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Environmental considerations related to floating offshore wind farms: a case study from waters around New South Wales, Australia

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ABSTRACT

Context. Australia will likely host new commercial offshore wind farm (OWF) developments, including possible floating turbines off the coast of New South Wales (NSW). However, early planning has already resulted in strong community opposition, largely because of perceived negative environmental impacts. **Aims.** This review provides a summary of research to inform the potential environmental impacts of floating OWFs in the waters around Australia, using NSW as a case study. **Methods.** We review information on regional environmental baselines for key receptors and characterise how environmental impact pathways identified by the Australian Government may apply to floating OWFs. **Key results.** Environmental impacts depend on many factors, including OWF characteristics and species and ecosystem traits. Some developments will need floating platforms, which have potentially different environmental impacts from those of bottom-fixed foundations predominately used overseas and planned elsewhere in Australia, particularly related to seabed disturbance, entanglement, underwater noise and barrier effects. **Conclusions.** The greatest challenge to impact assessment in Australia is the scarcity of local environmental information, particularly regarding species distributions and ecosystem functions in deeper marine environments where floating OWF development may occur. **Implications.** This review provides a first step for various sectors to understand the potential environmental impacts of floating OWF in Australia.

Keywords: artificial reef, benthic, fish, marine megafauna, offshore renewables, refuge effect, seabirds, underwater noise.

Introduction

As many countries transition to renewable energies, offshore wind farms (OWFs) are being installed to generate and transmit power from wind by using turbines and a combination of underwater and land-based infrastructure such as foundations, cabling and substations. Offshore wind developments are generally considered capable of yielding more energy per installed capacity than do onshore wind developments, owing to ocean winds being stronger and more consistent (Keivanpour *et al.* 2017). The first offshore wind turbines appeared as pilot projects in the 1990s in Denmark, Sweden, Netherlands and the United Kingdom (Kaldellis and Zafirakis 2011). Multiple large-scale wind farms are now commercially operating in waters across north-western Europe, with the United Kingdom and China having the most OWFs (Briggs *et al.* 2021). Several other regions are investing in offshore wind energy to meet net-zero targets and energy security, such as in South-east Asia and the United States.

As of 2025, Australia has no operational OWFs despite abundant wind energy resources comparable to those of the North Sea (e.g. 9–10 m s^{-1} in Briggs *et al.* 2021). To meet Australia's net-zero emissions target, in 2022 the Australian Government declared six priority areas in Australia for offshore wind development. The first offshore wind farm to become operational will likely be located off the coast of Victoria in Bass Strait (Golestani *et al.* 2021), but there are other projects across southern Australia in the early planning phase (Larkin *et al.* 2024). In some of these areas, floating OWFs will be the likely technology, but there remain significant knowledge gaps relating to the environmental impacts of these OWFs, particularly because they are developed at larger scales.

These early planning phases have already resulted in strong community opposition to OWFs (Condie *et al.* 2024), particularly in the Illawarra and Hunter zones near New South Wales (NSW) (Fig. 1), largely owing to perceived negative environmental impacts (Australian Marine Sciences Association 2023; Fidge 2024). Public debates have often been focused on questions around the accuracy of the available information on the environmental impacts of OWF, with suggestions that misinformation and disinformation were influencing public trust in renewable energy and especially offshore wind (Fernandez and James 2023; Morton *et al.* 2023; Garo and Roberts 2024; The Senate, Environment and Communications References Committee 2025; Voyer *et al.* 2025). Such debates generate confusion and tension about what the offshore wind projects are, how the planning process is structured and, more generally, how offshore wind could and could not affect marine environments (The Senate, Environment and Communications References Committee 2025).

While this article was under peer review, the sole feasibility licence offered for offshore wind energy in NSW was declined, thus postponing commercial development of offshore wind energy in NSW. Nevertheless, the proponents said they continue to view the 'Hunter region as well positioned

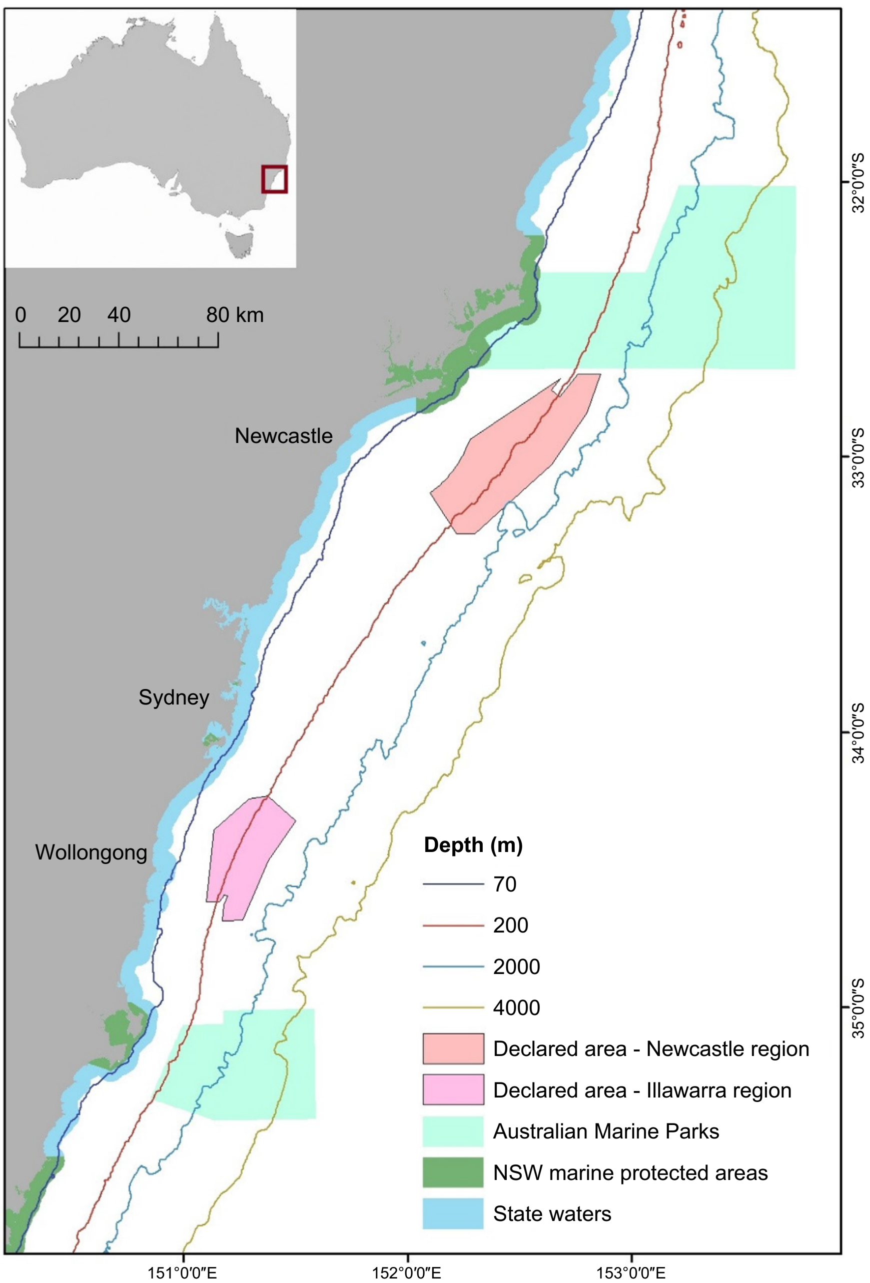

Fig. 1. Map of declared offshore wind energy zones in New South Wales as of August 2024 (pink polygons) and marine protected areas (green polygons). State waters extend to 3 nautical miles (~5.6 km) from mean high-water mark.

to lead Australia's energy transition . . . , [and one of the proponents] remains committed to exploring options for offshore wind . . . for the Hunter and New South Wales' (Novocastrian Wind Pty Ltd 2025). On the same day, the Australian Government released draft guidelines to inform research and demonstration licences for emerging offshore renewable energy technologies (Department of Climate Change, Energy, the Environment and Water 2025), thereby supporting an immediate path forward for floating offshore wind energy to be progressed in NSW.

This review aims to provide a summary of available research on the potential environmental impacts of floating OWFs, by using NSW as a case study (Fig. 1). We have focussed on NSW because floating turbines are the preferred technology in the deeper waters of the Hunter and Illawarra wind energy zones and because the perceived risk of environmental impacts is strong in that region. The information summarised here provides a first step for industry, government, community and research sectors to appropriately consider the potential environmental impacts of offshore wind on the marine environments in NSW waters. For the purposes of this review, an environmental impact is defined as any change that results in population- or community-level responses, whether positive or negative, resulting from human activities or natural events.

Because there are many studies and reviews of environmental impacts of OWFs, we have confined the scope of this review to focus on the following:

- floating wind turbines and associated infrastructure (e.g. dynamic cabling), noting that some of the environmental impacts are shared with fixed foundations, whereas others are unique (Maxwell *et al.* 2022);
- the marine region surrounding NSW and more broadly south-eastern Australia, drawing on regional and global studies to be contextualised for Australia;
- environmental impacts, with other impacts to economy, society and cultures considered only in the context of their link to environmental impacts (e.g. fishing restrictions will likely affect fish populations); and
- the potential impacts on Australian offshore environments and on the organisms that inhabit and depend on those environmental components; although OWFs have onshore infrastructure that may affect the surrounding environment, anthropogenic impacts in coastal and terrestrial environments are well-studied compared with those offshore.

Methods

A review of the academic and non-academic literature was undertaken to qualitatively assess the potential environmental impacts of floating OWFs in offshore waters (Szostek *et al.* 2024). We used Web of Science as the primary database to search and source publications, with the main search terms using various combinations of 'offshore wind farm', 'offshore energy', 'environment' and various targets (marine mammals, seabirds, fish, invertebrates). We identified further sources, including grey literature, from the Tethys Knowledge Base (see https://tethys.pnnl.gov/knowledge-base-all) and by 'snowballing' from the reference lists of identified articles (Hooper *et al.* 2017). We did not follow a formal systematic review process, because our aim was to identify the largest possible body of studies to permit a comprehensive review. A list of other relevant literature reviews on the potential environmental impacts of OWFs is available in the Supplementary Table S1.

Noting other impact classifications such as those provided by the IUCN (Bennun *et al.* 2021), we categorise the potential ecosystem impacts of offshore wind by using the 13 key environmental factors for impact assessment defined by the Australian Government under the *Environmental Protection and Biodiversity Conservation Act* 1999 (EPBC Act) (Department of Climate Change, Energy, the Environment and Water 2023*a*), henceforth referred to as 'impact pathways'. Findings from the literature review were then used to (1) provide an overview of how floating wind farm design (turbine features and location, mooring and anchor type, number of turbines) and developmental stage (planning, construction, operation and decommissioning) relate to potential environmental impacts, (2) apply results of the literature review to environmental baselines for key taxa and habitats around NSW waters, and (3) apply results of the literature review to impact pathways.

OWF design and environmental impact

Most offshore wind turbines are grounded (i.e. fixed to the seafloor), with ~80% using a monopile as their foundation (Bosnjakovic *et al.* 2022). However, offshore wind turbines are increasing in size and being placed farther from the coast in deeper waters, thus requiring new forms of floating foundations that are tethered to the seabed (Guo *et al.* 2022). As of 2025, Hywind Tampen in the North Sea is the world's deepest and largest operational floating wind farm, with a system capacity of 94.6 MW over its 11 turbines in waters up to 300 m deep. California aims to develop the world's largest floating OWF with up to 400 turbines by 2030 (King 2024), and consideration is being given to floating turbines in waters over 1000-m depth (Farr *et al.* 2021). In 2023, installed capacity of floating turbines around the world accounted only for 0.0121 GW, but this is expected to reach 264 GW by 2050 (Edwards *et al.* 2023). Most of the viable offshore wind energy resource available to NSW is in deeper waters (>60 m) and will require floating foundations because of the prohibitive cost and technical challenges of constructing foundations that reach the seabed (Briggs *et al.* 2021).

Floating wind turbines have a range of design types based on the turbine platform (spar buoy, tension leg platform, semi-submersible), moorings (catenary, taut-leg, semi-taut) and anchor points (drag-embedded, piled, suction caisson, gravity anchor) (James and Ros 2015) (Fig. 2). As with many emerging technologies, other designs are being proposed for floating OWFs, and these can be expected to converge over time to offer more cost-effective options (Barooni *et al.* 2023; Díaz and Soares 2023; Edwards *et al.* 2023). The choice of mooring and anchor systems have a particular influence on environmental impacts (Maxwell *et al.* 2022; Rezaei *et al.* 2023) (Fig. 2). Floating OWFs represent a rapidly evolving technology, and there are still only a handful of ecological studies at operating floating OWFs, all of these in the North Sea (see table 1 in Harris *et al.* 2025).

OWF developmental phases

There are four phases to wind farm development: planning, construction, operation and decommissioning, each being associated with distinct potential environmental impacts (Gill 2005). Regulatory approvals are required at various times during these phases. Although these will vary among states in coastal waters, the Australian Government has set out regulatory steps that apply in Commonwealth waters, generally 3–200 nautical miles (~5–360 km) off the coast.

In addition to being assessed by merit criteria set out in the *Offshore Electricity Infrastructure Act* 2017 (OEI Act), any offshore wind project that is likely to have a significant impact on matters of national environmental significance (MNES) as defined by the EPBC Act must undergo an environmental assessment and receive an approval before it can go ahead. MNES can include migratory species, threatened species and communities, and the Commonwealth marine environment. Projects must demonstrate how they will ensure that negative effects to protected matters will not be unacceptable.

Planning

OWFs have an extensive planning and surveying phase, often underpinned by reviews of available information and extended site surveys to acquire environmental baselines and geological information. This information is then used to inform project planning and environmental risk assessments (Kaldellis *et al.* 2016). Environmental baselines can identify potentially vulnerable species or ecosystems in the area planned for development, as well as crucial knowledge about animal behaviours and movements. This information can inform the best timing for construction and the configuration and siting of wind turbines.

Geophysical information is collected with multibeam sonar, sidescan sonar or sub-bottom profilers that produce sounds that reflect off subsea structures to obtain depth, images of the seafloor and shallow geophysical characteristics. These techniques are unlikely to significantly affect marine mammals or other organisms (Mooney *et al.* 2020; Ruppel *et al.* 2022; Lurton 2025). By contrast, marine seismic surveys are

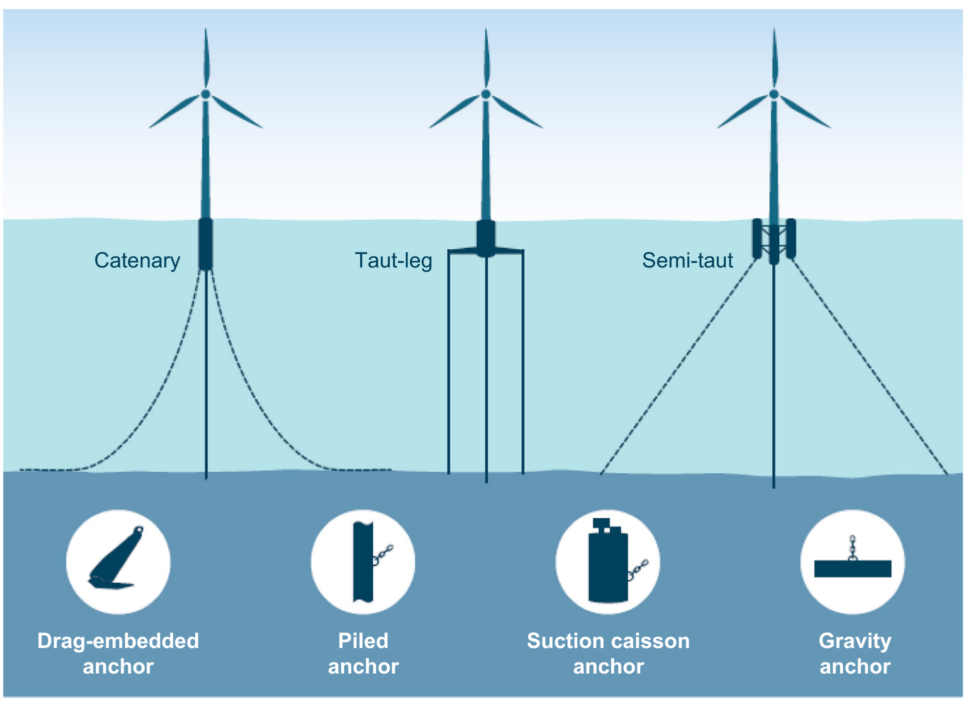

Fig. 2. Diagram of main types of mooring and anchor systems currently used for floating offshore wind turbines. See Rezaei *et al.* (2023) for more details about floating-OWF designs.

often used for petroleum exploration and may have complex environmental impacts (Carroll *et al.* 2017), but these are only rarely used in site surveys for OWFs (Mooney *et al.* 2020). Even when seismic surveys have been historically used for offshore wind planning, they need to penetrate the seabed only to the depth of the foundation (e.g. 50–100 m beneath seabed) and are therefore limited to a single airgun or small array, compared with petroleum exploration surveys, which can employ dozens of large airguns. In Australia, the EPBC referrals submitted and approved to date in the declared area off Victoria in Bass Strait have excluded the use of airguns altogether (see https://epbcpublicportal.environment.gov.au/all-referrals).

Construction

The construction phase comprises building, transportation and installation of the required infrastructure, and the magnitude and duration of stressors can vary greatly depending on the environmental conditions, foundation type, turbine and wind farm sizes, port infrastructure, and installation vessel capability (Hernandez *et al.* 2021; Chitteth Ramachandran *et al.* 2022). Turbines, substations and some other infrastructure are usually pre-assembled in port and then transported to the site.

Seabed disturbance and underwater noise are both expected to generally be lower for floating OWFs than for fixed-bottom OWFs (Table 1). High noise levels are typically associated with pile driving of monopiles into the seafloor (Robinson *et al.* 2012), but the construction of floating wind farms relevant to the Hunter and Illawarra OWF zones will involve little or no pile driving, depending on the anchoring system (Haberlin *et al.* 2022). Anchor chains may still need to be moored by impact hammering, but the process would be expected to create lower noise levels than does monopile hammering, because noise scales with mooring or pile size (Erbe *et al.* 2025*b*). Nonetheless, monopile foundations require only one pile to be driven (which might take 1 h or more; Erbe 2009), whereas anchor systems of floating turbines may require three for four (shorter and smaller) piles to be driven. However, after turbine installation, cable installation may disturb the seabed. Seabed cables can be exposed on the seabed or buried or covered to protect them from ship anchoring and fishing activity, typically to a target depth of 1–2 m.

Operation

The operational phase extends for the lifespan of an OWF, with turbines typically lasting 25–35 years (Pakenham *et al.* 2021; Australian Energy Infrastructure Commissioner 2023), although turbine upgrades ('repowering') may extend the lifespan beyond 40 years (Bennun *et al.* 2021). OWFs do not operate continuously and have a minimum wind speed at which turbines generate power (~3–5 m s^{-1}) and a maximum wind speed at which they are shut down to protect against damage (>25 m s^{-1}) (Band *et al.* 2021). Regular inspections are required to assess infrastructure and to maintain, repair or replace equipment, during which time part or all of the wind farm will not be operational (Ren *et al.* 2021; McMorland *et al.* 2023). Vessels and helicopters are usually used for maintenance operations, whereas remotely operated vehicles, underwater cameras and sonar systems contribute to regular inspections. Although inspection frequencies are unlikely to differ between floating and fixed turbines, the pattern of activity will be different, with the greater distances offshore of floating OWFs requiring larger vessels and longer transit times.

Decommissioning

During decommissioning, the infrastructure is wholly removed, partially removed, repurposed or even repowered for continued operation (Topham and McMillan 2017). International guidelines either legislate or promote complete removal at the end of life (Lemasson *et al.* 2022), and Australia's OEI Act requires complete removal of all structures when no longer in use. This policy is being questioned from an ecosystem perspective, because decommissioning is expected to have similar environmental impacts as the construction phase, with the added complexity of removing functional artificial reefs that have developed over decades of operation (Fowler *et al.* 2020). Knowledge from decommissioning of oil and gas structures can be brought to planning for OWF decommissioning (Stranddorf *et al.* 2024), and this is particularly useful in Australia where a rapidly growing body of research is investigating the environmental impacts of removing long-standing oil and gas platforms (Melbourne-Thomas *et al.* 2021; Sih *et al.* 2022). Decommissioning of large underwater structures typically comprises the use of heavy lifting vessels, dynamic positioning, remotely operated vehicles (ROVs) and subsea cutting tools. Depending on the foundation style, floating turbines will apply such machinery to varying degrees, although in each case this will be less than during removal of fixed turbines because of the reduced infrastructure.

Limited scientific studies have investigated the actual effects of OWF decommissioning, because most commercial wind farms have not yet reached their life expectancy (Dannheim *et al.* 2020), and repowering is a possibility to extend the lifespans of OWFs (Bennun *et al.* 2021). The environmental dimensions of OWF decommissioning are interconnected to other end-of-life OWF technical, economic, social and policy challenges (Vetters *et al.* 2024). Robust baseline assessments and ongoing monitoring programs to evaluate impacts are critical to informing the decommissioning phase (Ierodiaconou *et al.* 2023).

Measuring environmental impact

The greatest global environmental impact from OWFs relates to the sustainable transition to renewable energy that will

Table 1. Key differences between the potential environmental impacts of floating and fixed offshore wind turbines, including which matters of national environmental significance are directly relevant to impact pathways.

Impact pathway	Floating	Fixed	Commonwealth marine environment				
			Listed migratory and threatened species				
			Marine mammals	Seabirds	Sea turtles	Fish	Benthos
Physical presence – barrier effects and displacement of marine fauna	Barrier effects related to infrastructure near surface	Barrier effects strongly related to infrastructure throughout entire water column	X	X	X	X	
Turbine interactions – injury and mortality to birds and bats	No differences	No differences		X			
Underwater noise – mortality, injury, masking, stress and behavioural effects	Pile driving during construction highly dependent on anchor design Operational noise from anchor chains or cables	Pile driving required for fixed foundations during construction Minimal operational noise from anchor chains or cables	X	X	X	X	X
Entanglement[A]	More cables may increase risk of secondary entanglement owing to fishing gear	Fewer cables associated with fixed foundations, lower risk	X		X	X	
Invasive marine species	Stepping stone effect largely limited to near surface	Stepping-stone effect extends throughout entire water column				X	X
Physical presence – effects on hydrodynamics and sediment transport processes	Sediment disturbance during installation of anchors Scour effects of anchoring and mooring lines Hydrodynamic changes with floating platforms	Sediment disturbance during construction for fixed foundations Hydrodynamic changes with fixed platforms	X		X	X	X
Light emissions	No differences	No differences		X	X	X	
Seabed disturbance – loss of or harm to benthic habitats	Disturbance and scour owing to anchor points; mooring line abrasion	Larger area of disturbance owing to fixed foundations and scour protection				X	X
Habitat creation[A]	Benthic artificial reef effect at anchor points Strong floating artificial reef effects at platform and mooring lines	Benthic artificial reef effect at fixed foundation and scour protection Weaker floating artificial reef effect				X	X
Electromagnetic fields	No differences in electromagnetic field (EMF) emissions; however, pelagic environmental effects not previously considered and direct contact with cable possible	No differences in EMF emissions, however if cables buried then the seabed creates a physical barrier between the receptor species and the cable				X	X
Vessel interactions – injury and mortality to marine fauna	No differences	No differences	X		X	X	
Contaminants and debris[A]	Primary potential source pollution is limited to infrastructure near and above surface	Primary potential source pollution extends from above ocean (turbines) to seabed (fixed foundation)	X	X	X	X	X
Multiple impact pathways – Australian marine parks and their values	See differences listed above		X	X	X	X	X
Cumulative impacts[A]			X	X	X	X	X
Disturbance of underwater cultural heritage			Not directly applicable		Not directly applicable		
Physical presence – socio-economic: interference/ displacement of existing uses							
Physical presence – socio-economic: seascapes and visual amenity							

[A]Impact pathway is recommended for future inclusion in federal guidelines (Department of Climate Change, Energy, the Environment and Water 2023*a*).

reduce CO_2 emissions and the predicted severity of climate-change impacts, ultimately supporting the conservation of many species and ecosystems (Snyder and Kaiser 2009). In NSW, climate change has been linked to range shifts, mortality events and ecosystem shifts (Booth 2020; Davis *et al.* 2020*a*, 2022), similar to what has occurred all over the world (Pörtner *et al.* 2022).

However, at local or regional scales, environmental impacts of OWFs may be much more complex (Watson *et al.* 2024). Since Australia has yet to construct any OWFs, scientific studies from other parts of the world can help us understand the environmental changes that can occur and any potential impacts, but these must be interpreted within the context of Australia's unique habitats and species (Parsons and Battley 2013). We can also make inferences from the wealth of studies in Australia completed on the environmental impacts of other offshore energy structures (e.g. oil and gas platforms), along with research conducted on artificial reefs. For some potential impacts such as those associated with collisions or electromagnetic fields, we do not yet have enough observational data to understand risk or benefit (Buenau *et al.* 2022). Other potential impacts lack real-world studies and are based solely on modelling or laboratory studies with variable effects (e.g. wake effects owing to large infrastructure) (Haberlin *et al.* 2022).

Overall, the environmental impacts of OWFs depend on many factors, including the species and population, ecosystem, substrate, oceanographic conditions, device size and spacing, mooring design, array layout, and phase of operations (Benjamins *et al.* 2014). Impacts are likely to be complex and include both challenges and opportunities (Galparsoro *et al.* 2022) (Fig. 3). We cannot reliably predict environmental impacts until we know further details about the spatial extent of the OWF footprints in the Hunter and Illawarra, and the information throughout the remainder of this section therefore provides general guidance about potential future impacts in this region.

Environmental baselines

Assessing the impacts of offshore wind developments requires knowledge about the marine environment in and around the proposed development, including what organisms occur there and how they may use the area. These environmental baselines allow an impact assessment to focus on target species, communities and biologically important areas (e.g. nursery habitat), and they also provide the foundation to build a monitoring program aimed at detecting meaningful change during all stages of OWF development. Typically, such information is collected by observations or specimens, but there are emerging applications to OWFs overseas of environmental DNA (Cornelis *et al.* 2024) and autonomous systems (Hemery *et al.* 2022) that can be used in Australia's environment.

Biodiversity repositories such as the Ocean Biodiversity Information System (see www.obis.org) and the Atlas of Living Australia (see www.ala.org.au) provide a first step to catalogue species that have been recorded from areas earmarked for offshore renewable development. However, the observations in these portals are limited to presence or absence, and so the behaviour and distribution of organisms is generally unknown. Unlike other marine jurisdictions, Australia does not have available environmental information for many parts of its marine estate, nor does the government undertake environmental surveys to support discrete industry developments. Targeted environmental baseline and monitoring surveys are thus required by industry to assess and track the environmental impacts of offshore renewables, similar to what has been successfully implemented overseas (e.g. WinMon.BE in Belgium, WOZEP in Netherlands).

Despite limits on environmental information in Australian offshore renewable zones, existing regional knowledge can be compiled and knowledge gaps identified to inform more targeted surveys and impact assessments. A review of available information on oceanography, seabed habitats and threatened species across all six offshore wind declared areas provided an initial inventory of environmental data relevant to OWF developments (McLean *et al.* 2024). The following further details are provided here on the key environmental factors in the Hunter and Illawarra zones.

Marine mammals

To understand the impacts of OWFs on marine mammals, we need to know their migratory and behavioural patterns, including when and where animals may transit through proposed zones, or rest there to feed, breed or birth (e.g. Quintana-Rizzo *et al.* 2021). In Australia, we have good understanding of the occurrences of some coastal and charismatic megafauna, including marine mammals, that can be used to infer their distributions (e.g. Atlas of Living Australia, Australian Marine Spatial Inforation System, EPBC Protected Matters Search Tool). It is known that at least 21 species of cetacean and two species of pinniped are likely to occur in the Hunter and Illawarra OWF zones (McLean *et al.* 2024), including migratory species such as humpback whales (*Megaptera novaeangliae*; Bruce *et al.* 2014), southern right whales (*Eubalaena australis*; Carroll *et al.* 2011) and pygmy blue whales (*Balaenoptera musculus brevicauda*; Möller *et al.* 2020). However, we still have limited understanding of these animals' movement patterns and the behaviours that drive when and where they move among areas of key ecological and biological importance. Scientific programs are working to fill these knowledge gaps by analysing presence and movement data from marine mammals and other megafauna to infer where those important areas are (e.g. Megamove in Sequeira *et al.* 2025, OBIS-SEAMaP in Halpin *et al.* 2009).

Seabirds

A total of 34 species of birds were identified from public databases that are likely to intersect with the Hunter and

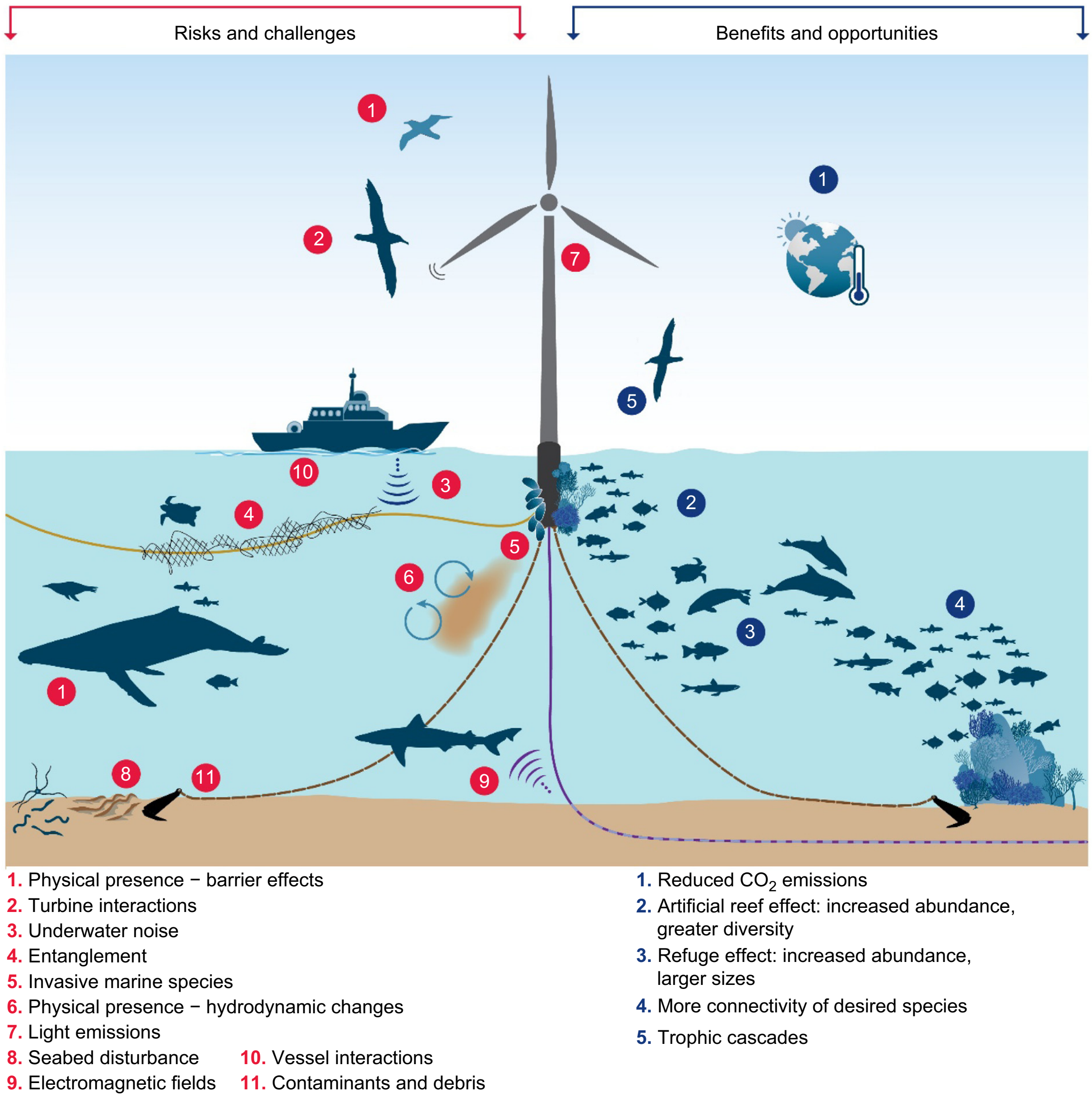

Fig. 3. Marine environmental impact pathways of offshore wind farms at the local scale of an individual turbine. The floating wind turbine is a stylised catenary mooring and is not indicative of actual designs that may be used in Australia.

Illawarra OWF zones (McLean *et al.* 2024), and more than 90 species of seabirds have been recorded in the broader region within the Australian exclusive economic zone (EEZ) off New South Wales (E. J. Woehler and N. Carlile, unpubl. data). Overall, Australian coastal waters are dominated by procellariiform seabirds (petrels, albatross, shearwaters). This group differs from those species prevalent in European waters, where much of our current knowledge and understanding about seabirds and OWFs are sourced (Miller *et al.* 2025).

Critically, results from overseas studies may apply only to very few species in Australia. These differences arise because (1) many seabird species in Europe are 'flappers', whereas Australia is dominated by species that spend much of their time gliding, including more time at higher altitude in strong winds (Ainley *et al.* 2015; Miller *et al.* 2025), (2) shearwaters and petrels that are common in Australia forage for significant periods at night (Warham 1990), and (3) seabirds in the Northern Hemisphere forage predominantly in nearshore and coastal waters close to colonies, whereas there are a greater number of seabird species that forage offshore and farther from colonies in the Southern Hemisphere.

We also lack information about how seabirds use NSW coastal corridors, although species can be broadly grouped into those that visit the region for foraging and those that also breed within the region. Many observations come from tourist boats where seabirds are deliberately attracted with food

(Gorta *et al.* 2019), but these data are highly biased and do not accurately reflect bird behaviours or species diversities in the region. Significant survey effort is required to gather unbiased data using standardised methods (Woehler 1997; Camphuysen *et al.* 2004; Daudt *et al.* 2024) and opportunities exist to do this by using collaborative research frameworks and sharing costs among OWF developers in the region.

The collection of baseline data over relevant spatial and temporal scales is crucial to understand potential impacts on NSW seabirds, but methods must be relevant to local species. Gould's petrel, for example, has rarely been seen in daytime citizen science 'pelagic' trips off Port Stephens, despite the vessels passing the principal nesting grounds in departing and returning from port (25 records from 7 years of monthly surveys: Gorta *et al.* 2019). This result is not unexpected because the species approaches land only under the cover of darkness, foraging in the southern Tasman Sea (Priddel *et al.* 2014). Many of the species foraging offshore in Australia's EEZ and farther offshore appear very similar, and survey methods must be able to distinguish seabirds to the species level to effectively inform project impact assessments. Survey methods that are able to identify seabirds only to the genus or family level are unlikely to be effective in this context.

Sea turtles

Four species of sea turtles are known to visit NSW waters, including the Critically Endangered hawksbill turtle (Mortimer and Donnelly 2008), the Endangered green turtle (Wallace and Broderick 2025), and the Vulnerable loggerhead turtle (Casale and Tucker 2017) and leatherback turtle (Wallace *et al.* 2013). Turtle nesting sites in NSW have been recorded as far south as the central coast region (NSW TurtleWatch). Turtles are vulnerable to any disruption to their movement patterns or behaviour because this may reduce rest periods, limit energy and interfere with reproduction (Díaz *et al.* 2024). A recent global assessment of migratory megafauna identified important migratory corridors and residence areas along south-eastern Australia, including NSW (Sequeira *et al.* 2025). As with marine mammals, further research is needed to understand migratory patterns of these species and how this could relate to OWFs.

Fish

The proposed NSW OWF zones cover mesophotic (30–150 m) and rariphotic (150–300 m) ecosystems (Bell *et al.* 2024), which have been shown to support novel fish communities characterised by a mixture of shallow coastal species, mesophotic and rariphotic specialists, and deep-water species that are found nowhere else (J. Williams *et al.* 2019).

Most of what we know about fish communities in the NSW offshore wind zones can be derived from research and baseline surveys of the Hunter Marine Park directly to the north of the Hunter zone (Fig. 1). These surveys showed that offshore demersal fish communities were statistically distinct from those in the inshore coastal regions (J. Williams *et al.* 2019, 2020) and also confirmed that the EPBC Act-listed grey nurse shark and white shark use reef on the outer shelf region (Otway *et al.* 2003; J. Williams *et al.* 2020) (NSW Department of Primary Industries and Regional Development, unpubl. data). In the Illawarra region, research focuses on large expanses of reef that extend to the 100-m contour (Broad *et al.* 2023). Historically, the fisheries research vessel Kapala conducted regular trawl surveys across the NSW continental shelf to monitor fish abundances from 1975 to the early 2000s (NSW Department of Primary Industries 2004), but we still have very little understanding about the fish communities inhabiting the NSW continental shelf (>200 m) in NSW. A number of large canyon features in northern NSW have been mapped, including off the Newcastle coastline (Glenn *et al.* 2008) (Fig. 4). In other regions, these canyon features have been shown to support a rich diversity of fishes and marine mammals (Trotter *et al.* 2022), owing to the higher productivity from nutrient-rich water that is pushed into the canyons (Kämpf 2010).

A recent ecological risk assessment of offshore wind farm impacts on Australian elasmobranchs identified 39 species of potential concern, of which the following four occur in NSW waters: oceanic whitetip shark (*Carcharhinus longimanus*), estuary stingray (*Hemitrygon fluvium*), green sawfish (*Pristis zijsron*) and great hammerhead (*Sphyrna makarran*) (Werry and Meager 2025). Of these, only the shark species are likely to occur in the NSW declared offshore wind zones or neighbouring areas.

Benthos

Much of our knowledge of the benthic habitats and associated invertebrates around NSW comes from shallow waters (<30 m), particularly related to towed video within state waters (Jordan *et al.* 2010; Davis *et al.* 2020*a*, 2020*b*) and underwater visual censuses (Edgar *et al.* 2020). McLean *et al.* (2024) provided an inventory of benthic species likely to occur in the Hunter and Illawarra OWF zones on the basis of public databases, as well as a list of introduced species that may overlap these zones, all of which are benthic invertebrates or algae. Marine imagery from the Hunter Marine Park to the north of the Hunter OWF zone shows that rocky reefs almost always support benthic organisms (e.g. algae, sea whips, octocorals, sponges), but in deeper areas, hard substrate is often draped in sediment with fewer epifauna (J. Williams *et al.* 2020). Deeper soft sediment areas in the Hunter Marine Park are more likely to support habitat-forming invertebrates than are shallow soft sediment areas (J. Williams *et al.* 2020). Sediment grabs offshore from the Port of Newcastle are dominated by polychaetes and crustaceans with very few molluscs, with areas of anchor disturbance showing higher abundance and lower diversity than neighbouring undisturbed areas (Davis *et al.* 2025). Near the Illawarra OWF zone, studies on the potential effects of anchor scour have shown diverse sponge gardens at depths of 35–50 m, surrounded by expanses of soft sediment habitat (Broad *et al.* 2023).

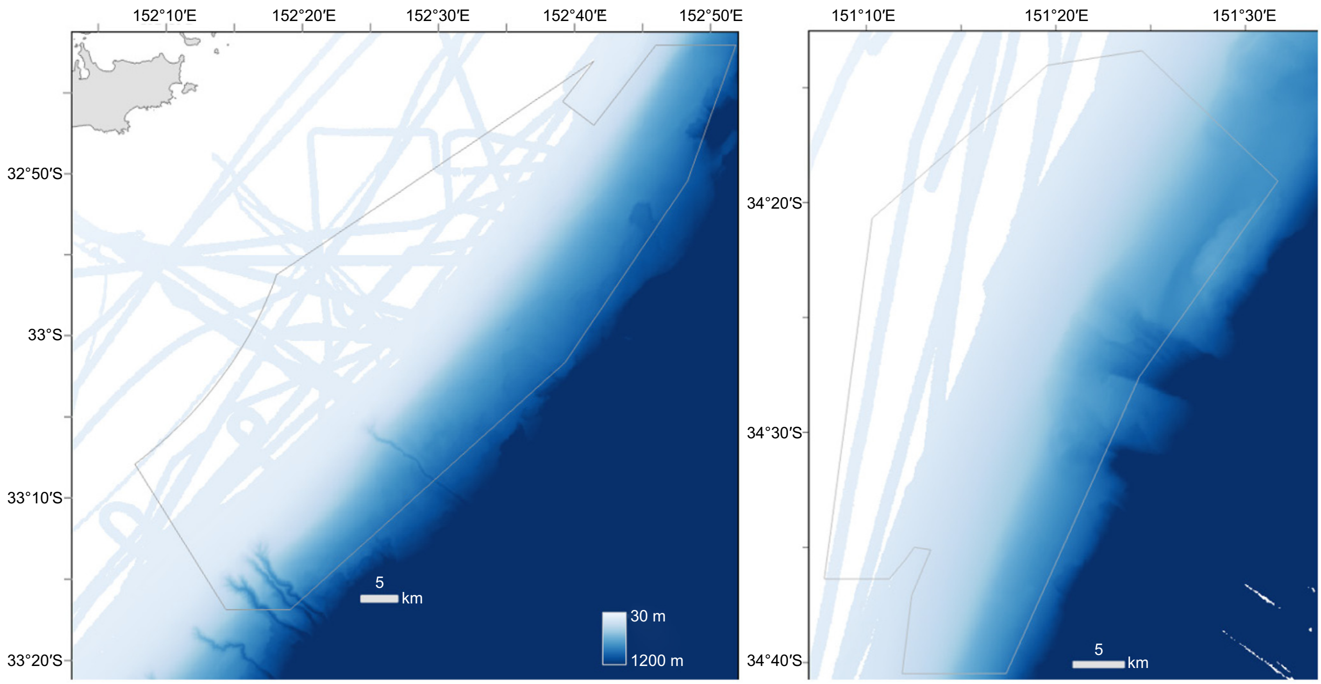

Fig. 4. Available high-resolution bathymetry shown in blue in the (left) Hunter declared offshore renewable zone, and (right) Illawarra offshore renewable zone. Declared areas are outlined in grey. Continental slope is represented by the transition from medium blue to dark blue, with North West–South East shelf-incising canyons visible. The underlying white shows areas for which no high-resolution bathymetry exists.

Benthic communities are highly dependent on seafloor geomorphology and substrate, and so, with limited benthic ecological data such as those in the NSW OWF zone, seabed mapping can provide broad proxies for benthic habitat (McArthur *et al.* 2010). Rocky reefs are prevalent along the NSW continental slope, including within the Hunter and Illawarra OWF zones (Linklater *et al.* 2019), although the location and extent of most rocky reefs >60 m have not been mapped (Jordan *et al.* 2010). The soft sediments along the continental shelf of NSW are influenced primarily by sand ripples and waves, sediment grain size, and varying amounts of boulders, cobbles and pebbles (Marine Estate Management Authority 2017). Indeed, risks to benthic ecosystems may be quite different between the Hunter and Illawarra declaration zones, depending differences in seabed type, with the Illawarra OWF zone containing more intermediate and deep rocky reefs than the Hunter OWF zone (Jordan *et al.* 2010; Marine Estate Management Authority 2017). Most of the shallower parts of the OWF zones around NSW have yet to be mapped in high resolution (Fig. 4), and this is crucial to understand the distribution of rocky and soft sediment ecosystems in these areas.

Impact pathways

In this section, we review how the impact pathways (Department of Climate Change, Energy, the Environment and Water 2023*a*) (Table 1) apply to the development of offshore floating wind turbines in NSW. Importantly, every impact pathway is underpinned by the need to understand the cause–effect relationships that could lead to impacts on the distribution and behaviour of affected organisms, as well as the environmental baselines of the habitats on which they depend (Dannheim *et al.* 2020).

Physical presence: barrier effects and displacement of marine fauna

We do not know whether OWFs significantly alter the migratory routes of whales, but precautionary approaches have been used overseas during construction phases to identify locations and seasons of highest sensitivity for certain species (Petruny *et al.* 2014; Best and Halpin 2019; Huang 2022). This may prove challenging in Australia because of the large marine expanses of our key ecological features and biologically important areas, but baseline data are crucial to address uncertainty about important locations and migration times. For example, waters off NSW are a known thoroughfare for humpback, blue and other whales travelling between Antarctic feeding and Australian breeding grounds (Chittleborough 1965; Johnson *et al.* 2022). The spatial and temporal extents of migration may expand as populations of humpback, fin and other whales continue to increase (Gosby *et al.* 2022; Aulich *et al.* 2025*b*), and changes might also be expected with climate change altering the pattern of movements and resting locations for these species (Aulich *et al.* 2025*a*). Limited research has indicated that physical barriers caused by floating OWFs are likely to have fewer impacts to migrating marine mammals and other megafauna than do fixed-bottom OWFs (Maxwell *et al.* 2022), and pinnipeds in the Bass Strait have been shown to spend significant time in the vicinity of offshore infrastructure, particularly along pipeline and cable routes (Arnould *et al.* 2015).

Migrating, foraging and dispersing seabirds may be displaced by OWFs. OWFs sited in foraging areas may alienate the habitat by preventing seabirds from foraging in the area. Displacement of seabirds will occur when flying birds are forced to fly over or around OWFs, increasing the energetic costs associated with individual flights. Although further research is needed, there is also the possibility that the 'turbulent air' downwind of turbines after the extraction of the wind's kinetic energy may affect a seabird's ability to forage in the waters immediately surrounding the OWF. Offshore wind turbines have a far greater impact area downwind of the turbines than do those onshore (Porté-Agel *et al.* 2020). This could pose an issue for those individuals that rely on dynamic soaring to access a specific food source within or near a turbine field, such as the annual cuttlefish die-off around the Illawarra (Nicholls *et al.* 1992).

It is unlikely that floating OWFs will act as a physical barrier to fish movements, although our understanding of how other impacts pathways (noise, electromagnetic fields), hydrodynamic and sediment changes) may affect fish connectivity is limited (Lennox *et al.* 2025). The recent monitoring for the Hywind Tampen floating OWF found that demersal fish communities are stable and comparable between sites and time within and outside of the OWF (Hestetun *et al.* 2025).

Turbine interactions

This impact pathway as defined is limited to birds and above-water interactions with infrastructure (Department of Climate Change, Energy, the Environment and Water 2023*a*). Knowledge on the at-sea behaviours and distributions of seabirds at sea can be obtained from a subset of seabird species present around Australia. Such data are critical to understand the spatial and temporal patterns of marine habitat use throughout the year by seabirds breeding around Australia and farther afield.

Larger taxa such as albatross and many species of petrel and shearwaters can be fitted with tracking devices using satellites to determine locations. Smaller species require the use of smaller devices to prevent impacts on foraging flights. The only seabird species that have been GPS tracked in NSW are those that breed on the coastal islands (silver gulls and crested terns, see O'Hara 2016; and little penguins in Phillips *et al.* 2022). In addition, Gould's petrel, a nationally threatened species that occurs only in NSW, has been extensively researched and had conservation measures applied at its main breeding location off Port Stephens (Priddel *et al.* 1995, 2000, 2006; Carlile *et al.* 2021). Although extensive tracking has been undertaken for this species (Priddel *et al.* 2014), this has not included accurate GPS devices.

The environmental impacts of OWFs on seabirds depend on the flight height in relation to the rotor sweep area and the ability of birds to detect and avoid the turbines (Dierschke *et al.* 2016). A study of birds expected to be affected by OWF in Australia was informed by European methods and underpinned by daylight observations that were restricted to winds of less than 24 km h^{-1} (Reid *et al.* 2023). It concluded that many Procellariformes species common in NSW waters will be at low risk, although this analysis has high uncertainty because of the absence of quantitative data on flight heights.

Gulls, terns and penguins are not expected to be significantly affected from turbine strike because of lack of flight or general flight characteristics of their families (Johnston *et al.* 2014; Reid *et al.* 2023). However, shearwaters, petrels and storm petrels on breeding islands within NSW waters have the greatest collision risk, as more than half of each year they forage in and daily use the coastal corridors as access to waters outside Australia's EEZ for foraging and during migration periods (Marchant and Higgins 1990; Miller *et al.* 2025).

A precautionary approach will be warranted during operations, including the seasonal shut-down of operations in periods of high winds for OWFs located in known seabird migration paths (e.g. passing near Eden in September annually, where millions of short-tailed shearwaters passage to return to breeding islands in southern Australian waters; Skira 1991) and near breeding areas (e.g. near principal nesting locations in Hunter waters between October and May where Gould's petrel habitually climbs to several hundred metres off the water before arriving on their islands early each evening (N. Carlile, pers. obs.).

Underwater noise

Anthropogenic noise can affect marine fauna in multiple ways. High-intensity, impulsive signals with rapid rise times of amplitude can cause trauma to internal tissues and organs, and strong exposures (high levels or long duration) can cause noise-induced hearing loss characterised as temporary or permanent threshold shifts (TTS or PTS). Depending on severity and taxon, this may or may not recover with time after exposure. Noise may further increase stress hormones and change animal behaviour over temporal scales of seconds to months and spatial scales of metres to tens of kilometres (Erbe *et al.* 2022*a*). Continuous noise, such as that from vessels, can reduce communication spaces and limit detection of acoustic cues such as those needed for foraging and predator avoidance (Simpson *et al.* 2016). Guidelines for exposure levels at which some of these responses may be observed have been laid out for marine and mammals and fishes (Popper and Hawkins 2019; National Oceanic and Atmospheric Administration 2023); however, there are significant knowledge gaps and responses are often species-, environment- and context-specific (Southall *et al.* 2021).

Pile driving for fixed foundations is a strong focus for many studies investigating the impact of underwater noise associated with OWFs, but this does not necessarily apply to floating OWFs. Instead, operational noise may be the main source. The underwater sound level emitted during the operation of wind turbines is generally continuous but varies with wind and power generated, characterised by one or more tonal components typically at frequencies lower than 1000 Hz (Pangerc *et al.* 2016; Tougaard *et al.* 2020), which can shift in frequency depending on wind and rotation speed (Sigray and Andersson 2011). Whereas fixed turbines emit operational noise into the water column and substrate (Tougaard *et al.* 2020), floating turbines only partially project into the water column, with a weak conductive connection to the seafloor. Operational noise from floating wind turbines is highly variable (Pace *et al.* 2023) and can be up to 25 dB lower than that from fixed turbines (for the same power rating and wind speed) (Tougaard *et al.* 2020), with modelling indicating that operational noise from floating wind farms in the Mediterranean Sea could reach 100 dB re 1 μPa as far as 67 km from the wind farm, but is still noticeably lower than sound levels from ambient sound in areas with intense shipping traffic (Baldachini *et al.* 2024, 2025). Source levels from vessels range from <150 to >195 dB re 1 μPa m (Chion *et al.* 2019; Parsons *et al.* 2021; MacGillivray *et al.* 2022), and operational noise from large vessels can be up to 45 dB higher than operational noise from wind turbines of up to 10 MW (Tougaard *et al.* 2020).

The distances at which marine mammals, fishes and invertebrates are affected by noise from the construction, operation and decommissioning of offshore wind turbines is dependent on the species' hearing abilities, the presence and level of other noise sources in the area (e.g. vessels) and local sound propagation conditions (Erbe *et al.* 2022*b*). Future research to fulfil knowledge gaps on the impacts of wind turbines on marine fauna are outlined in Thomsen *et al.* (2023) for marine mammals and Popper *et al.* (2022) for fishes and invertebrates.

For marine mammals, pile driving during the construction phase (if required to install anchors in floating OWFs) and vessel noise can cause auditory injury, temporary threshold shift, stress and behavioural changes in marine mammals in the vicinity (Verfuss *et al.* 2016; National Oceanic and Atmospheric Administration 2023; Erbe *et al.* 2025*a*; Houser 2025). Overseas research has shown evidence of temporary but not permanent displacement of seals and porpoises during OWF pile driving activities (Möller *et al.* 2020), with animals returning after construction noise ceased (Russell *et al.* 2016; Vallejo *et al.* 2017). Similarly, the spatial occurrence of cetaceans, including different species of whales, is known to vary depending on the ambient sound (van Geel *et al.* 2022).

By contrast, operational noise from wind farms presents less risk of noise-induced acute hearing loss in marine mammals (Madsen *et al.* 2006; Marmo *et al.* 2013; Thomsen *et al.* 2023). However, Thomsen *et al.* (2023) modelled potential TTS and PTS for 20-MW turbines, finding that whereas these effects are likely to be negligible for 10-MW turbines, TTS could be observed at ranges of up to 700 m for low-frequency cetaceans. This could bridge spatial distances between individual turbines, so that the whole wind farm can be considered an impact area. Further, operational noise may cause disruption to marine mammal behaviour at greater distances, with impact areas predicted to extend to 1 km beyond an OWF area for cetaceans and 3 km for seals (Stöber and Thomsen 2021).

By estimating the propagation of turbine sounds and comparing received levels with the National Marine Fisheries Service (2024) guidelines for behavioural disturbance of marine mammals by continuous noise, Stöber and Thomsen (2021) estimated that, in the North Sea, a single 10-MW gear box turbine may lead to a behavioural response in marine mammals at distances of up to 6.3 km (and 1.4 km for direct drive turbines). These ranges will vary significantly with the acoustic environment and are likely to be lower for floating, rather than fixed turbines. Models of median source levels of monopile 9–10-MW wind turbines (Tougaard *et al.* 2020) were 8–27 dB higher than those of floating turbine configurations for similar-sized power (Risch *et al.* 2008). This would significantly reduce the distances at which marine mammals display a response. Additional reductions in noise can be made using noise-reduced mooring components (e.g. steel cables instead of chain links on portions of the mooring lines).

Aquatic birds have developed adaptations for underwater sound detection and, as more species are studied, they are being found to be sensitive to acoustic signals and respond negatively to noise, such as little penguins (*Eudyptula minor*) and gentoo penguins (*Pygoscelis papua*) and great cormorants (*Phalacrocorax carbo sinensis*) (Larsen *et al.* 2020; Sørensen *et al.* 2020; Wei and Erbe 2024). Thus, construction noise may affect the foraging of little penguins that are unable to vacate the area because of the proximity of their breeding sites (Pichegru *et al.* 2017). Cormorants are also known to be sensitive to underwater sound (Johansen *et al.* 2016; Larsen *et al.* 2020). Both species are known to be inshore foragers, foraging regularly within 20 km of breeding sites for little penguins, and small populations are known to utilise coastal islands in Hunter (little penguins and great cormorants) and Illawarra (little penguins) OWF zones. The potential overlap between the species and the OWF zones is likely to be minimal. No empirical studies are available on the responses by shearwaters to underwater noise, but it is reasonable to predict similar responses to those of penguins and cormorants. The shearwaters are more likely to forage within the OWF zones.

For sea turtles, sound produced during OWF operations overlaps with hearing in green and loggerhead turtles (Tougaard *et al.* 2020; Díaz *et al.* 2024), and turtles have been shown to alter their behaviour in response to vessel noise within the same frequency band as that of wind farm operations (Papale *et al.* 2020; Díaz *et al.* 2024). However, the effects of operational noise from OWFs on turtles remains unknown.

For fish, noise from pile driving during the construction phase (if required) can negatively affect behaviour and physiology by sound pressure or particle motion (Neo *et al.* 2014, 2015; Herbert-Read *et al.* 2017; Popper and Hawkins 2019) up to distances of 3 km from pile driving activity (Ainslie *et al.* 2020). However, the floating turbines to be used around NSW waters will involve little or no pile driving, meaning noise impacts will stem primarily from vessel traffic and operational noise.

Vessel noise has been found to have a variety of effects on fishes that can be dependent on life stage and life function (Pine *et al.* 2021; van der Knaap *et al.* 2022*a*). Some studies have shown minimal effects of operational noise (e.g. Wahlberg and Westerberg 2005; Copping *et al.* 2021), whereas others suggest a greater impact (e.g. (Siddagangaiah *et al.* 2022). The fixed position of OWFs may provide the time for fish to acclimate, limiting some of the behavioural and biophysical effects (Mooney *et al.* 2020); however, it remains unknown whether long-term exposure can cause behavioural changes for animals in the broader wind farm area (Sigray and Andersson 2011; Mooney *et al.* 2020; Tougaard *et al.* 2020) and, in studies of vessel noise, long-term relatively low-level exposure has led to reduced hearing sensitivity in Australian snapper (*Pagrus auratus*) (Mensinger *et al.* 2018).

Importantly, noise experiments on captive animals may not reflect responses in the wild (Przeslawski *et al.* 2018*a*). To address this, scientists use acoustic tagging to monitor fish movement patterns in response to noise (van der Knaap *et al.* 2022*b*), and responses may be different among fish species (Iafrate *et al.* 2016).

Benthic invertebrates may also be susceptible to high-intensity acute sounds such as pile driving and chronic sound associated with vessel noise, particularly owing to particle motion and substrate vibration, but research is currently limited (Popper *et al.* 2022; K. A. Williams *et al.* 2024). The impacts of noise associated with marine seismic surveys on scallops, oysters and lobsters in Australian waters have shown sublethal effects (Day *et al.* 2017, 2022), minor effects (Fitzgibbon *et al.* 2017) or no conclusive effects (Przeslawski *et al.* 2018*b*; Parsons *et al.* 2024), and these results may be transferable to pile driving associated with OWFs. There is some evidence that pile driving may affect parental stress and larval development of scallops and other invertebrates (Gigot *et al.* 2024), but these noise exposure experiments have been confined to aquaria, which are very challenging to translate to real-world impacts on populations (Carroll *et al.* 2017; Przeslawski *et al.* 2018*a*).

Entanglement

Inter-array cables and mooring lines from floating turbines are sturdy and large, but there is still a potential risk of entanglement or impact when animals are beneath surface waters (Maxwell *et al.* 2022). Nevertheless, modelling has shown that primary entanglement risk is low and may be further reduced with taut mooring lines and deep inter-array cables (>100 m) (Harnois *et al.* 2015; Copping *et al.* 2021; Farr *et al.* 2021). The more likely hazard is from derelict fishing gear that catches and aggregates on wind farm infrastructure (Matsuoka *et al.* 2005; Gilman 2015). This secondary entanglement poses an entanglement risk for marine fauna (Kaiser *et al.* 1996), particularly large baleen whales (Benjamins *et al.* 2014; Cassoff *et al.* 2011) and sea turtles (Hays *et al.* 2023). Regular monitoring and clearing of debris would help mitigate this risk. However, there is currently insufficient data to evaluate the risk of entanglement in floating OWFs (Farr *et al.* 2021). This potential impact pathway is currently not included in government guidelines (Department of Climate Change, Energy, the Environment and Water 2023*a*).

Invasive marine species

The network of turbines within an OWF may affect connectivity because individual turbines can act as stepping stones for both native and invasive species to colonise areas normally not accessible (De Mesel *et al.* 2015). Connectivity changes can occur during the operational phase of OWFs after infrastructure is installed, and they may persist for the life of the structure (Coolen *et al.* 2020). OWFs may also work in combination with other artificial structures to affect connectivity (Bishop *et al.* 2017), although this is less likely around the Hunter and Illawarra OWF zones, owing to lack of offshore petroleum infrastructure. Much of the work relating to invasive species on OWFs focuses on fixed foundations and associated scour protection, which has been found to have minimal risk (i.e. 4% of species on scour protection layers in the Noth Sea were non-indigenous in Zupan *et al.* 2024).

Connectivity can also be affected during the decommissioning phase when any connections established with the OWFs may be reduced with removal of structures (Fowler *et al.* 2020). This may be detrimental for populations that occur nowhere else (i.e. endemic populations) and became reliant on the additional connectivity provided by OWFs. Although removal of structures will ultimately reduce the connectivity of exotic and potentially invasive species, the transport of removed structures to shore risks the spread of those organisms currently attached or closely associated with OWFs.

Physical presence: effects of hydrodynamics and sediment transport processes

OWFs may also affect surrounding communities and ecosystems through local hydrodynamic changes; however, these impacts are highly dependent on the density, design and location of OWFs (Shields *et al.* 2011). OWFs have been shown to alter the hydrodynamics and sediment deposition around some wind turbines (Vanhellemont and Ruddick 2014; Bärfuss *et al.* 2021), but these are usually minor and localised compared with fluxes associated with ocean currents (Ivanov *et al.* 2021). Other studies have found that impacts of hydrodynamic changes on fishes owing to OWFs cannot be distinguished when compared with natural environmental variability (van Berkel *et al.* 2020). However, there have been reports of turbid wakes of suspended sediment detected off individual fixed turbines, spanning several kilometres (Vanhellemont and Ruddick 2014), and the epifaunal communities colonising the monopiles may be a key source of the sediment (Baeye and Fettweis 2015). There is growing interest in the shelf-wide effects of multiple wind turbines and the downstream hydrodynamic changes to ocean fronts, productivity and wider ecosystem effects (Isaksson *et al.* 2025).

Hydrodynamic changes caused by the physical structures of the wind turbines could theoretically change the distribution or density of plankton on which baleen whales feed, but recent modelling suggests that any such changes are likely to be up to an order of magnitude less than changes caused by natural variability and climate change (Brodie *et al.* 2023). Indeed, studies overseas have shown that some marine megafauna such as porpoises may be attracted to wind farms because of prey species that aggregate around the infrastructure (Lindeboom *et al.* 2011) or decreased vessel traffic (Scheidat *et al.* 2011). In Australia, similar findings have shown that oil and gas infrastructure in the Bass Strait attracts fur seals (Arnould *et al.* 2015).

Light emissions

The lighting from vessels and turbines associated with OWFs may disrupt behaviours of some taxa. Sea turtles may be particularly sensitive, including hatchlings, which may become disoriented by artificial light at night (ALAN) (Kamrowski *et al.* 2012), although most research has focussed on ALAN from coastal urban development rather than on ALAN offshore (e.g. T. Shimada *et al.* 2023). Fledgling seabirds may also be affected by artificial light up to 15 km, with the nearest studies to NSW undertaken in New Zealand Aotearoa (Heswall *et al.* 2022; Atchoi *et al.* 2024). For fish, ALAN may alter their behaviour, biology and physiology (Gaston *et al.* 2017; Bassi *et al.* 2022). Some species of fish are attracted to lights as they seek prey, but ALAN can also illuminate fish and increase their exposure to predation. For invertebrates, light pollution may cause some negative impacts (Easton *et al.* 2024), particularly through reduced diel vertical migration (Ludvigsen *et al.* 2018).

The National Light Pollution Guidelines for Wildlife offer guidance to proponents on how to best manage artificial lighting and environmental impacts, and these include a precautionary 20-km threshold for lighting near important habitat for listed species, including sea turtle nesting sites (Department of Climate Change, Energy, the Environment and Water 2023*b*). Importantly, the declared OWF zones in NSW are 20 km or more from the coast (Fig. 1).

Seabed disturbance

Floating systems may disturb the seafloor through anchor setting, transmission cables or the wave-induced movement of mooring lines as they scour the seabed, but the ecological impact of this disturbance depends on the type of turbine used and the total number of turbines (Maxwell *et al.* 2022). Of the three mooring systems used in floating systems, a catenary mooring has the largest seafloor footprint because of the potential for the mooring lines to drag along the seabed, whereas a taut-leg mooring with suction pile anchors has the smallest footprint (James and Ros 2015) (Fig. 1). For soft sediment ecosystems, the impacts can vary among sediment types, stressing the importance of replicated monitoring at each discrete wind farm (Rogers *et al.* 2008; Schultz *et al.* 2015; Vandendriessche *et al.* 2015). Changes to bedforms and sediment grain-size distribution caused by offshore infrastructure have been shown to alter species composition, abundance and diversity in eave-dominated soft sediment ecosystems of the western Atlantic (Cerrato *et al.* 2024).

Distinct fish assemblages are associated with gravel or fine sand habitats in NSW waters (Schultz *et al.* 2015). Theoretically, the presence of hard structures could displace fishes associated with these soft sediments (van Hal *et al.* 2017), but this is unlikely to apply to soft sediment fishes in and around NSW waters because of the use of floating wind farms and the large expanses of soft sediment habitat that dominate the outer continental shelf around NSW (Jordan *et al.* 2010). Studies modelling species distribution in north-eastern USA have indicated that the range of fish and macroinvertebrate taxa associated with offshore wind development areas may be strongly influenced by changes to habitat distribution, physical drivers and lower trophic level changes (Friedland *et al.* 2021).

Habitat creation

In addition to seabed disturbance causing harm to or loss of benthic habitat as defined in Department of Climate Change, Energy, the Environment and Water (2023*a*), floating OWFs also introduce new hard substrata through floating platforms, mooring lines and other infrastructure, which are colonised by sponges, sea squirts and other marine invertebrates (Degraer *et al.* 2020; Maduka *et al.* 2023). This in turn provides structure for fish and other mobile fauna to inhabit (Mangi 2013; Causon and Gill 2018), but in some instances, invasive species may be more likely to occur on artificial structures associated with OWFs (Wilhelmsson and Malm 2008; Andersson *et al.* 2009). This artificial reef effect may also apply to neighbouring infaunal communities, with sediments near offshore wind jackets in the North Sea supporting more abundant and richer communities than those further away (Lefaible *et al.* 2023). Most studies on OWFs as artificial reefs focus on fixed foundations rather than floating platforms. However, a review of floating artificial reefs (FARs) showed that they are expected to provide the same variety of ecosystem services as do fixed systems, including those related to food provisioning, nutrient cycling, habitat provision and climate regulation, with the increased light availability near the surface potentially offering stronger ecosystem services related to primary production (Komyakova *et al.* 2022). Many characteristics of floating structures determine their success as artificial reefs (e.g. material, size, complexity, vertical orientation), with concrete and ceramic showing the most positive relationships with biodiversity variables (Komyakova *et al.* 2022; Margapuram *et al.* 2024).

Offshore wind infrastructure is colonised first by microfouling organisms, which produce a biofilm which then facilitates the settlement of microorganisms and macrofauna, including successional stages of invertebrates. Marine growth on mooring lines from a conceptual floating wind turbine off western France showed three distinct biofouling zones (hard-bodied species dominating near the water surface, mobile organisms prevalent at intermediate depths, and soft-bodied species in deeper region up to 30 m), with coverage and thickness increasing in the deeper zone after 4 years (Dubois *et al.* 2025).

Associated with invertebrate assemblages, there are often more fish immediately around fixed wind turbines (Ashley *et al.* 2014; Methratta and Dardick 2019; Mavraki *et al.* 2021), which can lead to increased catches (Hooper *et al.* 2017; H. Shimada *et al.* 2022; Werner *et al.* 2024). This increase in abundance and diversity is due to reef-associated species living around the hard structure of OWFs within a seascape that is usually dominated by soft sediments and open water (Stenberg *et al.* 2015) and can be considered a nature positive effect (Pardo *et al.* 2025). Floating turbines do not have much constructed habitat on the seafloor, but they can act as fish aggregation devices by attracting open water (i.e. pelagic) fishes (Fayram and de Risi 2007; Wilson *et al.* 2010). Floating OWF are likely to provide significant habitat for pelagic and mesopelagic species such as marlin, tuna, yellowtail scad, dolphinfish and yellowtail kingfish by acting as an artificial reef (Becker *et al.* 2017; Dempster 2004). There are predictions that with fish aggregation and, potentially, spill-over into adjacent waters that this may lead to increased catches (Hooper *et al.* 2017; H. Shimada *et al.* 2022; Werner *et al.* 2024); however, there were no differences in catch per unit effort of commercial fish or squid owing to operation of a pilot fixed foundation offshore wind farm in the United States (Wilber *et al.* 2022). Evidence to determine impacts of significance to fisheries species populations or stocks remains limited (Gill *et al.* 2025).

Electromagnetic fields

Subsea power cables transmit either high voltage direct current (HVDC) or high voltage alternating current (HVAC). The HVAC is the industry standard at present for fixed offshore wind, particularly the inter-array cables between turbines. HVDC is emerging as the favoured technology for floating offshore wind as it is more efficient over longer distances and has higher power capacity (Gill *et al.* 2014). Regardless of the type of transmission, subsea power cables generate electromagnetic fields (EMFs) as electricity is transmitted through the cable network within the turbine array and the export cable(s) to shore (Gill *et al.* 2014). Electromagnetic fields have two main components, the magnetic field and the electric field, both of which may affect the behaviour and migration of some vertebrates and invertebrates (Albert *et al.* 2020; Gill and Desender 2020). The primary emission associated with electricity transmission is the magnetic field, which then induces electric fields in the surrounding environment (Gill *et al.* 2014). The highest field strengths are close to the cable, and models predict that these reduce to lower levels within a few metres of a subsea cable (Normandeau Associates Inc. *et al.* 2011). However, recent field work has shown that the power cable EMFs can propagate further, over a matter of tens of metres (Hutchison *et al.* 2020*a*). This will depend on the transmission type (HVAC or HVDC), with a HVDC transmission system emitting higher EMFs than does the comparable HVAC one (Normandeau Associates Inc. *et al.* 2011). In addition, the receptors may respond differently to the different intensities, such as avoidance of higher levels and attraction to lower levels (Hutchison *et al.* 2020*b*). Therefore, when considering the potential environmental impact of EMFs, it is important to understand the environmental reality of the EMF emissions, which requires knowledge of the transmission system in the context of the environmental receptors of interest, i.e. taking the perspective of the receptor (Hutchison *et al.* 2021).

Animals that undertake large-scale migration, such as turtles, teleosts (e.g. salmonids, thunnids) or marine mammals, use the globally ubiquitous Earth's natural magnetic fields (Verhelst *et al.* 2025). These taxa and others may also use localised magnetic field changes for orientation and cues while moving around their habitat (Klimley *et al.* 2021). In terms of electric fields, taxa such as the elasmobranchs (e.g. sharks and rays) are theoretically the most vulnerable to the range of electric field intensities that are associated with subsea power cables, owing to the specialised electroreceptive organs that they possess (Hutchison *et al.* 2020*a*).

Current knowledge shows that some taxa respond to interaction with anthropogenic EMFs at different life stages (e.g. Cresci *et al.* 2025); however, the evidence base is very patchy to determine whether there are any impacts. This is because there are several cause–effect pathways and the evidence is based on a mixture of limited laboratory studies (Xu *et al.* 2025), some *in situ* experiments and very few field studies on a small range of species (Albert *et al.* 2020; Hutchison *et al.* 2020*b*). To define whether an impact has occurred, it is necessary to determine if there are negative effects of OWF undersea cables at the population level; however, such evidence is absent (Ohman *et al.* 2007; Albert *et al.* 2020, 2022; Copping *et al.* 2021). As existing research is limited, further targeted investigations are required to determine whether EMFs have an important environmental impact on animal populations (Klimley *et al.* 2021) and on those of commercial importance (Hutchison *et al.* 2020*b*) in Australian waters. It will require understanding of the life stages that are most likely to encounter the EMFs and the level of response, whether that is behavioural attraction or avoidance, physiological, biochemical or developmental outcomes (Gill and Desender 2020).

Vessel interaction: injury and morality to marine fauna

Collision risk may increase during periods of increased vessel traffic throughout construction and maintenance operations. Vessel strikes from many marine activities, including those associated with OWFs, present a risk to most marine mammals, especially smaller whales, dolphins, porpoises and seals (Schoeman *et al.* 2020), and sea turtles (Hazel and Gyuris 2006; T. Shimada *et al.* 2017). For some of the whale species using NSW waters, there is evidence of altered foraging behaviours (e.g. time between feeding lunges) in association to the presence of vessels (Stamation *et al.* 2007) and of their vulnerability to shipping impacts (Pirotta *et al.* 2019).

Seabird interactions with vessels are well known but largely relate to fishing activities, and the attraction of baited hooks and discards are the attraction for the seabirds. Vessel strike during construction and maintenance is unlikely for little penguins because the vessels concerned are relatively slow moving and can easily be avoided. Collision risk with vessels by seabirds is greatest in periods of fog and mist when conditions reduce visibility to flying seabirds at night. Deck lights are diffused and can result in an increased risk of disorientation by flying birds.

Contamination and debris

In addition to potential marine pollution from noise, light and sediment, OWFs may also pose a risk through chemicals and debris. Compilations of potential OWF-related chemical emissions identified over 200 organic and inorganic contaminants (Hengstmann *et al.* 2025), including plastics and corrosion products (Gül and Gül 2024). Field measurements around the Putidao OWF in China found that sediments were only 'lightly polluted compared with baseline values' of heavy metals (copper, chromium, zinc) (Wang *et al.* 2023). Although current assumptions suggest low and highly localised environmental impacts from chemical pollution, monitoring data are limited (Kirchgeorg *et al.* 2018).

Another potential source of pollution comes from broken infrastructure becoming marine debris, or microplastics shedding. Estimates of annual microplastic emissions from a 15-MW offshore wind turbine are ~240 g, with overall microplastic emissions from all Dutch offshore wind turbine blades in the North Sea equating to ~1000 times lower than total offshore microplastic emissions in the Netherlands from other sources (Caboni *et al.* 2025). Floating platforms may also have unique potential environmental impacts related to microplastic particles released from synthetic mooring cables (Paredes and Vianello 2025). Marine contaminants and debris are currently not included in government guidelines as a potential impact pathway (Department of Climate Change, Energy, the Environment and Water 2023*a*).

Other

Multiple impact pathways: Australian marine parks and their values. According to Australian government guidelines, 'multiple impact pathways' refers to any single or combined impact pathway affecting Australian marine parks (MPA, i.e. marine parks in Commonwealth waters) (Department of Climate Change, Energy, the Environment and Water 2023*a*), noting that Australia also has networks of state-managed marine parks. This pathway is unique among the others because it is focussed on locations outside declared OWF zones. In other countries, offshore wind farms are located adjacent to or near marine protected areas, and there are concerns that any impacts from noise, hydrodynamic changes and ecosystem effects may extend into the protected area or onto migratory species that use the protected area (Püts *et al.* 2023). To help address such concerns, recent studies have recommended that OWFs in the Mediterranean should not be placed inside marine protected areas or in their peripheral buffer zones, to be defined for each MPA (Lloret 2025; Lloret *et al.* 2025). The OWF zones around NSW are not adjacent to marine parks but they are in their proximity; the Hunter OWF declaration zone is 2 km from the Commonwealth Hunter Marine Park (CHMP) and 17 km from the state Port Stephens Great Lakes Marine Park (PSGLMP) (Fig. 2). In planning an OWF in Australia, exposure scenarios for each relevant impact pathway could be modelled for protected species with known thresholds related to impact pathways to determine whether impacts could extend to marine parks. A useful list of protected threatened and migratory species that are likely to occur in the Hunter and Illawarra declaration zones and nearby marine parks has been compiled by (McLean *et al.* 2024).

Another aspect of this impact pathway relates to social and economic considerations, with OWFs potentially displacing any prior fishing effort to neighbouring areas that may have previously been lightly fished or unfished. Fishing displacement and its effects are hard to predict (Haberlin *et al.* 2022), but may be particularly relevant for OWFs near marine protected areas in which some fishing is allowed (i.e. non-sanctuary zones in NSW) because it may negate the environmental benefits of such areas (Greenstreet *et al.* 2009). It is possible that displaced fishing effort could have some impact on the adjacent areas of the CHMP, but displaced fishing effort in the PSGLMP is unlikely to have a great impact because of the differences in depth and habitat and the greater separation between the OWF zone and the park.

Cumulative impacts. As defined in Department of Climate Change Energy the Environment and Water (2023*a*), cumulative impacts are included only in the context of Australian marine parks. We suggest adopting a more general definition of this impact pathway to include cumulative impacts among marine environments (i.e. not limited to marine parks); alternatively, an additional impact pathway 'cumulative impacts' could be included in guidelines.

Although many direct environmental impacts of wind turbines seem localised to the site or of short duration (Rezaei *et al.* 2023; Knights *et al.* 2024), these effects may be cumulative, both over time and across multiple installations (Hasselman *et al.* 2023). However, our knowledge of cumulative impacts is minimal and not well-considered both in terms of current policy and the supporting science evidence base, particularly given the logistical challenges involved with effective research over space and time (Bergstrom *et al.* 2014; Willsteed *et al.* 2018). Most investigations examining potential long-term cumulative effects have done so indirectly on structures that have been installed for long periods of time such as in the North Sea (Gu atu *et al.* 2021). Reports of cumulative impacts across multiple installations are typically speculative, based on models, reviews of individual studies each investigating a single installation, or expert opinions (e.g. Fowler *et al.* 2018; Le Marchand *et al.* 2025). Although monitoring overseas of a floating turbine demonstration suggested that there may be limited environmental impacts during the construction or operational phases, cumulative impacts remain uncertain (Rezaei *et al.* 2023; Sinclair 2025).

A focus on ecological function and cumulative impacts could be undertaken with a combination of hypothesis-driven research and ecological modelling (Dannheim *et al.* 2020). As of 2025, there is limited legislative capacity to deal with cumulative impacts from Australian OWFs, although NSW state guidance applied may be useful to adapt to offshore renewables (NSW Department of Planning and Environment 2022). Results from NESP Marine and Coastal Hub Project *Development of regional modelling and risk assessments to inform offshore renewable decision-making*, due for completion in 2026, are expected to inform an Australian framework for cumulative impacts from OWFs.

Disturbance of underwater cultural heritage. OWF development may disturb areas of cultural heritage, including shipwrecks, sacred sites and general Sea Country interests, including underwater cultural heritage sites associated with ancient shorelines (Nunn and Reid 2016). The areas under consideration for OWF development near NSW are important to coastal Aboriginal communities, and Sea Country cultural values are inseparable from environmental values. As such, consideration of environmental impacts must involve Traditional Owners (Fischer *et al.* 2022; Marsh *et al.* 2022; KPMG 2024). The concept of braiding or two-eyed seeing may be useful, in which two knowledge systems are brought together in a way in which the importance and integrity of each is recognised (Hopkins *et al.* 2019; Reid *et al.* 2021). In particular, the role of totemic species and songlines may be relevant to OWFs near NSW (Fuller 2020).

Physical presence: socio-economic: interference or displacement of existing uses. OWFs may have zones that reduce access to fishing grounds. These vary among jurisdictions (Gill *et al.* 2020; Van Hoey *et al.* 2021), and it is unknown what fishing restrictions may apply to future OWFs near NSW. In the Hunter and Illawarra zones, specific concerns have been raised around the impact on commercial fishing for lobster, prawns and some fish species. OWFs with restricted fishing access can cause a 'reserve effect', with associated benefits to fish and invertebrates (Fayram and de Risi 2007; Ashley *et al.* 2014; Coates *et al.* 2016; Methratta and Dardick 2019; Wang *et al.* 2022). The realised benefits depend on the life history of the species, previous fishing effort and the relative area protected from fishing.

Early indications show that exclusion areas may be relatively modest and associated with individual turbines rather than the OWF as a whole (Bowen and Claydon 2024). This may mean that the impacts on recreational fishers in particular may be positive, because they may benefit from the infrastructure acting as 'fish aggregation devices', although some forms of commercial fishing, especially trawling, are unlikely to be compatible with the operation of the OWF. There is also a growing body of work exploring opportunities for co-benefits and nature positive design, which maximise opportunities for other users, including fisheries and aquaculture, through co-location of complementary activities (de Groot *et al.* 2014; Zhang *et al.* 2017). This research points to the critical importance of co-designing these approaches with industry, Indigenous groups and relevant stakeholders. Governance frameworks for marine protected areas in Australia that emphasise co-design (Jones 2021; Bock *et al.* 2022) and coordination among state and federal jurisdictions (Yin and Techera 2020; Day 2022) may also be useful to adapt for OWF zones.

Physical presence: socio-economic – seascapes and visual amenity. Environmental impacts do not occur in isolation and are often associated with impacts on social, economic or cultural values. Human dimensions research on offshore wind have focused on a range of different social and cultural considerations, which intersect with and will be influenced by perceptions of environmental risk. Socio-economic concerns include impacts on visual amenity (Haggett 2011), disruption to place attachment (Dugstad *et al.* 2023), concerns of environmental impact and harm (Cronin *et al.* 2021), and perceptions of equitable, transparent and accountable processes (McCrea *et al.* 2024). Although there are unlikely to be significant differences between the socio-economic impacts of floating *v.* fixed OWF, floating technologies do have the potential benefit of being situated further from the coastline and are, thereby, less visually intrusive. Although social acceptance (sometimes referred to as social licence to operate) is often viewed as a challenge or hurdle to be jumped in the delivery of infrastructure projects such as OWF, it can also play a potentially positive role in delivering improvements in environmental outcomes. For example, international research has highlighted how environmental conflict can result in a raising of environmental and social standards beyond regulatory requirements if conflict can be engaged with in a constructive way (Tafon *et al.* 2022; Knol-Kauffman *et al.* 2023; Saunders *et al.* 2024).

Recent research in Australia has highlighted the value of participative and integrated ocean management approaches, such as marine spatial planning, as well as having a more explicit focus on equity consideration in the development of OWF (Griffiths *et al.* 2025; Voyer *et al.* 2025). Whereas a comprehensive assessment of socio-economic considerations relevant to OWF is beyond the scope of this paper, this research has highlighted the need for genuine and effective community engagement, including active negotiation and deliberation, as an important component of the planning process (Croft *et al.* 2025). This includes developing and collecting baseline social and economic data and prioritising ocean literacy programs that share the results and findings of scientific assessments with local communities in a timely and transparent way. There is also potential to link benefit-sharing arrangements with environmental activities. This could include targeting key environmental threats of community concern or restoration activities in socially and culturally significant areas, for example through emerging nature positive initiatives (Department of Climate Change, Energy, the Environment and Water 2022).

Ecosystem effects

There are far fewer studies on invertebrates and their associated habitats and ecosystems than on marine vertebrates (Galparsoro *et al.* 2022). A review of 233 studies, almost all on OWFs with fixed foundations, found that most impacts from wind farms affected benthic ecosystems only at a local scale (<100 m), although some of the evidence is regarded being of low confidence (Dannheim *et al.* 2020). A global review found that ecosystem function impacts during the construction phase of offshore wind development were predominantly negative, whereas operational-phase impacts were more variable depending on local conditions (Watson *et al.* 2024).

The potential direct environmental impacts of OWFs mentioned above may in turn affect aspects of ecosystem function, including food availability, predation, biological competition, reproduction and recruitment (Gill 2005; Baulaz *et al.* 2023). Importantly, these effects may be deemed either positive (e.g. artificial reefs increase fish abundance which attracts marine mammals and other predators; Raoux *et al.* 2017; Glarou *et al.* 2020; Harris *et al.* 2025) or negative (e.g. vessel activity and artificial reefs may increase likelihood of invasive species colonisation; Langhamer 2012) (Fig. 3). A modelling study found that ecosystem structure and functioning would likely change with the introduction of a floating wind farm in the Mediterranean Sea, in which low trophic level groups became more important, ecosystem maturity increased, and ecosystem activity and diversity increased, all of which 'will likely provide benefits to local fisheries focused on higher trophic level groups' (Adgé *et al.* 2024).

Managing environmental impacts

Environmental baselines and monitoring are the critical first steps to quantify and manage potential environmental impacts. They should be undertaken at multiple times before construction to provide baseline data and then again at various times during the construction and operation of the wind farm to allow potential environmental impacts to be detected (Methratta 2025*a*). A substantial toolkit of technologies can identify and measure changes in marine habitats at OWFs, although many methods have limitations in high-energy environments (reviewed by Hemery *et al.* 2022). Monitoring efforts should be carefully considered, so that measured variables can be linked to ecologically meaningful impacts such as population effects or ecosystem function (Lindeboom *et al.* 2015; Methratta 2025*b*; Wilding *et al.* 2017). A suite of national standards has been developed for Australian marine monitoring (Przeslawski *et al.* 2018*a*, 2019), including robust survey design (Foster *et al.* 2024), and these should be applied where possible to ensure data comparability among monitoring programs and facilitate cumulative impacts assessments (Ferguson *et al.* 2025).

The Australian Government has developed a mitigation hierarchy tool for potential developers to minimise negative environmental impacts of proposed activities, including the development of OWFs. After preliminary analysis to determine maximum potential impacts, developers should avoid and then manage impacts, after which they should offset any residual impacts.

Mitigation of environmental impacts can be undertaken through adjusting the location, timing and design of OWFs, as well as by using additional technologies, as follows:

- The *location* of wind turbines themselves can mitigate environmental impacts. For example, locations with sensitive habitats and sedentary organisms with vulnerable life-histories should be avoided. There are numerous decision-making frameworks for wind farm locations globally and within Australia (Messali and Diesendorf 2009; Golestani *et al.* 2021), and these could be adapted specifically for OWFs around NSW.
- The *timing* of pre-operational activities, particularly those associated with high-intensity underwater noise (e.g. pile driving) can be undertaken during months that minimise impacts on migratory whales (Best and Halpin 2019), particularly those of highest conservation concern around NSW, such as blue whales, southern right whales and sperm whales.

- The *design* of offshore wind turbines can include alternative anchoring or floating foundations, which may have less environmental impact than have other designs (Farr *et al.* 2021). Some infrastructure can also comprise materials and shapes to optimise the structures to attract invertebrates and fish (Glarou *et al.* 2020) or to minimise settlement in the case of exotic or invasive species.
- *Additional technologies* can reduce impacts of some environmental impacts. For example, bubble curtains (BBCs) are a noise-mitigation technology shown to reduce noise impacts to cetaceans and other animals during pile driving (Nehls *et al.* 2016; Dähne *et al.* 2017), whereas acoustic deterrents can be highly effective at keeping seals and dolphins a safe distance away from an area during construction (Brandt *et al.* 2013; Hiley *et al.* 2021).

Offsetting of environmental impacts occurs when a negative impact cannot be avoided or minimised, and an alternative activity creates a positive impact equal to or greater than the negative impact. This can include efforts to produce biodiversity gains to counteract development impacts such as creating or restoring degraded habitat outside a development area (Jacob *et al.* 2020). Also called 'compensatory mitigation', this approach has been recommended as a tool for regulatory frameworks for OWFs and birds (Croll *et al.* 2022). Offsetting can also include financial compensation to affected stakeholders, as has been used to offset potential impacts to the fishing industry by marine seismic surveys (French and Sullivan 2022).

Remediation occurs when environmental impacts are reversed or eliminated, and for OWFs, this applies only during the decommissioning stage (Hall *et al.* 2020). However, complete removal of infrastructure as currently required in Australia does not always equate with remediation, because it may conflict with conservation and restoration policies relevant to species and habitats dependent on wind farm infrastructure (Fowler *et al.* 2020). In Australia, remediation of the environmental impacts of OWFs remains decades away when the yet-to-be-constructed wind farms reach end of life, but must be considered during the planning phases under the *Offshore Electricity Infrastructure Amendment Regulations 2024*.

Challenges and recommendations

Despite concerted efforts to map and characterise Australia's vast marine estate (Lucieer *et al.* 2024), approximately only 1/3 of Australia's marine jurisdiction has been mapped in sufficient detail to inform decisions (Geoscience Australia 2024). We still have limited knowledge about what species and habitats occur in many areas or how they may use those areas (McLean *et al.* 2024). This limitation applies to most of the OWF zones and is one of the most significant challenges in assessing the potential environmental impacts of OWFs in Australia, floating or fixed (National Offshore Petroleum Safety and Environmental Management Authority 2023; Australian Marine Conservation Society 2025). Knowledge of the offshore seabed, ecosystems and populations where OWFs will likely be installed around NSW and elsewhere in Australia remains poor (Fig. 4). According to the *Environmental Protection and Biodiversity Act* 1999, this limited knowledge means that scientific uncertainty cannot be used to postpone measures preventing environmental degradation (i.e. precautionary principle). As such, before OWF activities commence, targeted and repeated environmental surveys (over multiple seasons and years) must be undertaken to map the seabed and characterise key marine habitats (e.g. rocky reef, soft sediments), populations (e.g. fish marine mammals) and functional use of the area by key species (e.g. migrations, nesting) (Hemery 2020; Methratta 2025*a*). Available environmental information can help identify the knowledge gaps to be filled by these baseline surveys, and innovative techniques such as those associated with satellite data should be considered (Medina-Lopez *et al.* 2021).

In addition, targeted tracking programs for species that are likely to be affected are urgently required to better understand how OWFs may affect the movement of ecologically or commercially important Australian marine mammals, seabirds, reptiles, fish and invertebrates. For some species of seabirds, targeted island-based research will be necessary to fit devices to birds at their breeding grounds. Additional research is required on the use of radar (Largey *et al.* 2021) to determine approach of seabirds at risk of turbine strike before they reach OWF operations. Animal tagging and tracking will similarly improve our understanding of movement and migration through offshore areas where OWFs will be installed. National programs such as the IMOS Animal Tracking Facility already have established digital infrastructure to share acoustic telemetry from turtles, sharks and other fish; and with support this could be expanded to other taxa.

Current monitoring and research programs are generally focused on a small number of species of marine mammals, seabirds or fish that are not often known indicators of overall biodiversity or ecosystem health. In addition, monitoring of a single licensed area is often not at the spatio-temporal scales at which many ecosystem processes and functions occur; this means that we cannot detect ecosystem-level changes (Haberlin *et al.* 2022). This results in stakeholders that are 'data rich, information poor' (Wilding *et al.* 2017). Our understanding of the potential impacts on marine ecosystems also stems from general ecological knowledge and overseas studies on fixed-foundation OWFs (Table S1), rather than information about Australian ecosystems and floating OWFs.

Further research priorities have been identified by Australia's Offshore Infrastructure Regulator, including those specific to offshore wind (e.g. benthic habitat enhancement, electromagnetic field impacts, real-time monitoring to detect birds near turbines) and offshore developments in general (light pollution, noise impacts) (National Offshore Petroleum Safety and Environmental Management Authority 2023).

For floating OWFs, the technology is rapidly advancing, and broad commercial rollouts have yet to be completed, making impacts even more difficult to predict for future assessments. Clarifications and efficiencies in process and management, along with early consideration in engineering design, will help ensure cheaper, efficient, yet responsible environmental impact assessments:

- Government guidelines on impact pathways could be refined to add entanglement, contaminants and debris, and cumulative impacts, with the latter being not just applicable to marine parks as currently defined (Department of Climate Change, Energy, the Environment and Water 2023*a*). Consideration should also be given to how best to account for positive impacts such as habitat creation (Bennun *et al.* 2021), either as a new separate impact pathway or a revision to the existing 'seabed disturbance' pathway.
- A clear and streamlined process is required to identify potential environmental impacts and manage them. This is particularly relevant to Australia where site-specific environmental baselines and monitoring are required and the government does not subsidise environmental baseline studies, in contrast to some other countries. For comparison, as of 2024, the United States government had completed separate environmental reviews for 10 commercial-scale offshore wind projects.
- Consistent and agreed environmental baselines monitoring, and impact assessment methods must be applied to allow comparability among sites and regions (Przeslawski *et al.* 2023). Environmental baseline survey efforts are currently siloed in Australia, even for adjoining leases.
- National coordination of environmental data must be supported, as exemplified in other countries (e.g. Belgium and the Netherlands offshore wind research and development programs). Many marine sectors require coordinated data collection and delivery, but the emerging nature of the offshore renewables industry in Australia provides an opportunity to develop such coordination in a strategic, inclusive and streamlined manner. Environmental data sharing builds trust with communities, contributes to environmental sustainability and reduces cost (Courtney and Sen 2023), all of which are beneficial to the emerging offshore renewables industry in Australia. State-based intiatives such as the Shared Environmental Analytics Facility Project in Western Australia have already had success collaborating with the offshore energy industry to share their data. To facilitate national coordination of environmental data for offshore renewables, a collaborative steering group with an independent chair is required to ensure equal opportunity within the industry. National coordination also requires support for digital infrastructure to develop fit-for-purpose data portals with embargo options (e.g. Realtime Opportunity for Development Environmental Observations) and information hubs (e.g. Marine Data Exchange from United Kingdom, Tethys Knowledge Hub from United States). Australia may benefit from a government model such as that required in the Netherlands and Belgium that requires open access data and reports.

Supplementary material

Supplementary material is available online.

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