reported upon within the literature. Furthermore, significantly more state changes were reported for the operational phase of offshore wind farms compared to oil and gas, despite the disproportionate long-term research effort between these structure types (Supplementary data spreadsheet).

As more changes were reported for offshore wind farm operation ($n = 54$) than for the same stage of an oil and gas ($n = 32$) platform, it is implied that the operation of an offshore wind farm has a greater effect

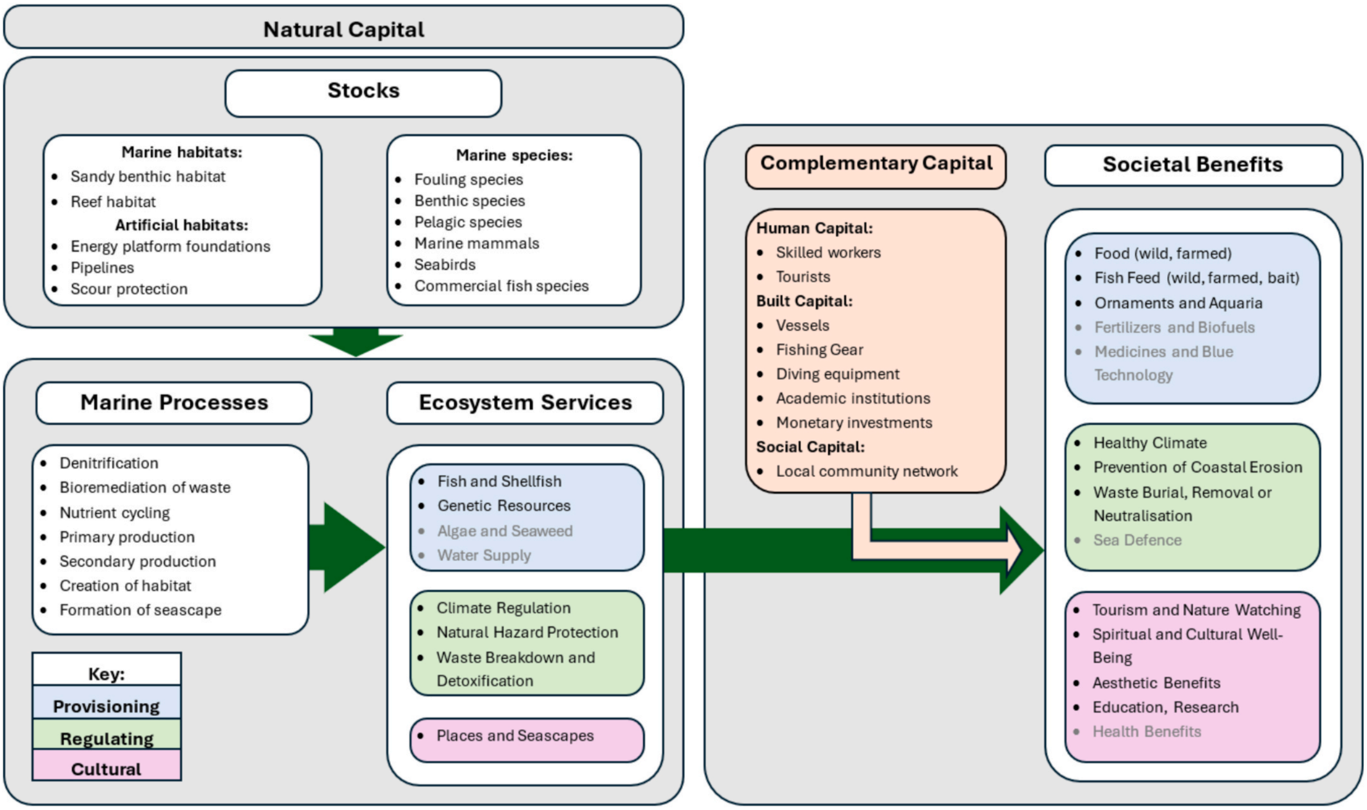

Fig. 6. The natural capital resources, ecosystem services and societal benefits associated with offshore energy structures. Services and benefits in grey were not reported by the literature reviewed (adapted from Burdon et al., 2024b; Supplementary data spreadsheet).

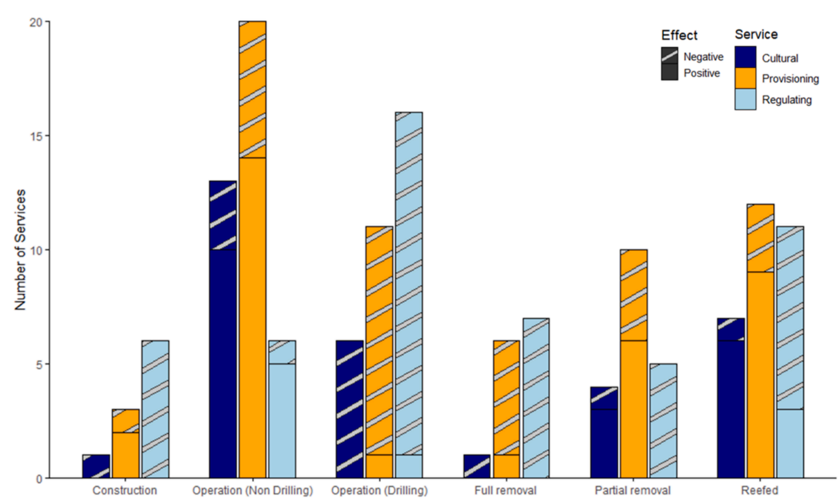

Fig. 7. The number of ecosystem services affected per life stage of offshore oil and gas platforms, with a colour key indicating the three categories of services and a patterned key indicating whether the effect was negative or positive.

on ecosystem services than the operation of an oil and gas platform. However, with the inclusion of pressures introduced during the drilling stage (n = 28), which occurs during operation, the negative effects from an oil and gas platform would outweigh those from an offshore wind farm in the same life stage. Furthermore, the nature of changes reported during each structure's operational periods differed greatly. For offshore wind farms, 40% of changes to services reported had a negative connotation. Conversely, 61% of changes to services during oil and gas operation were negative, with 58% of these changes occurring during drilling activity.

3.6. Ecosystem service groups of focus

Within the studies reviewed, the services identified were delivered by five main groups, with a portion being underpinned by the entire habitat (Fig. 9). Within oil and gas literature, services upheld by fish (n = 62 services), benthic (n = 35) and fouling (n = 26) species were the focus. Conversely, for offshore wind literature, services provided by the whole habitat (n = 27) were the most frequently recorded as they related to the aesthetic value of the marine environment, which disproportionately influenced cultural services over regulating or provisioning

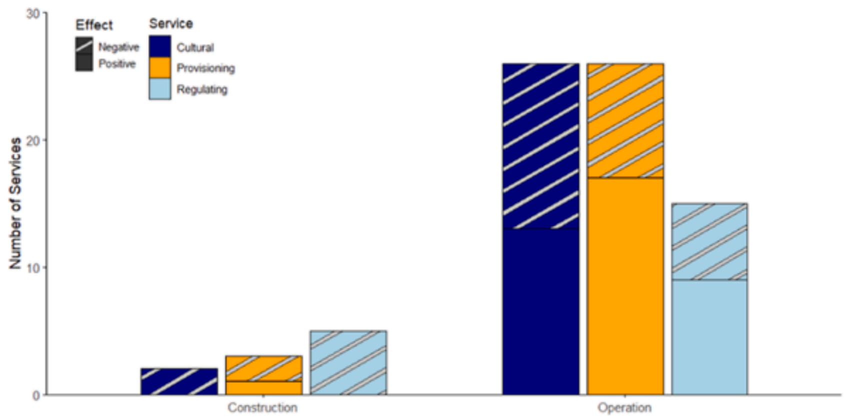

Fig. 8. The number of ecosystem services affected per life stage of offshore wind farms, with a colour key indicating the three categories of services and a patterned key indicating whether the effect was negative or positive.

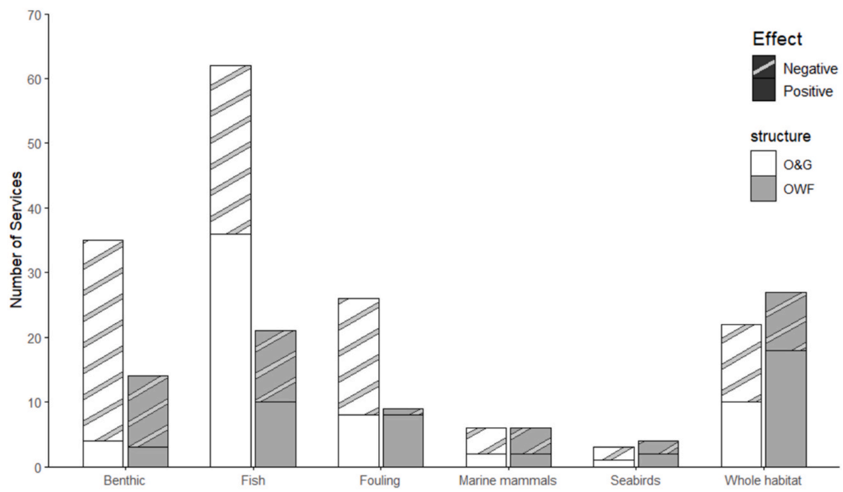

Fig. 9. The taxonomic group that provides each ecosystem service reported for oil and gas (O&G) platforms and offshore wind farms (OWF) and a patterned key indicating whether the effect was negative or positive.

services (Supplementary data spreadsheet).

3.7. Societal benefits by life stage

3.7.1. Oil and gas platforms

Ecosystem services relating to food provision were the most affected ecosystem service by an oil and gas platform (Fig. 10). Pressures on commercial fish and shellfish stocks ranged from: creation of reef-like habitat, increased competition for space, noise and chemical pollution, and the removal of the structure during decommissioning (Supplementary data spreadsheet). These pressures led to state changes affecting commercial fish and shellfish stocks, resulting in negative Impacts on human welfare through reduced food provision services. Overall, 51% of these effects occurred during the operational phase of the platform's life cycle.

The removal, burial, and neutralisation of natural and anthropogenic waste was also affected during each stage, with the operational drilling stage resulting in the greatest state change within the environment (Fig. 10). The state change from a healthy to depleted benthic community, caused by sediment accumulation during construction and drilling activities, resulted in a reduction in water filtration (Supplementary data spreadsheet). The introduction of additional waste through drill mud accumulation, oil spills and structural erosion was also a contributing factor to poor water quality in several studies. However, oil and gas platforms also positively contributed to waste removal through the growth of biofiltering species on the platform's foundations.

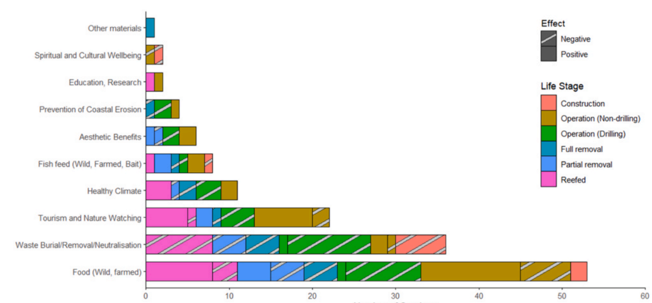

Fig. 10. The effects to human welfare due to changes in ecosystem services by oil and gas platforms, with a colour key indicating the proportional effect of each life stage and a patterned key indicating whether the effect was negative or positive.

3.7.2. Offshore wind farms

Similarly to oil and gas platforms, food provisions were the most affected ecosystem service by offshore wind farms (Fig. 11). Pressures relating to food provision were only reported during the operation period, with 57% positively influencing food provisions. Wind farms created pressures within the environment, acting as barriers to vessel movement and fish aggregation devices (Supplementary data spreadsheet). This led to the displacement of fishers in the area, changing the accessibility and abundance of fish stocks residing near the structure.

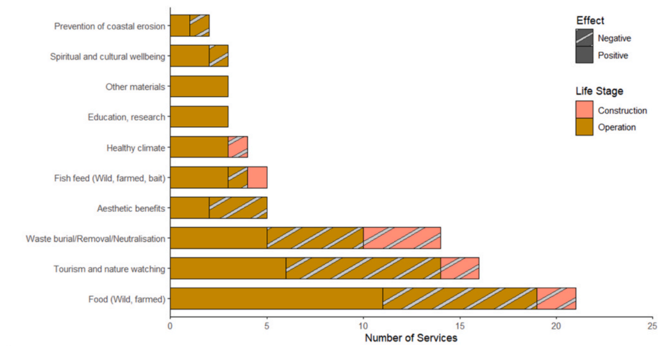

Fig. 11. The ecosystem services affected by offshore wind farms, with a colour key indicating the proportional effect of each life stage and a patterned key indicating whether the effect was negative or positive.

The visual effect of offshore wind farms (n = 9) was also heavily referenced within the literature, with 77% having a negative connotation (Fig. 11; Supplementary data spreadsheet). The most reported state change was the placement of a structure on the coastline, which reduced its aesthetic appeal, the sense of place that individuals felt for the area and the local interest in recreational activities.

Pressures which related to regulating services were less frequently reported within the literature. However, wind farms did enhance several regulating services within the marine environment, through the growth of a fouling community on the structure's foundations, which enhanced the regulation of waste, denitrification, and carbon sequestration potential (Supplementary data spreadsheet).

4. Discussion

This study applied the DAPSI(W)R(M) framework to structure and analyse the environmental and socio-ecological systems linked to offshore energy structures. The framework proved effective in understanding their effects on natural capital, and consequently, on the provision of ecosystem services and societal benefits. From the literature reviewed, offshore energy structures contribute to a multitude of ecosystem services, providing breeding, foraging and nursery grounds for different trophic levels (Fujii, 2015; Love et al., 2007; Todd et al., 2016). Offshore structures also contribute to increased social engagement with the marine environment, through their use as recreational dive and fishing sites in many locations (Ajemian et al., 2015; Sommer et al., 2019; Stanley and Wilson, 1989). However, the addition of an artificial structure into the natural environment also contributed to the reduction in several natural processes, and the replacement of a native benthic community with hard substrate associated species (Causon and Gill, 2018; Fujii, 2015; Macreadie et al., 2011). Offshore oil and gas platforms caused disturbance to benthic habitats across all life stages, with drill mud accumulation and noise pollution contributing to reductions in water cycling and waste burial by benthic species (Gates and Jones, 2012; Schaanning et al., 2008). Additionally, wind farms were perceived to de-value the marine environment, leading to reduced spiritual and recreational enjoyment of the shoreline by the local community (Kempton et al., 2007; Kermagoret et al., 2014; Klain et al., 2018).

Many of the ecosystem services observed around structures are associated with the fouling communities present on their foundations, serving as foraging, spawning and nursery grounds for many species (Love et al., 2007; Todd et al., 2009; Madgett et al., 2022). These communities also hold aesthetic appeal in warmer climates, as they mimic natural coral reef habitats, attracting recreational divers and fishers (Stanley and Wilson, 1989). Despite their climatic differences, the same functional groups (e.g. mussels, anemones, sponges, coral) are present on offshore energy structures globally, it is only the species that change with location (Mallat et al., 2014; Torquato et al., 2021). For example, the dominant bivalve on North Sea platforms is the blue mussel *Mytilus edulis*, whereas on New Zealand platforms it is the green-lipped mussel *Perna canaliculus* and on American Pacific platforms it is the California mussel *Mytilus californanus* (Hopkins and Forrest, 2010; Schutter et al., 2019; Page et al., 2019). Thus, information gained worldwide is applicable to the North Sea, so long as climatic and cultural differences are accounted for.

4.1. Knowledge gaps

4.1.1. Types of services of focus

Within the literature reviewed, there was a focus on ecosystem services that directly produced high monetary benefits for society, such as those relating to fishery stocks and recreational enjoyment of the seascape (Fig. 10; Fig. 11). Additionally, this review highlighted the disproportionate attention bought to the visual obstruction that offshore wind farms pose to coastal communities and tourists, as opposed to physical effects faced by marine life such as noise and water pollution (e.g. Kempton et al., 2007; Gee and Burkhard, 2010; Kermagoret et al., 2014). Thus, the findings demonstrate how human preferences can be prioritised over more substantial environmental effects.

4.1.2. Taxonomic group of focus

This finding was echoed when contemplating the taxonomic group responsible for delivering each ecosystem service, with those relating to commercially valuable species vastly outweighing any other group (Fig. 9). This is likely due to the accessibility of fish populations for sampling compared to other species, with more studies on benthic, fouling and marine mammals expected as more data becomes accessible on these groups through research and industry collaboration (e.g. Dannheim et al., 2025). The review highlighted several studies which showcased the value that fouling communities have to their surrounding environment throughout their lifecycle, via the food provisioning for higher trophic levels (Causon and Gill, 2018), secondary habitat provision, bioremediation of waste and sequestration of carbon (Mangi, 2013; Watson et al., 2024).

The role of these structures as blue carbon stores is a growing field of research given the current climate crisis, however, their role as carbon sequesters was only referenced by eight papers in the review. Thus, studies which investigate the role that fouling communities play in carbon sequestration, how that role changes over time, and the environmental consequence of marine growth removal during decommissioning are necessary to inform best practice guidelines in response to our changing climate.

4.1.3. Study length

Furthermore, there is a need for long-term studies, which investigate how ecosystem services change over time. It is understood that the community matures over time, with r-selected species replaced by k-selected species (Whomersley and Picken, 2003). Therefore, it can be inferred that the ecosystem services produced will also change as the community matures, with most reaching a plateau as the climax community becomes established. However, ecological succession can take an average of 4–5 years (Ralph and Troake, 1980; Pedersen et al., 2006), and only one study was found that captured this process (Zupan et al., 2023). The monitoring of marine growth communities is compulsory for offshore developers through maintenance surveys and associated marine growth reports, but these are not peer-reviewed, often undertaken by non-specialists and not made publicly available.

However, a study on benthic communities found that species diversity increased with proximity to offshore wind turbines, with this increase remaining consistent over a 13-year period (Jammar et al, 2025). Marine growth communities are known feeding grounds for higher trophic levels, such as Harbour and Grey seals (Russell et al., 2014), Atlantic cod and pouting (Reubens et al., 2013) and Plaice (Buyse et al., 2023). Further studies targeting how marine growth's role in the environment changes as it matures would deepen our understanding of the long-term ecological role of these structures. Such studies could also inform maintenance schedules for offshore structures, as the removal of marine growth during cleaning activities could alter how other species interact with the structures, affecting the services and benefits provided from this habitat (Viola et al., 2018).

4.1.4. Life stage of focus

The operational period was the primary focus for both oil and gas and offshore wind studies (Fig. 7; Fig. 8), despite the literature suggesting that the construction period has a strongly negative effect on the environment and society (Nunneri et al., 2008; Busch et al., 2011; Vad et al., 2018; Baulaz et al., 2023; Richard et al., 2024). Additionally, the construction phase only accounts for 2–3 years in the structures 20 + year lifespan, so many reported effects would likely only be temporary. It is also worth noting that the number of effects reported for each life stage is likely a reflection of the funding availability and current regulatory requirements, as the number of papers available for each life stage varied considerably (Supplementary data spreadsheet).

Research into oil and gas decommissioning was limited, despite its relevance in the current climate. By 2040, >2000 oil and gas platforms will need to be decommissioned globally (Vidal et al., 2022). This scale of activity presents significant environmental, economic and societal challenges, including habitat alteration, waste management, and impacts on local economies, yet the comparative outcomes of different decommissioning approaches (full removal, partial removal, or reefing) remain poorly understood (Fig. 10; Fig. 11). Consequently, there is an increasing need to further assess the environmental and societal consequences of the available decommissioning approaches. In comparison, the expectation is that many wind turbines will be reverse engineered due to their simplified structure, allowing decommissioning impacts to be inferred from those reported during construction (Kerkvliet and Polatidis, 2016). If wind turbines can be reverse engineered, this will still result in the removal of the established marine growth community, which brings unknown environmental consequences. Discussions around alternative decommissioning approaches have been largely constrained to oil and gas structures, despite there being as an estimated 712 offshore wind projects due to be installed into the marine environment across the globe in the near future (Díaz and Soares, 2020). Wind turbine designs are likely to continue evolving as more countries invest in renewable energy, leaving repurposing as an unlikely choice when decommissioning.

Oil and gas decommissioning presents a greater challenge, due to the possible presence of drill cutting piles and the advanced age, weight and design of oil and gas platforms compared to offshore wind turbines. Due to the advanced age of some oil and gas platforms, it is likely that marine protection and associated regulations have significantly evolved since their installation, adding to the complexities that must be considered during decommissioning (Burdon et al., 2018). The emerging popularity of the rigs-to-reefs approach (out with the OSPAR region) was reflected by the literature, with multiple studies discussing its suitability for the North Sea (Aabel et al., 1997; Løkkeborg et al., 2002, Smyth et al., 2015), along with existing reefs in the California Blight (Frumkes, 2002; Macreadie et al., 2011; Love and York, 2005;Claisse et al., 2014) and Gulf of Mexico (Dauterive, 1999; Ajemian et al., 2015).

Rigs-to-reef research has primarily been conducted in warmer climates, highlighting the need for continuing research which addresses the current rigs-to-reef debate in the North Sea. The ecosystem services associated with a reefed platform will be dependent on the local environment (Mangi, 2013; Watson et al., 2024), so current studies may not be directly applicable to the North Sea. For example, offshore platforms in the Gulf of Mexico are historical recreational fishing and diving sites (Stanley and Wilson, 1989), with platform associated fish populations heavily researched in this area (e.g. Dauterive, 1999; Ajemian et al., 2015). However, the isolation of North Sea platforms due to distance from shore may reduce their use by recreational fishers and divers, resulting in a diminished cultural importance to local populations compared to their tropical counterparts. Thus, there is a need for a case-by-case approach to assessing the most suitable decommissioning practice, with location-specific ecosystem services included in the assessment process from development through to decommissioning. The case-by-case approach would be applicable for both oil and gas and offshore wind infrastructure and is an aspect not currently accounted for in existing regulations and assessments.

4.2. Development of alternative decommissioning approaches – industry and policy drivers

Several overarching policies exist within the North Sea (e.g. OSPAR Decision 98/3), however, their interpretation differs between countries (Slater and MacDonald, 2018), so the discussion will present the UK as a case study for how ecosystem services will be accounted for within new and emerging polices in the North Sea.

4.2.1. Industry vs policy

The countries bordering the North Sea, although bound by the OSPAR regulations, approach decommissioning slightly differently. The UK allow scour protection, mattresses, pipelines and concrete foundations to be left in situ following decommissioning, whereas other bordering countries (e.g. Belgium, Denmark) set full removal as the legal standard (Fowler et al., 2020).

As policy on decommissioning is highly variable between regions, energy companies which operate over several jurisdictions must tailor decommissioning plans to the legislation relevant to the platform's location. An example is the Gaupe Field production platforms, which reside across the UK and Norway's maritime border. Thus, two separate decommissioning plans were submitted to UK and Norway governments, highlighting the complexities of projects that cross jurisdictions. It is worth noting that the environmental effects of offshore structures are not constrained to a countries' boundary and instead can be far-reaching, and current policies and regulations are not designed to support effective management across country boundaries.

4.2.2. Established regulations

Several regulations and policies have been introduced to safeguard marine biodiversity. Those relevant to the provision of protected species, habitats and areas in UK waters are presented in Table 3. The full complexity of marine environmental regulations is covered by Boyes and Elliot (2014).

4.2.3. Emerging UK biodiversity focused policy

The increased awareness of the environmental challenges and benefits of offshore energy structures has resulted in a movement towards nature-positive approaches, both within industry and government (e.g. Natural Environment (Scotland) Bill, 2025; DEFRA, 2022). Substantial change in marine biodiversity has been noted within the last century, with much of this attributed to the expansion of human activities into the marine environment (Pan, 2023). Here we summarise three of the UK's most recent biodiversity focused policies.

Marine Recovery Fund

The increased competition for marine space has led to the utilization of protected areas for offshore wind development. This has led to concern over the effectiveness of these areas for their purpose, as many are designated for the conservation of a particular species or feature. Thus, the Energy Act (2023) has proposed a Marine Recovery Fund, which would funnel contributions from wind farm operators into restorative activities in other locations, to compensate for the degradation of marine protected areas due to offshore wind developments.

Environmental Improvement Plan

Conserving biodiversity is a global issue, which has been addressed most recently in the UK with a 25-year environmental plan. The

Table 3
The established UK regulations and frameworks relating to the development of offshore energy structures in the North Sea.

Regulation / Framework	Type	Industry	Ecosystem services (Y/N)	Jurisdiction	Year	Summary
OSPAR Decision 98/3	Regulation	All in marine environment (bar fishing and shipping)	N – focus on returning to a "clean seabed" following decommissioning	All countries bordering North-East Atlantic and EU members (UK ratified)	1998	• Annexes 2 and 5 set out management of petroleum structures • The full cost to prevent, control or reduce impacts of pollution borne from offshore activities falls solely on the polluter ("polluter pays" principle) • Advocates for the return to a clean seabed following decommissioning (precautionary principle)
UN Decision 15/4: Kunming-Montreal Global Biodiversity Framework	Framework	Those that impact targets	Y – Target 11: restore, maintain and enhance ecosystem services	All UN member states (UK has ratified framework)	2022	• Creation of 25-year environmental plan Targets include restoration of ecosystem services and biodiversity in marine environments • Framework includes 23 targets to improve natural environment within one generation
EU Habitats Directive	Regulation	All impacting protected areas	N – focus on preservation of species and habitats	EU members (ratified by UK)	1992	• Designation of protected species, prohibited disturbance, damage or removal of species • Introduction of special areas of conservation (SAC)
EU Wild Birds Directive	Regulation	All in marine environment	N – focus on preservation of diversity and habitats	EU members (ratified by UK)	1979 Amend. 2009	• Introduction of special protected areas (SPA) • Environmental assessment on developments impact on bird populations
The Petroleum Act	Regulation	Oil, hydrocarbon and natural gas	N – Environment not referenced	United Kingdom	1998	• operators required to submit a comprehensive decommissioning plan • Estimate of decommissioning cost • location of installation section or pipeline derogated
The Marine Works (Environmental Impact Assessment) Regulations	Regulation	All significant developments	Y – recognizes that ES can be affected by developments	United Kingdom	2007	• Incorporation of ES into Environmental Impact Assessments
Mitigation Hierarchy Framework (Temple et al., 2012)	Framework	All	Y – "Rehabilitation" section of the framework	Used throughout the United Kingdom	2008	• Identifies the impacts of an activity and ways to avoid, minimise or mitigate against said impacts • Used by government and private sector to assess environmental impacts
National policy statement for renewable energy infrastructure	Guidance	All – focus on offshore wind	Y – addresses value of ES delivered by structure	England and Wales	2008	• Guidance document for submitting application for offshore wind development
Marine and Coastal Access Act	Regulation	All in marine environment	Y – encourages incorporation of ES into decision making	UK	2009	• Ratified SPA and SAC into UK law
Guidance notes: Decommissioning of Offshore Oil and Gas Installations and Pipelines	Guidance	Oil and Gas	N – biological composition of surrounding habitat stated in report	United Kingdom	2018	• Guidance for operators submitting decommissioning report • precautionary principle – the seabed is returned to its natural state following cessation of production (Environment Act, 2018)
Environment Act	Regulation	All	Y – ties environmental recovery to people's use of natural environment	United Kingdom	2021	• Environmental Improvement Plan • Realistic targets that can be objectively measured and achieved • Reaffirms the "polluter pays" principle
Energy Act	Regulation	Offshore wind	Y – sustainable offshore development, to protect and enhance ES	United Kingdom	2023	• Plan for sustainable offshore wind development • Introduced marine recovery fund
ORIES (Szostek et al. (2023)	Dataset	Offshore wind	Y – tool references known impacts on habitats, biodiversity and ES	United Kingdom	2023	• Decision support tool, for developers to assess the environmental impacts of wind farms
Marine (Scotland) Act	Regulation	All in marine environment	N – focus on preservation of species and habitats	Scotland	2010	• Marine spatial planning framework, operators must obtain licence • Species and habitat protection through marine protected areas
Natural Environment (Scotland) Bill, 2025	Regulation	All	Y – focus on repairing natural environment and enhancing public wellbeing	Scotland	2025	• Modification of existing legislation follow EU exit • Restoring and regenerating biodiversity in Scottish waters • Incorporation of Marine Net Gain into Environmental impact assessments

Environmental Improvement Plan (DEFRA, 2023) provides a roadmap to deliver the 25-year vision (HM Government, 2018) and implement the Environment Act (2021). The plan was informed by the Kunming-Montreal Global Biodiversity Framework, which outlines 23 targets to improve the condition of the natural environment within one generation (UN Decision 15/4, 2022).

Target 11 of the framework aims to "restore, maintain and enhance ecosystem services". As shown by this review, offshore energy structures underpin essential ecosystem functions and processes through the creation of novel habitats (Fig. 7; Fig. 8). Their value to society and the environment though ecosystem service delivery should be utilised, not ignored.

Scottish Environment Bill

Considering the monopolisation of marine spaces to further net zero initiatives, environmental protections are expected to be strengthened by the emerging Natural Environment (Scotland) Bill, which focuses on restoring and regenerating biodiversity in Scottish waters (Natural Environment (Scotland) Bill, 2025). The Bill also aims to modify current legislation relating to environmental impact assessments, which were amended following departure from the EU (Natural Environment (Scotland) Bill, 2025). One such example is the proposed incorporation of 'Marine Net Gain' into environmental impact assessments, which is gaining popularity in North Sea bordering territories (DEFRA, 2022).

The concept of 'Marine Net Gain' puts the burden on the operator to not only mitigate negative effects that arise from their activities, but to ensure that the natural environment is left in a better state than it was prior to development.

Such aims could be achieved by enhancing the role of offshore structures as support systems for ecosystem service delivery, through conserving the marine growth community that forms the basis of the surrounding food web. Tailoring structural aspects to encourage the settlement success of organisms or organising maintenance schedules around the breeding or spawning seasons of keystone species would support the development of a sustainable food web around the structure. However, any steps taken to achieve net gain would be constrained to the structure's lifespan, with the decommissioning stage the key to achieving lasting marine net gain. Arguably, the most impactful change would be to employ alternative decommissioning methods to reduce the disturbance to marine life and allow the reef-like habitat to remain intact. As displayed by the literature, habitat preservation through the implementation of alternative decommissioning approaches allows for the continuation of existing natural functions and processes and associated ecosystem services following platform cessation. The retention of this productive ecosystem would allow the energy structure to have a lasting positive effect to the marine environment, long after its economic lifespan has ended (e.g. Soldal et al., 2002; Ajemian et al., 2015; Pereira et al., 2023).

5. Conclusions

This review has highlighted the socio-economic and environmental role that offshore energy structures play on a global scale, expanding our understanding of how platforms may contribute to ecosystem service delivery in the North Sea. The application of the DAPSI(W)R(M) framework demonstrates how Drivers such as energy demand and associated industrial Activities exert multiple Pressures on marine ecosystems, leading to State changes that ultimately affect human welfare through altered ecosystem services. Such an approach generates evidence directly relevant to policy development, as it identifies the stages of the structure life cycle where management Responses (Measures) could most effectively mitigate environmental pressures. Integrating this framework into policy processes can therefore support more adaptive, ecosystem-based management, ensuring that decisions about decommissioning, spatial planning, and marine resource use are grounded in a clear understanding of the socio-ecological consequences of industrial activity.

To build a holistic understanding of the communities associated with offshore structures, future research should target benthic and fouling groups, as the review's findings would suggest that these groups contribute significantly to a multitude of provisional, cultural and regulating services, often acting as the foundation for the ecosystem. As these communities develop over several years, long-term studies which span several life stages are also necessary, to inform how ecosystem services change over a structure's life. Without an understanding of how an offshore structure's role within the natural environment and society changes over its life cycle, we cannot make truly informed decisions regarding the management of these structures. The emergence of new policy provides a unique opportunity to embed ecosystem services into legislation, acknowledging the value that offshore energy structures have across all life stages.

CRediT authorship contribution statement

Megan Squire: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Alethea Madgett:** Writing – review & editing, Supervision, Methodology. **Daryl Burdon:** Writing – review & editing, Supervision, Methodology. **Beth Scott:** Writing – review & editing, Supervision, Methodology. **Joseph Marlow:** Writing – review & editing, Supervision. **Kate Gormley:** Writing – review & editing, Supervision, Methodology.

Funding

We acknowledge the generous support of alumni and friends in establishing the University of Aberdeen's Interdisciplinary Institute, which enabled this research, including Dr Jane Hellman Caseley (MBChB 1956), Professor Patrick Meares (DSc 1959), Nancy Miller (MA 1942), Norman Robertson, Dr Ian Slessor (MBChB 1956) and Anne Young (MA 1957). Funding is also acknowledged from the European Union Horizon Europe project: MARine Biodiversity and Ecosystem Functioning leading to Ecosystem Services (EC HE – Project 101060937 — MARBEFES – https://www.marbefes.eu) with UK funding from UKRI (grant number 10048815).

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101811.

Data availability

Individual spreadsheets for data relating to oil and gas platforms and wind farms have provided in the supplementary materials.

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