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Frameworks and best practices for cumulative impact accounting in offshore energy development

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ABSTRACT

Offshore renewable energy holds promise for achieving emission reduction targets. However, offshore industries transform land and seascapes with resultant trade-offs for both nature and people. Cumulative impacts have long been a challenging issue for environmental management, creating uncertainty around development limits across scales and risks to financial investments and the environment. This is particularly true for nascent industries and governments striving to meet tight deadlines for international commitments. Here, we provide recommendations for improved accounting of cumulative impacts for offshore development based on scientific best practice including: 1) clear pathways from activity to impact, 2) accounting for the full suite of cumulative impacts, 3) integration across realms and jurisdictions, 4) systematic planning processes to guide fair and equitable development opportunities within and across sectors, and 5) transparent and reproducible assessments. We demonstrate opportunities and challenges of implementing our recommendations using offshore wind project proposals in Australia, where the development of the offshore wind industry is in progress. Our recommendations outline key considerations for cumulative impact accounting in offshore energy development globally and can increase potential for positive outcomes for people and nature across these rapidly expanding sectors.

1. Introduction

Industries are rapidly expanding into the ocean [1,2] due to its potential to provide sustainable food and low-carbon energy to meet national and international targets [3]. Renewable energy is a key solution to reducing carbon emissions from energy generation [4–6], with offshore wind energy currently the primary ocean renewable energy source. The development of wind energy across the globe grew by over 64 gigawatts (GW) in 2022 [5] and avoided > 200 Mt CO_2 emissions in 2021–2022 [7].

Power generation from wind farms can contribute to stabilizing the global climate [8], but also transform land and seascapes. Offshore energy development on a large scale has impacts on ecosystems and existing and future ocean and coastal users [9–11]. These impacts can be negative, such as bird strike mortality or loss of fishing grounds, or positive, like creating nurseries for fishery species [12,13]. The combined impact of human activities occurring together (i.e., 'cumulative impacts' or 'cumulative effects') on the environment has long been a particularly challenging issue for environmental management, limiting successful accounting and management of impacts across pressures and users [14–16].

Pressures induced by industry activity can interact to produce unpredictable outcomes to both the environment and other industries. For example, water quality changes from sedimentation during offshore wind farm construction can compound with other industries that generate similar pressures - such as trawl fisheries, shipping, and dredge spoil dumping [17,18]. Unclear accounting and management of cumulative impacts is also a risk for developers, because it creates uncertainty about development limits in a region and risks to financial investments [19–21]. There is often little guidance from regulators and government

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agencies on how to complete an adequate assessment of cumulative impacts including what components to consider, where to access data, what evaluations are needed during different phases of development and operation, and how individual projects interact with each other and other industries [16,22]. Concurrent development of multiple projects also limits opportunities for establishing baselines of change – whether from a pristine state, from environmental impact of existing and/or proposed users, or against background environmental change. Implementing adaptive management to learn from early developments and better inform later monitoring and management proposals is limited. Assessing and accounting for cumulative impacts is therefore critical for the environmental and socio-economic longevity of the blue economy.

Here, we provide recommendations for improved accounting of cumulative impacts based on scientific evidence and international best practice. While these recommendations are universally applicable (across locations and other renewable energy sectors), we showcase their potential application with a case study of offshore wind energy in Australia by reviewing environmental effects statements submitted by development proponents in the state of Victoria.

In Australia, and other countries where offshore wind is still in the development and planning stages (e.g., Brazil, Pakistan, Malaysia), the uncertainty surrounding cumulative impacts is heightened, but substantial opportunities remain to implement effective policies and procedures for sustainable offshore energy production. Unlike the U.S. [23], the U.K., Canada, or the EU [16], Australia has no national mandate for cumulative impact assessments (despite ambitions to do so, and some efforts at the state level). Based on our review and analysis, we recommend existing, structured frameworks for better cumulative impact accounting across the development and approvals process and discuss the challenges and opportunities of such approaches.

2. Methods

We assessed several aspects of offshore wind farming and the Blue Economy in Australia to provide recommendations for improved cumulative impact accounting. All analyses were performed in R 4.3.0 [24]. All code to reproduce analyses is available on GitHub at https://github.com/cdkuempel/Kuempel_offshore_wind_CIA.

2.1. Review of environmental assessments

We reviewed the five offshore wind farm environmental effect statement referral forms (hereby EES) that were submitted to the Victorian Department of Transport and Planning for further approvals as of November 2023. This included Vic Offshore wind farm, Star of the South, Seadragon, Southern Winds, and Greater Gippsland Offshore wind project. The forms were accessed through the Victorian Government planning portal (https://www.planning.vic.gov.au/environmental-assessments/browse-projects, Table S1). For each EES, we reviewed and assessed how potential impacts were documented and presented but recognise that further information and analysis may be completed in the future as part of the development assessment process.

2.2. Impact pathways

Offshore wind energy has distinct phases throughout the project lifecycle: pre-construction, construction, operation and maintenance, and decommissioning. Each of these phases has unique activities (e.g., boat surveys, pile driving, etc.) that result in environmental and socio-economic pressures (e.g., habitat disturbance, noise pollution, visual disturbance, etc.) that can impact nature and people and which require management [25].

Many structured frameworks have been proposed in the scientific literature to understand the relationships between human activities, environmental pressures, their impacts on nature and people, and potential management solutions. However, they are not generally applied in a development approvals context. Such frameworks include the driver-activity-pressure-state-impact-response (DAPSIR) framework [26–28], risk-based cumulative effect assessments [15], and source-pressure pathways [16]. We showed how one of these frameworks, the DAPSIR framework, could theoretically be applied to an offshore wind farm project across stages, focusing on the activity, pressure, impact pathway (Fig. 1A). We then translated the impacts identified in the Gippsland offshore wind farm EES (Table S1) using this framework to assess key leverage points for potential impact reduction, focusing on the construction phase for illustrative purposes. Since our goal was to demonstrate application of the DAPSIR framework, we grouped pressures into general categories based on those listed in the EES and simplified impacts into four broad groups (human health, social assets, ecosystem health, cultural heritage). We intended for this exercise to be illustrative not comprehensive.

2.3. Potential cumulative effects on species

To assess the potential of cumulative effects on species, we collated information on the species assessed across key industries in the Bass Strait Victoria. These industries included proposed offshore wind farm development projects that are still in early stages of approvals, and established fishing and oil and gas sectors (Table S1). For fishing, we reviewed environmental assessments for the Southern and Eastern Scalefish and Shark Fishery, Bass Strait Central Zone Scallop Sub-Fishery, Southern Squid jig Sub-Fishery, and Midwater Trawl Sub-Fishery of the Small Pelagic Fishery. For oil and gas, environmental assessments included Beach Energy Otway Offshore Operations, GBEnergy Golden Beach Offshore Drilling, Cooper Energy Bass Strait/Gippsland region, and GBEnergy Golden Beach Geophysical and Geotechnical Investigations (Table S1).

While all species are not all necessarily negatively impacted by wind farms, collating these species lists gives a preliminary scope of potential cumulative effects for species whose distributions may fall within the boundaries of multiple projects or multiple industries. For the purposes of our review, we adopted the Australian EPBC Act 1999's definition of a species, thus certain subspecies and distinct populations were included as unique "species" in our analysis. Entries not identified to at least the species level (e.g., *Solegnathus Sp.* 1), those listed as extinct under the EPBC Act (*Conilurus albipes,* the white-footed rabbit rat), and those only listed as threatened at the state-level (not within the EPBC Act) were excluded from the analysis.

We collated all species that were assessed within each project and aggregated them within each industry (offshore wind, fishing, oil and gas). We then counted the number of unique species within each project/industry and the cumulative number of unique species across all projects/industries. Finally, we categorized each species by habitat zones based on the "systems" listed in the International Union for the Conservation of Nature Red List database [29] and EPBC status [30] to assess differences between industries. Species belonging to the class Aves were classified as seabirds if their habitat zones included the 'Marine' environment. Species with more than one habitat type (terrestrial/marine, freshwater/marine, terrestrial/freshwater, terrestrial/freshwater/marine) were classified as "mixed".

2.4. Number and area of ocean uses

We mapped the location and overlap of prominent ocean users in Australia's Exclusive Economic Zone (EEZ) for which we could access data. This included active underwater cables, aquaculture, commercial fishing, Indigenous Protected Areas, (IPAs), marine protected areas (MPAs), oil lease areas, petroleum pipelines, ports and terminals, recreational boat use, recreational parks, shipping, and declared and proposed wind farm areas (Table S2). We calculated the ocean area (km^2) occupied by differing numbers of concurrent uses (i.e., area covered by 0, 1, 2, 3, etc. uses), as well as the area occupied by each industry. We

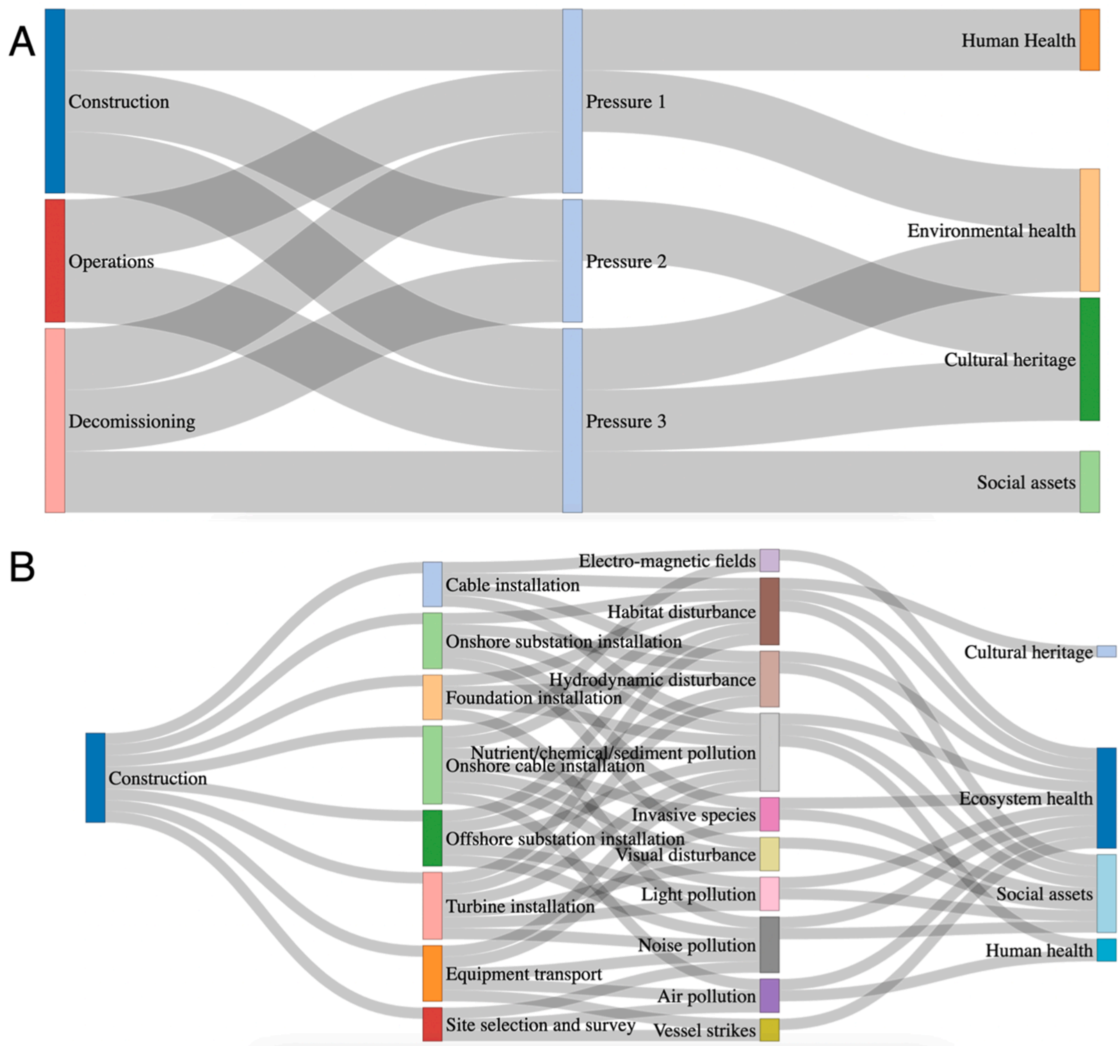

Fig. 1. Schematic demonstrating how a modified DAPSIR framework could be used for offshore wind farm environmental impact assessment. A) Theoretical example of drivers, pressures, and impacts from offshore wind. B) Application of the DAPSIR framework based on information reported in the Greater Gippsland offshore wind farm environmental effects statement considering the Construction phase and its associated activities, broad pressure and impact groups.

used vectorized spatial data to compute area measurements, preventing the inflation of values that could occur with rasterized data.

Commercial fishing, presence was based on the average fishing effort (vessel numbers) for the most recent year where data were available (2014–2017). We acknowledge that these data may differ from activity in recent years. Since recreational boat use is so prevalent in Australia, we used the 95th percentile of tracked boat use to capture the hotspots of recreational boating activity. We created a 1 km buffer around point and line data (shipping, underwater cables, and some aquaculture locations) to enable better estimations of coverage, and to account for the width of shipping lanes and prohibited areas around underwater cables (Table S2). For example, for underwater cables there is a recommended buffer between 750 m and 1 nautical mile (~1.8 km) distance between infrastructure [31], although pipelines and cables are generally much smaller. We recognize that these buffers may be an over or underestimate depending on area and industry. Finally, we generated a matrix of every industry pair combination and summed the number of intersects to show the overlap occurrences between industries (Table S3). For visualisation purposes, we classified each industry as present or absent within a 1 km grid and summed overlapping grid cells to determine the number of ocean uses within each grid cell.

3. Results

3.1. *Impact pathways*

We found shortfalls in defining impact pathways for offshore wind EESs in Victoria, Australia. While the EESs recognized changes throughout a project's lifecycle and assessed potential receptors (e.g., species, infrastructure), they often used confounding terminology (i.e., stressor vs impact), and dispersed potential impacts across several documents and tables that did not clearly breakdown pathways between activities, pressures, and potential impacts.

The DAPSIR framework was applied to the Greater Gippsland wind farm EES (Fig. 1A and B). During the construction phase, eight activities were identified that could lead to potential impacts including cable installation (onshore and offshore), equipment transport, substation installation (onshore and offshore), foundation installation, turbine installation, and site selection and surveys. These activities have the potential to cause ten environmental pressures (air pollution, light pollution, vessel strikes, hydrodynamic disturbance, visual disturbance, electro-magnetic fields, habitat disturbance, invasive species, and/or nutrient/chemical/sediment pollution).

From the information listed, we found that onshore cable installation contributed to the greatest number of pressures (7), followed by turbine installation (6), and offshore substation installation (5) (Fig. 1B). The environmental pressures most frequently identified as having impacts were nutrient/chemical/sediment pollution (7), followed by habitat disturbance (6), noise pollution (5), and hydrodynamic disturbance (5). Nutrient/chemical/sediment pollution and habitat disturbance also contributed to the greatest number of potential impacts, with pollution listed as contributing to ecosystem health, social assets, and human health and habitat disturbance contributing to cultural heritage, ecosystem health, and social assets. Nine pressures were linked to ecosystem health, while seven were linked to social assets, and one to cultural heritage (habitat disturbance).

3.2. Potential cumulative effects on species

Our review identified three distinct types of cumulative impacts: 1) within a project, 2) across projects in the same industry (intra-industry), and 3) across industries (inter-industry) (Fig. 2).

For offshore wind, most species assessed within EESs were documented across multiple wind farm projects (162 species, 73.6 %), while 58 species (26.3 %) were documented within just one project (Fig. 3A). Across individual projects the number of species assessed ranged from 100 (Seadragon) to 149 (Victoria Offshore Windfarm Project), with an average of > 127 species within a project area. Across all projects 220 individual species were identified (Fig. 3B). This included 11 critically endangered, 42 endangered, 70 vulnerable, 3 conservation-dependent, and 94 EPBC listed species (i.e., migratory, culturally significant, or ecologically important but not currently listed as threatened).

By including fisheries and oil and gas alongside offshore wind, the number of species assessed across the Bass Strait increased from 207 to 427 species (Fig. 3C). Like offshore wind farm projects, most species (231, 54 %) were documented across more than one industry, although a substantial portion of species were found within just one industry (196, 45.9 %). The number of species assessed across industries was similar, with offshore wind documenting 220 species, fishing 225 species, and oil and gas 288 species.

Most species assessed in offshore wind EESs occurred across more than one habitat type (101, 45.9 %), followed by terrestrial species (67, 30.4 %), marine (46, 20.9 %), and freshwater (6, 2.7 %). Fishing and oil and gas had similar numbers of multi-habitat species as wind farms. This included92, (40 %) for fishing and 117 (40 %) for oil and gas. However these industries had greater numbers of marine species, including 138 (60 %) for fishing and 91 (32 %) for oil and gas. Fishing did not record any potential effects to terrestrial species, while oil and gas listed 80 (28 %) terrestrial species.

3.3. Number and area of ocean uses

We found that 43 % (3,036,122 km^2) of Australia's EEZ was occupied by one use and 29.9 % (2,064,596 km^2) contained more than one use (maximum seven uses, Fig. 4A). We then assessed the spatial overlap between industries and found that commercial fishing, oil lease areas, and marine protected areas have high levels of overlap with other sectors (Fig. 4B). Commercial fishing had the greatest overlap with other sectors including proposed wind farm areas, shipping, recreational boat use, oil leases, and conserved areas (MPAs and IPAs). MPAs had high overlap with oil leases, recreational boat use, and shipping. Aquaculture appeared to have the lowest level of overlap with the other industries assessed.

4. Discussion

Based on our analysis, we propose relatively simple considerations and improvements for better accounting of cumulative impacts for offshore energy development in Australia and beyond. These include 1) clear pathways from activity to impact, 2) accounting for the full suite of cumulative impacts, 3) integration across realms and jurisdictions, 4) fair and equitable development opportunities within and across sectors, and 5) transparent and reproducible assessments.

4.1. Clear pathways from activity to impact

We identified shortfalls in defining impact pathways for offshore wind EES referral forms in Australia. Similar patterns have been documented in other countries, like the United Kingdom [16]. A clear framework across projects, such as the DAPSIR framework demonstrated here, could help identify potential gaps and streamline applications and assessments (including assessment of cumulative impacts within and across projects), without compromising assessment accuracy or increasing costs on proponents.

Structured impact pathway frameworks could promote more accurate and transparent cumulative impact assessments for government, industry, and researchers. This could include easier and more transparent comparisons across development portfolios (i.e., Fig. 2), determining whether assessments align with scientific evidence, designing monitoring protocols, identifying stakeholders for consultation processes, and recognizing potential gaps and leverage points in assessments to inform approvals and management. While reducing the most devastating pressures is still the main regulatory priority that would require further assessment, the DAPSIR framework makes it easier to identify potential interactions between activities, pressures, and impacts

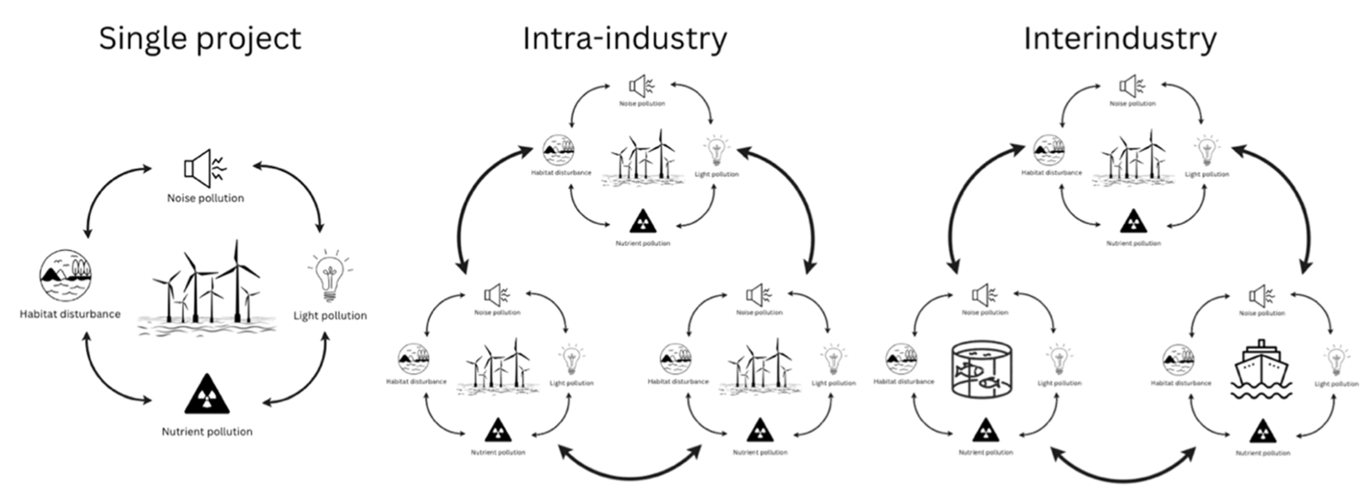

Fig. 2. Schematic of within project, between project (same industry), and between industry cumulative impacts. Habitat disturbance, noise pollution, light pollution and nutrient pollution are used as examples of potential impacts from offshore wind farms, offshore aquaculture, and shipping.

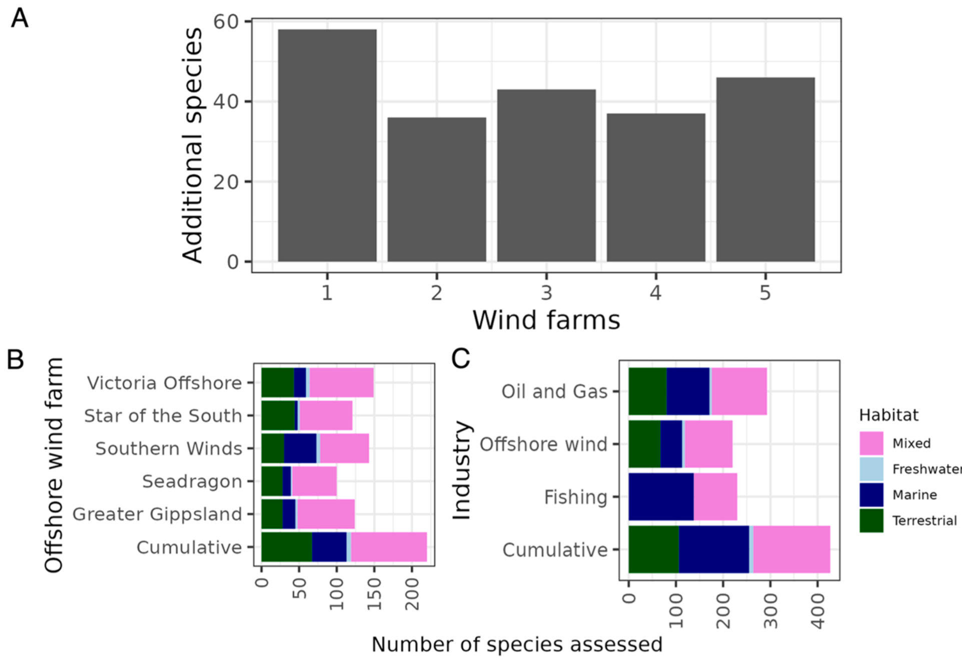

Fig. 3. Number of EPBC listed species assessed across blue economy environmental effects statements (EESs). **A)** The number of species assessed within EESs that occur within one offshore wind development farm area or multiple areas, **B)** the number of species assessed in each individual offshore wind farm EES and the cumulative number of unique species across all development applications separated by IUCN habitat type. **C)** the number of species assessed across major Bass Strait industry (fishing, oil/gas, offshore wind) EESs and the cumulative number of unique species across all industries separated by IUCN habitat type.

that could be used by industry and government for establishing management and monitoring priorities. For example, managing activities that contribute to the greatest number of pressures (e.g., cable installation, turbine installation for those assessed here) could result in the greatest reduction in cumulative impact, while considering the number of activities that contribute to each pressure and their importance in the impact pathway can also give insight into potential magnitude and feasibility of management.

Some level of impact is expected from new development, but structured frameworks to clearly understand them and their linkages to other existing and proposed impacts are critical for supporting a low-carbon energy transition that limits environmental, cultural, and socio-economic impacts. While we use broad categories, we recommend further distinction and comprehensive consideration of these groups for application in future referrals (e.g., ecosystem health could be broken down by key species or habitat types, and combined with vulnerability estimates of these groups to given pressures). Many guidelines on applying the DAPSIR framework already existing (e.g., in the scientific literature and through organisations like the OSPAR commission).

4.2. Consideration of the full suite of cumulative impacts

Our analysis showed that many species overlapped with multiple projects and multiple industries. There is also substantial spatial overlap in the activities of different industries. These overlaps exemplify the importance of integrating assessments and coordinating management. Interactions between industries can be mutualistic, competitive, or antagonistic [32]. Activities that benefit each other from operating in close proximity (i.e., through sharing resources) can also result in reduced cumulative impacts (e.g., from a smaller spatial footprint) [33,34]. The impacts from one activity or industry alone may not induce drastic changes in habitats and species, but in combination across projects (e.g., multiple shipping lines or wind farms) or industries, the potential for surpassing ecological and socio-economic limits increases [32,35,36].

Several countries progressing offshore wind development require holistic and ecosystem-based approaches that explicitly include cumulative impacts - but standardized methodologies for cumulative impact assessments are lacking. The European Union is one of the most progressive regions in terms of cumulative impact assessments, providing frameworks to address multiple pressures within the Marine Strategy Framework Directive (MSFD), which have been used by member states to address cumulative impacts within environmental assessments in recent years [37]. France has developed a cumulative impacts prioritization framework for two offshore wind turbine projects [38], while Sweden has employed cumulative impact assessment tools into ecosystem-based marine spatial planning [39].

In Australia, cumulative impacts are not explicitly considered or nationally mandated. However, at the state level, Western Australia amended the Environmental Protection Act 1986 to explicitly introduce cumulative impact assessment as part of the EES process (Environmental Protection Amendment Bill 2020 (WA)) [40]. This included environmental monitoring programmes to assess cumulative impacts at a regional scale rather than a project basis. Prior to this amendment, the requirement to understand cumulative impacts was implied. However, guidelines and methodologies for assessment, and mandates for implementation to support the amendment are yet to be developed.

Regulations requiring cumulative impact assessments across the full suite of impacts (within project, intra-industry, interindustry) are needed at the national and state-levels. Generally, within project cumulative impacts are the focus of development approvals, but explicit policies and regulations that address all three levels (project, inter-industry, intra-industry) are needed to balance environmental and socio-economic trade-offs. In many countries, including Australia, individual project thresholds currently include triggers like project overlap with threatened species, which requires further investigation and management for project approval. Industries often have individual regulatory thresholds like fishing quotas, pollution discharge limits, habitat protection zones and speed limits. Recommendations on how to scale these triggers across projects and industries are needed and should be explored further in future work. Intra- and inter-industry impacts may be best assessed by government bodies and decision makers, which

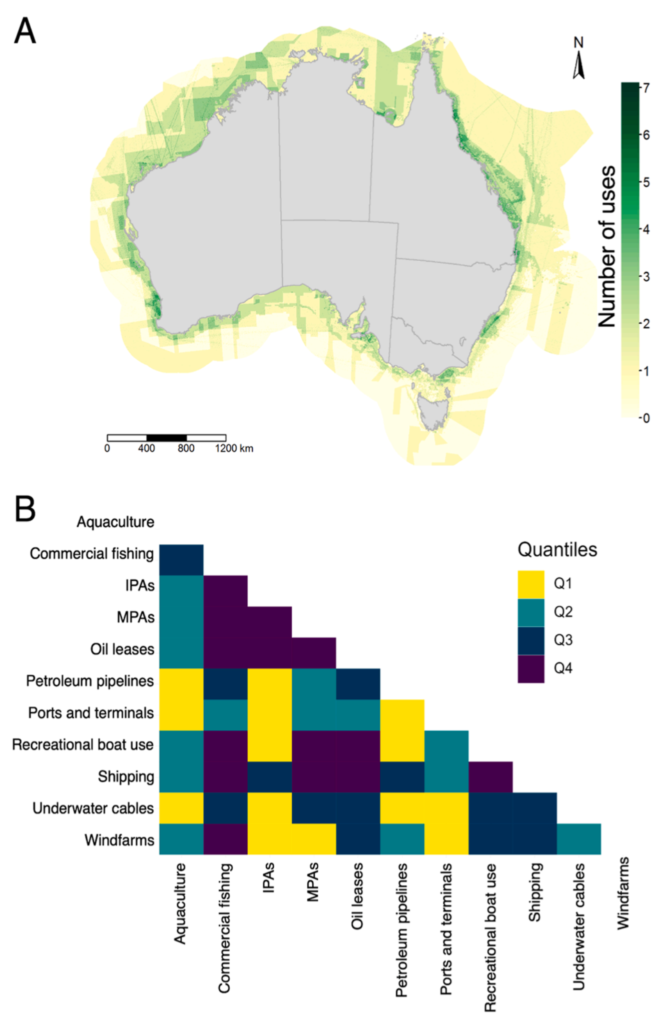

Fig. 4. **A)** Map of number of existing users in marine areas and **B)** the degree of spatial overlap between industries (quantiles of number of overlapping grid cells between industries, where higher quantiles represent greater overlap).

would require adequate capacity, funding, and data management, transparency, and sharing.

In addition to cumulative environmental impacts from human uses, there are also environmental risks to development projects that can threaten the longevity and financial viability of blue economy industries [36]. For example, fisheries and aquaculture can degrade the ecosystems that they depend on for production, while increased risk of extreme weather events may affect offshore wind production [41]. Ocean accounting is developing frameworks to assess feedbacks between natural capital and human activities [42], with climate-related and nature-based financial disclosures representing promising new tools to assess risks and dependencies of industries [43]. Much could be learned and impacts potentially avoided from integrating methodologies across these disciplines.

4.3. Integration across realm and jurisdictional boundaries

We found that most species assessed across industries occurred within multiple realms (i.e., terrestrial, marine, freshwater), which can greatly expand the environmental and socio-economic footprint of development projects. For offshore wind development, the impacts in the sea are often at the forefront of public conversations and environmental assessments since this is where wind turbines are located. However, onshore substations, cable installation and grid connections are necessary to transmit energy to end users and can result in environmental and socioeconomic impacts onshore. Further, significant infrastructure upgrades to ports are often required to meet offshore wind development needs (e.g., adequate space and load bearing capacity, sufficient water depth, land area for storage and operations, etc.) adding to the list and spatial extent of impacts. Consideration of impacts across the entire lifecycle of a product and supply chain (i.e., sourcing materials) is needed to truly understand and integrate management decisions.

The land and sea are notorious for being 'siloed' across many sectors including cumulative impact accounting for conservation (land-sea planning) [15] and food systems [44]. However, methods to integrate cumulative assessments across realms are improving [45,46] through, for example, integration of methods across conservation science and industrial ecology (i.e., life cycle assessments). Adapting these methods for the offshore wind sector would make offshore wind a leader in this space, albeit may be difficult depending on the timeline for implementation. Government agencies should acknowledge and provide support for such assessments. For example, a recent report by Australia's Department of Climate Change, Energy, the Environment and Water provided support for industry by outlining the key environmental factors for inclusion in cumulative impacts assessments under the EPBC, but this could be improved by including onshore impacts [47]. Notably, all EESs for Victorian offshore wind farms acknowledged potential impacts and pressures across both land and sea, a promising step for integration across realms.

In addition to integration across realms, offshore wind projects often cross jurisdictional boundaries between state and federal waters. Just like the land and sea, these jurisdictions generally have unique policy and regulatory considerations that can impact both project development, approvals, and management and are often siloed. In Australia, offshore wind in commonwealth waters still requires corridors, substation development and expansion of port infrastructure in state waters, making it complicated for policy and regulation. These spatial and regulatory mismatches beg the question of where and how to operationalize joint management arrangements – questions currently being grappled with in places like Europe (e.g., Germany [48]) and Australia.

To provide some solutions, we can look to other sectors that experience similar issues. For instance, the World Heritage Listed Great Barrier Reef Marine Park has developed an explicit intergovernmental management agreement [49]. Similarly, there are individual agreements between states and the Commonwealth to manage fisheries (Offshore Constitutional Settlements). In the United States, the Clean Water State Revolving Fund (CWSRF) outlines financial assessments and agreements between the national U.S. Environmental Protection Agency and individual states for wastewater treatment (e.g., [50]).

Based on these structures we recommend countries adopt:

1. Clear, quantifiable objectives and guiding principles to steer collaboration and outcomes between jurisdictions, guided by the SMART framework (Specific, Measurable, Achievable, Realistic, and Time-bound) [51].
2. An intergovernmental forum for better integration and collaboration for decision-making across levels to clearly outline roles and responsibilities and avoid undermining existing arrangements (e.g., a high-level cross-agency committee or ministerial forum).
3. Explicit budget commitments and funding structures to maximize investments, equitably share financial responsibilities and set clear guidelines of responsibility. For example, the Great Barrier Reef and its joint Field Management program and Business Strategy includes explicit budget commitments (e.g., 50:50 contributions) and operational responsibilities from relevant government entities.

These recommendations could also facilitate data sharing and transparency across projects, sectors, and agencies, and thus a more inclusive, equitable and sustainable blue economy.

4.4. Fair and equitable development opportunities within and across sectors

We found substantial spatial overlap between ocean users across Australia's EEZ, which shapes future development and management. Opportunities to progress sustainable blue economy policy and practice lie in ensuring fair and equitable development opportunities within and across sectors. Ultimately, such decisions are made by regulators, but a well-informed, systematic, and transparent planning process can help provide evidence-based decision making and equitable development opportunities for emerging and existing industries, thus supporting blue economy growth.

Resolving how existing and new industries are considered in cumulative assessments can be accomplished through evidence-led marine spatial planning (MSP) processes. MSP is a well-developed framework that provides a process to account for and manage cumulative impacts and maximize socio-economic benefits by involving relevant stakeholders and assessing trade-offs between sectors to support efficient and equitable use of ocean space [52,53]. MSP can aid decision makers in managing industry interactions (e.g., mutualistic, competitive, or antagonistic [32]) and providing fair opportunities (i.e., one industry is not unfairly benefitted or impacted unnecessarily) that stay within ecological limits. For example, in Algoa Bay, South Africa, an MSP pilot project allowed for involvement of a greater diversity of stakeholders, including some that had previously been overlooked, which increased social capacity around the MSP process [54]. Participation, inclusion, and an ecosystem-based approach are important principles of an MSP framework and are used to support an understanding of cumulative effects, which is also a goal in MSP. Spatial mapping of existing and potential ocean users is a foundational step of MSP approaches and can be used to help identify stakeholders for consultation, determine potential for conflicts or synergies between sectors (both existing and new users), and be combined with additional information on biodiversity or other features to assess cumulative impact on environmental,socio-cultural and economic objectives.

Examples of offshore wind energy projects that utilised MSP processes include the US [55], the European Union [56], and many others [57]. Further, international agreements, such as the high level panel (HLP) for A Sustainable Ocean Economy, which has nearly 20 member countries, contain many priorities that could be supported by an MSP framework. Specifically, one of the five key areas of transformation identified by the Panel is ocean equity, which aims to ensure marginalized groups such as indigenous peoples and women have a seat at the decision making table [58]. The Panel also encourages development and implementation of Sustainable Ocean Plans and risk assessments (ocean finance goal) and increased cooperation, capacity building and transfer of knowledge between sectors [58], all of which can fit within an MSP framework and support cumulative impact assessments. Through this initiative, countries that are signatory to the HLP are developing national level Sustainable Ocean plans (including Australia - expected 2025), with guidelines to be place-based, ecosystem-based and knowledge-based, and with specific recommendations for best available science and knowledge around cumulative impacts to be incorporated into planning and decision making [59].

A major challenge for offshore wind MSP is a mismatch in time scales. Ambitious international goals set to be achieved in the next seven years (by 2030) can be at odds with national legislation and policy [60], and the lengthy stakeholder engagement and technical processes needed for adequate planning and cumulative impact assessments. Balancing these trade-offs is challenging, and could result in a narrow application of MSP and cumulative impact assessment to ensure a quick outcome for wind energy projects [61]. However, when applied correctly, MSP can be an enabling tool for a smooth decision-making process because it addresses conflicts early on. Moreover, industry and governments recognize that MSP can improve the level of certainty, transparency, and predictability of private investments [56] and reduce processing times and complexity. For example, MSP cut the cost of the offshore wind permitting process by two-thirds in the Netherlands [62]. These key elements eliminate barriers to allow the energy sector to reach a state of maturity quickly and effectively [56], while also supporting cumulative impact assessments.

4.5. Transparent and reproducible assessments

A common thread throughout our review and analyses was a lack of data sharing and transparency. Data collected for offshore industry development and management is inherently expensive to collect, making it economically inefficient for multiple parties to repeat similar monitoring efforts. While many environmental assessments rely on publicly available datasets, other necessary data to recreate analyses were not available publicly. Information that is published with the assessments is often not supplied in user-friendly formats – requiring extensive time and effort to manually extract information to better understand potential trade-offs and overlaps of development opportunities.

These are similar problems that plagued the reproducibility of scientific research. However, in recent years there has been a push towards open, reproducible research in scientific practices that could be extended to planning processes. There are many best practice guidelines for open and reproducible research, from data collection to post publication. These include robust and standardized methods for data collection, data and code documentation and management, data availability statements and responsibilities of data custodians. Adopting these practices would help development sectors streamline assessments, strengthen and expedite approval processes, and create high quality databases that can be used across sectors to track management responsibilities and outcomes and close knowledge gaps across the governance and production chain.

While there are many benefits to open and reproducible practices, there are also challenges in incentivizing and financing the necessary step change across industries and government agencies. For example, industry is often hesitant to share data due to lack of trust, concerns regarding competitive advantage, and unclear benefits [63]. Addressing these concerns and ensuring compliance to best practices is the responsibility of multiple parties throughout the development approvals process. While competitive advantage is still a concern, one potential solution may involve investors requiring more transparent environmental data practices, such as with nature-based financial disclosures [64]. This approach would be similar to that implemented by funders for scientific research [65–67]. Government agencies could also provide clear data collection guidelines, backed by consistent enforcement and data sharing agreements with relevant parties (i.e., industries, consultants). MSP, as discussed earlier, could act as a structured process for identifying, collating and sharing relevant datasets.

If industries buy into open data practices or are regulated to do so, there are still many challenges in relation to what government agencies do with the data. Even when open data practices are encouraged as part of project approval, there are issues around data capture and storage in these processes, indicating a lack of ability to use information for improved management outcomes [68]. To enable change, data management needs to be a national priority within countries, with adequate funding to incentivize capacity building (both infrastructure and technical skills). In addition, it is crucial that third-party data repositories are secure, thoroughly moderated, and implement robust user authorization procedures to maintain data integrity.

Many countries have ambitious data and digital goals. Australia's ambitions are outlined in the 2030 government strategy [69] and aim to increase data transparency and sharing, which would help with sustainable blue economy development. The Digital Environmental Assessments Program and Biodiversity Data Repository project also aims to help streamline the approvals process across industry, government, and public consultation (https://www.dcceew.gov.au/environment/epbc

/our-role/improvements). Similarly, some funds already exist at the state level to spur innovation in renewable energy, such as Victoria's Energy Innovation Fund and the Blue Economy Cooperative Research Centre data infrastructure design project, which could be used as a roadmap for similar management related funds in the future.

The surge of initiatives for increased data transparency and sharing is a step in the right direction. To enable assessment of cumulative effects on human uses and the environment, we recommend having consistent standards for monitoring and data reporting and ensuring any data collected are incorporated into these platforms – from project proposal through decommissioning. This should include mandatory long-term monitoring of ecosystem components (biological and physio-chemical) and ecosystem health metrics to further understand the impacts of development projects through time, in line with the EU and UK. For instance, following project award, proponents in Germany are required to monitor project impacts for three to five years to verify the assumptions made within the EES [70], to submit data to a centralized federal repository, and apply further mitigation measures or project biodiversity offsets if negative impacts exceed those stated in the EES.

Centralized repositories can be complex and difficult to manage. In Australia, such a repository could take inspiration from the Australia's National Integrated Health Services Information system (https://www.aihw.gov.au/reports-data/nihsi) and the Australian Bureau of Statistics Secure Environment for Analyzing Data Services (SEAD, https://www.abs.gov.au/about/data-services/secure-environment-analysing-data-sead). Clear guidelines are needed to promote consistency and transparency across state and national levels, making data publicly available where at all possible, ensuring sensitive data are securely stored, and following FAIR data management principles in line with the Data Availability and Transparency Act established in 2022 [71].

Data gaps are a common issue faced in cumulative impact and environmental assessments but should not preclude management. For example, data on recreational uses, commercial fisheries, and ecosystem states can be incomplete, outdated, or lacking. However, decisions should be made on best available evidence, and updated as new evidence becomes available (i.e., an adaptive approach). Detailing the full range of potential data inputs for an analysis and explicitly stating why data is included or excluded (e.g., outside of scope, data unavailable, poor resolution, etc.) can increase transparency and help identify these gaps, help decision makers understand the implications of missing data sources, and inform future research investment.

5. Conclusions

The nascent nature of the offshore energy sector in many countries and the rapid pace of development raise both challenges and opportunities for effective ocean management. Cumulative effects assessments remain an uncertain and complex aspect of environmental and socio-economic sustainability of natural resources.

In reviewing Victoria, Australia's offshore wind EES's, we found key data gaps in clearly defining impact pathways, assessing potential impacts across projects and industries, as well as across jurisdictions and realms. These shortfalls are similar to those that have been found in other offshore wind development processes, particularly in the UK [16]. We recognize that in Australia, these projects are in early phases of development approval. Further assessment of cumulative impacts in the development process should focus on closing key data gaps such as: baselines for ecosystem states [10], better reconciling spatial and temporal patterns in DAPSIR components and pathways, robust and transparent analysis of the expected intensity of stressors and vulnerability of species and habitats to assess impact across species life stages and industry life cycles, comparable assessments across projects and industries to facilitate integration, consideration of a counterfactual scenario (what would happen in the absence of development), and quantification of uncertainty. The recommendations here, alongside other principles and recommendations in the literature [16,72], provide scientifically based starting points to guide and help improve cumulative impact assessments while also streamlining regulation processes and better accounting for interactions between and across projects and industries.

Change is needed for cumulative impact assessments to meaningfully inform development approvals and management. While timelines are tight to meet international objectives and deliver renewable energy development as part of the energy transition, every effort should be made to identify and reduce the negative outcomes for the environment while building on socio-economic opportunities.

CRediT authorship contribution statement

Tess O'Neill: Writing – review & editing, Visualization, Formal analysis, Data curation. **Jackson Stockbridge:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Caitlin Kuempel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Christopher Brown:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Christopher Frid:** Writing – review & editing, Funding acquisition. **Laura Griffiths:** Writing – review & editing.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106571.

Data availability

All data and code to reproduce analyses is available on GitHub at https://github.com/cdkuempel/Kuempel_offshore_wind_CIA.

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