



Marine renewable energy and cumulative effects assessments: Summary of the state of play

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ABSTRACT

Cumulative effects result from interacting human activities across space or time, potentially involving multiple sectors, which can affect ecosystem components. Cumulative effects assessments (CEAs) systematically identify and evaluate the compound effects of multiple pressures that may occur within and across industries (and via interaction with climate change induced ecosystem shifts), causing large-scale environmental change. As offshore developments, such as marine renewable energy (MRE), expand there is increasing need for informative, robust cumulative effects assessments. These CEAs may come at great cost in terms of resources and data requirements, as well as the methodological challenges relating to the complex nature of ecosystem interactions. This paper provides a review of the current state of the science for MRE-relevant CEAs. While interest in CEAs has grown rapidly since 2000, data limitations often precluded quantitative approaches. The review highlights that MRE-related CEAs have so far used only a subset of the diverse toolbox of methods available, including expert elicitation, loop analysis, GIS-based techniques, and dynamic models. Developing MRE-specific considerations, addressing data gaps, refining assessments cost-effectively, and learning from integrated ocean management work remain important next steps. Critical research gaps identified include: the absence of standardized, jurisdiction-spanning approaches and terminology; insufficient methods for characterizing nonlinear and indirect cumulative effects; a lack of post-deployment validation of CEA predictions against realized outcomes; minimal accounting for interactions between MRE stressors and climate change; limited observational data on compound and cascading stressor-receptor interactions specific to MRE (e.g., impact-response relationships across life stages and at array scale); and the absence of regionally defined, ecosystem-specific indicator reference points for acceptable levels of effect. Addressing these gaps and additionally nesting project-level (proponent-executed) CEAs within strategic regional (government supported) frameworks, standardizing approaches and terminology across projects and jurisdictions, ensuring transparency in framing and in communicating assumptions and uncertainties, using predictive models where possible, and building centralized data infrastructure to reduce duplication are all needed to advance the impactful use MRE-related CEA. Applying lessons from other industries can help efficiently implement CEAs for MRE while avoiding past errors.

1. Introduction

Industrial and infrastructure developments have required cumulative effects assessments (CEAs) as part of project applications since the

inception of environmental impact assessments (Burris and Canter, 1997). While absolute requirements around CEAs have varied widely between countries, it is generally true that there has been little guidance on the form of CEAs in most jurisdictions, although there are some rare

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exceptions (JPI Oceans, 2024). This is despite their importance in avoiding future environmental or other (e.g., navigational) impacts, and the lack of historical guidance has led to uncertainty around conducting CEAs. Nonetheless, appreciation for rigorous CEAs is growing among researchers, practitioners, and regulators (Declerck et al., 2022).

Emerging industries such as marine renewable energy (MRE) have no explicit requirements or guidance for CEA, although some jurisdictions are beginning to require them (Caine, 2020). Typically, effects of MRE are measured one by one, such as potential effects of underwater noise, electromagnetic fields from power export cables, changes in habitats, or collision risk to marine animals from rotating tidal turbine blades (Garavelli et al., 2024). Little attention has been given to the effects that installing and operating MRE devices may add to existing anthropogenic or natural perturbations in marine systems, with potential cumulative or indirect effects that cannot easily be predicted from single observations or measurements.

Investigating cumulative effects in the marine environment, including those associated with MRE, addresses the UN Sustainable Development Goals (<https://sdgs.un.org/goals>) particularly Goal 7 (Affordable and Clean Energy) by facilitating the responsible development of marine energy. In addition, MRE can support Goals 13 (Climate Action) and 14 (Life Below Water), as well as Goal 10 (Reduce Inequalities) as MRE has the potential to bring affordable energy to remote coastal areas and islands where conventional fuels contribute to decreases in public health, air quality, and water quality.

However, for MRE to reach its potential while avoiding unintended consequences - that could undermine SDGs and other sustainability objectives - the industry must use CEA well. The best way to do that is to leverage learning from other sectors, avoiding duplication of past effort as well as ad hoc sub-optimal implementation, and to identify MRE-specific gaps. The intent of this review is to provide the MRE industry with this basis. Information on CEA is often widely dispersed or focused on specific details of sub-assessments making a synthesis difficult to achieve. This review, and its recommendations, helps proponents and regulatory agencies alike access a coherent understanding of the current state of play, the MRE-specific gaps and where adoption of already well-developed methods from other sectors will save long development times and avoid implementation challenges that have already been conquered. Moreover, it positions MRE to extend CEA, advancing the field overall.

1.1. CEAs in the marine context

The dynamic nature of marine ecosystems and the rapid growth of marine industries make the challenges around, and need for, CEAs even greater. The marine environment is “fluid”, in that it is dispersive at a scale not observed for terrestrial environments. Furthermore, because of the diversity in life histories and ontogenetic shifts in marine flora and fauna, some marine ecosystems are particularly sensitive to disturbance. The broad range of current human users and the accelerating use of marine systems (Jouffray et al., 2020) makes these areas vibrant and diverse, but further complicates system dynamics. The fluid and interconnected nature of the marine environment multiplies the potential that cumulative effects will be felt in unpredictable ways. In sensitive marine ecosystems, the potential for cascading effects of stressors, including those introduced from anthropogenic forces such as offshore energy development as well as climate change, is high (Menden-Deuer et al., 2023). CEA is the most reliable means to begin to assess these potential risks. The result is that CEAs for marine infrastructure development are complex, especially as effects can be multifaceted – with social, cultural, economic, and environmental implications (Turschwell et al., 2023).

CEAs have historically focused on combined impacts of multiple projects of the same type (Hope, 2006; MacDonald, 2000). However, cumulative effects can also arise from different activities – such as MRE, offshore wind, fisheries, shipping - and interactions with physical phenomena (e.g., climate change). This is a motivation for a shift in the

thinking of resource management agencies towards a “systems perspective”, with more attention being paid to interactions between activities within and across sectors, drivers (e.g., climate-influenced environmental drivers), and cumulative effects (Stelzenmüller et al., 2020) to ensure anthropogenic marine use is sustainable long term. Accordingly, cumulative effects are assessed under a variety of legal and policy instruments including project-level Environmental Impact Assessment (EIA) and wider Strategic Environmental Assessment (SEA) processes. Indeed, in some national and transnational contexts – such as the EU’s Marine Strategy Framework Directive (MSFD, 2008/56/EC) or OSPAR Convention – it is difficult to separate discussion of cumulative assessment from that of broader planning and environmental assessments. Recognition of, and need for, a more consistent approach to ecosystem-based management (EBM) has also driven more consideration of cumulative effects particularly as part of Maritime/Marine Spatial Planning (MSP) approaches or systemic sectoral planning, both of which are better able to manage cumulative effects at larger scales (Korpinen and Andersen, 2016). EBM aims to maintain an ecosystem in a healthy, productive and resilient condition so as to provide humans with the goods and services needed and therefore requires consideration of the cumulative effects of different sectors on the marine environment. Depending on the approach to design and implementation, MSP can reconcile and potentially avoid conflicting objectives, provide the framework for forward planning, and give marine decision-makers and users greater certainty on where to develop or not. Ideally, marine spatial plans should be informed by CEAs, which would then signal where additional assessment is required for individual marine developments. Whilst MSP will not reduce the uncertainty around cumulative effects, it should provide a mechanism to share data and information and make more informed decisions. These are just some examples of how CEA cannot be disconnected from broader planning and environmental assessments, which are inter-linked. This means there is pressure, especially for emerging industries which are receiving the focus of current interest in CEA, to find successful ways to integrate across scales and relevant frameworks.

MRE is one of the many industries active in ocean spaces, but one receiving increasing development interest as nations around the world look to energy sources that are aligned with energy transition needs. MRE also provides a good energy alternative for remote areas and islands (LiVecchi et al., 2019), as well as for offshore infrastructure and sensor uses (Copping et al., 2019). While offshore wind is perhaps the best known and widely deployed industrial form of offshore renewable energy, MRE involves energy generation using waves, ocean currents or gradients in salinity or temperature (Copping and Hemery, 2020; Garavelli et al., 2024).

As MRE development advances and device deployments become more common, consideration of cumulative effects is becoming more topical – in planning for arrays, addressing consenting concerns, and fitting into a richer marine spatial planning tapestry. Unfortunately, data and analytical resource limitations pose challenges in most instances and having an appreciation for the range of available tools – and their respective strengths and weaknesses, data and computational complexity – is beneficial for those tasked with conducting CEAs.

1.2. Terminology

Terminology used when discussing cumulative effects (Table 1) may be somewhat confusing. Some of the terminology has evolved over time in the research literature while simultaneously having specific meanings in regulatory documents for some jurisdictions.

Research and regulatory applications originally focused on the term “cumulative impacts”, but within academia and some national jurisdictions, the more neutral term “cumulative effects” is now more commonly used to appreciate that not all outcomes are necessarily deleterious (Stelzenmüller et al., 2018). In some jurisdictions, particularly in the United Kingdom and the European Union (EU), the

Table 1
Glossary of terms related to cumulative effects.

Term	Definition
Cascading effects	An initial change or action can trigger a chain reaction, leading to further effects and potentially significant consequences.
Compound effects	Incremental actions that over time can combine to lead to significant outcomes.
Cumulative effects	Changes to ecosystem components caused by a combination of actions overlapping temporally or spatially (or both) (including climate change). In the context of development proposals and regional planning, it is often typical to also consider the potential contribution of future actions.
Cumulative impacts	Similar to cumulative effects, but often typically used when considering undesirable results of an effect.
Cumulative effects indicator	Metric used to assess combined effects over time.
Cumulative effects assessment (CEA):	A systematic method for identifying and evaluating the compound effects from multiple pressures or anthropogenic activities. This can be undertaken on a project scale (e.g., as part of an environmental impact statement [EIS]) or regional scale (e.g., as part of a strategic environmental assessment)
Environmental impact assessment (EIA)	An assessment process that examines the anticipated environmental effects of a proposed project across its entire lifespan – from the design stage, through operations to decommissioning. Typically required as part of a legal approvals process depending on the scale and/ or nature of the project. There is often a regulatory requirement to assess the cumulative (and other) effects of the project as part of the overall EIA. In the European Union (EU), the term EIAR is now used instead of EIS (which was the EU term for the EIA documentation submitted for the authority to assess). To avoid country specificities, we will use the term 'environmental assessment' (EA) to refer to this document.
Indicator reference point	There are two forms of reference point - this can be the acceptable level of effect for a specific indicator or they can make a limit beyond which effects would be considered unacceptable.
Marine spatial planning	Process of analyzing and allocating human activities in marine areas, on a temporal and spatial scale.
Multi-sector spatial planning	Process of coordinating several sectors across a geographic area to analyze and allocate human activities
Pressures	An external factor (such as climate change or human activity), or combination of factors, causing negative impacts to ecosystem functioning or components.
Strategic environmental assessment (SEA)	A process for considering a proposed plan's broad scale effects on the environment, including biophysical, economic, social, and political considerations. There can be additional jurisdictional requirements of SEA (e.g. in the EU SEA 'should include secondary, cumulative, synergistic, short, medium and long-term permanent and temporary, positive and negative effects' (Annex I)). CEA can inform SEA.
System feedback	The output from, or action of, one part of an ecosystem impacts the input, or action, of another, causing changes in the system's composition, behavior or stability.
Systemic sectoral planning	Holistic approach for planning and development within a specific sector that considers interdependent elements and emphasizes cross sector stakeholder collaboration.

terminology is not as interchangeable, with impacts resulting from the influence of an effect (i.e., an event or activity) on a receptor (e.g., ecosystem component). This is just one of many instances where there are divergences around terminology and methodology between jurisdictions, practitioners, and academics.

Cumulative effects result from multiple anthropogenic activities interacting across space or through time at one location (or geographic area), due to sequential or overlapping activities (Stelzenmüller et al., 2020). These can arise from different aspects of a single development

(Komyakova et al., 2022), multiple developments of one type (e.g., multiple independent MRE projects, or the construction of an array), or interactions across sectors (such as fisheries, tourism, shipping, energy, and conservation) (Halpern et al., 2008). Cumulative effects include those from past, present, and reasonably foreseeable future actions combined, together with the project of interest (Kaveney, 2015). The most complicated cumulative effects arise from combinations of direct and indirect effects of many activities in a region over time. They can occur from concurrent activities (Halpern et al., 2008), through spatial connectivity where impacts disperse and interact elsewhere, or through temporal connectivity where previous activities' legacy interacts with new ones (Turschwell et al., 2022). Some effects may manifest later after a "lag effect" (delay before a response is manifest) or only when facilitated via another intervening activity (Borgwardt et al., 2019).

There are many types of cumulative effects (Table 2), but they can be classified as either additive or nonlinear (Halpern et al., 2008). Most of the variation across the different kinds of cumulative effects comes from how nonlinear effects may be expressed, as described in Table 2. From the past two decades of research into environmental cumulative effects, it is clear that additive effects are typical in physical systems (MacDonald, 2000), but nonlinear outcomes are more common in ecosystems (Côté et al., 2016; Crain et al., 2008; Orr et al., 2020).

1.3. Brief history of the assessment of cumulative effects

The expansion of urban and terrestrial industrial developments in the 1970s–1980s led researchers and risk assessors to increasingly recognize the need to address cumulative effects (Cooper, 1998). Progress was slow until the 1990s due to methodological challenges (such as the requirement for large data sets and high computational demands when considering effects at ecosystem scales) and because such effects were not seen as a pressing issue. Since then, ecological risk assessments for

Table 2
Examples of different forms of cumulative effects (Halpern et al., 2008; Hasselman et al., 2023).

Effect Type	Definition	Example
Additive (linear)	The outcome is equivalent to the sum of the individual effects in isolation (i.e., combined effect of A and B = effect A + effect B).	The magnitude of the effect on growth or survival of most marine taxa under moderate deoxygenation and ocean acidification.
Dominant (non-linear)	The effect due to one process is so strong it overwhelms the outcome of any other drivers (i.e., the combined effect of A and B = max(A, B).	The smothering of seagrass by sediments kills the meadow even if all other conditions are ideal for growth.
Synergistic (non-linear)	The effects of two separate drivers interact and amplify each other (i.e., combined effect of A and B > effect A + effect B).	When mortality due to local human activities (e.g., boat collisions, fishing) combines with reduced survival due to climate change (e.g., via heat stress) to take a population to such low levels that reproduction is impaired and the population decreases more rapidly.
Antagonistic (non-linear)	The effects of two separate drivers interact and act to dampen the individual effects (i.e., combined effect of A and B < effect A + effect B). Mitigative antagonistic effects can even reduce the combined effect below that of any one of the individual effects, while super antagonistic effects may even lead to an overall opposite outcome (e.g. a benefit rather than detriment).	The beneficial effects of artificial habitat can be reduced by sedimentation.

individual sectors, and CEAs, have become more common - integrating science, policy, and management for decision-making and planning (Hope, 2006; MacDonald, 2000).

Looking at risk assessments more broadly, from the 1980s to the early 2000s, tiered risk assessment approaches became standard practice (Bascietto et al., 1990; Hope, 2006). These began with a qualitative assessment, often presented as a risk table, before progressing to more quantitative assessments (Hope, 2006). The qualitative step can be used to rapidly screen and prioritize aspects, or to provide a "broad but shallow" strategic assessment (Breen et al., 2012). Risk tables list hazards associated with a stressor (a physical, chemical or other aspect of an activity that can affect an ecosystem component, also known as a receptor), or stressor combinations, exposure factors, and associated qualitative risk ratings based on combinations of severity and likelihood (Cox, 2008). While expert-based risk tables have been superseded by sophisticated quantitative methods in specific domains, such as ecotoxicology (e.g., Beyer et al., 2014) and marine engineering (e.g., Dobson et al., 2024), they persist when data are limited and because quantitative means of dealing with nonlinear interactions are nascent.

While CEAs in the marine space have begun with largely qualitative methods (as described in more detail in later sections), the rapid expansion of ocean industries and the need to handle multiple interacting aspects of individual developments, as well as multiple uses of ocean and coastal areas, have created a policy motivation for calls for more quantitative and repeatable approaches. Many nations' policies require CEAs as part of environmental assessments for developments, though specifics on what the CEA must contain are vague. This is true across the English-speaking world (e.g., United States National Environmental Policy Act of 1969, 42 USC § 4321 et seq) and in the European Union (through the Environmental Impact Assessment Directive (2014/52/EU) and Strategic Environmental Assessment Directive (2001/42/EC)) as well as several Asian nations (e.g., China (Marine Environmental Protection Law of the People's Republic of China), Korea (Environmental Impact Assessment Act, Act 14532, 2017), Japan (Environmental Impact Assessment Act, Act No. 81 of 1997)). The ultimate scope of these CEAs is typically dictated by the assessment's terms of reference, focused on effects the project may contribute to, and is often judged against current conditions rather than a fixed historical baseline (Durning and Broderick, 2015). Over the past two decades, critique of project-based CEAs has highlighted several issues, including a lack of transparency and consistency, superficial expert assurances of "no potential cumulative effects", a within-industry (single activity) focus, lack of historical baselines, shifting baselines as each project is judged against its current conditions, and poor communication of uncertainty (Baxter et al., 2001; Durning and Broderick, 2015; Hague et al., 2022; Jones et al., 2018; Stelzenmüller et al., 2020). As standardized approaches emerge, user-friendly tools increase in availability, and explicit links between SEAs and project-level CEAs are made, the issues bedeviling CEAs are being addressed (Borja et al., 2024; Hammar et al., 2020; Stelzenmüller et al., 2020). Unfortunately, in many jurisdictions, this is not yet the case.

Scientific interest in marine CEAs rose sharply from the 2000s as compound pressures more frequently caused conflicts and environmental degradation, leading to development of new methods (Callahan and Sexton, 2007). CEAs also expanded from consideration of ecological (Samhuri and Levin, 2012) to socio-ecological systems (Stelzenmüller et al., 2018). These CEAs were driven by scientific interests (Halpern et al., 2008) or were requested as part of broader regionally focused efforts to comply with larger policy changes such as the EU's MSFD (2008/56/EC). The broad scope necessitated by these large-scale assessments saw many attempts stop at the qualitative step, as data limits precluded more quantitative approaches (Stelzenmüller et al., 2018). These CEAs relied on expert elicitation of system structures, causal mechanisms and potential outcomes (Cook et al., 2014). Of 154 marine CEAs reviewed in (Stelzenmüller et al., 2018), the majority combined GIS activity maps (the distribution and overlap of activities) with expert

information on interactions. Recently, the need for repeatability and transparency (Borja et al., 2024; Stelzenmüller et al., 2018) has driven novel integrative methods, such as qualitative models (known as signed digraphs) analyzing stability and response to perturbations (e.g., ecosystem-level responses to increased offshore wind activities (Niquil et al., 2021; Raoux et al., 2018)), structured workflows for repeatability (Brignon et al., 2022) and quantitative estimates (Ferguson et al., 2025; Piet et al., 2021), numerical models exploring local or species-specific effects (e.g., of offshore platforms (Serpetti et al., 2021; Topping and Petersen, 2011)), and spatiotemporal analyses of cumulative environmental effects of specific activities (Gusatu et al., 2021) or alternative development scenarios (Hammar et al., 2020; Le Marchand et al., 2025).

1.4. Objectives

In an effort to give the use of CEA in MRE a firm foundation going forward, this paper summarizes the history of CEAs, the currently available approaches, and emerging best practices for use and evaluation of CEAs in a MRE context. Note that while this examination will involve lessons from offshore wind developments, the paper was motivated by a desire to focus on CEAs as they pertain to those forms of ocean energy that do not involve wind (e.g., wave, tidal). This is because that is the focus of the OES-Environmental project which oversaw the work. This is an international collaborative project amongst member nations of the International Energy Agency's Ocean Energy Systems (OES) Technology Collaboration Programme. The OES-Environmental project synthesizes information and scientific research about MRE and the environment on a global scale into reports and documents available from Tethys Knowledge Hub (Whiting et al., 2019). Working group delegates contribute information to the knowledge hub and regular meetings, with delegates coming from each of the participating nations: Australia, Canada, China, Denmark, France, India, Ireland, Japan, Mexico, Monaco, Portugal, Singapore, Spain, Sweden, the United Kingdom, the United States of America and the European Commission. More details available at <https://tethys.pnnl.gov/about-oes-environmental>.

There are different forms of CEAs based on the scope to be assessed, as summarized for the MRE context in Table 3. Even from this short list of examples, it is clear that, as for all industries, the purposes and associated limitations of CEAs for MRE will vary based on the assessment context. For instance, the method applied and the data available for a CEA undertaken to inform project planning applications will differ from those for a CEA that is part of regional marine spatial planning, or for validating operational planning assumptions during operations (once substantive monitoring data is available), or for research purposes. The present study consists of a literature review to create a brief inventory of approaches (and contexts) relevant to MRE, with a focus on the environmental effects. The human dimensions of CEA are important - potentially encompassing social, economic and cultural aspects and including consideration of diverse aspects such as livelihood effects and opportunities, interactions with other industries, competition for access and workforce implications, as well as combined use effects on port facilities and through supply chains (Freeman et al., 2024). There are also critical considerations around inclusion, equity, justice and the role and rights of local coastal and indigenous communities (Richardson et al., 2022). The combined breadth of all these dimensions can be overwhelming. Moreover, giving each aspect the richness of synthesis required in a review was beyond the scope of this study and the disciplinary strengths of the authorship group, and this review is confined to environmental aspects.

2. Methods

An inventory of publicly available examples was created using a literature search undertaken following the PRISMA protocol (Moher

Table 3

Examples of different forms of CEAs and how they may be used in the context of MRE. Note: numerical modeling is noted as in principle for some types as it could in theory be done for conceptual understanding or to look at large scale patterns, but data limitations can make this quite difficult to accomplish. BBN is used here for Bayesian Belief Network or Bayes Net.

CEA Type	Example contexts	Data Required	Relevant Methods
Cumulative effects on the existing baseline of the many activities required to deliver a single MRE project from construction, through operations to decommissioning.	Project planning/ application; or as part of ongoing project monitoring and regulatory review.	• Baseline of ecosystem components. • Information on relevant activities associated with project stages. • Matrix of stressor-receptor (ecosystem component) interactions. • Impact-response functions (as this dictates the level of realized effect). • As for a single project but focused on the single value of interest. • List of all other relevant activities overlapping the proposed project's locations.	• Expert based methods (e. g., surveys). • Interaction matrices. • Numerical modeling.
Cumulative effects of multiple MRE projects in the same region on a single environmental value (e.g., marine mammals or seabirds).	Project planning/ application or strategic CEA.	• As for a single project but focused on the single value of interest. • List of all other relevant activities overlapping the proposed project's locations.	• Expert based methods (e. g., surveys). • Interaction matrices. • GIS-based analyses. • Numerical modeling.
Cumulative effects of multiple MRE projects in the same region on multiple/ all environmental values.	Project planning/ application or regional sectoral plan.	• As for a single environmental value but for all values at the location (this is typically quite hard to access in full). • List of all other relevant activities overlapping the proposed project's locations.	• Expert based methods (e. g., surveys). • Interaction matrices. • GIS-based analyses. • Numerical modeling (in principle)
Cumulative impact of multiple projects of multiple types (i.e., MRE, but also fishing, mining, transport, tourism, climate change, etc., potentially also including terrestrial influences) on a single environmental value (e.g., marine mammals or seabirds).	Conservation or recovery plan; research projects.	• Baseline status of the ecosystem component. • Information on relevant activities in the region. • Matrix of stressor-receptor interactions. • Impact-response functions for each stressor (where possible).	• Interaction matrices. • Qualitative models. • GIS-based analyses. • Numerical modeling (in principle)
Cumulative impact of multiple projects of multiple types (i.e., MRE, but also fishing, mining, transport, tourism, climate change, etc., potentially also including terrestrial influences) on multiple/all environmental values.	SEA, Marine spatial planning, as part of monitoring and review processes; research projects.	• Baseline status of all ecosystem components. • Information on relevant activities in the region. • Matrix of stressor-receptor interactions. • Impact-response functions (and whether additive or non-additive).	• Interaction matrices. • Qualitative models. • GIS-based analyses. • Numerical modeling (in principle)

et al., 2009). On 18 February 2022, and again on 5 April 2024 and 25 October 2025, a search was carried out for literature published between 1999 and the search date (i.e. 2022, 2024 and 2025 respectively) using Web of Science, Google Scholar, and Semantic Scholar based on the search phrases: (cumulat*) AND (effect* OR impact*) AND assess* AND (renewable* AND energ*). While this provided many more references than were immediately relevant to MRE – including terrestrial assessments – all were retained in case useful methods and lessons could be transferred to the MRE context. The search results were supplemented by papers and planning documents shared by OES-Environmental delegates or available from the Tethys Knowledge Hub (<https://tethys.pnnl.gov/>).

The search and referrals identified 926 documents of which 145 were potentially relevant (based on document titles and keywords). The retained (relevant) documents were classified as either: (i) of marginal relevance (i.e., the paper refers to a generic multi-stressor assessment, a single factor, or discusses engineering design and not cumulative effects in the sense of a CEA); (ii) on topic (i.e., the paper deals with MRE or offshore wind energy, CEA methods, indicators or inclusion in a CEA); (iii) is a useful additional component (e.g., focusing on policy components rather than technical methods); (iv) is focused on interactions with vulnerable and threatened species; or (v) is focused on guidance for practitioners. Documents that were solely focused on the social, economic, and/or cultural dimensions were classified as 'marginally relevant' since they were out of scope for this environment-focused study.

3. Results

3.1. Topics covered in the literature review

The use of CEAs for MRE is not as widespread in academic literature as compared to general marine spatial planning or more mature industries. Consequently, it was necessary to draw heavily on papers dealing with offshore wind energy, which has been in operation for longer, at larger scales than current MRE projects, and in more locations.

All of the relevant papers retained have been published since 2007. The majority dealt with technical design, arrays, wind energy, or interactions with vulnerable species. Nineteen were practitioner (project-level CEA) focused. Twelve dealt with planning in some form, with two providing content on successful planning frameworks. The few papers considering multiple ocean use types were all published since December 2018, with the majority published between 2023 and 2025. The majority of even the most recent reviews – such as (Blakley and Noble, 2025; Kuempel et al., 2025; Morejón et al., 2025; Murray et al., 2025; Willstead et al., 2018) – looked at CEA more broadly. The small number of papers focused on offshore renewable energy generation of all kinds (including offshore wind) provided broad reviews of existing methods (Masden et al., 2010) or critiqued consenting processes, noting gaps and needs (Caine, 2020; Willstead et al., 2018). A key concern raised was the lack of detailed, geographically relevant data on environmental effects, such as electromagnetic fields, underwater noise, changes in oceanographic systems, changes in habitat, and species impacts (e.g., collision risk, entanglement, displacement, and behavioral changes) (Copping and Hemery, 2020). The range of sensitivity across life stages of marine organisms further complicated analyses (Copping and Hemery, 2020). Consequently, expert information was often used, though qualitative system models (Raoux et al., 2018) and quantitative ecosystem models (Raoux et al., 2020) are increasingly employed to incorporate feedback and time dynamics.

The move towards quantitative measures aligns with the maturation from initial planning assessments to monitoring and long-term performance assessment. While a small number of papers discussed potential indicators to track in the context of offshore wind and MRE (Nogues et al., 2021), most relied on metrics defined under the EU's Marine Strategy Framework Directive (e.g., specific seabirds or benthic community state). This reflects the European origin and longer commercial

deployment history in that region. These indices may not be universally appropriate, and defining acceptable levels of effect (indicator reference points) for performance metrics has not been adequately addressed at relevant scales or will require region-specific considerations due to ecosystem specificity (Fu et al., 2019). The desire for more universally recognized processes for defining reference points and limits is likely to become more established, as there are already attempts to define methods of identifying 'safe operating spaces' in a CEA context (Greaves et al., 2025).

3.2. MRE cumulative effects assessment content

Both project-level and academically motivated CEAs begin with hazard analysis or identifying what may pose a cumulative risk (Brignon et al., 2022; Hope, 2006; Kaveney, 2015; Korpinen and Andersen, 2016; Stelzenmüller et al., 2020). While array design papers (Haslett et al., 2018; Haverson et al., 2017) explicitly consider the influence of one device on another, and on the surrounding environment, most CEAs do not progress beyond hazard analysis to evaluate actual risk or realized effects. This is partly because they are used for proactive planning ahead of development approval, rather than post-deployment assessments (when data on a development's footprint becomes available), and because there has been insufficient time to track change due to MRE generation over time. As shown by offshore wind, this will change as the earliest deployments mature (Smith, 2022). Even if only for planning purposes, validation of CEA results is important, as recent studies suggest commonly used CEA approaches may not reflect actual (realized) risks for some ecosystems (Stockbridge et al., 2021).

3.3. Cumulative effects assessment tools

Science-based assessments attempt to use more clearly standardized, transparent, and quantitative approaches. A general outline of the typical and most recommended approach is provided in Fig. 1. While more assessments are moving to quantitative analysis and review, to date MRE relevant assessments have used a subset of the more widely available methods applicable to CEA. The four most common approaches applicable in the MRE context are described in more detail below, while a total of 15 methods are listed in Table 4.

3.3.1. Expert elicitation

One of the most commonly used approaches remains expert elicitation. This may be the initial step of a larger process (hazard analysis) or the entire analysis itself. Typically, experts identify connections between activities or drivers and associated stressors, and may score aspects like likelihood of stressor occurrence, level of exposure of each ecosystem component to the stressor, or sensitivity of the components to the stressors (Singh et al., 2017; Turschwell et al., 2023; Turschwell et al., 2022). This can occur through workshops or targeted surveys to ensure comprehensive coverage as in (Turschwell et al., 2022) or to address specific information gaps (Kaveney, 2015). Such an approach could be taken at an early stage of an MRE project, once site location and project layout are known but data collection has not started yet. This approach is also currently the most widely used for bringing First Nations knowledge into CEA in any domain, not just MRE (Arnold et al., 2025; Carlson et al., 2025; Kwon et al., 2025; Tulloch et al., 2024). Repeatability can be an issue with expert elicitation, as it can depend on who is in the group involved and subjective responses. These effects are known, however, and there are standardised approaches to minimising these drawbacks - such as careful initial group selection (Hasson et al., 2025); repeated iterations of consultation to allow for clear sharing of knowledge (Mukherjee et al., 2015); the Fuzzy Delphi Method (i.e., integrates fuzzy logic approaches to resolve ambiguity in expert opinions (Tuni et al., 2023)); or the use of software platforms to allow immediate, continuous interaction and quicker consensus building, rather than waiting for sequential rounds (Turschwell et al., 2023). More recent hybrid methods - for example combining Delphi with other techniques such as Analytic Hierarchy Process (AHP) or Failure Mode and Effects Analysis (FMEA) - also allow for more robust, repeatable and quantitative results (Nursanti et al., 2018; Saaty, 1988).

3.3.2. Loop analysis

A widely used tool for capturing connections and feedback around offshore wind energy is loop analysis (Niquil et al., 2021; Raoux et al., 2018). This tool uses signed digraphs - networks showing 'positive' (where an increase in one node leads to an increase in the connected node; for example, increase in the amount of vessel traffic increases the potential for collision) or 'negative' (where an increase in one node leads to a decrease in the connected node; such as expansion of sediment

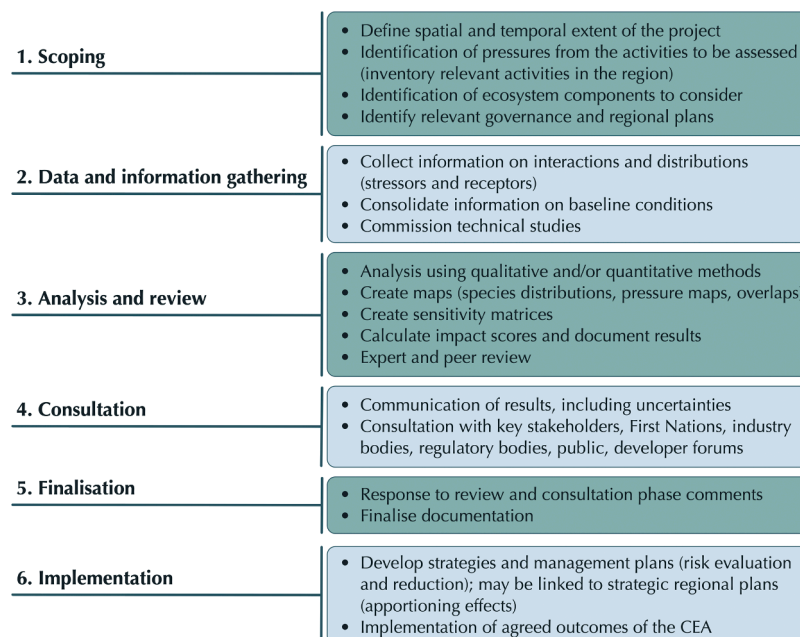


Fig. 1. Example of the recommended steps of a CEA. (Kaveney, 2015; Marine Management Organisation (MMO) 2014, Foden et al., 2011; Rijksoverheid (Netherlands Ministry of Economic Affairs and Climate), 2015).

Table 4

Summary of major types of CEAs – including both those methods already used explicitly for MRE, as well as methods from other disciplines/sectors that are already used for CEAs, or could be readily adapted for use. The full set of methods is ordered roughly in order of increasing computational complexity. Note that, due to the width of the table, the table has been split into two sections, with each "type" (row), repeated in each section, and an example reference for each type of assessment given in the second section of the table. Table reproduced with permission from (Fulton et al., 2021).

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
Expert elicitation (effects and interaction matrices or lists) e.g. (Brignon et al., 2022; Singh et al., 2017)	Experts, ideally from diverse backgrounds, are asked to contribute their knowledge (e.g. via workshop or survey) on potential threats, connections (impact pathways) etc. Most useful for providing expert judgement when data are lacking, or for validation/ review of results	Typically, independent, additive or facultative only	Mainly direct; depending on participants indirect effects may also be captured.	Typically, a non-spatial snapshot, but spatial variants possible. Non-dynamic, would need to repeat for different time periods	Elicited / conceptual. Explicitly defines links between pressures and values/effects.
	Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible though often physical and ecological only	Data Demands Low (quantitative data unnecessary), but best served if the participants are drawn from diverse and experience rich backgrounds (so can address all aspects in required detail)	Uncertainty Handling Qualitative via IPCC* style confidence rating. Structural uncertainty often poorly considered. Some consideration of domain bias is possible via clustering.	Updatable/Testable, Validated Method is easy to apply, but objective repeatability difficult (growing literature on Delphi processes helps)	Predictions or Attribution Possible? Predictions possible within a foresighting framework, but often not undertaken. Cannot perform objective attribution
Qualitative system modelling e.g. (Raoux et al., 2018)	Signed diagraphs showing the positive/negative connections between different system components (pressures and values). The outcome of those interactions can be explored via press perturbation analysis (where a pressure is increased or decreased and the model predicts the direction of change of the values)	All possible (dependent on outcomes of press perturbation analysis)	Mainly direct (indirect and non-linear possible via press perturbation analysis)	Non-spatial snapshots (would need to repeat for other locations, time periods)	Elicited / conceptual. Explicitly defines links between pressures and values/effects.
	Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible	Data Demands Low (quantitative data unnecessary), but best if supported by knowledgeable participants and background literature or response data	Uncertainty Handling Not in isolation (needs to be linked with BBN ¹)	Updatable/Testable, Validated Press perturbation outcomes testable, but best if linked with BBN (as then updatable)	Predictions or Attribution Possible? Qualitative (directional) predictions and (some) attribution possible (more effective if linked with BBN)
Cumulative impact and structured decision-making (CISDM) framework e.g. (Anthony et al., 2013; Uthicke et al., 2016)	Uses qualitative and probabilistic (BBN) modeling to provide a systems-level understanding of how cumulative stressors affect habitats and ecosystems of interest (originally the Great Barrier Reef). The modeling provides information on precautionary spatial and temporal boundaries ('zones of influence') for the assessment of development proposals. The zones are integrated with a structured decision-making process to support informed choices regarding a range of possible intervention/	All possible (dependent on outcomes of press perturbation analysis). BBN's cannot represent feedback directly.	Mainly direct (indirect and non-linear possible)	Can be explicit if information for mapping available, but as originally applied was implicit (though was applied "per region" originally so had some high-level spatial resolution)	Elicited / conceptual foundation, but can be based on quantitative modelling if available. Explicitly defines links between pressures and values/effects.

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Table 4 (continued)

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
Interaction matrices	management/development scenarios. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible, but has typically been ecological	Data Demands Mixed. Can begin with qualitative, but best if can integrate quantitative data (though that can become data intensive quite quickly if multiple values considered)	Uncertainty Handling Explicit uncertainty index produced – combination of uncertainty regarding model input values, observational/expert error, distribution of conditional probabilities used, and structural uncertainty	Updatable/Testable, Validated Produces testable outputs with associated likelihoods and the model content/parameterization can be updated with new information.	Predictions or Attribution Possible? Generates predictions and attribution is possible if sufficient data is available on which to base the analysis
	Summary of basic understanding of ecosystem components versus pressures with the potential impacts of the interactions summarized in each cell of the matrix. This can be in detail or simple “high, medium, low” etc. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible though often physical and ecological only	Typically, independent, additive or facultative only Data Demands Low, but best if drawn from knowledge across multiple fields	Mainly direct; depending on participants indirect effects may also be captured. Uncertainty Handling Qualitative via IPCC style confidence rating.	Typically, a non-spatial snapshot, but spatial variants possible. Updatable/Testable, Validated Method is easy to apply, can be validated as new information becomes available	Elicited / conceptual. Explicitly defines links between pressures and values/effects. Predictions or Attribution Possible? Predictions possible within a foresighting framework, but often not undertaken.
	Exposure, usage and vulnerability maps e.g. (Tuda et al., 2014) Simple overlays of spatial maps of usage or environmental properties; often treated additively. May encompass all pressure or only those considered relevant to a particular value. May also be combined with multi-criteria decision analysis if using it in combination with marine spatial planning. Useful for presenting spatial maps of all potential impacts across areas of interest including overlaps. These can be quantitative outputs. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), Species or habitat typically	Additive Data Demands Moderate to high. Can be descriptive spatial data but could also use quantitative GIS maps if available for each pressure and value, as well as weightings per pressure for each species	Linear and direct Uncertainty Handling Poor or non-existent	Spatial snapshot Updatable/Testable, Validated Poor or non-existent	Empirical Predictions or Attribution Possible? No
Weighted cumulative pressure mapping (OHI, ODEMM) e.g. (Halpern et al., 2008)	Related to exposure maps, but goes further to consider relative contribution of effect. A spatial map of the presence (or intensity) of an activity is multiplied by the vulnerability (or impact weighting) for the value of interest and then the cumulative effect calculated by summing across uses per spatial cell. This is the most commonly applied CEA approach; more than half of all publications are variants of	Additive	Linear and direct	Spatial snapshot (can extend over a longer period dependent on when data were collected)	Empirical

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Table 4 (continued)

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
	the original (Halpern et al., 2008) and there are also a significant number of CEAs using analogous methods developed independently. The approach can be combined with scenarios to consider the advantages or disadvantages of potential future development options (Hammar et al., 2020).				
	Values Considered (geochemical/physical, species, habitat, economic, social, cultural), Species or habitat	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		Reasonably high – requires quantitative GIS maps for each pressure and value, as well as weightings per pressure for each species	Poor or non-existent	Poor or non-existent	No
Statistical modelling - hierarchical statistical assessments e.g. (Hunsicker et al., 2016; Teichert et al., 2016; Woolley et al., 2016; Rezaei and Javadi, 2024)	Use of statistical methods to model exposure (spatial overlap) and response relationships between pressures and values; resulting outputs are measures of absolute risk. We have included here the use of machine learning models to categorise and predict the ecological and environmental impacts of new MRE devices.	Have often been applied independently or additively, but if sufficient information exists other interaction types can be represented	All possible with sufficient available data (linear and additive easiest)	Typically, a spatial snapshot (spatial time series possible)	Empirical
	Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible, but has typically been applied to physical aspects, species or habitats	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		High – the more available empirical data the more robust the resulting estimates	Explicit	A strength of this approach, as it can generate predictions based on a likelihood with an associated quantified uncertainty	Generates predictions and attribution is possible if sufficient data is available on which to base the analysis
Bayes Nets (BBN) (e.g. Anthony et al., 2013)	BBNs are networks of causal linkages with each node of the network associated with a transition matrix of conditional probabilities that indicate the likelihoods of an increase, decrease or no change in the state of the node (given the state of connected nodes).	All possible (dependent on interaction of transition matrices); cannot represent feedbacks directly.	Mainly direct (indirect and non-linear possible)	Non-spatial	Depending on data sources – conceptual, empirical, mechanistic
	Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		Can be constructed from a variety of data sources (from purely expert based to quantitative). Amount of data required depends on data source type and model complexity	Explicit	Produces testable outputs with associated likelihoods and the model content/parameterization can be updated with new information.	Produces simple one step predictions of change. Attribution is possible in many cases
Ecological Risk Assessment (ERA/ ERA-like) (e.g. (Hobday et al., 2011)	A tiered assessment approach that aims to rapidly identify potentially vulnerable species, prioritizing them for more rigorous assessment and management responses. Tier 1 (the entry tier) consists of an expert driven Scale Intensity	Additive	Linear and direct	Snapshots (depending on the method these may be spatial)	Empirical

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Table 4 (continued)

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
Integrated Ecosystem Assessment (IEA) (e.g. Holsman et al., 2017)	Consequence Analysis (SICA); for any species considered to be risk under Tier 1 a Tier 2 analysis is carried out – for data poor species this is a Productivity-Susceptibility Analysis (PSA), but for species with catch and distributional data a Sustainability Assessment for Fishing Effects (SAFE) estimate of fishing mortality is made. Further (Tier 3) quantitative analyses are possible for species considered high risk under Tier 2 assessments, these are usually in the form of a formal fisheries assessment (population dynamics) model. Variants on this approach estimate absolute risk, allowing for cumulative pressure to be ascertained additively. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), Species or habitat	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		Hierarchical, with low data demands at lower assessment levels and more data required as more quantitative (higher levels) applied	Improving (originally rarely considered, but now uncertainty around base data is being represented more explicitly)	Yes, if applied iteratively over time	Not typically
Quantitative – Specific impact response models or Models of Intermediate Complexity of Ecosystem (MICE)	A system-wide iterative assessment that requires ongoing stakeholder engagement, scoping, identification of indicators for monitoring/assessment, ecosystem assessment (status/trends/performance per indicator vs management objectives), risk assessment (regarding likelihood each indicator will reach/remain at an unacceptable level), uncertainty assessment, evaluation of management options, monitoring and evaluation through time. There is strong overlap with CEA in terms of methods that could be used in the assessment steps (CEA could inform IEA). Values Considered (geochemical/physical, species, habitat, economic, social, cultural), Species or habitat typically	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		Depends on methods used (only additive in the simplest methods); all interaction types possible (if sufficient information available to base model detail on).	All possible, depending on underlying model formulation (only linear and direct for the simplest methods)	Depends on the method used (the simplest are non-spatial snapshots, higher-level methods are spatiotemporally dynamic)	Mechanistic
Quantitative – Specific impact response models or Models of Intermediate Complexity of Ecosystem (MICE)		Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
	Small number of interacting species (e.g. trophic connections, habitat dependencies, technical interactions within fisheries),	Can be applied hierarchically, but typically high due to the number of components involved All interaction types possible (if sufficient information available to base model detail on)	Explicit All possible, depending on the underlying model formulation	Is intended to produce testable outputs and to be updated with new information Typically, only time dynamic	Depends on the method employed, the higher-level methods allow for prediction and attribution Mechanistic

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Table 4 (continued)

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
models (e.g. Plagányi et al., 2014)	potentially also with environmental drivers and/or multiple fleets. Used to consider management questions. Involves robust quantitative (statistical) fitting of model variables in line with best practice fisheries assessment methods. Useful for exploring cause and effect relationships, identifying combinatorial effects and robust quantitative results. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible, but species or habitat typically (economic also common, but sociocultural rare to date)	Data Demands Requires reasonably good quality time series of values and pressures of interest (for statistical fitting), which might be hard to access for rare species All interaction types possible (if sufficient information is available to base model detail on)	Uncertainty Handling Explicit All possible (is dependent on model formulation but non-linear responses are common)	Updatable/Testable, Validated Produces testable outputs and can be updated with new information. Time dynamic, many models are also spatial	Predictions or Attribution Possible? Prediction standard, attribution amongst explicitly represented pressure possible Mechanistic
Quantitative - whole of system models (e.g. Blanchard et al., 2014; Coll et al., 2014; Fulton et al., 2017)	Consider key/representative parts of the entire system in a variety of ways (either as age structured populations, biomass pools, size- or trait-based bins); to date primarily focused on climate and fisheries relevant system dynamics, but can represent the footprint of other human uses too. Useful for exploring cause and effect relationships, identifying combinatorial effects and robust quantitative results. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible, but greatest focus has been on physical, species, habitat and economic	Data Demands High – requires data for all modeled aspects	Uncertainty Handling Possible, can be constrained by computational cost of running alternative parameterizations or model structures All possible (is dependent on model formulation)	Updatable/Testable, Validated Produces testable outputs and can be updated with new information. Conceptual models non-spatial, but dynamic models are time dynamic, models may also be spatial	Predictions or Attribution Possible? Prediction standard, attribution possible Elicited/conceptual and mechanistic (different ones used in different steps of the process)
Bioregional assessments (e.g. Barrett et al., 2013)	A multistep CEA process involving (i) define, characterize and explain conceptual models that establish causal pathways describing the chain of interactions and events connecting the activity to potential effects on system components (anthropogenic and ecological); (ii) generate quantitative, semi-quantitative, or qualitative analyses of the likelihood of effects; (iii) assessments of the likelihood of risks to system components due to proposed developments, (iv) provide information on the level of confidence of scientific advice on these effects; (v) identify monitoring programs,	All interaction types possible (if sufficient information available to base model detail on)	All possible (is dependent on model formulation)	Conceptual models non-spatial, but dynamic models are time dynamic, models may also be spatial	Elicited/conceptual and mechanistic (different ones used in different steps of the process)

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Table 4 (continued)

Type	Description	Interaction Type	Response Type	Scale & Resolution	Method Type
	assessment review frequency and additional risk assessment studies that could be undertaken outside of the main bioregional assessment process to help minimize any effects. Originally undertaken for coal seam gas and coal mining developments on water resources. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible (anthropogenic and ecological)	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		Mixed. Can begin with qualitative, but best if can integrate quantitative data (though that can become data intensive quite quickly if multiple values considered)	Explicit	Produces testable outputs with associated likelihoods and the model content/parameterization can be updated with new information.	Prediction standard, attribution possible
Meta-analysis based (e.g. Moher et al., 2009; Claudet and Fraschetti, 2010; Culhane et al., 2024)	Use meta-analysis to synthesize the ecological consequences of anthropogenic threats to species or habitats. This can be combined with structured frameworks (e.g. the driver-activity-pressure-state-impact-response (DAPSIR) framework) that use meta-analyses to systematically gather the information and populate the framework tools. Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible (though dictated by what is present in the literature; typically effects on species or habitats)	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		All possible (as based on observations)	Direct (shape can be linear or non-linear though shape not reported in the original application)	As defined by observations but reported in aggregate	Empirical
		High (as there must be sufficient to undertake a meta-analysis)	Explicit (ranges of response in meta-analysis)	Can be updated with new literature as it becomes available	Produces simple one predictions of response shapes. Attribution is possible as effect defined per pressure
Potential recovery rate (e.g. Foden et al., 2011)	Pressure assessment generated by collating information on anthropogenic pressures on system components of interest (originally seabed) and linking with maps of the distribution of the component or proxies (e.g. sediment types). Then consider cumulative effects possible under 4 scenarios - single greatest, additive, antagonistic, and synergistic Values Considered (geochemical/physical, species, habitat, economic, social, cultural), All possible (though dictated by what is present in the literature; typically effects on species or habitats)	Data Demands	Uncertainty Handling	Updatable/Testable, Validated	Predictions or Attribution Possible?
		All (via scenarios)	Direct, linear and simple non-linear possible	Typically, a spatial snapshot (spatial time series possible)	Empirical
		High – requires data for all effects considered	Some – via considering different scenarios for the form of the interaction type	Testable. Updates possible once new data becomes available	Produces simple predictions which can be tested via comparing with independently estimated recovery rates

*IPPC = Intergovernmental Panel on Climate Change

†BBN = Bayes Nets (BBN) – see entry below for more details

removal during infrastructure construction reduces habitat in the immediate vicinity) connections between activities and ecosystem components. This flexible approach can combine different knowledge and information types (Dambacher et al., 2009). The added power of the approach is that well established analytical processes check stability and estimate effects of increasing or decreasing nodes (e.g., increasing energy infrastructure) on all other nodes (Dambacher et al., 2009). Loop analysis can be used standalone or combined with Bayesian Networks, which allow for more quantitative estimates of effects and cross checking of the validity of the original qualitative model given available observations (Anthony et al., 2013). In the MRE context, loop analyses can be used at the planning stage, when the main stressors and receptors have been identified, to assess potential cumulative effects at various scales, but also identify points of intervention to mitigate such effects or indicators to be used in monitoring programs to check for the presence or likelihood of a cumulative effect.

3.3.3. Map-based methods

GIS-based approaches are widely used for CEAs (Halpern et al., 2008; Hammar et al., 2020) because their relatively easily digestible map-based outputs are appealing formats for potential audiences, including stakeholders, interest groups, and regulators (Tversky, 2001). Simpler additive GIS methods are commonly adopted (Halpern et al., 2008; O'Hara et al., 2021), despite broad recognition that they cannot address indirect effects and feedback, which make up a sizeable portion of known marine effects (Brown et al., 2013; Crain et al., 2008; Hodgson and Halpern, 2018; Hodgson et al., 2019; MacDonald, 2000). This is because of the desire to simultaneously address scope and ease of use, particularly given the often time-limited and capacity-stretched regulatory agencies which must use the information.

GIS-based approaches have been extended in sophisticated ways such as combining them with co-designed scenarios of alternative multi-sector spatial planning and offshore energy development options (Hammar et al., 2020), which involve projecting spatial maps of environmental impacts for different planning alternatives. Such an approach may enable the evaluation of trade-offs between environmental and other objectives. In addition, hierarchical methods that incorporate GIS and system models are being developed in an attempt to maintain ease of use while considering indirect effects and system feedbacks (Fulton et al., 2023; Marine Management Organisation (MMO), 2014). While these analyses follow structured (reproducible) workflows and have been completed for both current state and proposed planning schemes (e.g., a regional overview of the cumulative effects of offshore wind development (Piet et al., 2021)), they are typically still undertaken or presented as snapshot outcomes.

3.3.4. Explicitly dynamic approaches

In those cases where marine hazard analyses are extended to estimate risk, traditional risk assessment approaches remain in use, either the likelihood-consequence approach (Astles et al., 2006; Williams et al., 2011), particularly for rare or unobserved events (Knights et al., 2015), or exposure-effect analysis, which is typically employed for assessing ongoing pressures (Smith et al., 2017). Conversely, terrestrial assessments attempt to more formally join bias-corrected expert knowledge and modeling products to provide quantitative, evidence-based risk scores (Barrett et al., 2013).

Moving from qualitative and semi-quantitative to fully quantitative assessments involves the use of dynamic numerical models at the heart of the assessment. Numerical models, initially developed for specific ecosystem components (e.g., oceanographic properties) or stressors (e.g., fisheries), are now being adapted to evaluate the cumulative effects of multiple activities including MRE. Indeed, as the underlying principles can be easily redirected onto MRE developments, CEAs in an MRE context are well placed to leverage the rapid expansion in the diversity and availability of marine ecosystem modelling platforms that has occurred over the past 20 years (Le Marchand et al., 2026, 2025).

Models like Ecospace, originally designed for fisheries and conservation, are already being applied to project potential future cumulative impacts of multiple use platforms (including both aquaculture and MRE) off Scotland (Alexander et al., 2016; Serpetti et al., 2021). This kind of approach has been taken further to project potential future cumulative effects under current industry-wide timelines for development (e.g., for offshore wind (Gusatu et al., 2021)). Bayesian system models are increasingly used the same way (Trifonova and Scott, 2024; Trifonova et al., 2025).

Another potential dimension of attaining quantitative predictions in such complicated circumstances is Artificial Intelligence (AI)- and Machine Learning (ML)-based approaches. The latter have already been used to expand the predictive capacity in fields relevant to MRE (Ryu et al., 2026) - such as hydrodynamics and water quality (Azma et al., 2026; Azma et al., 2026; Mohammadi et al., 2025). Moreover, Large Language Models are actively being used to create process based ecological subsystem models or to assist with rapid creation of ecosystem models (e.g., (Spillias et al., 2026; Spillias et al., 2026)). Alternatively, statistical models - including Artificial Neural Networks, ML and other AI-based approaches - could be used to generate indices then used in large quantitative assessments, or map-based assessments - in much the same way as Random Forest models have been used to look for impacts of other human uses such as fishing (Pitcher et al., 2012) or in generating water quality indices (Azma et al., 2026). A natural extension of this is to start to use them as a basis for assessments (Rezaei and Javadi, 2024). All this suggests that AI/ML-based methods will be making substantial contributions to MRE CEA within the coming decade. However, to be of maximal benefit to human decision makers, they will likely still have to walk the tightrope between optimal data fit and clarity for human understanding (Adams et al., 2017).

3.4. Project-level assessment methods

While CEAs are required for project-level consenting/licensing applications in many jurisdictions (i.e., project-level CEA as part of an Environmental Impact Assessment (EIA)), their scope and implementation often differ from strategic-level CEAs undertaken by researchers or governments for planning purposes, even if there are some shared fundamental concepts (Kaveney, 2015; Korpinen and Andersen, 2016; Morejón et al., 2025; Murray et al., 2025; Stelzenmüller et al., 2020; Vaca-Cabrero et al., 2025). Moreover, while both may involve expert opinion, many of the tools used differ in implementation between these different kinds of CEAs (for instance compare the tools described in Korpinen and Andersen (2016) and Rijksoverheid (Netherlands Ministry of Economic Affairs and Climate) (2015)). Furthermore, jurisdiction-level tool development typically focuses on strategic CEAs rather than project-level CEAs (e.g., Tools4MSP, Symphony, and the other tools listed in Casimiro et al. (2021), or Vaca-Cabrero et al. (2025)).

Individual jurisdictions typically have their own guidance documents (Dibo et al., 2025), which acknowledge the potential for small effects to have substantial cumulative outcomes, and provide information on their ideal form of a project-level CEA. While there is not a globally accepted standard, common steps are often present in specific guidelines for many jurisdictions, forming a general workflow (outlined in Fig. 1).

Nevertheless, a substantial number of accessible project-level CEAs still take a relatively cursory approach, with opaque and high-level presentation of assessments - a common assessment being very simple statements such as "no 'significant' cumulative effects anticipated". This is despite repeated critiques of CEAs (across a range of industries) over the past twenty years (e.g., (Fulton et al., 2021; Kaveney, 2015; Stelzenmüller et al., 2020)).

This heterogeneity in assessment quality persists due to factors like inconsistent requirements (terms of reference) and terminology across assessments and sectors, a lack of support for a routinely applied

method, and absence of a clear mandate from regulatory agencies (and across sectors) to nest project-level CEAs within strategic regional CEAs (Hague et al., 2022). Such a nested approach would also more easily (and tractably) ensure that system-wide cumulative effects and objectives are not missed, without imposing inappropriately expensive or complex assessment requirements on MRE proponents.

MRE can also learn from and avoid poor public perception, legal frustration (e.g., when lawsuits are put forward by interest groups dissatisfied with the rigor), and negative environmental outcomes challenging other industries (Kaveney, 2015), by instituting more rigorous, standardized methods that fit naturally within regional contexts. For example, adopting coordinated data collection during assessments (so that there are industry- and society-wide benefits of investment in monitoring data) would also help address cross-scale issues, which become more pressing as marine spaces become increasingly crowded and contested.

A first step toward unified or easily connected CEA approaches between project-level and government- or academic-led strategic assessments would be a spatial approach similar to the one used in the Baltic Sea (Bergström et al., 2019), which included CEA at multiple scales as part of MSP and future development options for the region, explicitly include MRE amongst the activities considered. This makes the most value of visual maps and increasing availability of spatial data (either quantitative or in the form of expert-driven mapped information gathered in ways such as surveys), while usefully communicating effects in a pragmatic and industry-acceptable manner. Such transparent and pragmatic spatial analyses, are akin to the workflow outlined by Piet et al. (2021), showing that the different types (project-level and strategic) CEAs can use common working styles in addition to following essentially the same overall assessment steps (Fig. 1). This should have the dual benefit of increasing transparency and aiding the capacity of stakeholders (many of whom are expressing increased interest in the true sustainability of growing marine industries) to comfortably interpret both project-level and strategic CEAs.

4. Discussion

The desire for understanding of cumulative effects has driven the development of CEA approaches for various reasons for decades. The increasingly crowded nature of marine spaces and the growing presence of new industries, such as MRE, has increased the desire for easily applied CEA approaches - as evidenced by the recent release of handbooks and toolkits (JPI Oceans, 2024). While the individual CEA methods reviewed here were not all developed in the context of MRE, they can all be safely applied to it. The logic behind the individual approaches holds independent of the specific industry they have been created for. Indeed, it would save MRE considerable time and effort to adopt or modify methods that have been developed in other contexts as those methods are well understood and their limitations and needs already clear.

While we have primarily focused on CEA previously applied in a marine context there are lessons that can be drawn from terrestrial sources. The steps in Fig. 1 are summarised from many sources, one of which is the Australia mining industry, and Table 3 also includes methods drawn from terrestrial industries. There are some components common to all CEA, where marine applications can leverage the extended experience on land. This is particularly the case where terrestrial use can identify potential weaknesses or issues of application (e.g. guidelines for the mining industry warn about shifting baselines if a new activity is being introduced into an already crowded or altered state (Kaveney, 2015)). However, the advective nature of marine systems, with the water potentially spreading footprints well beyond the physical bounds of any development, complicate system dynamics and assessments versus terrestrial systems. This makes transfer of methods from land to sea more problematic, though one of the greatest barriers being simple familiarity, with marine researchers and practitioners often less

familiar with terrestrial methods, applications and literature. The reverse is also true."

4.1. Limitations

There are many technical barriers to CEA uptake (Borja et al., 2024). However, they have a common theme, with the delay in adopting more advanced CEA approaches for the marine environment, and MRE in particular, attributable to the scale and complexity involved, as well as the paucity of detailed supporting knowledge. The combination of these aspects exceeds the capabilities of any single tool to cover all aspects of marine cumulative effects (Hodgson and Halpern, 2018).

Consequently, current CEA approaches often simplify one or more dimensions of the assessment to make the task tractable, for instance, by limiting the number of interacting sectors, reducing spatial or temporal extents, or omitting nonlinear interactions or indirect effects (Korpinen and Andersen, 2016). Few methods span multiple sectors, their interactions and trade-offs, or include multiple domains of knowledge either at the hazard analysis stage or during more quantitative assessment or planning stages (Turschwell et al., 2022). As a newer industry, MRE is least likely to be included in fit-for-purpose CEA methods. Although, as demonstrated by (Kuempel et al., 2025), approaches used in other contexts can be repurposed. These authors found that many structured frameworks that can consider interactions and multiple scales have been proposed in the academic literature (such as risk-based cumulative effect assessments (Stelzenmüller et al., 2020)) but have not generally seen uptake in a development approvals context. However, some of these frameworks, such as the driver-activity-pressure-state-impact-response (DAPSIR) framework, are familiar to practitioner groups and can be used in an offshore wind (Kuempel et al., 2025) or MRE context.

While modeling has been used to consider nonlinear interactions, multiple scales and sectors in other contexts – such as aquaculture (Steven et al., 2019) or coastal development (Fulton et al., 2017) – it remains computationally challenging and accessible only to highly skilled modelers; however, this has not prevented the integration of model outputs into planning processes (Stelzenmüller et al., 2020). Resource constraints may also limit model use in some jurisdictions, although a hybrid approach combining available information across government departments (or other information holders) could maximize utility in less resource-restricted nations. An alternative approach is to use modelling to try to help bridge some of the knowledge gaps, as has been done in some physiochemical domains (e.g., (Majdi et al., 2022)); although for those methods to work, there has to be an information base to work from, which is yet to evolve for certain aspects of MRE, especially at array scales.

Despite progress made to date, significant knowledge gaps remain (Copping and Hemery, 2020). Perhaps the greatest knowledge gap is in assessing nonlinear interactions across drivers and sectors in a clear and cost-effective manner. This not only pertains to technical methods but also to who needs to be involved in the assessments (e.g., scope for engagement with local communities, indigenous peoples, other industries in the region, etc.) and how to communicate the findings (including uncertainty) to non-technical audiences. Stelzenmüller et al. (2020) provides a useful list of common factors that lead to uncertainty (which we have reshaped in the context of MRE):

- Policy context and drivers for the CEA (including problem framing stage, boundaries determined by policies and legislation) and defined risk criteria to be used in assessing cumulative effects (which may be set by terms of reference in project assessments). The lack of MRE policies (either policies with specific MRE considerations in those jurisdictions where offshore renewable energy policy is in place, or the complete lack of any relevant policy in other jurisdictions) sees this become a significant source of uncertainty for MRE.

- Cause-effect (impact-response) relationships, including externalities influencing responses from outside the immediate CEA context. The state of the science is improving for MRE, but without larger devices and arrays coming online, many gaps remain (Copping and Hemery, 2020; Hasselman et al., 2023).
- Input data quality, which may be lacking or highly variable across different ecosystem components, relevant pressures, stressor effects, and in terms of the effectiveness of any potential management measures. Another aspect that will not become clearer until a greater number of operational MRE deployments exist.
- Recognized ignorance (also known as structural uncertainty), which acknowledges fundamental uncertainty around the true mechanisms and relationships in the system and their representation in the CEA.
- Knowledge gaps, which may (potentially) be addressed by targeted research or information gathering. This is a well-recognized issue for MRE, with suggested directions for research detailed in Copping and Hemery (2020).
- Inherent variability in the system (e.g., seasonal, interannual, interdecadal). The dependence of MRE on physical processes that are both a constant presence but explicitly variable (such as currents, tides) exposes this form of energy generation to variation at those scales that are currently least skillfully forecast (DeMott et al., 2021; Kavanaugh et al., 2016).
- Statistical (analytical) uncertainty (or parametric uncertainty), which is the most typically reported form of uncertainty (represented via sensitivity analysis).
- Scenario uncertainty, which is due to the (limited) range of possible configurations and outcomes of development, planning, and management explicitly considered in an assessment.

MRE is already facing pushback in some communities because of uncertainties around some environmental interactions (Copping and Hemery, 2020), so properly communicating uncertainties in the context of a CEA is crucial. Even when analysts put significant effort into addressing the many forms of uncertainty (Flores and Mendoza, 2025), communicating uncertainty can be difficult. Approaches that draw heavily on the Intergovernmental Panel on Climate Change-like confidence matrices have been proposed as a good way of effectively communicating uncertainty (Pethybridge et al., 2020; Stelzenmüller et al., 2020). These matrices lay out what is known about the reliability of the CEA process and underlying data (Fig. 2). This approach to communicating uncertainty is also seeing wider use in other impact and assessment fields – such as when discussing the projections of ecosystem models used to look at the combined effects of fisheries and climate (Pethybridge et al., 2020).

4.2. Recommendations for marine renewable energy CEAs

As the MRE industry continues to expand, the volume of CEAs, both project-level and strategic, will grow. There is also increasing demand (at least in some jurisdictions) to comply with integrated policy requirements. This means actively addressing MRE-specific considerations in CEAs is an important step that cannot be delayed, despite remaining data gaps. In addressing MRE specific data and assessment gaps, researchers and analysts can leverage developments taking place in parallel in other industries and the growing interest in and maturity of CEAs and integrated ocean management more broadly. MSP could act as a key driver here as, conceptually, it is an approach that integrates different activities as well as spatial and temporal scales. MSP also seeks to make data and information available, which could over time help CEA better integrate ‘local’ EIA scales to wider ‘strategic’ regional assessments.

Drawing on gaps noted in this review of CEAs, and recommendations presented in previous reviews (Baxter et al., 2001; Hague et al., 2022; Jones et al., 2018; Stelzenmüller et al., 2020), a number of recommendations regarding the future of MRE-related CEAs can be made:

- CEAs must balance reasonable resource requirements for proponents with delivering meaningful input on true cumulative effects while ensuring consistent quality and content of assessments comparable across proposals and locations.
- CEAs should consider multiple stressors from multiple activities, which is likely best delivered by connecting project-level and strategic-level CEA processes. This will require government agencies to take an active role. In nations without legal requirements for CEA, there is a need to institute the strategic assessments that project-level CEAs sit within. In those locations where such tiered approaches already exist, then government agencies have a role in ensuring commitments around assessing cumulative effects are fully adhered to. In addition, those responsible for implementing MSP have an implicit duty to ensure all assessments are integrated with consenting/licensing and inform future policy directions. This will also allow for individual developments to contribute to broader networks of understanding, minimizing unnecessary duplication, strengthening information sharing and avoiding unintended costly consequences of ocean development.
- Approaches should have standardized terms of reference and terminology across projects, sectors, and jurisdictions.
- There must be transparency in framing and context (e.g., scales, environmental drivers, human activities, pressures, and ecosystem components), as well as documentation.
- Risk criteria need to be set in conjunction with stakeholders and decision-makers prior to conducting any analyses.

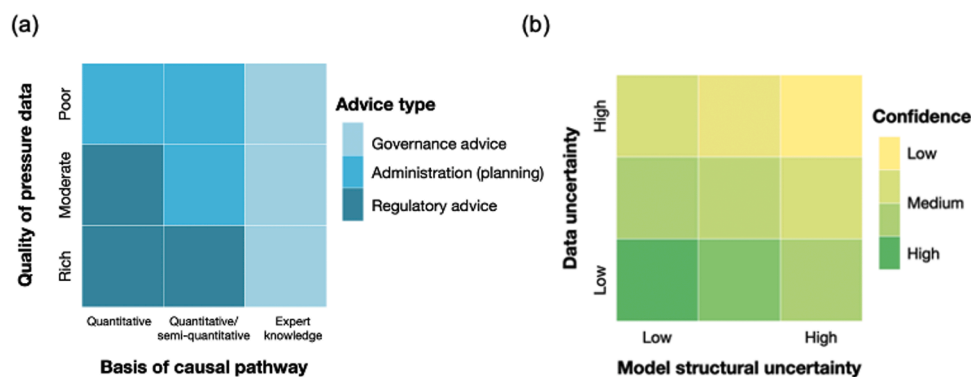


Fig. 2. Examples of confidence tables put forward as a means of communicating CEA or modelling output. Redrawn to be in the same orientation (i.e., in terms of the axes of data quality vs structural uncertainty) from (a) (Stelzenmüller et al., 2020) (redrawn with orientation rotated for consistency with panel (b)), and (b) from (Pethybridge et al., 2020).

- The use of predictive models should serve as the basis for CEA wherever possible, otherwise there is a need to ensure professional judgment is based upon best available science.
- In all instances, the method(s) used, assumptions, limitations, uncertainties, knowledge gaps, and assessment confidence should be transparently documented.

In addition, key infrastructure and research activities to support CEAs for MRE include:

- Centralized data stores for monitoring and CEA-associated data as outlined by the SEAWAVE project (Fox, 2021), facilitating comprehensive assessments and reducing duplication of efforts and wasted resources at the project level. Globally many data platform initiatives exist (e.g., the United States's PRIMRE (<https://openei.org/wiki/PRIMRE>), the EU's MARENDATA (<https://marendata.eu/>), the United Kingdom's MEDIN data portal (<https://portal.medin.org.uk/portal/start.php> also accessible via the UK Marine Data Exchange <https://www.marinedataexchange.co.uk/>) and France's ResCORE (<https://rescore.france-energies-marines.org/en/>)). By prioritizing the maintenance, extension, and integration of such systems across platforms for greater accessibility, systematic databases can be created as a source and archive for relevant data, guiding future standards around CEA best practices (Hague et al., 2022). Ensuring interoperability among the existing platforms will assist with this effort. It is relevant to note that existing MSP data portals could be also used as a way to ensure MRE-related studies are more widely available, and vice versa with respect to other sectors.
- Field studies focused on identification and attribution of effects of single versus multiple pressures, helping to catalog which effects can be handled additively or require more complex relationships.
- Development of tools to assist in operationalizing CEAs at both project and planning levels, making them more quantitative, predictive, and cost-effective.
- Development of methods for defining acceptable levels of effect (indicator reference points) for performance metrics regionally (aligning with broad ecosystem boundaries) and at scales relevant to MRE, to account for ecosystem specificity in ecosystem structure, function and response. Adoption or translation of methods from other marine industries (such as fisheries) may progress such undertakings significantly.

These efforts can contribute to more confident decision-making and agile planning processes, which are crucial in the rapidly changing marine economy and global climate change context.

While initially utilizing simpler tools like GIS mapping and linear additive methods for MRE-related CEAs may be pragmatic, thought should be given to progressively incorporating more dynamic or nonlinear assessments. Lessons from established industries suggest that such assessments can avoid perverse outcomes and precluded opportunities (e.g., as demonstrated in fisheries (Fulton et al., 2014)). Loop analysis, expert-based construction of interaction matrices, and map-based methods of considering the activity zones of effect and how these may interact with ecosystem values (such as vulnerable flora and fauna, or socially and/or culturally important activities) are tools that can be used as the basis of CEA for smaller or demonstration-scale MRE projects (as has been the case for wind developments (Niquil et al., 2021; Raoux et al., 2018)). They can also form the initial stages of more adaptive processes put in place for larger or longer-lived projects (Fulton et al., 2015; McIntosh et al., 2019). More advanced model-based analyses, allowing for in-depth quantification and consideration of non-stationary and evolving risks across multiple system properties, should be considered best practice for long-term, large-scale MRE projects (Turschwell et al., 2022). These dynamic modeling platforms demand more resources and data but can be managed through a combination of system-scale models for initial planning and periodic

review cycles, along with more targeted models (Holsman et al., 2017; Le Marchand et al., 2026; 2025) for specific species or activities of concern within an adaptive process.

The incorporation of models, whether semi-qualitative (e.g., the combination of signed digraphs and Bayes Nets, *sensu* (Anthony et al., 2013)) or quantitative (Le Marchand et al., 2025), allows for the consideration of indirect effects, which have rarely been addressed in CEAs (Fulton et al., 2021; Jones et al., 2018) until relatively recently, especially not in the MRE context, although examples are beginning to slowly grow. However, there is a lack of observational information on compound and cascading effects from different stressor-receptor interactions around MRE and multi-use activities (Hasselman et al., 2023). This gap must be filled in the coming years, as lessons from work on climate change-induced effects have shown that not only might the individual stressor-receptor interactions be nonlinear, but the presence of additional stressors might change a relationship, amplifying outcomes (Griffith et al., 2012; IPCC (Intergovernmental Panel on Climate Change), 2022).

Data remains a limiting factor for all CEA methods (Halpern and Fujita, 2013), and while standardized methods are called for, providing detailed data lists is difficult due to the system specificity of marine ecosystems. Fortunately, data collection can be prioritized around "essential ocean variables", such as physical and chemical oceanographic properties (e.g., current strength, temperature, salinity, oxygen levels); presence or abundance and life history characteristics (mortality and reproductive rates) of key species (primary producers, biological habitats, key commercial species, vulnerable species); and levels of human activity. Best practice guidelines exist for the identification of such variables – for example see the processes outlined in (Hayes et al., 2015) and the selection criteria and classes of variables to track in (Constable et al., 2016) with MRE specific considerations provided in (Copping and Hemery, 2020). Additional information on energy transfer (e.g., via diet composition), species movements, and ecological community composition would be ideal but may be beyond the capacity of individual proponents, necessitating collaborative regional agreements across multiple user and government groups.

5. Conclusion

CEAs have evolved to become indispensable tools in addressing the complex, interconnected impacts stemming from industrial and infrastructure developments, particularly in the dynamic and sensitive marine environment. As the MRE industry expands, fostering the adoption of robust and comprehensive CEAs will be crucial in ensuring sustainable development while minimizing environmental, social, cultural, and economic trade-offs. Doing so represents substantial reductions in opportunity costs for the MRE industry - remediating unintended consequences and dealing with lost productivity due to undesirable impacts to the surrounding environment, adjacent industries or other users of the area that derive not only economic but social and cultural benefits from the system. By learning from other industries, MRE can avoid wasting resources (e.g., spent on duplication of previous efforts), and better targeted investments (based on the recommendations) can move MRE forward more quickly, again saving time and resources.

Despite the growing importance of CEA, several gaps remain in current methodologies, including the lack of standardized approaches, limitations in assessing nonlinear and indirect effects, and insufficient integration across project-level and strategic assessments. MSP could reconcile these limitations and enable collaborative data-sharing frameworks as a pathway toward more consistent and multi-scaled CEA applications. Looking toward the future, greater emphasis on transparency, adaptive strategies, region-specific approaches, and more dynamic modeling methods will help CEAs better capture the cumulative nature of the environmental effects of MRE developments. Coordinated policies and technological advancements must prioritize data collection, stakeholder engagement, and predictive modeling tools to

enhance assessment quality and efficacy. In addition, it is critical that CEAs do not end as a planning step, but are verified post-deployment, making the shift from hazard analysis to evaluate actual risk and realized effects. Without taking this step the CEAs remain unvalidated and there are missed opportunities in learning ahead of the deployment of increasingly large arrays.

Following the recommendations above and applying the lessons learned from other industries' CEAs will enable MRE to avoid repeating past errors – avoiding undesirable outcomes and better meeting the multiple system objectives held across the many interested parties present within a system – while also remaining feasible for MRE proponents to implement efficiently. By leveraging lessons from established industries and embracing innovation in CEA practices, MRE can align with global sustainability goals while ensuring that marine ecosystems remain resilient and productive for generations to come.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used claude.ai in order to create an outline from the original OES-Environmental White Paper on the topic (which was authored by the same group as this paper). After using this tool/service, the authors fleshed the outline out in full to create the current paper, reviewing and editing all of the content, inserting examples and references etc as needed. The authors take full responsibility for the content of the publication.

CRediT authorship contribution statement

Elizabeth A. Fulton: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Lenaig G. Hemery:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Andrea E. Copping:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Hayley K. Farr:** Writing – review & editing, Investigation. **Jennifer Fox:** Writing – review & editing, Investigation. **Lysel Garavelli:** Writing – review & editing, Investigation. **Daniel J. Hasselman:** Writing – review & editing, Investigation. **Raeanne Miller:** Writing – review & editing, Investigation. **Anne Marie O'Hagan:** Writing – review & editing, Investigation.

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.

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Data availability

No data was used for the research described in the article.

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