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# Offshore decommissioning horizon scan: Research priorities to support decision-making activities for oil and gas infrastructure

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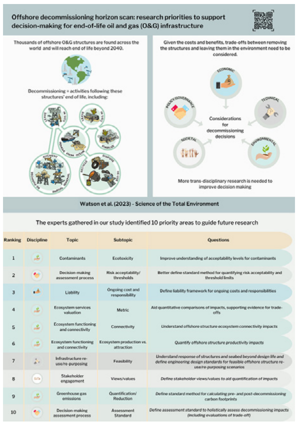
## HIGHLIGHTS

- Decommissioning is imminent for thousands of ocean-based oil and gas structures.
- Removal of these structures may not be 'best case' for the environment or society.
- Transdisciplinary knowledge is required to provide evidence for decision-making.
- This expert-informed horizon scan provides consensus of priority research required.
- Addressing these priorities will require the dismantling of discipline/sector silos.

## GRAPHICAL ABSTRACT



Offshore decommissioning horizon scan: research priorities to support decision-making for end-of-life oil and gas (O&G) infrastructure

Thousands of offshore O&G structures are found across the world and will reach end of life beyond 2040.

Decommissioning = activities following these structures' end of life, including:

Given the costs and benefits, trade-offs between removing the structures and leaving them in the environment need to be considered.

Considerations for decommissioning decisions

More trans-disciplinary research is needed to improve decision making

Watson et al. (2023) - Science of the Total Environment

The experts gathered in our study identified 10 priority areas to guide future research

| Ranking | Discipline | Topic | Subtopic | Questions |
|---|---|---|---|---|
| 1 | | Contaminants | Ecotoxicity | Improve understanding of acceptability levels for contaminants |
| 2 | | Decision-making assessment process | Risk acceptability/ thresholds | Better define standard method for quantifying risk acceptability and threshold limits |
| 3 | | Liability | Ongoing cost and responsibility | Define liability framework for ongoing costs and responsibilities |
| 4 | | Ecosystem services valuation | Metric | Aid quantitative comparisons of impacts, supporting evidence for trade-offs |
| 5 | | Ecosystem functioning and connectivity | Connectivity | *Understand offshore structure ecosystem connectivity impacts* |
| 6 | | Ecosystem functioning and connectivity | Ecosystem production vs. attraction | *Quantify offshore structure productivity impacts* |
| 7 | | Infrastructure re-use/re-purposing | Feasibility | *Understand response of structures and seabed beyond design life and define engineering design standards for feasible offshore structure re-use/re-purposing scenarios* |
| 8 | | Stakeholder engagement | Views/values | *Define stakeholder views/values to aid quantification of impacts* |
| 9 | | Greenhouse gas emissions | Quantification/ Reduction | *Define standard method for calculating pre- and post-decommissioning carbon footprints* |
| 10 | | Decision-making assessment process | Assessment Standard | *Define assessment standard to holistically assess decommissioning impacts (including evaluations of trade-off)* |

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## ABSTRACT

Thousands of oil and gas structures have been installed in the world's oceans over the past 70 years to meet the population's reliance on hydrocarbons. Over the last decade, there has been increased concern over how to handle decommissioning of this infrastructure when it reaches the end of its operational life. Complete or partial removal may or may not present the best option when considering potential impacts on the environment, society, technical feasibility, economy, and future asset liability. Re-purposing of offshore structures may also be a valid legal option under international maritime law where robust evidence exists to support this option. Given the complex nature of decommissioning offshore infrastructure, a global horizon scan was undertaken, eliciting input from an interdisciplinary cohort of 35 global experts to develop the top ten priority research needs to further inform decommissioning decisions and advance our understanding of their potential impacts. The highest research priorities included: (1) an assessment of impacts of contaminants and their acceptable environmental limits to reduce potential for ecological harm; (2) defining risk and acceptability thresholds in policy/governance; (3) characterising liability issues of ongoing costs and responsibility; and (4) quantification of impacts to ecosystem services. The remaining top ten priorities included: (5) quantifying ecological connectivity; (6) assessing marine life productivity; (7) determining feasibility of infrastructure re-use; (8) identification of stakeholder views and values; (9) quantification of greenhouse gas emissions; and (10) developing a transdisciplinary decommissioning decision-making process. Addressing these priorities will help inform policy development and governance frameworks to provide industry and stakeholders with a clearer path forward for offshore decommissioning. The principles and framework developed in this paper are equally applicable for informing responsible decommissioning of offshore renewable energy infrastructure, in particular wind turbines, a field that is accelerating rapidly.

## 1. Introduction

Thousands of offshore fixed and floating platforms, approximately 200,000 km of subsea pipelines, and a multitude of other associated subsea infrastructure have been installed within the world's ocean over the past 70 years to explore and produce oil and gas (O&G) (Fig. 1). Initially concentrated in the Gulf of Mexico, where the first platform was installed in 1938, these structures are now located within the marine territories of over 50 countries (Gourvenec et al., 2022).

The operational life for offshore O&G structures and associated infrastructure can range from 15 to 50 years (Nelson et al., 2021). 'Decommissioning' refers to activities that follow cessation of operations, including making subsea wells secure and deciding the fate of end-of-life structures (Birchenough and Degraer, 2020). The United Nations Convention on the Law of the Sea (enacted in 1982), and the International Maritime Organisation's (IMO) Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone (EEZ; adopted in 1989), set the basis for decommissioning guidelines and requirements under international maritime law. These require that infrastructure on any continental shelf or in any EEZ be removed at end of field life; however, requirements do not include subsea pipelines and other associated subsea infrastructure, or infrastructure located within a country's territorial waters (Beckman, 2013; Lyons, 2014; Trevisanut, 2020). Further, for many coastal sea areas and countries, regional and national decommissioning legislation, respectively, is minimal (IOGP, 2017, 2021).

The international legal basis for full removal is to ensure safety of navigation and to prevent marine pollution due to abandonment of such structures (Techera and Chandler, 2015). Leaving infrastructure in place can be considered a valid alternative if certain requirements are met and permitted. These include, inter alia, decommissioning practices in accordance with international standards, including demonstration of due regard to fishing, protection of the marine environment, respect for the rights and duties of others, and assurances that the depth, position, and dimensions of any remaining structures are publicised (Beckman, 2013; Lyons, 2014; Trevisanut, 2020); therefore, several options under international law exist for decommissioning offshore infrastructure: complete removal for onshore re-use, recycling or disposal; partial removal, split between onshore and relocation offshore for disposal or re-use; partial removal, split between onshore and in situ decommissioning for disposal or re-purposing (Techera and Chandler, 2015; Gourvenec, 2018) (Fig. 2).

Decommissioning of offshore O&G infrastructure will continue beyond the end of the century with additional installation of offshore O&G infrastructure (principally gas) forecast into the mid-century (DNV, 2021; Gourvenec et al., 2022). Decommissioning is a complex operation in remote and harsh environments with an associated global cost estimate of US $210 billion, half of which is for plugging and abandonment (P&A) of subsea

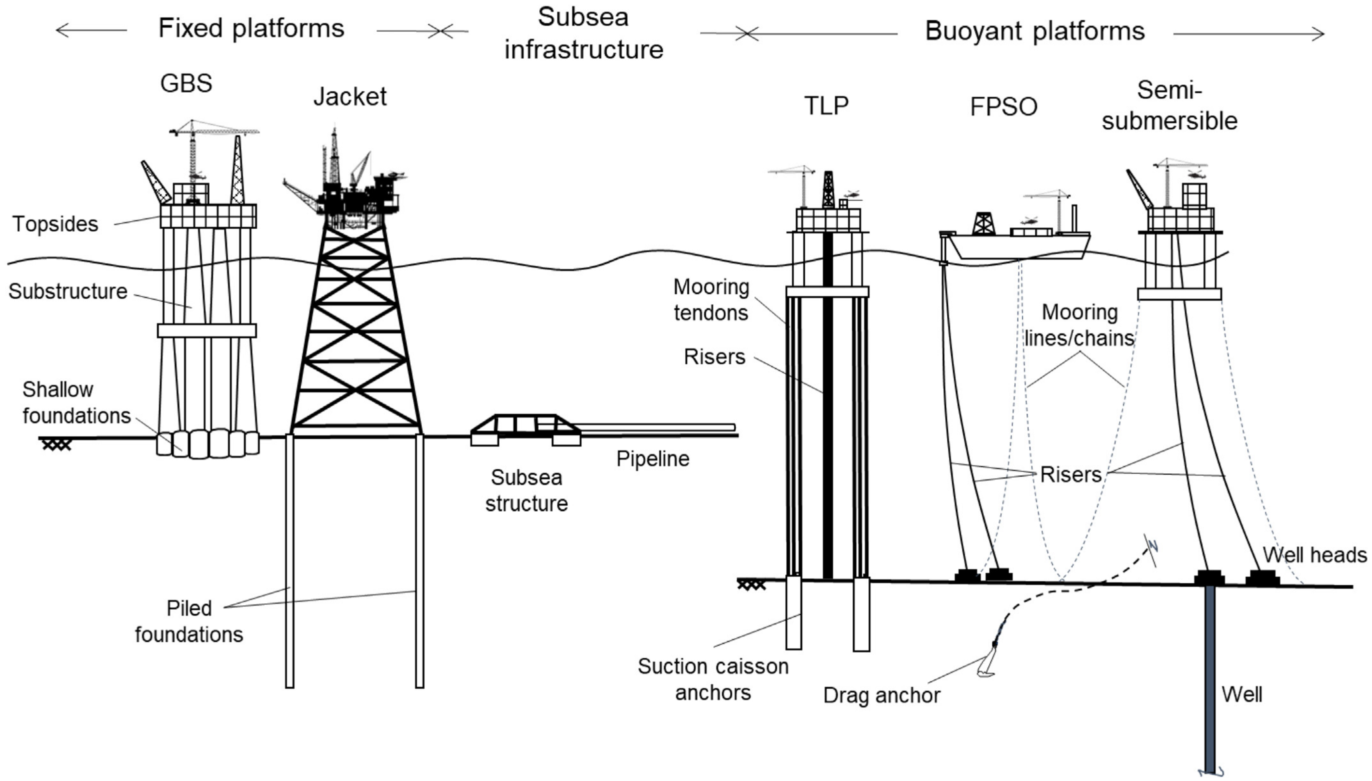

**Fig. 1.** Schematic displaying various different types of offshore O&G structures and other associated subsea infrastructure (not to scale). GBS is a Gravity Based Structure, FPSO a Floating Production Storage and Offloading system while TLP is a Tension Leg Platform. Note: The terms 'infrastructure' and 'structure' are used throughout, as referring to this group of structures.

wells which are decommissioned in situ by necessity (Gourvenec et al., 2022). In some jurisdictions, where decommissioning costs are subject to tax legislation that enables tax relief, the government and taxpayers pick up a portion of the cost of decommissioning (Techera and Chandler, 2015; Gourvenec et al., 2022). Cost savings may be realised by not removing infrastructure (either partially or fully; Fig. 2), and there is also a growing body of evidence supporting environmental and societal benefits of leaving the established ecosystems that have developed around such infrastructure within the marine environment post its operational use (Fortune and Paterson, 2020; Fowler et al., 2020; Schläppy et al., 2021; Elrick-Barr et al., 2022). These benefits need to be weighed against the potential for negative impacts, including infringement on other marine users, contaminants released to the marine environment, and liability issues associated with the ongoing maintenance and responsibility for re-used infrastructure (Nicolette et al., 2023).

The environmental, societal, technical, and economic impacts associated with various infrastructure decommissioning options, together with the associated policy/governance frameworks, are all interconnected (Röckmann et al., 2015; Elliott et al., 2020b). Further, there can be geographic variations in what is considered an appropriate or acceptable decommissioning option reflecting varying environmental and social perspectives, and technical capabilities to decommission safely (Gourvenec, 2022a). It is increasingly clear that decommissioning decisions cannot be made purely on an economic basis, without also considering the technical feasibility of options, the resulting benefits and impacts to the environment and society, and whether supporting governance frameworks and policies are in place.

The current decommissioning decision-making process, which can include variations of Comparative Assessments, can lead to the creation of silos with insufficient integration between science, academia, industry, and policy (Cormier et al., 2019; Elliott et al., 2020b). Historical research aimed at improving the decommissioning decision-making process has been predominantly industry-funded, either directly or indirectly, or developed to inform policy; therefore, the scope of research tends to be based on an industry, or policy-centric viewpoint or, alternatively, involve a narrow disciplinary field (Lyons, 2014; Sommer et al., 2019; Lemasson et al., 2022). To address this complex topic comprehensively, more research is required that covers the transdisciplinary nature of decommissioning, i.e., the environmental (ecology, biology, geology, etc.), societal, economic, technical, and policy/governance aspects of decommissioning. The present study aims to identify priority knowledge gaps, through a horizon scan, i.e., a process of eliciting opinions from a broad range of global experts, across all disciplines involved on the topic, to build consensus on priority research areas for current and future (the 'horizon') research. The study brought together global experts across all relevant fields of work and technical disciplines to identify the top research priorities that must be addressed to advance and improve decision making for decommissioning of offshore infrastructure.

## 2. Horizon scan process

Horizon scans have become a powerful tool for reaching expert consensus on research priorities. The most influential examples of horizon scans come from the biological sciences field to identify emerging global environmental conservation issues (e.g., Sutherland et al., 2010, 2022). Most horizon scans are based on Delphi-style techniques (or variations thereof, e.g., Macreadie et al., 2019, Trevathan-Tackett et al., 2019) that seek to identify research priorities through a repeatable, transparent, and inclusive process. Here we used a horizon-scan process with leading global experts on the decommissioning of offshore O&G infrastructure (excluded from the scope was P&A of subsea wells), from across a range of fields (science/academia; industry; and policy-making) and technical disciplines (environmental; societal, technical, economic; and policy/governance). Experts were selected based on their: publications on the topic; extent of relevant work (within academia, industry, or a relevant competent

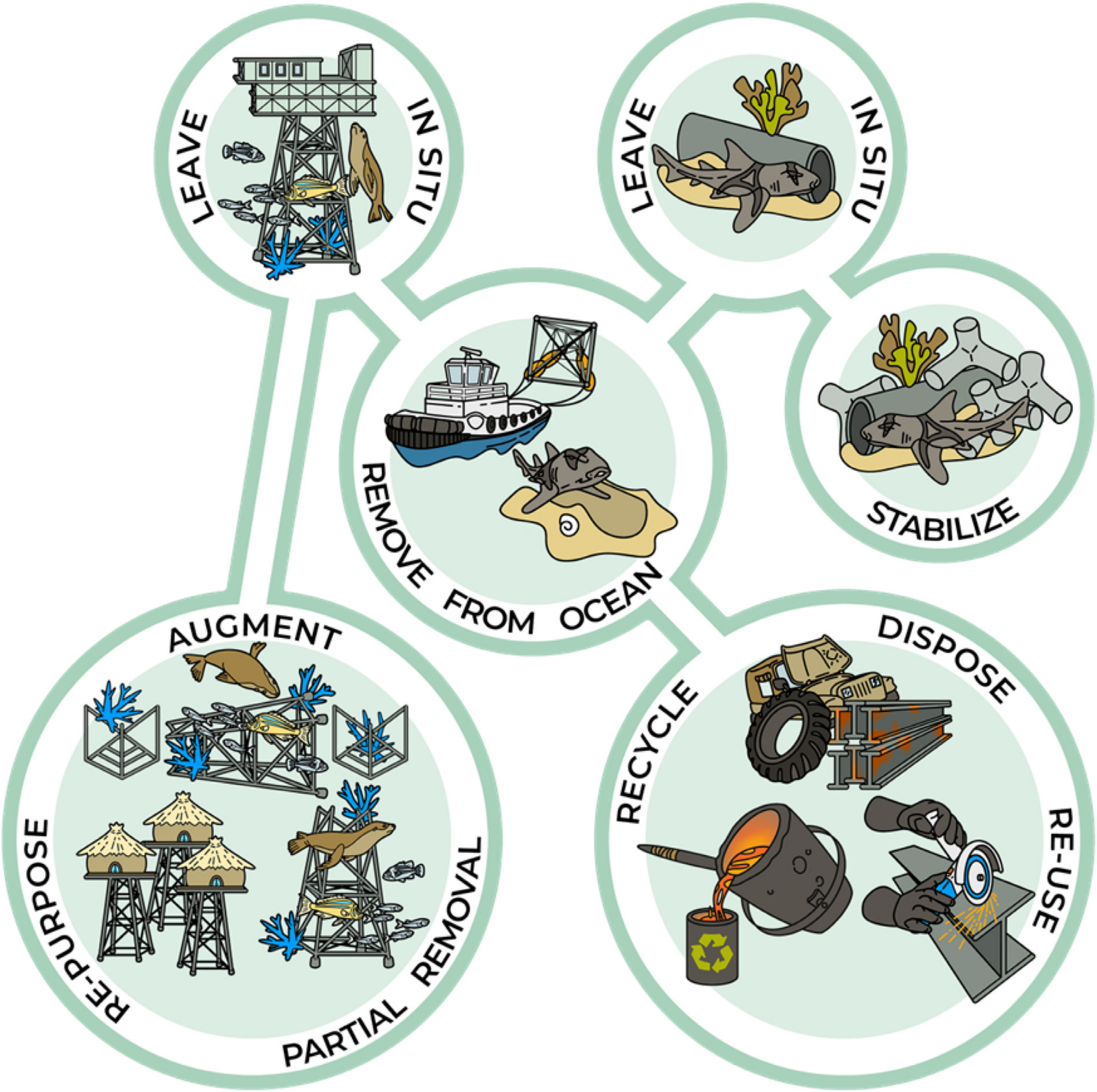

**Fig. 2.** Range of alternative options for decommissioning offshore platforms and subsea pipelines. Not pictured here is the potential for augmenting any retained structures with purpose-built modules to enhance the 'reef'.

authority); or substantial involvement (e.g., chair) of an international industry association specialising in decommissioning. The aim of the expert selection process was to ensure representation across all geographical regions, fields of work, and technical disciplines, as applicable to offshore decommissioning activities (Fig. 3).

Based on these criteria, an invitation to participate was sent to identified experts ($n = 65$), from which $n = 35$ responded, providing: a list of the most important questions/research areas on decommissioning in their view, and a completed experience matrix, indicating offshore O&G decommissioning-related experience by geographical region(s), field(s) of work, and technical discipline(s). The disciplinary/technical background of the experts who provided responses for the horizon scan is provided in Fig. 4 and S-Tables 1,6.

The full list of collated questions ($n = 257$; from the 35 experts' responses; S-Table 3) were categorised into five disciplinary areas, 15 topics, and 38 sub-topics, grouped according to similarity by the project team leaders (SW, DM, EC, PM; S-Table 2). Categorised responses were subsequently presented to experts at an online workshop, where further discussion on the transdisciplinary nature of the topic, and how best to address within future research, was facilitated (S-Tables 2,3). Following the workshop, the experts voted ($n = 32$), providing their opinion of the most important sub-topics needing to be addressed by future research to fill critical knowledge gaps (S-Table 4). At this point, due to conflicting time commitments, three withdrew from the vote with their self-identified expertise representing East Asian Seas, South Pacific, and Global regions, and spanning all fields of work and technical disciplines. All votes were collated, and the sub-topics were ordered based on total numbers of votes (S-Table 5), which formed the consensus for the top ten research priorities (Fig. 4). The disciplines of experts voting on the top ten priority areas is illustrated in Fig. 4, with high proportions of the experts having environmental, and technical expertise, but with other disciplines also well represented (S-Table 6). For each research priority, a discussion of existing knowledge on the topic (and gaps within) is provided, together with a recommendation for research to acquire knowledge as necessary to inform the decommissioning decision-making process.

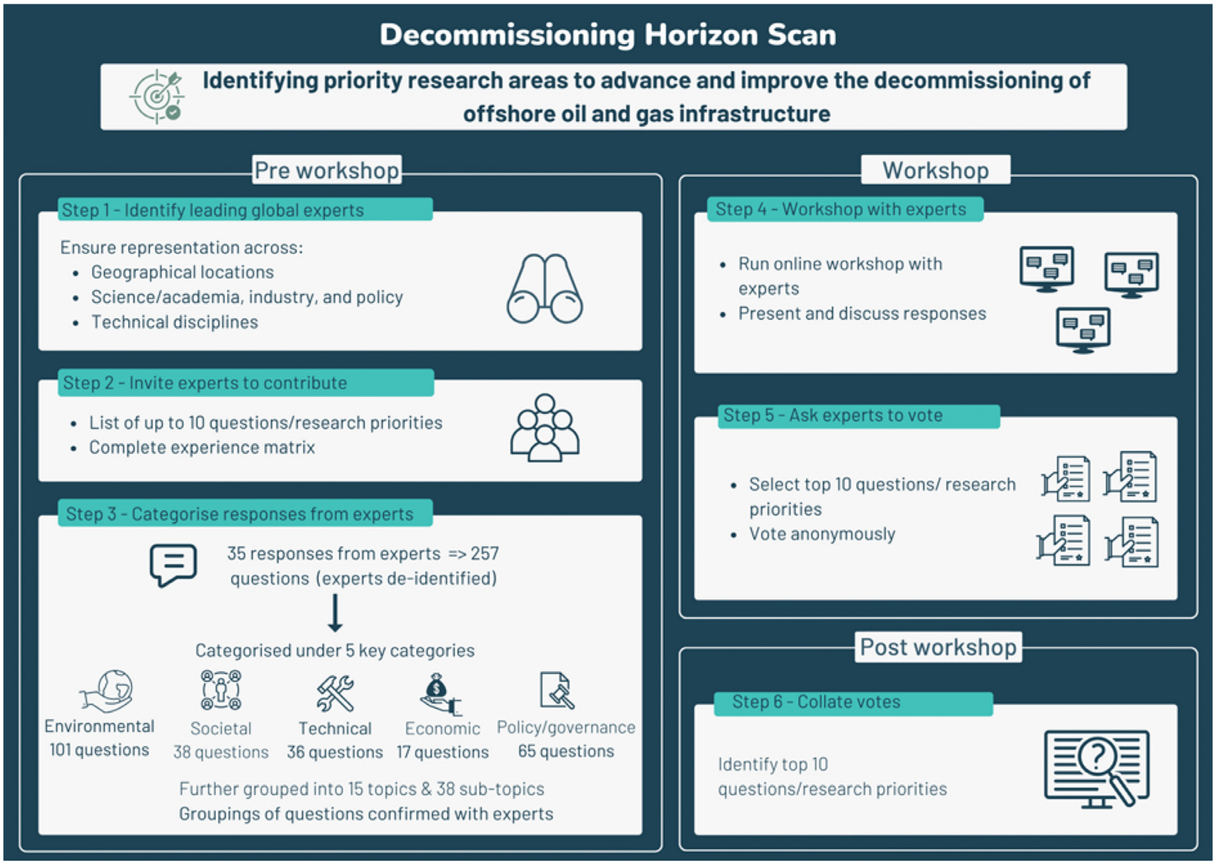

**Fig. 3.** Overview of the horizon scan process (as used by others, e.g., Sutherland et al., 2010).

## 3. Results & discussion: decommissioning research priorities

The top ten research priorities for informing decommissioning decisions and advancing our understanding of the potential impacts of different decommissioning scenarios is summarised in Fig. 5.

### 3.1. Contaminants

What contaminants could be released during decommissioning and what are their associated harmful impacts on marine organisms following exposure (at an individual and population level); and how should acceptable limits for concentrations of such contaminants be determined?

Contaminants may be released into the marine environment from various sources, either immediately or over time (10s to 1000s of years), as a result of decommissioning offshore facilities and their associated subsea infrastructure (Fig. 6). Such contaminants can include residual chemicals, remaining reservoir constituents, and Naturally Occurring Radioactive Materials (NORMs), which may be present as scales within production pipelines, and waste streams from flushing of processing equipment or pigging of pipes (Fig. 6). Residual trace contaminants may still be present even after cleaning and flushing procedures. Contaminant release can also originate from metals within degraded infrastructure from slough and reinforcing fibres, flaking anti-fouling paint, and other coatings such as polymers and corroded steel structures. In addition, metals and organic chemicals may be released through re-suspension of drill cuttings (mixtures of rocky material excavated around the well), and drilling mud, if present (MacIntosh et al., 2021; Melbourne-Thomas et al., 2021; Schläppy et al., 2021; Koppel et al., 2022). Whilst there are existing regulatory requirements that cover basic environmental protection from offshore waste and produced water, all contaminants need to be identified and assessed carefully as part of the risk assessment framework (e.g., OSPAR Commission, 2019).

During the life of subsea infrastructure (including well tubulars, seabed manifolds, rigid and flexible flowlines, and gas-export pipelines), contaminants may form as scales or films on the inside surfaces of this infrastructure (Schmidt, 2000; Yang et al., 2020; Koppel et al., 2022). Flowline scales dominated by barite ($BaSO_4$) and calcite ($CaSO_4$) may contain NORM radionuclides of the $^{238}U$ and $^{232}Th$ decay series, predominantly $^{226}Ra$ and $^{228}Ra$ respectively, which may co-precipitate with barite and calcite. Such NORMs may exist for 1000s of years and decay into a series of radionuclides with differing chemical (i.e., influencing solubility and bioavailability) and radiological dose (i.e., depending on the radionuclide and dosimetry) characteristics (Koppel et al., 2022).

Mercury (Hg) may also form in subsea-production tubing, especially in gas-export pipelines/trunklines, where gaseous mercury is separated from liquids and solids within topside infrastructure and follows the hydrocarbon gas pathway. Where export pipelines are uncoated internally, mercury may precipitate on corroded-steel surfaces, often resulting in relatively insoluble mercuric sulfide (HgS; cinnabar or metacinnabar) contamination (Kho et al., 2022). Decay products of radon ($^{222}Rn$), such as lead ($^{210}Pb$) and polonium ($^{210}Po$), may also be present on the uncoated internal surfaces of gas-export pipelines.

Current knowledge of these contaminant sources and their ecotoxicological impacts on marine organisms following exposure is in its infancy (Melbourne-Thomas et al., 2021; Schläppy et al., 2021; Gissi et al., 2022; Koppel et al., 2022). Furthermore, the spatial extent and temporal legacy of such contaminants has not often been studied, although there is evidence of drill cuttings impacting biological communities over 1 km away, and over timescales of decades (Henry et al., 2017). Understanding the long-term, site-specific environmental fate and consequence of these contaminants of primary concern is key to adequately assess risks from each of full removal, partial removal and leave in situ decommissioning options. Laboratory-based studies are required to generate data, especially for NORMs, which have received minimal

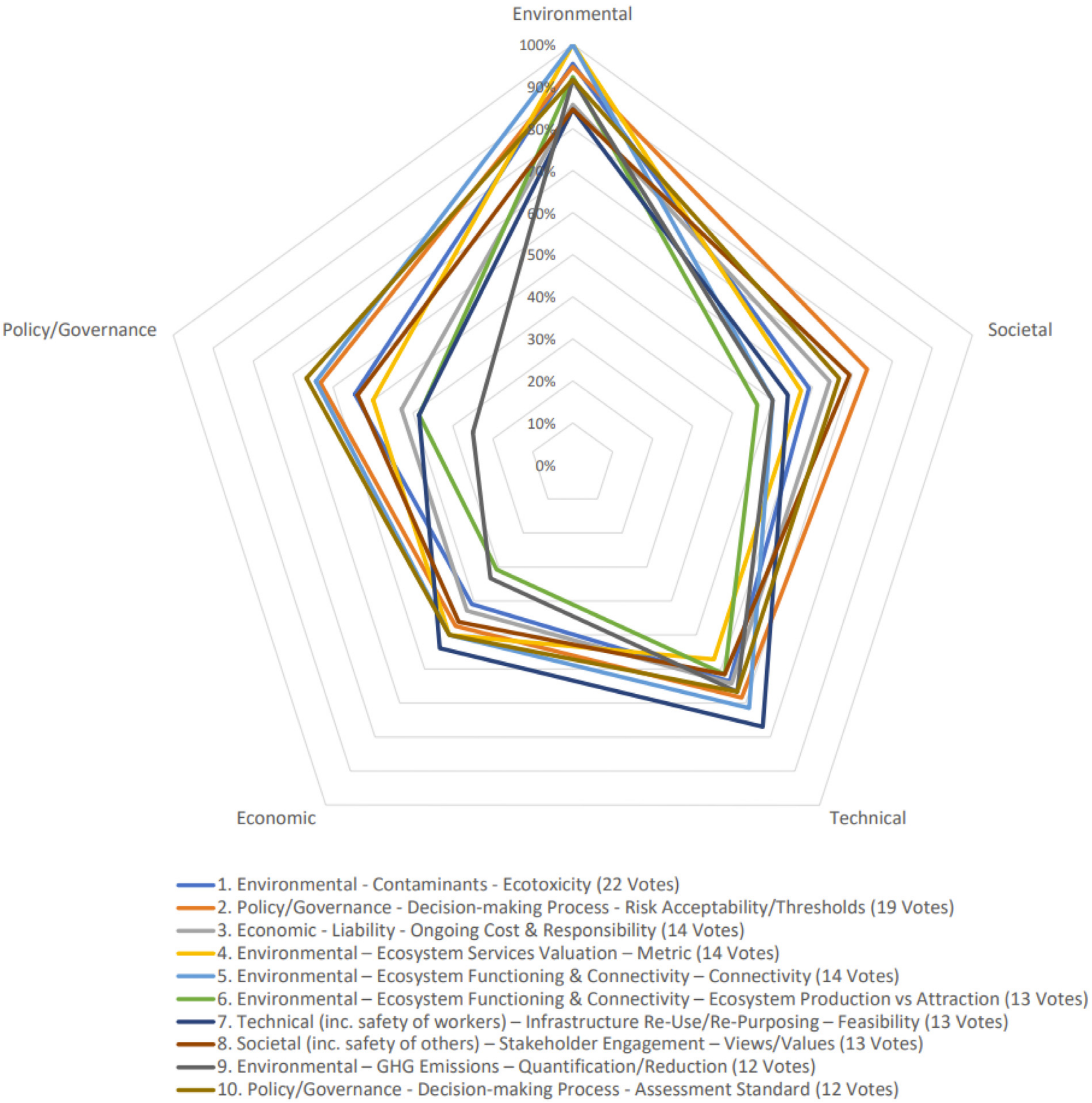

**Fig. 4.** Discipline background of experts for each of the top ten research priorities. For example, for research priority 1, 22 votes were received with 95 % of experts who voted claiming Environmental expertise, 59 % with Societal, 64 % Technical, 41 % in Economics and 55 % in Policy/Governance. Experts could nominate more than one discipline, as relevant to their area of expertise.

attention in marine systems (MacIntosh et al., 2021). Complementing such studies includes in situ investigations of before and after impacts of contaminant concentrations, pre- and post-removal, because such operations can re-suspend contaminants and a post-removal restart of seabed fishing at the site may increase resuspension of contaminants in local sediments. There is therefore a pressing need to understand what contaminants could be released during, and following decommissioning, and their associated impacts on marine organisms following exposure (at an individual and population level; Table 1). Further, research is needed to define acceptability levels (i.e., contaminant threshold concentrations), and how such levels should be determined, to inform decision making.

### *3.2. Risk acceptability & thresholds*

What thresholds should be applied when determining acceptable environmental, societal, technical, and economic risks and trade-offs for offshore structure decommissioning decisions-making, and how can these risks be quantified?

In making decisions regarding which decommissioning option is ‘better’ or ‘best’, a minimum threshold for environmental, societal, technical, and economic risks that are deemed acceptable needs defining; however, there is no globally-accepted method for how to quantify, nor qualify, the full range of potential risks requiring evaluation (Cormier et al., 2019; Hodgson et al., 2019; Elliott et al., 2020b; Martins et al., 2020). We note, however, that more restrictive requirements do exist under some jurisdictions (IOGP, 2017, 2021). Such as the North east Atlantic countries covered under the OSPAR Convention, where OSPAR Decision 98/3 prohibits the dumping, and the leaving wholly or partly in place, of disused offshore installations; however, leaving portions or all of an installation in place is permitted provided that a proper assessment (i.e., determining that leaving in situ is preferable to re-use, re-purposing or recycling or final disposal on land) is conducted and approved.

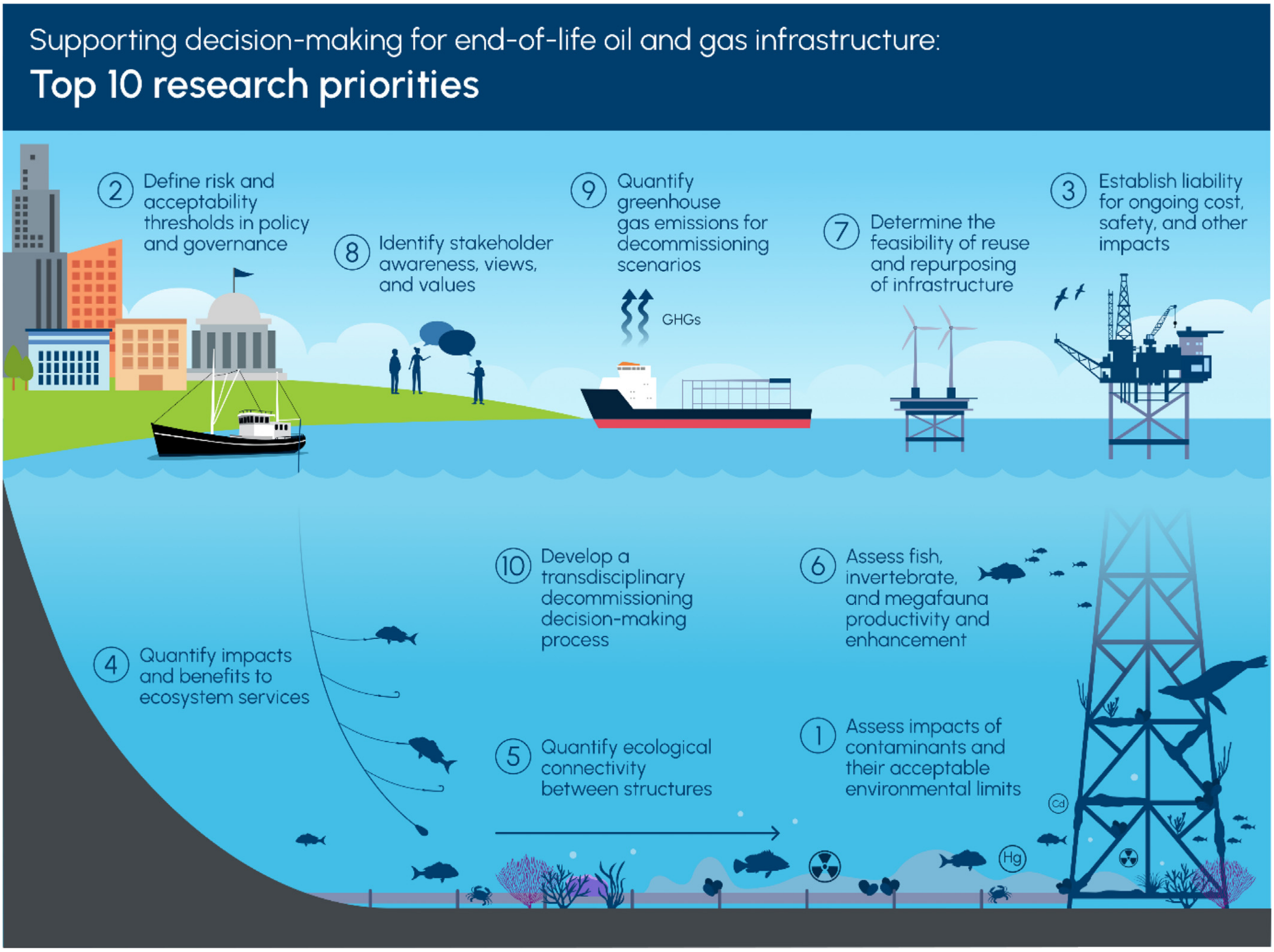

**Fig. 5.** Top ten research priority areas to inform decommissioning decisions and advance our understanding of their potential impacts.

Many environmental, societal, technical, and economic factors associated with offshore decommissioning activities do not have well defined baselines from which to measure potential impacts (Burdon et al., 2018; Cormier et al., 2019; Elliott et al., 2020b). This prevents development of a comprehensive understanding of risks associated with decommissioning activities (Elliott et al., 2020a; Elliott and Birchenough, 2022). Further difficulties arise in assessing these risks due to shifting baselines, as explained by Klein and Thurstan (2016).

(Un)acceptable levels of risk must be defined for the multitude of factors involved in decommissioning offshore structures, identifying parameters that are able to be measured and monitored. In order to do this, an accepted target or baseline must be pre-determined from which to judge a tolerable threshold for change, acknowledging this will need ongoing review due to changing baselines (Elliott et al., 2020a; Elliott and Birchenough, 2022). Without setting such thresholds, no comparable method can be relied upon to reject unacceptable decommissioning options (Gibbs and Browman, 2015; Cormier et al., 2019). Thus, identifying and quantifying acceptable environmental, societal, technical, and economic risk thresholds must be a priority for future research (Table 1).

A common approach to identify risk acceptability and thresholds that has arisen in frequency in recent years is through data analytics and machine learning (Martins et al., 2020; Vuttipittayamongkol et al., 2021). Vuttipittayamongkol et al. (2021) research, although developed from UK-specific data only, provides the wider industry a starting point for threshold identification and benchmarking guidance for such decisions.

### *3.3. Ongoing cost & responsibility*

What are the ongoing costs and responsibilities for maintenance and monitoring of re-used or disposed decommissioned structures, and where does liability hand-over occur and reside for the longer-term?

Determining the economic impacts related to decommissioning offshore infrastructure typically involves incorporation of immediate or short-term costs (Torabi and Nejad, 2021; Gourvenec et al., 2022). This generally includes the cost of full removal of structures (including transportation onshore for disposal, re-use, or re-cycling), making safe any remaining items (such as P&A of subsea wells and ensuring non-removed structures are below the seabed or secured from impacting others), and returning the seabed to its pre-activity state (Torabi and Nejad, 2021; Gourvenec et al., 2022). Industry also calculates costs of alternative approaches, such as relocating structures to a reefing location. These assets have the potential to provide a variety of economic benefits to society for hundreds of years, delivering a multi-generational flow of ecosystem service value over this period (e.g., Nicolette et al., 2023). However, ongoing, and longer-term economic impacts and benefits also need to be determined and considered within the offshore decommissioning decision-making process comparing full life cycle costs of an onshore disposal option against such alternative options. Such impacts and benefits vary substantially, depending on the post-decommissioned life of the structure, as will the responsibilities for future maintenance and monitoring. The associated ongoing costs are largely overlooked within current decommissioning

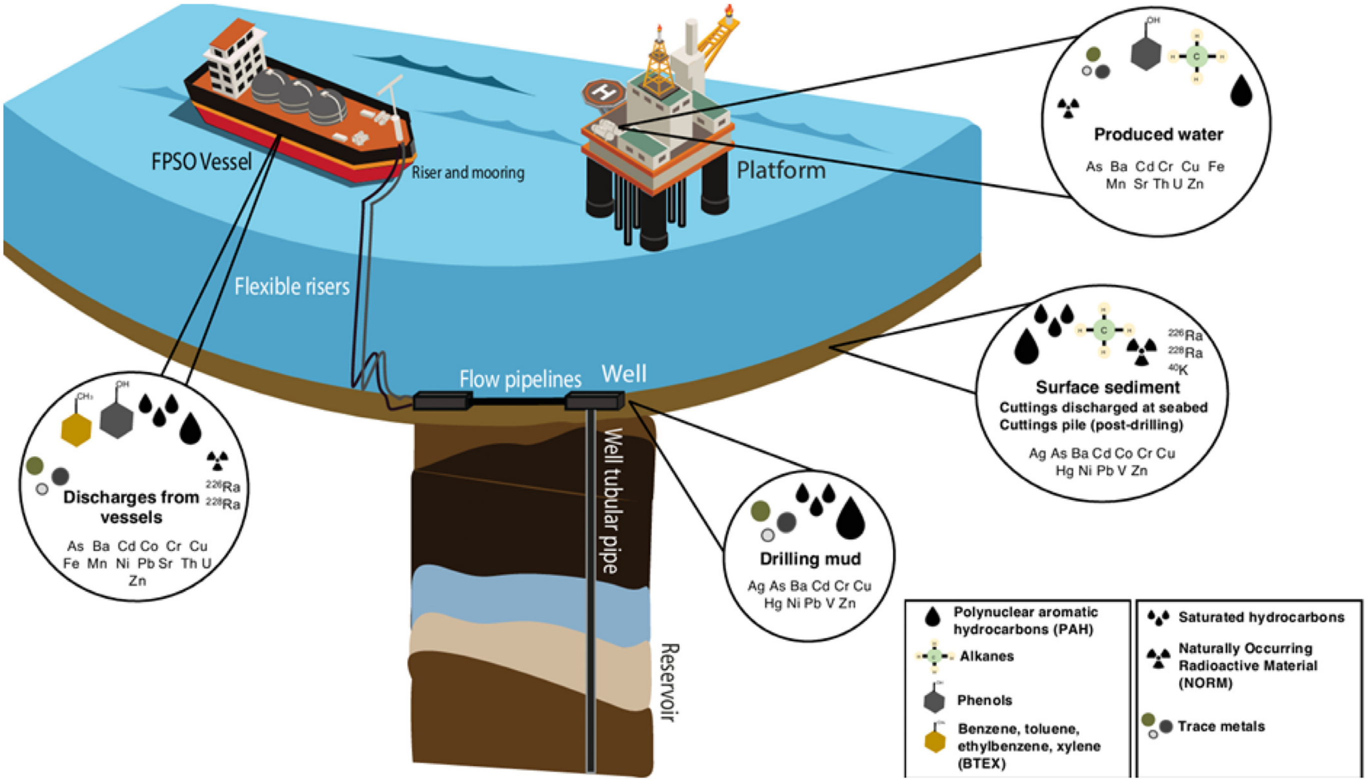

**Fig. 6.** Key environmental sources and offshore O&G associated activities related to potential release, discharge and/or accumulation of offshore petroleum-associated contaminants during operations that may be present at decommissioning. Adapted from MacIntosh et al. (2021).

decision-making processes due to a lack of knowledge and inconsistent or deficient regulatory guidance regarding requirements for and how to determine these factors (Torabi and Nejad, 2021; Gourvenec, 2022a; IOGP, 2022).

There are three main issues regarding liability: 1) ongoing costs of maintenance, monitoring or management of structures; 2) incidents that may occur that are associated with the structure; and 3) future decisions that may require changes in the end-state. For example, if a decision is made to leave infrastructure in place that is overturned 20 years later, necessitating removal, there can be significant cost repercussions and further, such decisions may create safety and logistical problems, especially if structures have degraded. Uncertainty exists within most legal regimes, as to when hand-over for liability occurs for such post-decommissioning and/or longer-term activities, together with responsibility for associated costs (Chandler et al., 2017; IOGP, 2017, 2021; Torabi and Nejad, 2021). Further definition of responsibilities is required to clarify various offshore structure decommissioning options and identify and understand implications for ongoing responsibilities for maintenance and monitoring of re-used, re-purposed or disposed decommissioned structures. This includes identifying liability hand-over point(s) (Table 1).

### *3.4. Ecosystem services & metrics*

What ecosystem services are gained or lost when decommissioning offshore structures; and can a metric be developed that assigns a value for such benefits/losses to aid comparability to social, technical, and economic impact?

Evidence of impacts resulting from anthropogenic activities, can inform the decommissioning decision-making processes. To achieve this, the ecosystem services gained or lost from different decommissioning options is required (Fowler et al., 2018; Fortune and Paterson, 2020; McLean et al., 2022). For example, hard structures provided by O&G may provide ecosystems with key habitat and improved foraging, or carbon sequestration (Blue Carbon) which would be lost with total removal of platforms. At present, few marine-based environmental impact assessments (EIAs) consider impacts on ecosystem services, with most conducted on a resource-by-resource basis, routinely addressing environmental and social resources separately. The integration of ecosystem services with EIAs has been attempted in several instances (e.g., Sousa et al., 2020) with limited success, attributed primarily to data gaps. Additionally, several values are not captured effectively by ecosystem services, leading to development of alternate schemes such as the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) and Nature's Contributions to People (Drakou et al., 2017; Díaz et al., 2018).

A series of EIA-associated tools account for ecosystem services, including (as examples) the Millennium Ecosystem Assessment, the Economics of Ecosystem Services and Biodiversity (TEEB), the System of Environmental-Economic Accounting (SEEA), and the Common International Classification of Ecosystem Services (CICES), as noted by Sousa et al. (2020). Developments in quantifying marine ecosystem services include the ocean-accounting process (Chen et al., 2020; Gacutan et al., 2022). However, these are high-level tools, and further targeted work is required to understand how these frameworks can be applied to decommissioning and its impacts. SSEA could potentially be adapted to develop metrics that aid a quantitative comparison between decommissioning options (Elliott et al., 2020b). This would enable evaluation of trade-offs between environmental, societal, technical, and economic impacts; increasing the transparency of the decision-making process (Burdon et al., 2018; Sommer et al., 2019; Van Elden et al., 2019).

Research into offshore infrastructure-related ecosystem services should also focus on methods that capture the changes in environmental, societal, and economic value. For example, offshore subsea structures may sustain significant secondary-fish production (Claisse et al.,

**Table 1**

Top ten research priorities and the outcomes that may be achieved via targeted research to address them.

| Research priority area | Research questions | Research activities/objectives to inform decision making |
|---|---|---|
| 1. Environmental > Contaminants > Ecotoxicity | What contaminants could be released during decommissioning and what are their associated harmful impacts on marine organisms following exposure (at an individual and population level); and how should acceptable limits for concentrations of such contaminants be determined? | Improved understanding of acceptability levels for contaminants |
| 2. Policy/Governance > Decision-Making Assessment Process > Risk Acceptability/Thresholds | What thresholds should be applied when determining acceptable environmental, societal, technical, and economic risks and trade-offs for offshore structure decommissioning decisions-making; and how can these risks be quantified? | Better define standard method for quantifying risk acceptability and threshold limits |
| 3. Economic > Liability > Ongoing Cost & Responsibility | What are the ongoing costs and responsibilities for maintenance and monitoring of re-used or disposed decommissioned structures; and where does liability hand-over occur and reside for the longer-term? | Define liability framework for ongoing costs and responsibilities |
| 4. Environmental > Ecosystem Services Valuation > Metric | What ecosystem services are gained or lost when decommissioning offshore structures; and can a metric be developed that assigns a value for such benefits/losses to aid comparability to social, technical, and economic impact? | Aid quantitative comparisons of impacts, supporting evidence for trade-offs |
| 5. Environmental > Ecosystem Functioning & Connectivity > Connectivity | How does offshore O&G infrastructure influence movement patterns of mobile and sessile species; and how would this be impacted by different decommissioning scenarios? | Understand offshore structure ecosystem connectivity impacts |
| 6. Environmental > Ecosystem Functioning & Connectivity > Ecosystem Production vs Attraction | What is the contribution that breeding fish and invertebrate species on offshore structures make to regional net-reproductive output and populations elsewhere? | Quantify offshore structure productivity impacts |
| 7. Technical (inc. safety of workers) > Infrastructure Re-Use/Re-Purposing > Feasibility | What potential re-use/re-purposing options exist for different offshore infrastructure; and which of these options have a design standard suitable for the re-used structure? | Understand response of structures and seabed beyond design life and define engineering design standards for feasible offshore structure re-use/re-purposing scenarios |
| 8. Societal (inc. safety of others) > Stakeholder Engagement > Views/Values | Do stakeholder views/values differ for different decommissioning options; what views/values are location- or structure-specific; and what views/values are based on scientific evidence vs perception? | Define stakeholder views/values to aid quantification of impacts |
| 9. Environmental >Greenhouse Gas Emissions >Quantification/Reduction | Is there a standard method for calculating the carbon footprint for structure decommissioning activities (including potential carbon sequestration) to ensure consistency with global climate change reporting requirements; and if not, what should be included within such standard? | Define standard method for calculating pre- and post-decommissioning carbon footprints |
| 10. Policy/Governance > Decision-Making Assessment Process > Assessment Standard | Is there a standard transdisciplinary decision-making assessment process from other industries that can be adapted/applied to decommissioning decisions for offshore structures; and if not, what is needed to develop one? | Define assessment standard to holistically assess decommissioning impacts (including evaluations of trade-off) |

2014, 2015; Champion et al., 2015), supporting apex predators (Todd et al., 2009), such that removal could result in hundreds of years of lost secondary-fish production. Further, incorporation of important secondary habitats, such as shell mounds around platforms which are known to be particularly diverse (Page et al., 2005; Meyer-Gutbrod et al., 2019), into ecosystem service evaluations should occur. Where removed, these ecosystem services losses can, in turn, affect socioeconomic values over multiple generations.

Given the breadth of ecosystem services associated with offshore habitats (Barbier, 2017; Layman and Allgeier, 2020; Buonocore et al., 2021), understanding the key metrics that differentiate between decommissioning options is essential (Nicolette et al., 2013b). In some arenas, e.g., Natural Resource Damage Assessments (NRDA) in the U.S. (Nicolette et al., 2023; although not a tool specifically for decommissioning), surrogate/proxy metrics are identified by stakeholders that reflect the flow of habitat-based ecosystem services and are used to evaluate changes in value over time (Efroymson et al., 2004). A net environmental benefit analysis (NEBA) comparative assessment approach has recently been adapted to offshore decommissioning (Nicolette et al., 2023), and related analyses have been applied to subsea structure decommissioning option decision making for sites in Australia, California, Caribbean, Gulf of Mexico, Gulf of Thailand, and the North Sea (IOGP, 2022; Nicolette et al., 2023). Use of surrogate/proxy metrics, within a service-to-service approach to represent the overall flow of ecosystem services, has been applied to support decision making for damage-assessment cases in the United States (Chapman et al., 1998; Chapman and LeJeune, 2007; Nicolette et al., 2013b, 2023). The European Union Environmental Liabilities Directive (EU ELD) also gives preference to service-service approaches in evaluating resource injury and compensatory restoration (Nicolette et al., 2013a).

### 3.5. Ecological connectivity

How does offshore O&G infrastructure influence movement patterns of mobile and sessile species; and how would this be impacted by different decommissioning scenarios?

The long-term presence of offshore structures influences ecological diversity, productivity, and connectivity through movement and dispersal (Henry et al., 2017; Sommer et al., 2019; Schläppy et al., 2021; McLean et al., 2022). Influence on species movement can be negative, for example, by facilitating the spread of invasive species across a region (Sammarco et al., 2012; Pajuelo et al., 2016; Anderson et al., 2017). Additional potential negative consequences concern emissions of sound, vibrations and light from structures which may alter natural migration pathways. On the other hand, presence of O&G structures in marine ecosystems may extend foraging opportunities for mobile species such as Australian fur seals (*Arctocephalus pusillus doriferus*, Arnould et al., 2015) and harbour porpoise (*Phocoena phocoena*, Todd et al., 2022). Further, concentrated presence of offshore assets could contribute to regional fisheries where infrastructure is an important source population (see Research Priority 6). Removal of infrastructure, particularly multiple structures and where these have been in place for decades, would likely have large impacts on some species movement patterns by altering the underlying reasons for such species being present or visiting these structures in the first instance (e.g., removal of habitat, foraging opportunities).

A recent review identified key research priority areas across the broad topic of connectivity (McLean et al., 2022), and indicated a need to determine how offshore structures influence movement patterns of fish and other marine vertebrates, and how they enabled connectivity of sessile biota. It is this gap that research needs to address to better inform offshore decommissioning decision making and minimise impacts to these species (Table 1). At present, we have limited knowledge of how O&G structures and their local ecological processes interact with the ecosystem at broader temporo-spatial scales. This has largely arisen through an absence of long-term monitoring data that has been collected throughout the life cycle of installations. Consequently, it is extremely difficult to determine the degree to which these structures represent beneficial or detrimental (or both) net impact and potential impacts of different decommissioning options. Such long-term monitoring should be instigated for all offshore structures, including those supporting the offshore renewable industry, to understand their impact on populations and connectivity to support eventual decommissioning decision-making.

### 3.6. Ecosystem production vs attraction

What is the contribution that breeding fish and invertebrate species on offshore structures make to regional net reproductive output and populations elsewhere?

Subsea anthropogenic infrastructure acts as artificial reefs (Todd et al., 2018; Love et al., 2019), providing structurally complex hard substrata for reef-associated species and settlement of sessile species (Leitao et al., 2007; Coolen et al., 2020; Simons et al., 2016). The high vertical relief of O&G structures enable access to the flux plankton (Champion et al., 2015) which in turn contributes to benthic production (Reeds et al., 2018; Puckeridge et al., 2021). There is therefore often a higher abundance of important fishery species compared to surrounding, often sand-dominated habitats (Meyer-Gutbrod et al., 2020; McLean et al., 2022). Fish production on O&G structures can be an order of magnitude greater than that of adjacent soft-bottom habitat (Meyer-Gutbrod et al., 2020) or lower relief natural rocky reefs (Claisse et al., 2014; Smith et al., 2016). Further, some proportion of the adult fishes produced by the structures likely emigrate (Love et al., 2019), potentially to other reef habitats further away (Lowe et al., 2009). However, the magnitude of these contributions to regional scale fish populations and fisheries are not well established. Doing so is challenging, as a regional scale increase in fishery production resulting from an artificial reef complex requires multiple years of fishery data from pre- and post-installation at the appropriate spatial scales (Roa-Ureta et al., 2019). For O&G structures installed decades ago, these data are typically unavailable. This is where the production-attraction debate is relevant (Bohnsack and Sutherland, 1985; Bortone, 1998, 2006).

The production-attraction debate refers to whether fish are merely attracted to an artificial structure or if the structure enhances fish production, and likely both occur at varying degrees over time. For example, it has been shown that rapid 'attraction' of fish communities occurs after only a few days after a new platform is installed (e.g., Todd et al., 2020), with the switch to 'production' of commercially important fish and invertebrates, and marine mammals, in only a couple of years (Todd et al., 2021, 2022). While attraction to a structure effectively redistributes existing production (Smith et al., 2015), this is only a net negative if the organisms then become more vulnerable to a fishery or if the structures cause lower survival, growth, or reproductive rates (Reubens et al., 2013). Enhancement refers to the creation of new, or relatively higher rates of, fish production resulting from the presence of the structure (e.g., Reubens et al., 2013, 2014; Claisse et al., 2014; Smith et al., 2016). Where infrastructure has been installed in predominantly sandy, oligotrophic habitats where reef environments are rare, infrastructure provides additional hard substrata that can potentially increase the carrying capacity of organisms that utilise such habitats (Leitao et al., 2007; Coolen et al., 2020; Simons et al., 2016). Answering the attraction versus enhancement question requires detailed knowledge of species biology, their movement at a range of temporo-spatial scales, fishing rates and, ideally, an understanding of population dynamics over time (McLean et al., 2022). Seemingly simple questions such as 'how resident is species x on this platform?' can be challenging to answer definitively, with numerous predictions and assumptions often needing to be made (e.g., Smith et al., 2015).

Understanding the level of reproductive output from populations on infrastructure and how important this is to a region (e.g., to populations elsewhere, to fisheries) remains a significant knowledge gap (Claisse et al., 2019; Fortune and Paterson, 2020; Fowler et al., 2020; Schläppy et al., 2021) (Table 1). Such assessments should consider the amount of time these structures have been in place and the extent of connectivity between fish populations on the structures and the broader ecosystem, as structure removal may have impacts beyond fish populations on the structures themselves, and subsequently on fisheries.

### 3.7. Re-use or re-purposing feasibility

What potential re-use options exist for different offshore infrastructure; and which of these options have a design standard suitable for the re-used structure?

Due to the many hazards involved in dismantling and re-using, re-purposing or disposing of offshore infrastructure onshore, the possible alternatives for re-purposing (Chandler et al., 2017; Sedlar et al., 2019; Gourvenec, 2018; Gourvenec et al., 2022), for offshore wind farms, aquaculture, or recreational fishing is important.

As outlined in Fig. 1, alternatives to complete removal are a) leave in situ, b) partial removal and relocation offshore, c) partial removal and in situ decommissioning, and d) partial removal, in situ decommissioning and augmentation. The technical aspects of physically carrying out any of these operations can present similar challenges. Key new technical issues influencing the feasibility of re-use of offshore infrastructure include, inter alia, understanding the practical extent of extrapolation of material and long-term/ongoing structure integrity beyond the original design life; mitigating or avoiding infrastructure dispersing into the water column in either large or small parts;, assessing the effect of evolving seabed profile and properties on infrastructure stability beyond its original design life or at another location (Gourvenec and White, 2017); and, optimising design of purpose-build 'reef' augmentation structures for ecological benefits (alongside ensuring structural stability and integrity) (e.g., Florisson et al., 2020). Other challenges include the feasibility of technology to assess, clean up and monitor hazardous constituents, hazardous substances, or hazardous contaminants in situ. Any new or amended use for decommissioned offshore structures requires a new or amended engineering design and maintenance plans to ensure it is suitable and safe for its re-purposed use (Gourvenec, 2018; Leporini et al., 2019; Colaleo et al., 2022b), and that the structure will not create a hazard as it inevitably degrades or collapses. A further key technical enabler for re-use of offshore infrastructure is therefore the inclusion of relevant design methods, i.e., solutions, processes, and methods, in international engineering standards and recommended practices.

The associated risk profiles of a structure's original design life, its condition at the time of decommissioning, and its post-decommissioned design life could be vastly different, and it is critical this is accounted for within the decision-making process (Chandler et al., 2017; Sedlar et al., 2019; Gourvenec and White, 2017; Gourvenec et al., 2022).

There are a range of specific research questions that need to be addressed to assess the feasibility of re-use/re-purposing options for offshore structures (Table 1). These include understanding:

- how different materials, substances and structures decompose/degrade in large or small parts over decades or centuries beyond their initial design life (Melchers, 2006; Paik and Melchers, 2014; Rosen et al., 2015);
- how different seabed sediments evolve over time frames relevant to offshore infrastructure decommissioned in situ, and how loading imposed on the seabed from the decommissioned infrastructure may affect the seabed profile and properties − in turn influencing the stability and integrity of the structure (Gourvenec and White, 2017; Gourvenec, 2022b);
- how the marine environment, epibenthic communities (marine growth) and other fauna impact (positively or negatively) the stability

- or integrity of decommissioned offshore infrastructure (Leckie et al., 2016);
- how augmentation structures can be engineered to contribute the most benefit to the ecosystem in which it resides;
- the technology required to assess and clean (or contain) hazardous substances for offshore decommissioning;
- the technology required to monitor the impact of our interventions on the ocean environment for the long term;
- the technology required to pursue recycle, re-purpose and re-use opportunities for infrastructure that is recovered to shore; and
- the testing and validation required in order to achieve confidence of the sector and inclusion in industry standards (Table 1).

There are numerous additional research needs, e.g., understanding how infrastructure left in situ may pose navigational or safety hazards and if these may change over time due to degradation or sedimentation; with these not included here as they more closely align with the research priority #12 (S-Table 5).

### 3.8. Societal views & values

Do stakeholder views and values differ for different decommissioning options; are they location- or structure-specific; and are they based on scientific evidence or perception?

Dialogue around decommissioning is not new, yet public attitudes and perceptions of decommissioning options are not fully understood, with limited studies conducted to date (see for example, Jørgensen, 2009, 2012, 2013; Ounanian et al., 2020; Elrick-Barr et al., 2022). Public perception can be also heavily influenced by disasters and contentious decommissioning cases, such as Brent Spar, which led to an overhaul of rules associated with disposal of installations (Osmundsen and Tveterås, 2003; Brownless and Paterson, 2004; Jørgensen, 2012; Ounanian et al., 2020). An understanding of values and perceptions across all stakeholder groups regarding the benefits and impacts of decommissioning offshore structures is vital for making informed decisions that are accepted by stakeholders and wider society, reflecting recent trends in other areas of ocean management (e.g., Röckmann et al., 2015; Birchenough and Degraer, 2020; Ounanian et al., 2020; Tung, 2021) (Table 1).

A recent review of the social and economic values of stakeholders regarding the benefits of offshore structures, found that these are informed by both perceived and actual benefits (Elrick-Barr et al., 2022). Risks and opportunities involve a combination of social (material, relational and subjective) and economic (use and non-use) values. Ounanian et al. (2018) discussed how knowledge frames shape stakeholders' interpretations of a problem and solution, which can lead to conflicts impeding collective action to address the problem.

Meaningful stakeholder engagement to gather insights, views and values relating to decommissioning is a fundamental component of other identified research priorities, including, ecosystem service valuation (see Research priority 4) and developing acceptable risk thresholds (see Research priority 2). Following this, it remains to be determined how views and values can be incorporated effectively within an objective multi-criteria decision assessment (Martins et al., 2020; Gourvenec et al., 2022), which is discussed under Research priority 10.

Stakeholder consultation is a key component of the impact assessment process within many countries and is required to be undertaken prior to decommissioning activities (Beckman, 2013; Lyons, 2014; Trevisanut, 2020). A desktop review of methodologies and assessment outcomes undertaken for existing offshore decommissioning activities could be a place to start for collating such views and values, as needed within future research to address this gap. Further, those working in the decommissioning space should draw on the expertise of marine social researchers and those experienced in stakeholder engagement, potentially including those from outside the decommissioning research and practitioner community, to ensure best practice is adopted. Crucially, it should be recognised that there will not be 'one size fits all' interpretation of stakeholders' views and values as they will vary with differing social, economic, cultural, geographical, and environmental contexts (Jefferson et al., 2015). Research is therefore required to understand what factors influence perceptions and attitudes towards decommissioning, and to identify meaningful pathways to policy and decision-impact for decommissioning (McKinley et al., 2020) (Table 1).

### 3.9. Quantification & reduction of greenhouse gas emissions

Is there a standard method for calculating the carbon footprint for structure decommissioning activities (including potential carbon sequestration) to ensure consistency with global climate change reporting requirements; and if not, what should be included within such a standard?

Decommissioning of offshore O&G infrastructure, while contributing a relatively small portion of greenhouse gas (GHG) emissions in comparison to its full life cycle, still needs to be evaluated in terms of its contribution to the global goal of reaching Net Zero GHG emissions by 2050 (Watson, 2020; Davies and Hastings, 2022) (Table 1). The boundary of a net-zero target includes global Scopes 1 (direct), 2 (indirect) and 3 (supply chain) emissions of the organisation in question. To quantify emissions associated with decommissioning an offshore structure, various sources need to be considered, including the emissions associated with post Cessation of Production (CoP) power generation, flaring and venting, offshore vessel operations and transportation, well decommissioning, onshore deconstruction, onward transportation, and the treatment and recycling of waste onshore. Any positive contributions towards net-zero goals, such as carbon sequestration potential of marine ecosystems formed around offshore structures decommissioned in situ, should also be considered (Cantle and Bernstein, 2015; Fowler et al., 2020; Davies and Hastings, 2022).

To evaluate these parameters, a clearly structured and standardized method for calculating GHG emissions for decommissioning offshore structures is required that takes into consideration the applicable local, national, and global requirements, as well as how transboundary considerations should be addressed (Fowler et al., 2020; Davies and Hastings, 2022) (Table 1). Such an effort would require a comprehensive analysis defining all sources of GHG emissions during decommissioning activities, the majority of which are generated by the supply chain and represent Scope 3 emissions. That is, a combination of all vessels, helicopters, and internal combustion-based equipment used within each decommissioning option, together with their associated operating specifications, fuel requirements, emissions profiles, and totals of all emissions from the processing of various wastes, including marine growth (Cantle and Bernstein, 2015). In addition to this, qualitative analysis of all sources of GHG emissions potentially sequestered should be undertaken (Fowler et al., 2020; Davies and Hastings, 2022). Combining these analyses would result in a net-carbon footprint being identified for each decommissioning option or project being evaluated (Table 1) following a transparent and standardized approach.

### 3.10. Transdisciplinary decommissioning assessment standards

Is there a standard transdisciplinary decision-making assessment process from other industries that can be adapted/applied to decommissioning decisions for offshore structures; and if not, what is needed to develop one?

Many peer-reviewed studies have evaluated the suitability of existing decision-making assessment processes for the decommissioning of offshore structures (such as, Comparative Assessments, Multi-criteria Decision Assessments, Life Cycle Assessments, amongst others, e.g., Fowler et al., 2014; Martins et al., 2020; Capobianco et al., 2021; Colaleo et al., 2022a; Lemasson et al., 2022; Vidal et al., 2022). A common finding of these studies is that the multitude of factors involved with offshore decommissioning have not, to date, been considered comprehensively. This is due to both missing information (knowledge gaps) and complexities of assessing linked but transdisciplinary issues combined with the ambiguity, or 'knowing differently' of stakeholder views (van den Hoek, 2014; Brugnach et al., 2008;

Floor et al., 2018; Ounanian et al., 2018). Further, the site-specific nature of marine resources found in association with offshore installations varies significantly both within and between geographic regions, further complicating our ability to assess potential loss (via removal) of environmental and social value and ecosystem services (e.g., Downey et al., 2018). The 'what is needed to develop one' component of this 10th priority can be informed by achieving the research priorities identified in this current paper and perhaps this important priority cannot be addressed properly without such additional knowledge.

## 4. Conclusion

The horizon scan presented in this paper identified research priorities to support decision-making for end-of-life of O&G and could be widely applicable to other artificial structures. Priorities reflected a range of environmental, technical, policy/governance, societal, and economic challenges based on views of 35 experts operating across the major global offshore O&G jurisdictions, covering a range of technical disciplines (e.g., environmental sciences, life, physical and social sciences, engineering), and spanning representative viewpoints from key sectors (i.e., policy, industry, and academia). On completing this study we reflect that priorities of experts are quite focussed on decommissioning in-situ topics and suggest this likely reflects both a common 'base-case' for full removal (therefore less information required for approvals) and a general lack of knowledge with respect to in-situ impacts and implications.

Environmental considerations and potential impacts were identified as the most common (five out of ten) and highest-ranked (#1) research priorities, and included: contaminants, ecosystem service valuation, ecosystem function, ecological connectivity, and GHG emissions. Policy, governance, technical and societal considerations also made their way into the top ten research priorities, and included improvements to guide the decision-making process, better stakeholder engagement, clarity around financial liabilities, and feasibility of repurposing structures.

Research priorities were placed into a top ten list for manageable review, but do not dismiss the importance of research suggestions that fell outside this list. Those coming in at numbers 11 and 12 were very close in terms of number of votes to number ten (S-Table 5). These included 'Environmental – Contaminants – Distribution' and 'Societal – Impact on Others – Marine Users'. Priority number 11 captured the thoughts and priorities of experts with respect to a need for understanding how contaminants are released, distributed, and persist and the factors influencing these processes (e.g., temperature, pressure, biota). Research priority 12 was around a need to understand the ongoing extent and nature of interactions between other users (shipping, fishing, public) and any retained infrastructure with consideration of issues associated with potential collisions, entanglements, and other interactions (e.g., contaminants). We encourage readers to scan the full list of research priorities that can be found in S-Table 5.

Other important considerations did not arise through the horizon scan process but emerged as a result of consideration of transdisciplinary priorities. For example, how is it possible to weigh the environmental impact of decommissioning offshore against the environmental impact of onshore disposal? Does or should in situ decommissioning be less damaging to the environment (holistically) than an onshore alternative? While these aspects may be considered during a Comparative Assessment, an appropriate quantitative method for such comparisons has not, to our knowledge, been published.

The research priorities varied in terms of level of resourcing required, duration, and predictability of outcomes. For example, some research priorities were straightforward, well-known to all sectors, and are supported currently by research investment. Others were 'on the horizon', lacking investment, and highly uncertain in the risk-return ratio for research effort. Since these issues were common to all geographic regions, there is good sense in operators and other parties working together to share costs and other responsibilities to address these research questions.

Although we categorised research priorities into disciplines, most were transdisciplinary in nature, and thereby highlighted the need to avoid working in discipline/sector silos. For example, the highest ranked priority was contaminants (ecotoxicity), and was classified as an issue affecting the environmental discipline, but it also underpinned the second highest ranked priority, which was the decision-making process concerning acceptable thresholds and risks and was classified in the policy/governance discipline. This is the case with most research priorities; they are global, complex, cross-sector, interdependent, and transdisciplinary.

Our roadmap for future decommissioning research, goes beyond the current issues and concerns across decommissioning activities. It is effectively 'an authoritative consensus plan' for research that will inform decision making. While this paper provides a starting point, the challenge will be executing this complex, transdisciplinary research plan. Significant funding will be needed, backed by a community of practice (spanning industry, government, and academia) committed to transparency, sharing of information (including data), coordinating research efforts, and regular interaction. Some examples of these types of data sharing have proven a useful starting point under the recent UK INSITE data initiative, bringing the O&G sector to support applied research (Murray et al., 2018).

Action is needed as the number of structures due for decommissioning is increasing and will persist to the end of the century given current predictions for offshore hydrocarbon developments. In reality, many decisions will have to be made with limited understanding of the consequences whilst ensuring flexible policy frameworks are in place that can be agile to emerging evidence. However, if in the future we wish to reflect on a 'history of good decision making', then we must dramatically increase the intensity, scale, and trans-disciplinarity of our research efforts.

## CRediT authorship contribution statement

SW, DM, PM conceived the idea; SW conducted the literature search and analysis of results; SW, EC, AM, SG, prepared figures with input from DM, PM. SW reviewed the literature while DM led the first incomplete draft of the manuscript. All authors were involved in data creation (questionnaires, workshops) as well as reviewing and contributing to the writing of the manuscript.

## Data availability

Data will be made available on request.

## Declaration of competing interest

Watson (first author) – received funding from the National Environmental Science Program (NESP)

Marnane (co-author) – is an employee of Chevron Technology Energy

Fokkema (co-author) – is an employee of Shell Global Solutions International

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## Appendix A. Supplementary data

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