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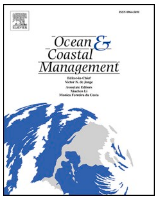

Review

Developing offshore renewable energy systems in Australia: Existing regulatory challenges and requirements for reliability assurance

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ABSTRACT

Australia has significant potential for the development of offshore renewable energy systems (ORES), and it can play an essential role in the global energy transition. The planning, design, installation, operation, and end-of-life management of ORES present substantial challenges in terms of the reliability of systems and the safety of operations. This paper focuses on identifying the gaps and challenges related to the structural integrity of ORES, highlighting potential areas for technological and managerial improvements. The paper investigates Australia's existing policies and regulations, identifies their shortcomings, and provides recommendations for their advancement. Key recommendations include implementing robust regulations, enhancing site-specific knowledge, adopting structural health monitoring (SHM) from the design phase, and fostering industry collaboration to accelerate ORES development and sustainability. The findings reveal high failure rates in ORES components, attributed to harsh marine conditions, material degradation, and extreme weather, underscoring the need for standardized protection and preventive measures. Integrating climate change impacts into dynamic risk assessments is crucial for accurate failure and consequent analyses. The study advocates learning from other engineering sectors to bridge existing gaps and align with sustainable offshore development goals. These recommendations aim to assist policymakers, regulators, and technology developers in realising safer and more sustainable ORES for Australia.

1. Introduction

There is a growing demand for sustainable energy around the globe, and offshore renewable energy systems (ORES) have emerged as a promising solution to meet that demand. The extensive oceanic regions offer opportunities to capture renewable energy from natural sources like wind, waves, tides, and even solar power. Among these, winds and waves are stronger and more consistent further out from the shoreline. Nearly 80% of the world's offshore wind resource potential is in waters deeper than 60 m, where the development of conventional bottom-fixed wind farms becomes economically unfeasible (Addamo et al., 2021).

In Australia, ORES has the potential to play a significant role as a key driver of sustainable transition for the national energy demands. Australia has the third largest Exclusive Economic Zone (EEZ), with over 80% being classified as offshore and subject to offshore winds, oceanic waves, and tidal currents (Behrens et al., 2012; Blakers et al., 2017). ORES projects have significant potential to assist Australia in achieving its net zero emissions targets by 2050, reducing emissions by 43% by 2030 and reaching 82% of electricity generation from renewable sources (Proposed offshore wind area). Thus, the Australian Government proposed a new set of horizons for the deployment of ORES. For instance, the goal set by the Department of Industry, Science, Energy and

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Resources is to enable 2 GW of offshore energy harvesting by 2030 and up to 100 GW by 2050 (Offshore Renewable Energy Strategy, 2020). These supports have prompted Australian and international businesses to initiate projects such as the Star of the South project, which is planned to be the first utility-scale offshore wind farm (OWF) in Australia. The project, proposed to be located 7–25 km off the south coast of Gippsland, Victoria, within an offshore renewable energy zone declared by the Australian Government, will have a capacity of up to 2.2 GW, potentially powering over 1.2 million homes and reducing up to 10 million tonnes of carbon dioxide annually (Star of the South).

Developing ORES projects in Australia offers a promising solution for green energy transition challenges, necessitating meticulous planning to address project complexities, emphasizing safety and sustainability. Performing tasks such as installation, inspection and maintenance for certification of such large energy farms in the harsh offshore environment is often labour-intensive, hazardous, and uneconomical (Abaei et al., 2017). For society to benefit from ORES developments, the systems, from cradle to grave, must be safe and resilient to the extreme environmental loads that occur during the entire lifecycle. The current lack of efficient strategies for efficiently deploying, operating, and decommissioning the ORES assets in remote conditions poses a barrier to Australia's successful large-scale deployment of offshore energy capabilities.

The increasing number of energy devices has a direct impact on the design and operational aspects of ORES, presenting notable challenges in terms of effective surveillance and enhanced reliability of operating systems. A thorough comprehension of these challenges is vital to establish regulatory frameworks and facilitate the smooth implementation of future ORES projects. Several attempts have been made to identify the key challenges and gaps in ORES development and regulations in Australia. One significant example highlighting the necessity for a systematic approach in ensuring the safe transition of grid integration and the advancement of offshore energy technologies is a recent report by the Australian Energy Market Operator (AEMO) (Integrated System Plan, 2020). However, it is worth noting that this report does not specifically address the integrated system of ORES. Similarly, another study by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) investigated the environmental impact, social aspects and stakeholder engagement for developing more sustainable offshore energy farms in Australia (Offshore Renewable Energy, 2019). It suggested ways to enhance the environmental and social outcomes of offshore energy farms through better assessment, engagement, and guidance.

Driven by Goal 7 of the UN 2030 Sustainable Development Goals (SDG) (Nation), which focuses on reliable and sustainable energy solutions, governments have actively supported numerous ORES projects. These projects aim to address challenges and advance knowledge in offshore and marine resource research and development (R&D) (Mexican Center for Innovation in). However, these initiatives face unique challenges related to design, operation, policy regulation, and standards needed for developing blue economies in Australia and worldwide. In particular, re-purposing decommissioned petroleum platforms for marine research, wind energy and green hydrogen production, as well as the development of Multi-Purpose Offshore Platforms (MPOPs) to harness multiple energy sources (e.g., wave, wind) for seafood and energy production is a major focus of the R&D projects. These concepts require significant investigation into their safety and sustainability (Aryai et al., 2021). To achieve its target of generating clean energy from marine resources with minimal impact on human assets and environmental sites, Australia needs a comprehensive approach to ensure the safety and sustainability of ORES. This approach should include methods, procedures, and guidelines for co-locating facilities and operations, integrating vertical infrastructure and shared services, and addressing technical concerns from risk and reliability perspectives (Kumar et al., 2023a, 2024). Therefore, the industry must ensure the structural integrity of these systems, which is a significant challenge in harsh ocean environments.

In this context, the major contribution of this paper is as follows.

1. A comprehensive review and analysis of the existing knowledge gaps and challenges in ORES development is conducted, focusing on safety and reliability aspects.
2. The status of international and Australian standards and regulations related to ORES is investigated, identifying major engineering challenges in their design and operation.
3. An overview of ORES risk and reliability is provided, detailing their failure modes and causes across the design, operation, and decommissioning phases of ORES life cycle.
4. Placing emphasis on identifying potential risks due to structural failures of ORES, followed by providing recommendations for corrective and preventive measures that can enhance the safety and sustainability of future ORES.
5. The findings can guide policymakers, regulators, and technical stakeholders in navigating the critical gaps of developing ORES, advancing intelligent condition monitoring for the improvement of reliability, sustainability and safety in the Australian offshore renewable energy sectors.

The remaining sections of the paper are structured as follows: Section 2 offers a concise introduction to ORES development activities in Australia; Section 3 presents an overview of the regulatory status and requirements for ORES; Section 4 delves into the details of critical ORES systems, their failure modes, and reliability; Section 5 emphasizes the significance of structural health monitoring (SHM) in ORES development; Section 6 provides insights into international guidelines pertaining to the health monitoring of ORES; Section 7 outlines major impediments to ORES development, and finally, Section 8 concludes the review.

2. Research methodology

A systematic review was conducted on the literature of ORES risk and reliability assessments. Table 1 outlines the criteria for inclusions and exclusions in this review. The studied literature spans 34 years, from 1990 to 2024, following an extensive search of peer-reviewed academic sources. The search utilized Boolean keywords including "Offshore renewable energy", "Offshore renewable infrastructure AND Marine structures" "Offshore wind" "Floating solar OR Floating wind" "Wave energy OR Wave energy converters" "Tidal energy" "Law AND policy", "Regulation", "Risk AND Safety analysis OR Risk assessment", "Marine bio-fouling AND Corrosion ", "Materials AND Structures", "Marine structure design" "Climate change" "Reliability", "Operations and maintenance", "Condition monitoring", "Failure mechanisms",

Table 1
Inclusion and exclusion criteria for conducting this literature review.

Criteria	Decision
Presence of predefined keywords in the title, keywords, or abstract	Inclusion
Research focused on the safety and reliability of ORES	Inclusion
Investigations into the status of international and Australian standards and regulations related to ORES	Inclusion
Studies that address at least one phase of the ORES lifecycle risk/reliability aspect	Inclusion
Research addressing structural failures in offshore technologies	Inclusion
Studies detailing failure modes and causes across design, operation, and decommissioning phases of ORES	Inclusion
Papers focusing solely on general renewable energy topics without specific relevance to offshore systems	Exclusion
Research not addressing safety, reliability, or regulatory aspects of ORES	Exclusion
Non-peer-reviewed articles, opinion pieces, and editorials	Exclusion
Duplicate papers found during the search	Exclusion
Research not available in English, inaccessible papers, and meta-data	Exclusion
Theses, dissertations, and other unpublished works	Exclusion
Published before 1990	Exclusion

"Decommissioning", "Rigs-to-reefs", "Mooring line", "Aquaculture", "Failure mode and effects analysis", and "Multi-use OR Multi-Purpose Offshore Platforms".

The general screening process and selection flow for relevant literature are depicted in Fig. 1. Initially, 1083 records were identified (250 from Google Scholar using advanced search techniques, 280 from ScienceDirect, 253 from Web of Science, and 300 from Scopus). After excluding grey literature, extended abstracts, presentations, keynotes, non-English papers, and inaccessible publications, 727 articles were retained for further title screening. Subsequently, 261 articles met the eligibility criteria for abstract review. After the abstract screening, 158 articles were selected for full-text review. Among these, 143 articles were assessed and downloaded for further screening. During the full-text review, duplicate papers and articles lacking clear ORES reliability assessment were manually excluded. Ultimately, 130 publications met all the inclusion criteria for this review.

3. ORES developments in Australia

Australia's ambitious energy transition plan requires collaboration across various industries including transport, civil and offshore engineering, renewable energy, R&D, and consultancy organisation government bodies. The government has funded many ORES projects to support sustainable offshore industries and marine resources. Fig. 2 illustrates the proposed and declared region designated for ORES development by the Australian government under the Offshore Electricity Infrastructure (OEI) Act 2021 (Australia's offshore wind areas). The Australian Marine Action Plan aims for 9 GW of offshore wind power by 2040 (Abaei et al., 2017). The Victorian Offshore Wind Energy Initiative targets at least 2 GW capacity by 2032, featuring 18 MW turbines and infrastructure to support multiple projects, positioning Victoria to host Australia's first OWF.

The Australian southern coastline, from Geraldton, Western Australia, down to the southern tip of Tasmania, offers significant wave energy potential, potentially meeting up to 11% of Australia's energy demands by 2050 (Behrens et al., 2012). The Australian Government has targeted the development of more than 8000 offshore wave energy structures by 2050 (Behrens et al., 2012). More than 200 wave energy converters (WECs) are currently in various stages of testing and demonstration, with several having been scaled up and tested at sea, and four of which were grid-connected (Behrens et al., 2012; CSIRO; Hayward and Osman, 2011). For instance, Oceanlinx developed the larger grid-connected WEC machine (viz. MK3), successfully installed at Port Kembla, New South Wales, in March 2010, with a total generation capacity of 2.5 MW (Manasseh et al., 2017). A 250 kW WEC by BioPower Systems, funded by the Australian Renewable Energy Agency (ARENA), was deployed in December 2015 near Port Fairy, Victoria, and was connected to the grid through a local aquaculture business (Manasseh et al., 2017). However, Oceanlinx and BioPower Systems have ceased operations. The Perth Wave Energy project served as a one-year demonstration project and was the world's first commercial-scale wave energy array connected to the grid (Agency ARE; Technology). Additionally, the UniWave200 pilot demonstration on King Island, Tasmania, includes a 200 kW oscillating water column-based wave energy converter connected to the local grid ((ARENA) AREA).

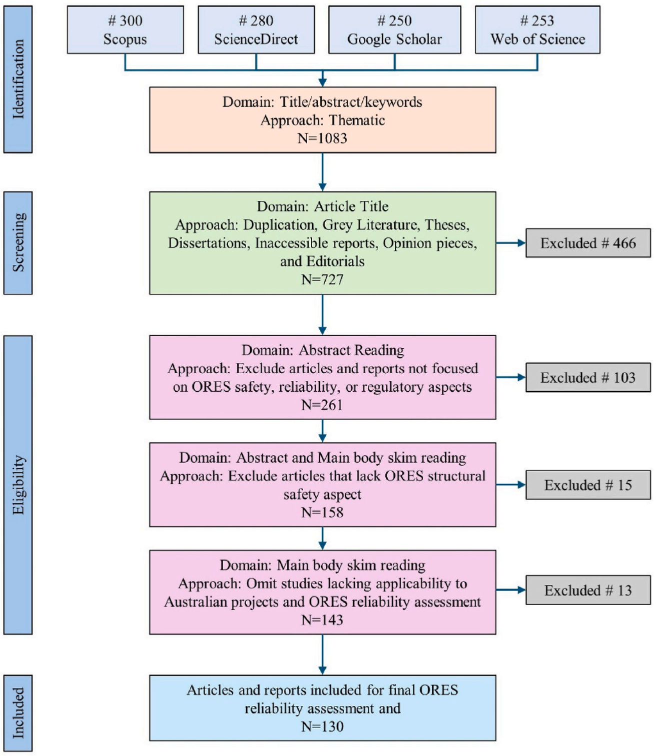

Fig. 1. The flowchart of literature review methodology and database filtering process. Source: Modified from Moher et al. (Mengist et al., 2020).

Currently, Australia has no commercial-scale tidal energy projects in operation, but several projects are in various stages of development, including research, feasibility studies, and demonstration pilots. For instance, the ARENA-funded Tidal Turbine Reef (TTR) feasibility study, introduced a design for a tidal site situated 200 m off the coast in Pearl Pass at a water depth of 13 m (ARENA). However, the TTR concept is highly site-specific and relies on assumptions, requiring further investigation. While a detailed assessment of Australia's tidal energy resource remains lacking, potential regions with substantial tidal currents include the eastern and western sides of Bass Strait, Torres Strait in northern Queensland, and Kings Sound on the northwest shelf (Manasseh et al., 2017). Atlantis Resources, a tidal power developer, tested its Aquanator tidal power technology in San Remo, Victoria, in 2002. This grid-connected technology was rated at 100 kW which was replaced later in 2008 with a 150 kW machine (Manasseh et al., 2017). In 2011, Elemental Energy Technologies tested its 2 kW ducted turbine, the 'Sea Urchin' in Newcastle, NSW, Australia (Manasseh et al., 2017). The Clarence Strait Tidal Energy Project in Darwin aims to create a demonstration pilot and eventually construct a 30–50 MW tidal power station by 2030, with plans to expand to over 450 MW by 2050 as energy storage and transfer technology advances (Tethys).

4. Overview of ORES regulatory status and requirements

To ensure the availability, performance, and safety of ORES, comprehensive regulations and standards are essential. These frameworks provide guidelines for design, operation, and maintenance, ensuring best practices and sound risk mitigation strategies are in place. They enforce consistency, enabling effective safety monitoring and corrective and preventive measures. Regulations also boost investor confidence by adding a level playing field and the long-term viability of ORES projects. However, there are currently no specific regulations or standards certifying ORES safety or offering guidelines for each stage of their life cycle. This regulatory gap hinders the development of reliable and safe ORES infrastructure. Establishing coherent regulations and standards is crucial for the sustainable growth and success of ORES projects (McGreevy et al., 2021). ORES growing infrastructure interconnectivity and interdependences at the national and international levels render them increasingly susceptible to unpredictable risks such as cyberattacks (e.g., the 2021 Colonial Pipeline ransomware attack and the 2020 SolarWinds software supply chain attack) and COVID-19 pandemic disruptions (Watney, 2022). Understanding and mitigating these emergent threats necessitate a holistic critical infrastructure resilience approach (Ninkovic, 2021). While frameworks like the Security of Critical Infrastructure Act (2018) exist (Security Legislation

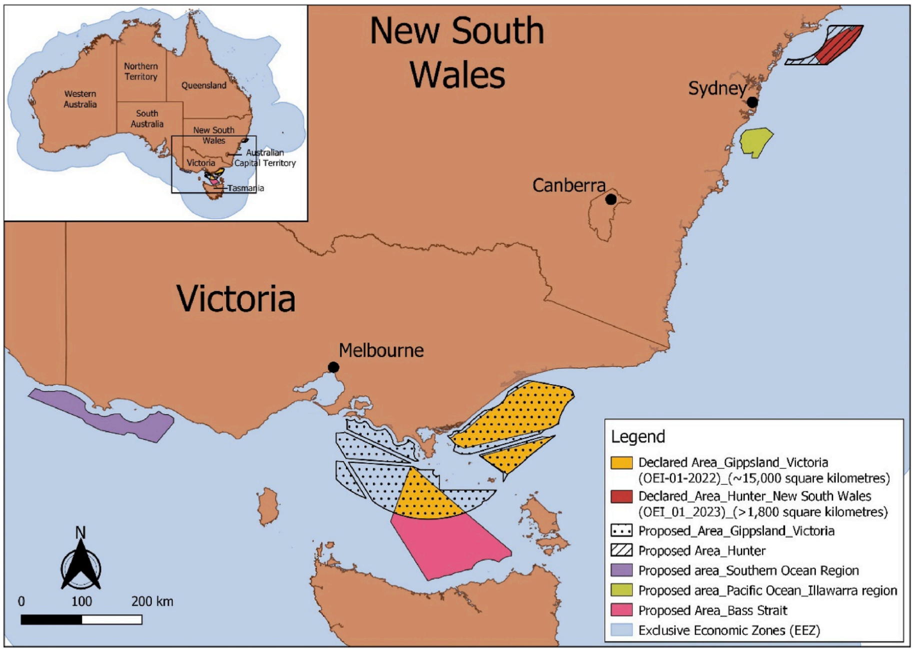

Fig. 2. The priority areas proposed or declared suitable for ORES infrastructure development in Australia by the Minister for Climate Change and Energy, under the OEI Act 2021 (Australia's offshore wind areas).

Amendment, 2022), their effectiveness in ORES remains unclear, necessitating further assessment of their applicability to sector-specific risk management within ORES regimes.

The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) primarily regulates offshore oil and gas (O&G) installations and has recently been tasked with regulating offshore wind projects. However, it does not offer sufficient guidance on the design, installation, maintenance, operation, and decommissioning of ORES. This can increase the risks of failures and disruptions, which can significantly impact energy security, consumer costs, and trust. The standards and regulations for ORES development and operation in Australia were criticized for their uncertain full scope and impact (Goodman, 2022). However, the passage of the Offshore Electricity Infrastructure Act 2021 has attempted to address the regulatory gap (Goodman, 2022). The existing standards (e.g., International Electrotechnical Commission/IEC), based on conditions in Europe and North America, may not apply to the Australian context, where site conditions can significantly deviate or surpass them (Committee Draft). For instance, Australia experiences severe tropical cyclones, typically occurring in the northern regions such as Queensland, Western Australia, and the Northern Territory, which can bring heavy rainfall, strong winds, and storm surges. Australia experiences a mix of semi-diurnal and diurnal tides, varying by region, while Europe predominantly has semi-diurnal tides.

In Australia, tidal conditions vary significantly, with mild tidal ranges in the south and high ranges, up to 10 m, on the northwest coast (Marine Science Australia; Explainer: tidal range). Southern regions like Victoria and South Australia experience large winds and waves. Current standards lack guidance on climate change-driven extreme events and deeper water installations with floating structures, crucial for ORES development in Australia. This can lead to suboptimal operation, reduced reliability, increased risk, or over-design of ORES. Because the location and intermittent nature of the production farms put a different demand and load on electrical systems, the industry must consider these implications on the integrity of assets, as well as the availability and operability of the energy units at each specific site. Furthermore, site conditions significantly influence the efficiency, safety, and reliability of wind and wave farm projects (Kumar et al., 2023b, 2023c). Additionally, Australian standards and regulations lack guidance on advanced technologies and materials, such as composite materials and advanced control systems, limiting innovation and performance enhancement of ORES designs.

Therefore, new Australian regulations for ORES development will need to introduce the essential Site-specific Design Assessments (SDAs), which will help designers and developers verify that their ORES unit complies with all applicable recommendations for a specific site, ultimately ensuring project success and sustainability (Kumar et al., 2023b, 2023c). SDA can be defined as a service that covers the assessment of load assumptions, safety criteria, performance analysis of system and offshore structure design. The final assessment of SDA will then ensure environmental parameters influencing the entire energy farm, such as wind speed and turbulence, wake effects and wave storms, and their associated uncertainties are fully accounted for (Fuglsang et al., 2002). For further clarification of these shortcomings, a critical review has been performed on the most important Australian standards for assessing the design and operations of ORES and the identified gaps are listed in Table 2.

Australia's only standard for offshore wind projects, developed by NOPSEMA, is primarily qualitative and lacks technical projections. NOPSEMA regulates safety, health, and environmental management for offshore infrastructure and operations, including energy installations (About NOPSEMA, 2021). Table 3 highlights NOPSEMA's relevant standards and their gaps for advancing ORES in Australia.

4.1. ORES decommissioning

The future decommissioning or end-of-life planning of ORES facilities involves a range of possibilities, including complete removal, leaving in situ, and repowering or repurposing the assets (Sommer et al., 2019; Topham and McMillan, 2017). However, the exploration of these alternative decommissioning schemes is influenced by various factors, including structure type, size and condition, prevailing local environmental and site characteristics (e.g., proximity to coastline, water depth), oceanographic factors, regulatory requirements, contractual terms, and the technical and financial viability. Unlike in the European context, where complete removal (e.g., North Sea) is favoured and in the

Table 2
A summary of the Australian standards and guidelines for the development of ORES highlighting the identified gaps.

Standards	Knowledge and Technical Gaps
AS/NZS 1170.2:2011 - Structural design actions Part 2: Wind actions (Structural design actions Part 2, 2011)	- Lack of sufficient guidelines for extreme wind impacts in certain regions of Australia, such as Bass Strait (Otway Basin), Gippsland, and Hunter, which are the primary targets for Australian offshore energy projects. - Lack of sufficient guidelines for designing offshore renewable structures (both fixed and floating platforms) that are resilient to wind/wave-induced fatigue damage in the long-term. - The standard, based on European and North American conditions (DNV, 2020a), and may not address Australia's unique environmental challenges. For instance, severe tropical cyclones in northern regions, extreme tidal conditions, and powerful winds and waves in southern areas could lead to suboptimal ORES designs.
AS/NZS 4997: Guidelines for the design of maritime structures (Guidelines for the design of, 2005)	- While existing standards provide guidelines for designing maritime structures, including ORES and multi-purpose infrastructure, they may introduce uncertainties related to environmental conditions and climate change impacts. These uncertainties can lead to unforeseen risks and potential failures. Therefore, updating standards to address the specific challenges of ORES in Australia is crucial. - The standard lacks operation and maintenance guidelines for ORES, increasing the risk of failures and disruptions if used without further amendments. - No guidelines available for fatigue damage and the associated failure of structural members due to stress concentration and damage accumulation under the action of repeated loading. - No guidelines exist for designing ORES regarding accidental limit states, essential for evaluating the survival of structures in damaged or abnormal environmental conditions (e.g., immediate park-off the ORES structures in storm wind condition) - No guidelines exist for disruptions due to deterioration or loss of routine functionality, such as exceeding normal operation criteria. Evaluating deformations and vibrations beyond tolerance is crucial, as unacceptable deformations can reduce power output and increase failure risks for components like drive trains.
AS/NZS ISO 19901.1:2015 Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations (Petroleum and natural gas industries, 2015)	- The standard, intended for petroleum and natural gas offshore structures, does not address the specific needs of ORES, such as wave energy converters. ORES have different design criteria, operational conditions, environmental impacts, and stakeholder expectations than offshore oil and gas structures (see section 3). Hence, a new standard tailored to ORES is needed for Australia. - the same as AS/NZS 4997, the standard lacks the providing of sufficient guidelines for failure modelling, risk mitigations, and maintenance strategy development of offshore structures.
AS/NZS ISO 31000:2018 - Risk management (Risk management, 2018)	-The guideline is too generic for risk management and lacks details on the specific risks associated with ORES projects in Australia, particularly for integrated energy farms. This gap increases the likelihood of overlooking critical risks. - There is a lack of guideline for developing robust quantitative risk assessment and management processes to ensure the safety and reliability of ORES.
AS/NZS ISO 9001:2016 - Quality management systems (Quality management systems, 2016)	- The standard does not have specific requirements for ORES projects, which can lead to uncertainty and gaps in quality management. This shortage involves the inclusion of safety and reliability in quality management. For ORES, which operate in harsh environmental conditions, safety and reliability aspects tie strongly with the quality of the service to be provided by the firms (operators).
AS 5732:2018 - Aquaculture - Part 1: Site selection and site evaluation (Aquaculture - Part 1, 2018)	- Although this standard guides the site selection and evaluation of aquaculture projects, it can merely be relevant for the aquaculture component co-located offshore platforms. There is a gap for more specific guidelines on the integration of this industry with ORES to ensure sustainable and efficient use and sharing of resources.

US, where reefing is in trend, Australia requires removal of the asset under s572 of the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (Cth) (Chandler et al., 2017; Techera and Chandler, 2015), although allows these structures to remain if equivalent environmental outcomes can be achieved (Department of Industry S, 2022). For this stage of an asset life cycle, proper planning and execution of decommissioning is crucial, as some of the requirements need attention during the initial design phase. Since the infrastructure and their associated systems vary in age and technology, each requiring unique engineering solutions and corresponding legal measures, an incomprehensive decommissioning program can result in substantial risks, financial obligations, and adverse reputational impacts. In Australia, the safety case requirement by NOPSEMA states that offshore facilities must be designed, constructed, inspected, and maintained in a way that minimizes health and safety risks associated with the removal to an as low as reasonably practicable (ALARP) level (NOPSEMA, 2020). However, there is a lack of established standards and regulations for the ORES safety case that should account for the decommissioning challenges (Wifa and Hunter, 2020). Limited deterioration rate and failure data hinder ORES decommissioning insights, but expert judgments and analogous systems/operations, including oil and gas, mining, nuclear, and aerospace, may offer valuable knowledge for developing the guidelines (Vinnem, 2007).

4.2. Role of regulations in ORES development acceleration

Addressing regulatory gaps in ORES development is a critical step for promoting investment and innovation. Clear and consistent regulations reduce uncertainty, streamline permitting processes, and enhance market confidence, which will attract long-term investors. Sound regulatory frameworks will facilitate access to financing by providing clear compliance guidelines, essential for developers who seek funding. Additionally, regulatory supports encourage innovation by easing

Table 3
Identified gaps in existing NOPSEMA standards and guidelines for ORES development.

NOPSEMA Guideline related to ORES projects	Identified knowledge/technical Gaps
Risk assessment *Document No: N-04300-GN0165 A122420*	Only general aspects are considered, while the unique risks associated with structural and critical system failures are not discussed, such as the potential impact of extreme weather conditions or marine life on the infrastructure.
Operational risk assessment guidance note *Document No: N-04300-GN1818 A639100*	No technical risks associated with ORES development, such as the potential impact of tidal or wave energy on the infrastructure and failure modes resulting from extreme environmental loads, are addressed.
Safety case lifecycle management *Document No: N-04300-GN0087 A86483*	No recommendations are made for managing the safety of ORES infrastructure, such as the challenges with the maintenance and repair of offshore wind turbines or wave energy converters. Under s226 of the *Offshore Electricity Infrastructure Act 2021* (Cth) (OEIA), the Safety Case has been replaced with a complex arrangement that applies the risk-based *Work Health and Safety Act 2011* (Cth) (WHSA), with s230 excluding vessels, vehicles, or mobile structures *before it arrives at a site* from the s12 scope of the WHSA. Prior to 'arrival at a site', other relevant Commonwealth and state legislation applies.
Offshore project proposal decision-making *Document No: N-04790-GL1816 A630598*	No specific considerations are provided for approving ORES projects, such as the potential impact on marine ecosystems or the integration of renewable energy into the existing energy grid and the cost-life cycle due to the degradation of facilities. Marine Spatial Planning (MSP) requirements are not contained in the OIEA, and s115 of the OEIA requires the project proponent to submit a Management Plan.
Damage to Safety-Critical Equipment Document No: N-09000-GN1914 A729008	Limited guidance is available on the specific risks associated with offshore renewable energy infrastructure, such as the impact of marine growth or corrosion on the equipment and fatigue load assessment.

market entry for new technologies and solutions. Preventing monopolistic practices through fair regulations will foster competition, leading to cost reductions and continuous improvements in quality. The inclusion of regulations with broader policy goals, such as carbon emission reduction and sustainability, will further attract investments from entities focused on environmental, social, and governance (ESG) criteria.

Smoother grid integration can be achieved through regulations, which enhances overall market efficiency and reliability. This is particularly important for ORES, where integration with existing energy grids can be complex. Governments can create a more predictable and stable environment that mitigates risks for investors by implementing regulatory guidelines. Such stability is vital for offshore renewables market which heavily depend on investment in research and development, driving innovation in new technologies and operational practices. Robust regulatory frameworks enhance safety and reliability by enforcing high standards and regular inspections (which reduce the risk of failures and accidents), they facilitate economic growth, supporting the ORES sector to meet future energy demands safely and sustainably.

5. Overview of ORES reliability

The ORES development process includes development, manufacturing, construction, operation, maintenance, repowering, and decommissioning. Each phase presents potential risks that need to be addressed in guidelines and standards. Table 4 lists the key factors that should be considered from a wider perspective to incorporate the associated uncertainties when developing ORES. Based on the identified key factors, material impurities, manufacturing imperfections, construction defects, assembly inaccuracies, and O&M are the primary causes of failure and degradation in ORES components. These challenges create difficulties in ensuring the safety of offshore wind operations, primarily because potential faults or failures may not be immediately apparent. For instance, a mooring system failure can occur without warning, posing a significant risk to the safe and reliable operation of offshore wind turbines (OWTs). Identifying and addressing such faults or failures becomes crucial to prevent accidents, minimize downtime, and maintain the integrity of the offshore wind infrastructure. The hidden nature of these issues underscores the need for comprehensive monitoring, inspection, and maintenance strategies that can detect and mitigate potential risks before they escalate into critical failures (Yeter et al., 2022).

ORES can experience failures due to various factors such as environmental forces, material wear, fatigue, corrosion, and human error. The specific failure modes and their impacts vary based on the structure type (fixed or floating) and its configuration. Their careful consideration is of significance as they have the potential to present risks to the safety and longevity of future Australian ORES and their operational activities. For instance, Ramboll (Svendsen et al., 2022) provides a summary of the most significant structural failure modes for offshore structures, including cracking, member separation, missing members, dents and bows, grouted connection, overloading, foundation scour, and excessive/unexpected and vortex-induced vibration issues. It was observed that fixed structures could potentially experience most different failure modes, while floating structures and loading systems may encounter fewer such modes. Typical causes identified for these failure modes include fatigue and/or corrosion, vessel impact/dropped objects, settlement and subsidence, wind, wave, or current actions. Additionally, the study identifies three global accidental events that can cause significant damage to offshore structures: storms, earthquakes, and vessel

Table 4
Key factors that may cause risks and uncertainties at different stages of the ORES life cycle.

Development Aspects	Manufacturing (materials and components fabrications)	Construction (Assembly, transportation, installations)	Operation & Maintenance	Repowering and Decommissioning
Site selection & feasibility Layout design and optimization MetOcean research studies	Component manufacturing, such as rotors, blades, towers, foundations, sub-structures, Nacelle, control systems, etc. Steel manufacturing Concrete substructures Moorings & anchors Power cables and substations	Coupled assembly (e.g., turbine and towers) Substructures and system assembly (e.g., gearbox) Transport and installation of components or substructures Flexible system installations (e.g., cable, mooring lines and anchors) Support vessels (tugs, towboats, barges, etc.) Motion control equipment	Inspection strategies for components and infrastructures Online monitoring of operations (e.g., dynamic loads on mooring systems) Certification of processes (e.g., control systems, grid connections and optimum power generations from farms)	Recycling/waste management Repower plan the project (involves upgrading or replacing existing ORES installations to enhance their efficiency and output) Logistical aspects Decommissioning service
	Significant impact on component/substructure degradations			

impacts. These findings emphasize the importance of developing advanced predictive models to inform risk-based design for ORES and health monitoring of offshore floating systems.

Defining failure modes and requirements for floating substructures in Australian guidelines requires consideration of common types of floating structures. These floating offshore structures can be integrated with various support systems, including innovative solutions such as grounding barges, buoyancy modules, and specialized vessels that reduce draft requirements. However, these advancements may introduce uncertainties and risks during ORES projects in Australia. To ensure the structural integrity and safety of ORES throughout their life cycle, a proactive approach involving risk-based inspection, monitoring, maintenance, and industry-wide knowledge sharing is essential (Duguid, 2017). Practical guidance is needed for inspection scope, depth, timing, and risk-based planning to extend the operating life of ORE.

5.1. Design considerations and challenges

ORES necessitates comprehensive met-ocean data collected on-site, both above and below the water surface, to design the system for its operational lifespan, considering factors like strength and fatigue. Typically, these datasets are sourced from the O&G sector, but the met-ocean characteristics in this industry can differ from those in the ORES. For instance, the specific wind characteristics of API met-ocean datasets (designed for the O&G industry) commonly referenced in the United States are less critical compared to the wind industry specific requirements. Consequently, the offshore wind sector requires more precise wind data for structural design, encompassing aspects like wind shear, turbulence, and hurricane conditions. Additionally, various other data, including temperature, tidal conditions, currents, and atmospheric factors, are crucial during the ORES design phase (Sirnivas et al., 2014). The lack of comprehensive, publicly available met-ocean datasets in Australia impedes the planning, design, and economic evaluation of ORES projects, leading to reliance on incomplete information and costly measurements. There is a necessity to collect and present quality met-ocean data from various sources (existing and new) in suitable formats (maps, databases, etc.) to support the ORES industry.

Currently, there is no one-size-fits-all design that suits all locations and environmental conditions while maintaining cost-effectiveness. It may take years for industry standards to emerge based on project suitability, manufacturing efficiency, and regional preferences. For instance, while topside designs for fixed and floating offshore wind projects share similarities, the design of floating substructures differs significantly. As outlined by RUK FLOW Industry Roadmap (Industry Roadmap, 2024), the industry is exploring various floating substructure concepts, with no standardized solution expected to dominate in the early years of floating structure adoption. Semi-submersible floating offshore renewable structures appear favoured, while other concepts like barges, TLP, and SPAR are also of interest.

Manufacturers experienced in producing fixed support structures may be familiar with steel substructures for both fixed and floating offshore wind technologies. However, it is essential to recognize that using concrete designs presents a unique challenge, especially in the Australian context. Currently, there is a lack of established design concepts and successful global implementation cases for concrete-based offshore wind structures, with a notable exception, which is the Hywind Tampen project in Norway that features floating concrete substructures. This lack of information and design uncertainty, combined with aggressive marine environments and the potential for corrosion, can impact structural integrity and durability. Both steel and concrete concepts for OWT foundations remain viable, and developers often choose based on cost-effectiveness and regional capabilities.

Foundations are critical for the overall stability and financial viability of ORES projects, presenting technical challenges in their design. The design challenge factors related to floating WT platform, for instance, include design tools, complexity of buoyancy tank, mooring line system, anchor, float-out, weather window tolerance, onsite installation simplicity, decommissioning, maintainability, resistance to corrosion and ice, water depth independence, sensitivity wave and bottom conditions (Butterfield et al., 2007). Driven by the principles of limit state design philosophy, the ORES foundation design criteria aim to meet the requirements of the ultimate limit state (ULS), serviceability limit state (SLS), fatigue limit state (FLS), and robustness and simplicity of installation. Designing ORES support structures presents an immediate challenge in predicting dynamic responses to combined wind and wave loads, especially in the presence of multiple load sources and nonlinearities. For instance, OWTs foundation structures are dynamically sensitive, with natural frequencies closely matching wind, wave, and rotor loading frequencies. This proximity can lead to dynamic amplification of responses and increased fatigue damage, emphasizing the importance of accurate natural frequency prediction and maintaining a safe margin from forcing frequencies (Bhattacharya et al., 2020). Thus, accurate simulation of various ORES operating states and environmental conditions is vital, requiring the development of new methods for predicting life cycle loads in such complex systems.

Designing effective and robust WECs presents several significant challenges, including infancy technology, technical maintenance, and harsh environmental factors. Overcoming the challenge of efficiently harnessing energy from varying ocean waves, especially at lower frequencies and larger displacements, is crucial. Furthermore, WECs operate in extreme offshore conditions, necessitating robust mooring systems and anti-corrosion measures. Finally, optimizing WEC designs is a critical concern with potential performance implications.

The design aspects for mooring structures encompass factors such as design loads, criteria, lifespan, maintenance, and operation. Specific ORES mooring design criteria are established about limit states, including the ULS, accidental limit state (ALS), and FLS, as described in offshore design standards (DNV, 2013). Mooring structures are exposed to cyclic, nonlinear loading conditions, mainly due to waves. To ensure the effective mooring of floating WECs, various designs and materials have been proposed. Analytically modelling mooring system behaviour involves various models, categorized as static, dynamic, or quasi-static, depending on complexity and interactions among parameters, variables, and environmental inputs. In the O&G industry, mooring systems are often modelled using a quasi-static approach, suitable for large structures with low velocities (Qiao et al., 2020). In the ORES, where structures are lighter (e.g., WECs), there is a need for a more distinctive response with higher velocities and lower loads. Dynamic analysis, accounting for fluid effects, mass, and damping, is thus essential for determining maximum mooring system tension.

ORES mooring design encompasses many challenges. First is collecting timely data, developing suitable criteria for floating structures, and assessing dynamic responses. To establish design criteria and evaluate severe environmental conditions, a design for long-term use that comprehensively examines the system dynamic response, such as in the North Sea, is essential to endure waves that can reach over 20 m in height, as predicted in a one-hundred-year scenario (DNV, 2013). Secondly, mooring design must strike a balance between flexibility for handling significant displacements and the capacity to resist hydrodynamic loads. Challenges arise from a wide range of environmental input frequencies, but modelling approaches can address these effects independently. Choosing the right combination of material strength and compliance, especially in harsh offshore environments, is also vital. Early consideration of moorings is crucial, as failures often occur within the initial ten years, with most happening in the first five years (Ma et al., 2013). In deepwater, higher pretensions and fatigue challenges, particularly with chain moorings, lead to the use of redundancy through mooring line groups. Ensuring pretension accuracy is thus essential to avoid fatigue damage. Additionally, addressing snap loads in cables, which can result from cable slack and sharp retightening, is critical (DNV, 2013). Anticipating and reducing snap loads during the design iteration of mooring structures for ORES is highly beneficial. Lastly, ensuring minimal to no twist in the mooring system during the final or pre-installation stages is vital for long-term mooring integrity, as twists in wire ropes can lead to issues like bird-caging and premature failure, while mooring chain twists can reduce fatigue and strength performance. Reliable tension measuring devices, especially for taut systems, are essential during deployment to achieve optimal mooring system performance while managing twist-related challenges (Qiao et al., 2020).

5.1.1. Reliability-based design optimization (RBDO)

Enhancing the reliability of ORES holds the potential to boost electricity generation in challenging sea conditions, extend operational lifespans, reduce costly maintenance, and lower financial risk. As the ORES remains in its early developmental phase, there exists an opportunity to leverage RBDO methods to achieve cost efficiencies and enhance market viability. RBDO is crucial for ORES as it accounts for uncertainties, unlike deterministic design optimization, which balances reliability and affordability. While it has been used for fixed-bottom ORES (e.g., OWTs and WECs) for design fatigue safety factors, schedule maintenance and inspections and structural design optimization, its complete implementation in floating ORES (particularly OWTs and tidal energy technology) remains challenging.

RBDO methods can drive technology convergence, boost reliability, and enhance market competitiveness in various offshore renewable energy technologies, building on foundational research as the industry evolves and matures. Employing RBDO to integrate reliability, cost, and performance considerations throughout subcomponent, device, and system design phases facilitates the pursuit of optimal solutions, particularly valuable for the nascent ocean energy technologies, including wave and tidal energy sectors, as they aim for technology design convergence (Clark and DuPont, 2018).

Uncertainty in a system's performance can lead to significant costs if not accurately quantified and considered during the design phase. For instance, Anholt Wind Farm faced increased costs due to a rushed preparation time, leading to higher bidding prices (around $340 million) compared to projects with longer preparation periods like Horns Rev 3 (Ostachowicz et al., 2016). RBDO techniques must evolve to accommodate emerging trends in the ORES sector, including larger systems or structures, installations in deeper offshore locations, floating platforms, and novel end-of-life applications, including lifetime extensions and repowering.

Reliability assessment in emerging ORES like wave and tidal energy systems is challenging as most of the analysis relies on generic subsystem or component data and failure rates often multiplied by high safety factors, resulting in wide ranges of availability estimates due to uncertainties surrounding these technologies. Additionally, these studies employed basic random failure rate models without accounting for common failure modes, mechanisms, or the possibility of cascading failures. The lack of comprehensive performance and reliability data poses design challenges for engineers working on unproven technologies.

In structural design, safety factors are typically borrowed from the offshore O&G industry, leading to over-designed and costly ORES due to higher safety margins calibrated for potential human and environmental risks. For instance, Marquez-Dominguez and Sørensen (Márquez-Domínguez and Sørensen, 2012) observed OWTs required fatigue design safety factors (as fatigue is a common failure for WT support structure) of 2.5 for wind-dominant loads and 3.5 for wave-dominant loads based on RBDO, lower than those for unmanned offshore O&G platforms. They also observed that three high-quality inspections during the device's lifespan could reduce the required safety factors.

In ORES applications, a key focus of RBDO is reliability-based inspection (RBI) and maintenance planning. RBI combines probability models such as Bayesian decision analysis and structural reliability analysis to optimize cost-effective inspection strategies and has been applied in OWT applications and offshore jackets (Clark and DuPont, 2018). RBDO techniques have been used across various turbine types, structures, and limit states, with researchers fine-tuning safety factors to establish technology-specific guidelines and reduce over-engineering costs. The research landscape on RBDO and RBI in offshore wind and wave energy offers several promising avenues for future exploration: 1) Investigating wake and shadow effects in layout optimization to enhance the reliability and performance of WT arrays; 2) Examining the impact of control strategies on the reliability and performance within RBDO and RBI frameworks, particularly in offshore wind applications; 3) Optimizing part replacement or warranty renewal decisions by integrating RBDO and RBI methods, thus minimizing costs and enhancing reliability; 4) Incorporating life extension and repowering considerations into initial array designs through RBDO techniques; 5) Applying RBDO approaches to the diverse designs of floating OWTs and platforms, fostering design convergence and collaboration; 6) Utilizing RBI techniques for more efficient modelling, prediction, and optimization of offshore wind and wave energy O&M processes (Clark and DuPont, 2018).

Fatigue failures are anticipated to be a prevalent issue in wave energy devices in the future, affecting welded joints and corroded bolts, with consequences akin to those in OWT components, necessitating lower safety factors than those employed in the offshore O&G sector. While wind-induced loads dominate OWTs, WECs primarily face fatigue due to cyclic wave loading (Moan et al., 1999). The existing RBDO research in wave energy primarily focuses on a specific WEC design, limiting its applicability to other WEC types or designs. The lack of design convergence among WECs presents an opportunity for the wave energy industry to prioritize reliability and explore common components among different designs, such as mooring systems, which could benefit various WEC designs as well as other technologies like tidal devices and floating WTs.

Research opportunities in tidal energy device design include applying RBDO to address fatigue limit states and calibrating and validating design safety factors. Additionally, exploring wake and shadow effects on power production and reliability in tidal turbine arrays, integrating advanced controls in RBDO for improved performance and longevity, and optimizing various design parameters while ensuring reliability due to greater design convergence in tidal turbines compared to other technologies are valuable avenues for further investigation (Clark and DuPont, 2018).

Testing subcomponents and devices in wave tanks and current flumes is essential for validating autonomous operation, supporting certification, and gathering reliability data for both academic and industry purposes. This data aids in validating numerical models for failures and identifying high-risk components during design to minimize downtime. Additionally, long-term demonstrations of system performance in challenging sea states (strong waves, winds, and tides) are crucial for gathering reliability data, developing industry standards, and assessing installation, operations, and decommissioning costs and methods (Clark and DuPont, 2018).

The absence of standardized designs and consensus intensifies the risk of inadequate engagement with potential manufacturers and subcomponent suppliers, hindering the formation of a robust supply chain. Moving from custom-made to standardized off-the-shelf components can enhance consistency, reduce costs, and minimize failures associated with low-volume manufacturing. Few industry-specific reliability databases and standards have been developed (as shown in Table 5), but adopting RBDO can further expedite advancements in ORES reliability R&D.

5.2. ORES failure modes

Considering failure modes is crucial for ensuring the reliability, safety, and longevity of ORES installations. It helps identify critical

Table 5
Standards and guidelines relevant to ORES design, reliability, and safety.

Guidelines/Standards	Scope/description	Reference
DNV-OSS-312: Certification of tidal and wave energy converters	This document presents the principles and procedures for the Certification of tidal and wave energy converters.	DNV (2008)
DNV-GL and Carbon Trust: Guidelines on design and operation of wave energy converters	This report provides guidelines for designing and operating WECs	DNV (2005)
The European Marine Energy Centre (EMEC): Guidelines for design basis of marine energy conversion systems	The design guidelines for wave and tidal energy devices, updating and expanding upon DNV-GL.	EMEC (2009a)
EMEC: Guidelines for reliability, maintainability, and survivability of marine energy conversion systems	This document provides reliability, maintainability, and survivability guidelines for wave and tidal energy devices, updating and expanding upon DNV-GL reports.	EMEC (2009b)
EC TC 114: Marine Energy – wave, tidal and other water current converters	Codifying these guidelines, the IEC created a comprehensive set of standards for wave, tidal, and other wave current converters.	Commission IE (2017)
DNV-OS-C101: Structural design of offshore units	This offshore standard provides principles, technical requirements, and guidance for the structural design of floating offshore units made of steel.	DNV (2023a)
DNV-OS-C201: Structural design of offshore units - WSD method	This offshore standard provides principles, technical requirements, and guidance for the structural design of offshore structures based on the working stress design (WSD) method.	DNV (2021a)
DNVGL-ST-0378: Offshore and platform lifting appliances	This standard covers the design, materials, fabrication, installation, testing and commissioning of offshore cranes and platform cranes	DNV (2020b)
DNV-OS-C401: Fabrication and testing of offshore structures	Provide an internationally acceptable standard giving the minimum requirements for the fabrication of offshore units, installations, and equipment by welding, including requirements for mechanical fastening, testing and corrosion protection systems	DNV (2023b)
DNV-OS-E301: Position Mooring	This offshore standard contains criteria, technical requirements, and guidelines on design and construction of position mooring systems	DNV (2013)
DNV-OS-E304: Offshore mooring steel wire ropes	This Offshore Standard contains criteria, technical requirements and guidance on materials, design, manufacture and testing of offshore mooring steel wire ropes, sockets, and pins	DNV (2020c)

components and weak points, enabling measures to improve system robustness, mitigate risks, reduce downtime, and enhance operational efficiency in diverse conditions.

5.2.1. Offshore wind energy systems

OWT has multi-functional systems; thus their risk and reliability are often assessed based on different system failure modes. For instance, Dinmohammadi and Shafiee (2013) conducted a risk assessment on sixteen sub-assemblies of offshore WTs, highlighting the tower, rotor blades, and generator as the most critical components with the highest failure rates. The primary factors contributing to these events are over-stressing caused by harsh marine environments, extreme weather conditions (including seasonal factors like icing and thunderstorms), and issues such as cracks, corrosion, and inadequate welding. Lazakis and Kougioumtzoglou (2019) identified tower, foundation, and rotor blades as the most critical components of offshore WTs in terms of safety due to their potentially catastrophic consequences. Through FMECA and BBN analyses, the high likelihood of failure in the pitch and yaw systems is confirmed, emphasizing the electronic system's vulnerability as a primary source of downtime. The foundation is found vulnerable to environmental factors due to its contact with the seabed and seawater, compounded by the absence of sensors to detect abnormalities. Moreover, reported critical hazards during installation and maintenance include vessel-vessel collisions, collisions with turbines and by other means of transportation like helicopters, vessel stability loss, equipment or object drops or swings, electrical shock, worker slips, trips, and falls, physiological hazards in confined spaces, and tower collapse. According to the authors, extreme weather conditions such as lightning, strong winds, and ice falls are perceived as the main causes of failures during WTs operations (Lazakis and Kougioumtzoglou, 2019). Dai et al. (2013) conducted a risk assessment of various collision scenarios between a service vessel and a monopile with a boat landing structure. The findings indicate that even low-speed collisions between turbines and service vessels can result in structural damage to the turbines. Bad weather conditions, limited visibility, and technical equipment failures are regarded as risk-influencing factors. To achieve the prescribed level of safety, a focus on limit state design, particularly ALS, is emphasized in the study and highlighted by a lack of ALS standards for operating service vessels in offshore renewable energy farms (Dai et al., 2013).

The technology of floating offshore WTs (FOWTs) is still at an early stage of development, and a complete understanding of their failure properties has not yet been achieved. Several studies explored the failure mechanisms of FOWTs in high sea depths and harsh marine environments. For instance, Kang et al. (2017) performed a reliability analysis of FOWTs, and the results highlighted the significance of electrical failures and identified material corrosion as a key contributor to system failure. The study also emphasized the high probability of mooring line fractures which can be caused by fatigue, corrosion, external impact, and extreme sea conditions. The study (Kang et al., 2017) recommended reinforcing the design of the generator assembly, floating foundation, and mooring system to enhance overall structural safety and reliability. In another study (Li et al., 2021a), the support structure of FOWTs is found to be the most crucial sub-system, with the mooring system, tower and transition piece, and floating foundations being the riskiest systems in descending order. The critical causes of failure in the floating support structure are attributed to unpredictable factors like device failures, material-related issues (fatigue, wear, corrosion), and environmental factors such as strong wind and waves. Failure in mooring lines and transition pieces is identified as the important failure mode where improved design and increased capacity of mooring line for higher reliability is recommended (Li et al., 2021a). Similarly, Zhang et al. (2016) reported that WT and tower had the highest failure modes, followed by the floating foundation and mooring system. Tower module failures were caused by factors including storms, strong winds/waves, ice storms, and material deterioration. Semi-floating foundation failures, resulted from typhoons, collisions, capsizing, and aircraft crashes, which make the installation of protection devices indispensable. Broken mooring lines, fatigue, and fairlead corrosion are the main causes of mooring system failures. This highlights the need not only for careful evaluation of component reliability with respect to structural deterioration during the design process but also for timely detection and repair of the line stresses and transition chain conditions. The results (Zhang et al., 2016) also reveal that collisions with non-service vessels are the significant factor impacting the reliability of FOWTs, and installation of collision protection devices is recommended.

Li et al. (2021b) conducted a comprehensive failure analysis of

FOWTs and identified WTs as the most critical system prone to failure, followed by the mooring system and floating foundation. Mooring systems are particularly vulnerable in complex and harsh sea conditions, while the floating foundation experiences a high frequency of failures, often related to device malfunctions that are difficult to detect. The mooring line, tower, generator, and gearbox were identified as components with high risk while bearing deformation, generator overheating, winding failure of the generator, gearbox overheating, open circuit of converter and transformer, tower collapse, tower crack, transition piece crack, floating foundation hitting, watertight and additional structures failure of floating foundations, abnormal and broken mooring lines ranked highest among failure modes. Material-related factors, such as wear, fatigue, corrosion, and destructive environmental conditions like lightning strikes and ice storms, were identified as the top causes of structural degradation of most failures in FOWTs (Li et al., 2021b). To prevent failures in FOWTs, recommended measures include strengthening mooring lines to prevent abnormal stress and wear, enhancing the design and welding quality of the floating foundation, tower, and transition pieces, implementing anti-corrosion treatment for the generator and its winding, preventive action against gearbox wear and fatigue, and improving the quality of the anchor pickup device and mooring winch (Li et al., 2021b). Shafiee (2023) conducted risk and reliability assessments of an OC3-Hywind FOWT with the spar-type platform and found that the tower structure and mooring system are more prone to fail, followed by rotor blades and gearbox. According to this study, external environmental conditions such as heavy storms, strong winds, waves, and fatigue contribute significantly to tower failures. Abnormal stress, anchor failure, and fairlead fatigue are identified as the primary causes of mooring system failures. According to Li and Soares (Li and Guedes Soares, 2022), the components of FOWTs have 26% higher failure rates than onshore WTs, where material-related factors are primary for failures, followed by environmental and human factors.

Offshore structures are prone to high technical risks from mechanical forces, corrosion and biofouling, and standardized rules for protection against them are currently lacking (Klijnstra et al., 2017). For instance, local defects like pitting, which may act as initial sites for fatigue cracking, and local corrosion attacks such as microbial corrosion effect on different offshore WTs foundations (particularly monopile, TLP and floating) and tower structures are still unknown. Similarly, a complete understanding of the effects of biofouling on floating foundation and mooring systems and how changes in seawater chemistry (e.g., salinity, nutrient content, sunlight intensity and duration, current and temperature) impact their lifetime is lacking. Past incidents have demonstrated that safety risks and compromised structural integrity of ORES can arise from incorrect coating selection, improper coating application, inadequate cathodic protection systems, corrosion of boat landings due to wear, impact, and seawater, as well as corrosion of secondary structure components like ladders and railings (Klijnstra et al., 2017).

5.2.2. *Wave energy converters (WECs)*

Enhancing the reliability and minimizing downtime of WECs are crucial performance attributes for the successful implementation of the technology on a commercial scale. The target reliability levels of WECs cannot be directly extrapolated from offshore WTs due to the distinct load characteristics, with WECs primarily focusing on absorbing wave loads compared to wind loads in WTs. According to a survey by Bliss (2020), mechanical components such as mooring lines, mooring connectors (shackles), and hydraulic parts are identified as the most vulnerable and risk-prone subsystems of WECs. The main causes of mooring failure include fatigue, wear, corrosion, overloads (particularly snap loads), manufacturing defects, design issues, and damages created during installation. These failures are primarily attributed to technical faults, impacts from extreme environments, including storms, cyclones, slamming waves, or accumulated degradation in the WEC (Bliss, 2020). In Réunion Island, for instance, the point absorber buoy of a WEC designed by French company DCNS and inspired on the CETO technology was reportedly swept away and damaged due to the waves whipped up by a cyclone. Although making a concrete judgment is not possible as the developers were minimaly involved in the deployment of the system, a cable that connected the point absorber buoy to the hydraulic pump, which is anchored to the seabed, was reportedly snapped. The absence of a quick-release mechanism was found to be the major cause of the incident (ReneEconomy: Clean Energy News and; CETO). Similarly, the buoys of the Sotenas point absorber WEC project in Sweden were torn during a storm (Tiron et al., 2015). The Pelamis attenuating WEC incident was attributed to the failure of a foam material used for creating buoyancy, which could not sufficiently handle deep water pressure. The hinged connection between the parts of that device wore out quickly due to fatigue. On the one hand, a design improvement and strengthening of WECs that can withstand extreme offshore conditions is required. However, designing for improved survivability often reduces the hydrodynamic performance of the device in terms of power extraction. Therefore, WEC technologies must find a balance between these two seemingly contradictory criteria if they aim to become more economically viable (Tiron et al., 2015). Additionally, the importance of new materials and manufacturing methods in WEC integrity must not be overlooked, as shown by the failures in previous developments such as the Pelamis.

For the optimal structural design of WECs, possible failure modes from the surrounding environment or partial failure of the structure, including foundation failure, vessel impact, loss of station keeping, loss of stability, fire, interference with debris, and seismic events, should be carefully considered (Ambühl et al., 2012). In the OPERA project (Khalid et al., 2019), stress rupture and fatigue were identified as critical failure modes for fibre ropes used in mooring systems. In their condition monitoring system, critical failure modes included cable failure, fatigue, and kinking for node load pins, as well as fatigue and corrosion for load shackles and power loss for the data acquisition system. According to Yang et al. (2016), WECs mooring lines are a critical component in terms of reliability, with the fairlead point experiencing the most serious fatigue damage. Point-absorber WEC floaters, as highlighted by Kolios et al. (2018), are prone to fatigue failure before their design life and are highly sensitive to wave loads and material properties.

Several aspects are recommended by other researchers to improve WEC design for enhanced reliability. It is recommended to increase the thickness of the floaters as reinforcement (Kolios et al., 2018). A risk assessment study by Okoro et al. (2017) on a point absorber WEC with hydraulic PTO and hemispherical buoy (Wavestar prototype) revealed that 50% of the system risk is concentrated in just 23% of the components, including those from the generator (seals, windings, magnet), motor shaft, and generator blade. Components such as wave buoy (floater), hinge frame, frame rivet, and weld joint are considered highly risky due to factors like internal and external corrosion aggravated by biofouling or microbiologically influenced corrosion (MIC), overloading or impact due to wave slamming, fatigue, welding defects, climate and external forces, and incorrect operations. The study recommends prioritizing the inspection, repair, and maintenance of the components that pose the highest risk rather than treating all components equally important with regard to failure. Another study identified the five most critical components, including hydraulic fluid, filter, valves, oil reservoir, and pressure line, where failure contributes to approximately 80% of the total failure risk of the point absorber WEC system (Okoro et al., 2019). Mueller et al. (Lopez-Chavez, 2022) conducted a reliability analysis of various PTO systems in a generic WEC and determined that the hydraulic PTO exhibited the highest failure rate compared to the linear generator direct drive or an oscillating water column PTO. However, their failure data do not reflect the real applications as they neglect the environmental and operation loading factors.

Rinaldi et al. (2016) found that the components causing the most downtime in the Pelamis attenuator WEC were, in descending order, the seals in the structure system and electric generator, hydraulic ram, accumulator, and hydraulic motor of the PTO system. Shen et al. (2022) identified the float system, power generation system, and hydraulic system as the most critical subsystems influencing the stability of point-absorber WECs. The hinge frame and generator were identified as key components with the highest risk level. The float and hinge frame are susceptible to wave load, salt fog, seawater erosion, and biological pollution due to exposure to severe sea conditions. Failure causes in the power generation system include poor lubrication, overloading or impact, corrosion in winding and magnets, wear in gears and bearings, fatigue in the shaft, and adjustment errors during welding and assembly (Shen et al., 2022). Kenny et al. (2017) validated the FMEA analysis of Albatern Squid 6 Series WEC using its 3-year sea trial failure record. Major structural and hydraulic failures were found to be more frequent, and minor electrical and instrumentation failures were less observed. Corrosion, fatigue, and wear were amongst over-predicted failures, expected in later stages of component service life, while human-driven failures such as design faults and assembly errors were observed most under-predicted.

In oscillating water column (OWC) devices, if the chamber design is not optimized to dissipate wave energy effectively and in the presence of harbour walls that amplify the waves, it can lead to wave reflection and over-topping, causing increased forces on the structure and potential damage (Estrada-Lugo et al., 2018). Fatigue from repeated wave loading can cause cracks and fractures, while corrosion and fouling can degrade OWC structural materials over time. Extreme sea conditions, including storms, high waves, and currents, may lead to mooring, anchor, and foundation failure, resulting in horizontal sliding, dislocation, overturning, scouring, and collapse of the structure. For instance, a storm destroyed an OWC WEC plant in Norway because of a failure in the bolted connection between the steel structure and the concrete foundation (Falcão and Henriques, 2016). Similarly, the PICO OWC prototype in Portugal failed due to structural damage in its submerged sections. The Oceanlinx OWC MK3 prototype broke free from its mooring lines in severe seas and sank off Port Kembla in New South Wales (Oceanlinx; News, 2015). In above-water or shore-based OWC WEC systems, like UniWave200 (WaveSwell), challenges persist due to potential failures in complex mechanical and electrical components caused by degradation, vibration, and resonance. Additionally, exposure to marine environments, including saltwater spray and humidity, may lead to biofouling and corrosion in turbine blades, mechanical linkages, and electrical equipment. The salt and moisture can wash away or contaminate lubricants, which impacts turbine integrity and operation, potentially damaging its bearings. External factors, including storm effects and electromagnetic interference from lightning strikes, can disrupt electrical systems and sensors, leading to potential malfunctions or failures of diagnosis and communicating systems.

5.2.3. *Tidal energy converters (TECs)*

Walker and Thies (2021) reviewed 58 tidal stream energy converters deployed between 2003 and 2020 and observed blades to be the weakest components in terms of structural reliability in tidal turbines. Particularly in horizontal axis devices, failures are reported to occur due to underestimation of the loads during design. Generator and monitoring failures were also evident. A large proportion of system failures were associated with higher flow rates, indicating the crucial role of considering flow velocity impact in reliability assessments of the systems. Reliability analysis on generic tidal turbines of the RealTide project revealed that electrical systems, rotors, and drive trains were the most critical components, and blades, power electronics converters, and generators were among the ten most critical sub-assemblies (Advanced monitoring). Failures in these systems were attributed to factors such as poor fabrication, improper design, overloading from excessive waves, vibration, corrosion, fouling, and marine growth. For foundation and support structures, failures were linked to cyclic loading from waves and currents, fatigue, weld defects, excessive marine growth, and impact from dropped objects.

It should be noted that the results and discussion provided here are based on very limited reliability data that were found available to the public (due to the sensitivity of the data and the age of the offshore renewable energy industries) and mostly reported in the literature based on the knowledge of experts. Due to scarce real operating data, firm conclusions about failures often cannot be drawn, emphasizing the necessity for detailed analyses to reduce uncertainties in predicting failure rates, consequences, and improving ORES reliability. The analysis should also consider the impact of climate change, as wave and current loads, sea temperature, material degradation and structural safety are sensitive to changes in the site's environmental conditions (Wilkie and Galasso, 2020). Climate change uncertainties and resulting environmental loads, including marine growth on marine structures, marine corrosion, particularly MIC and bio-fouling, change in ocean (both surface and across water column depth) temperature, sea water level, salinity, pH level, acidification, and wave height can have potential implications on the safe design and operation of offshore structures which necessitate attention in modelling, inference and decision-making. Machine learning models can reduce uncertainties by predicting changes in climate variables, including wind and waves (Donnelly et al., 2024; Yeganeh-Bakhtiary et al., 2022, 2023). Utilization of dynamic and time-dependent failure and risk analysis models and adaptive management strategies are highly advisable for enabling the development of safe and resilient marine structures in the everchanging global environment.

5.2.4. *Multi-purpose platforms (offshore wind and aquaculture systems)*

The use of ORES as MPOP and combined food-energy systems appears promising but requires innovative technologies, MSP, and risk assessment. While Australia presently lacks a comprehensive federal MSP that integrates ORES (Taylor, 2023), Victoria has emerged as a frontrunner in this domain by undertaking the development of the first state-level MSP to incorporate ORES (Government). The technical risks of failure are likely to increase or be unknown, mainly due to the complexity of systems and the interactions of multiple operations on each other. For instance, possible impact or strike between collocated elastic aquaculture structures (e.g., mussel and seaweed farm) and OWFs can cause immediate structural damage and removal of the anticorrosive layer, posing long-term risks if not repaired promptly (Klijnstra et al., 2017). The presence of drifting offshore aquaculture, characterized by rigid structures like fish farms, can introduce substantial risks that vary depending on cage type, size, and construction method. It is advisable to assess the potential impacts and consequences during the design phase of combined structures by conducting numerical studies, model scale and full-scale experimentation of the motion responses on integrated assets. The inclusion of aquaculture infrastructure with increased biofouling and marine growth can also pose a risk to the integrity of turbine foundations. Particularly for jacket structures, increased marine growth can cause additional frontal surface area in jackets and, subsequently, higher drag forces from waves and currents. A harsh environment, including severe storms with extremely high waves, along with a physically connected aquaculture and WT foundation structure, poses an increased risk due to potential large turning movements at the seabed, which could result in turbine collapse (Klijnstra et al., 2017). To ensure structural reliability and optimal infrastructure design life, it is essential to account for unconventional load measures, application of innovative materials and maximised maintainability for all systems within MPOPs. These considerations must be made during the early stages of project development to avoid extra costs or failure events during the operational parts of the asset life cycle.

5.2.5. *ORES decommissioning risks*

The decommissioning of ORES involves the removal and transportation of structures where lifting and loading are the most safety-critical operations, particularly for large facilities like OWFs (Topham and McMillan, 2017; Shafiee and Adedipe, 2022, 2023). The removal, partial or complete, process may involve unbolting, structural cutting, dismantling, lifting, and unloading of heavy components (e.g., turbine, transition piece, foundation, substation and mast) on transportation vessels and towing operations (Topham and McMillan, 2017). These repetitive activities for all ORES along with vessel repositioning at unfavourable metocean conditions, involve a wide range of safety threats and may lead to disruption or failure of decommissioning operations. For instance, Babaleye and Kurt (2020) identified capsizing, descent, collision and drifting of barges as major safety concerns related to lifting operations during offshore jacket removal. A risk assessment of capsizing scenarios also revealed that around 84% of the failures resulted from corrosion-induced thinning of the jacket leg walls (Babaleye and Kurt, 2020). The likelihood of internal corrosion to be present was 0.52, while external thinning was estimated to occur with 0.16 probability. Thus, a comprehensive assessment of structural capacity concerning corrosion and fatigue is recommended before planning removal operations. Shafiee and Adedipe, 2022, 2023 reported crane failure risk to be highest during OWF decommissioning operation, followed by vessel damage and collision/contact. Events like improper cuts, poor payload estimation, force imbalance acting on the vessel, and excessive marine growth were found to be responsible for vessel damage. Potential consequences are reported as water ingress, flooding, vessel instability (CoG/CoB misalignment), detached cargo, differential sticking, and sinking or capsizing. Inaccurate signals, obstructed vision, improper hooking, and vibration effects spotted the highest sensitivity on the crane failure, causing loss of integrity, swinging or dropped load, and structural weakness (Shafiee and Adedipe, 2022, 2023). The time between the end of the operation and the start of decommissioning of an offshore facility can last for 5–15 years, necessitating evaluations of structural integrity and safety aspects, as this timeframe involves minimum maintenance.

6. ORES structural health monitoring (SHM)

ORES face a challenge regarding the knowledge gap between available information and structural stability as they operate beyond their design life, especially with the increased likelihood of fatigue failures (Ersdal et al., 2019). Continuous monitoring systems are valuable for bridging this gap, although their use has been limited in the Australian offshore industry due to varying maturity levels and applicability. Deeper waters and varied floating structures introduce new challenges in system reliability and maintenance. For instance, expanding floating WTs can encounter size-related failures (Dallyn et al., 2015). The qualitative analysis in Table 6, based on in-service experiences with floating production units (Duguid and No, 2017), offers valuable insights into ORES failure assessment, emphasizing the significance of each failure type and potential consequences during offshore operations.

Table 7 outlines monitoring tools for offshore operations and the required operational parameters for anomaly detection. For ensuring structural integrity throughout the structure's life cycle, certain priority areas include predicting fatigue life for long-term durability, measuring displacement to detect grouted connection slippage, monitoring strain for deformation and stress due to external loads, assessing natural frequency under normal conditions, implementing corrosion protection, erosion prevention, cathodic protection, pH level control in water, monitoring water levels in foundations, identifying seabed microbiologically influenced corrosion, and addressing weld cracks and needed repairs (Duguid, 2017).

7. International guidelines for ORES monitoring

Codes, standards, and guidelines act as a link between theory and practical application. Although structural monitoring systems (SMS) and SHM are scientifically advanced, their use is not yet prevalent in the ORES due to the lack of comprehensive standards in this field. In recent years, there has been a rise in the availability of codes, standards, and guidelines for SHM. However, most of these documents mainly address civil infrastructure such as buildings and bridges. Unfortunately, there is a lack of codes and guidelines that consider SHM in the energy industry, except for one of the recent guidelines developed for structural monitoring and assessment of WTs and offshore substations (Structure monitoring and assessment of, 2020). The limited application of SMS in ORES, as well as the slow development of related codes, standards and guidelines and their practical implications, are attributed to various factors according to the DNV (Svendsen et al., 2022): existing codes and standards provide limited information on these topics; managing existing and new structures involves multiple parties with varying technical skills, financial interests and responsibilities, such as asset owners, designers and contractors of different sizes; and finally, there is a lack of awareness about the value creation and benefits that can be achieved through SHM.

Table 8 considers the overview of the most recent development in the standardization of structural monitoring regulations in other industries, such as bridge engineering and building design. Although the type of ORES and environmental loads are drastically different from other structures, such as bridges, these standards can be beneficial for lesson learning and developing appropriate guidelines for a safer and more reliable ORES development in the Australian blue economy. The study

Table 6
Evaluation of failure types, causes, and the importance of health monitoring for offshore floating units based on the study conducted by Dallyn et al. (2015) and Duguid et al. (Duguid, 2017).

Structural integrity failures	• Cracking and corrosion can be caused by factors such as fatigue, age, and exposure to harsh environments. • Regular inspections and maintenance are important to detect degradation phases. • Monitoring systems, such as strain gauges and acoustic emission sensors, are suggested to be used to detect early warning signs of structural degradation.
Mooring system failures	• Anchor line and chain failures can be caused by factors such as excessive tension, corrosion, and wear. • Winch and fairlead malfunctions can be caused by mechanical failures, electrical failures, and operator errors. • Regular inspections and maintenance of mooring equipment are critical to ongoing function and failure prevention.
Other station-keeping failures	• Failure of thrusters or DP systems can be caused by mechanical failures, electrical failures, and human and software errors. • Advanced monitoring systems, such as acoustic Doppler current profilers and motion sensors, can also be used to detect and rectify anomalies in station-keeping system.
Process equipment failures	• Issues with production piping, risers, and control systems can be caused by factors such as corrosion, wear, and blockages. • Risk-based maintenance is essential to manage the critical health condition of the equipment. • Monitoring systems, such as flow meters and pressure sensors, are suggested to be used to predict the degradation of process equipment units.
Environmental Load failures	• Wave and current-induced motions such as green water & VIV, global and local wave loads can cause excessive damage and fatigue loading on structures. • Other environmental factors, such as storms and sea ice, can also cause damage and failures. • Monitoring systems, such as weather buoys and wave sensors, are suggested to predict environmental conditions that may lead to extreme failures.
Stability and Ballasting failures	• Instability can be caused by changes in payload, shifting of ballast, or changes in environmental conditions. • Monitoring systems, including inclinometers and motion sensors, are suggested to be used to identify instability changes in the ballast systems or the entire floating structures.

Table 7
Condition monitoring systems applicable to ORES.

Damage type	Methods and Tools
Dynamic loads and vibration	Continual monitoring of vibration, eigenfrequency, and dampening of the structure. Sensors will be typically installed in areas of the structure identified as risk zones for fatigue stress. Sensors: Strain gauges, Inclinometer, Accelerometer, Temperature sensors.
Mechanical deformation of the structure	Monitoring the occurrence of relative vertical displacements between monopile (MP) and transition piece (TP). Sensors: Mechanical sensor “LVDT”, Laser sensor.
Corrosion	Measurement of corrosion rate, the potential for further corrosion, the functionality of the cathodic protection, and oxygen concentration inside the foundation. Sensors: H2 sensor, H2S sensor, Temperature sensors, Reference electrodes, pH meter, Water level sensor, O2 concentration sensor.
Erosion of seabed (i.e., Scour)	Observation of changes under dynamic currents and loads. Sensors: Acoustic echo sender/receiver.

shows a demanding increase in the number of codes, standards, and guidelines in other industries, indicating that SHM is becoming more applicable to such industries. One of the pioneer projects in developing guidelines on SHM standardization is the IM-SAFE. Despite the scope of the project being related to the transport infrastructure, there is a potential benefit in studying these SHM guidelines for the development of those applicable to ORES monitoring, risk assessment and maintenance planning. This means that the creation and implementation of safety standards are challenging procedures that necessitate agreement and dedication from these involved parties.

8. Major impediments for ORES development

Scheduled inspections are crucial for the ongoing operation of ORES, aiding in assessing remaining life and justifying life extension. However, challenges include the lack of standardized inspection approaches and limited guidance on monitoring system requirements. Regulatory compliance often drives monitoring system implementation, but there is a lack of specific guidance. Vendors influence system design, making a universal layout uncertain, although adaptability to support structure conditions is essential. Expertise is required to interpret monitoring data and assess the remaining design life (Duguid, 2017). Developing concepts should align monitoring with inspection, especially for health monitoring, and standardize data measurement, processing, and interpretation via sensor calibration.

Every industry must ensure the safety of its operations, a principle that shall applied to the development of ORES regulations. Operators are also responsible for ensuring that their employees adhere to Health, Safety, and Environment regulations, working with caution and care as detailed in the safety case for that operation (Norway, 2011; Norway and Authority, 2016). DNV has recently developed recommended practices (RPs) comprehensively addressing data quality assessment, data-driven algorithms, digital twins, sensor systems, and simulation models. These RPs are provided in (DNV, 2021b; DNV, 2021c) and offer general definitions and frameworks that can support the implementation of health monitoring on offshore structures in Australia.

Standardizing SHM is essential for gaining recognition from authorities and industry stakeholders. This requires collaborative efforts to establish systematic standards that enhance safety, decision-making, predictive maintenance, and risk management. (Ramboll, 2022). A unified framework for integrating digital solutions with SHM is likely to become an industry standard. Key areas for standardization include the

Table 8
Summary of the most recent guidelines developed for health monitoring of structures in industries other than energy (Svendsen et al., 2022).

Standards and Guidelines	Descriptions	Industry	Year
VDI 4551 - Structure monitoring and assessment of WTs and offshore substations (Structure monitoring and assessment of, 2020)	This standard provides guidance on how to monitor and assess the structural health of WTs and offshore substations. It covers a wide range of topics, including measurement techniques, data analysis, and the interpretation of monitoring results. The standard helps to ensure the safe and reliable operation of WTs and offshore substations, which are critical components of the renewable energy industry.	Renewable Energy	2020
TU1402 - Quantifying the Value of Structural Health Information for Decision Support: Guide for Operators (Sousa et al., 2019)	This standard provides a framework for operators to evaluate the cost-effectiveness of monitoring and maintenance strategies for infrastructure. It covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to evaluating the value of SHM, this standard can help operators make informed decisions about infrastructure maintenance and repair.	Infrastructure Management	2019
TU1402 - Quantifying the Value of Structural Health Information for Decision Support: Guide for Scientists (Thöns, 2019)	This standard provides guidance to scientists on how to develop and evaluate monitoring and maintenance strategies for infrastructure. It covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help scientists develop more effective and efficient monitoring and maintenance strategies.	Research Development recommendations for the engineering industry	2019

(*continued on next page*)

Table 8 (*continued*)

Standards and Guidelines	Descriptions	Industry	Year
TU1402 - Quantifying the Value of Structural Health Information for Decision Support: Guide for Practising Engineers (Diamantidis et al., 2019)	This standard provides guidance to practicing engineers on how to develop and evaluate monitoring and maintenance strategies for infrastructure. It covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help engineers develop more effective and efficient monitoring and maintenance strategies.	Practical recommendations for the engineering industry	2019
TRB - Transportation Research Circular: Structural monitoring (Number E-C246) (TRB. Transportation Research Circular, 2019)	This standard provides guidance on how to monitor the structural health of infrastructure, including bridges and tunnels. It covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help transportation agencies ensure the safe and reliable operation of their infrastructure.	Transportation Industry	2019
FHWA - Long-Term Bridge Performance (LTBP) Program Protocols, Version 1 (NO. FHWA-HRT-16-007) (Hooks and Weidner, 2016)	This standard provides protocols for the LTBP Program, which aims to collect long-term performance data on bridges in the United States. The standard covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help transportation agencies make informed decisions about infrastructure maintenance and repair.	Transportation Industry	2016
UNI/TR 11634:2016 - Guidelines for structural health monitoring (Guidelines for structural health monitoring, 2016)	This standard provides guidelines on how to implement SHM for infrastructure. It covers topics such as sensor placement, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help engineers develop more effective and efficient monitoring and maintenance strategies.	Engineering Industry	2016
GB 50982-2014 - Technical code for monitoring of building and bridge structures (Technical code for monitoring of, 2014)	This standard provides guidelines for monitoring the structural health of buildings and bridges in China. It covers topics such as data collection, data analysis, and risk assessment. By providing a standardized approach to SHM, this standard can help ensure the safe and reliable operation of buildings and bridges in China.	Construction Industry (e.g., bridge and building)	2014
RVS 13.03.01 - Monitoring von Brücken und anderen Ingenieurbauwerken (Monitoring von Brücken und anderen, 2012)	This standard provides guidance on how to monitor the structural health of bridges and other infrastructure in Austria. It covers topics such as data collection	Construction Industry (e.g., bridge and building)	2012

execution, verification, calibration, and documentation of monitoring systems, along with data processing techniques. Optimization of inspection and maintenance programs, understanding SHM benefits across various structures, defining common failure modes, and streamlining integration are also critical.

One of the most important factors for successfully implementing SHM is the planning phase, which involves mapping critical elements related to structural safety and selecting appropriate monitoring systems. This planning phase must be comprehensive, incorporating a range of factors such as the local environment, potential hazards, and structural design. Additionally, it is essential to consider the accuracy of measurement data and data quality. High-quality data ensures a more accurate and reliable analysis of structural health and can reduce uncertainty. The industry has identified data accuracy and quality as important areas in using SMS, and it is critical to implement these requirements in any new standards for ORES. Proper data management is also essential for the successful implementation of SHM. This includes the ability of a monitoring system to log, store, transmit, and process data, as well as data sampling, streaming, and integration. Early warning detection and damage detection are critical benefits of continuous data processing and analysis, while late data processing is beneficial for trend analysis, model updating, risk analysis, and calibration tasks.

The network configuration is another crucial aspect of SHM. Wireless sensors and monitoring equipment are becoming increasingly popular, but battery capacity and synchronization remain significant challenges. In some cases, cabled monitoring systems are more reliable, depending on the specific requirements of the system and subsequent analysis to be performed. It is necessary to carefully evaluate and select the appropriate network configuration for the specific ORES being monitored. Finally, data integration or fusion of data from multiple systems and vendors can be challenging due to different data formats and communication protocols. Recognised (common) data formats should be considered for data storage to ensure proper data management throughout the measurement campaign. By following these essential SHM factors through systematic codes and regulations, Australia can improve the safety and reliability of their future ORES, reduce risks associated with potential hazards, and ensure sustainable renewable energy production.

Most of the considerations outlined above are relevant in the global context, yet specific challenges arise within the Australian context. These challenges are characterized by unique environmental conditions, a lack of detailed and clear licensing schemes and regulatory frameworks for ORES and multi-purpose infrastructure life cycle activities, including construction, installation, commissioning, operation, maintenance, and decommissioning in the jurisdiction between state and commonwealth waters. Additionally, there is limited industry knowledge sharing for the purpose of risk-based inspection planning in Australia. Obstacles to incorporating inspections and monitoring into offshore standards in Australia include the specificity of SHM to individual cases, the complexity of SHM requiring skilled personnel and interdepartmental cooperation, and the potential cost of installing and maintaining monitoring equipment on offshore structures.

Table 9 summarizes the essential technical and regulatory reforms identified in this study. Addressing these critical needs is imperative for unlocking the full potential of ORES in Australia and ensuring a sustainable and responsible future for this promising renewable energy source.

Table 9
Recommended technical and regulatory reforms for ORES in Australia.

Prerequisite/Specification	Details
Enhanced Site-Specific Knowledge	• Allocate resources for regional data gathering and analysis of met-ocean conditions, including extreme weather events. • Invest in advanced tools to assess extreme load impacts on ORES for site-specific design optimization.
Robust Regulations and Standards	• Implement comprehensive ORES regulations addressing unique environmental and technical challenges. • Utilize safety case frameworks to prioritize project safety, reliability, and sustainability. • Introduce Site-specific Design Assessments (SDAs) tailored to each project site's environmental parameters, load assumptions and safety criteria.
Addressing ORES Vulnerabilities	• Identify and mitigate key failure factors, including material defects, manufacturing imperfections, construction defects, assembly inaccuracies, and operation and maintenance challenges. • Implement Reliability-based Design Optimization (RBDO) methods to improve ORES robustness and efficiency.
Knowledge Sharing and Collaboration	• Standardize ORES design elements and establish comprehensive reliability databases. • Foster industry-wide knowledge-sharing and collaborative approaches across stakeholders.
Leveraging Existing Monitoring Practices	• Adapt advanced Structural Health Monitoring (SHM) practices from other industries, such as civil and infrastructure, to enhance the effectiveness and efficiency of monitoring and maintenance activities in ORES. • Implement SHM to predict fatigue life, detect damage, monitor strain, and manage environmental risks.
Comprehensive Planning and Network Configuration	• Standardize and optimize communication networks for effective SHM data management. • Ensure comprehensive planning and stakeholder collaboration for successful SHM implementation.

9. Conclusion and recommendations

This paper critically discussed the challenges and opportunities related to ORES development and regulation in Australia. Major gaps in the Australian standards for ORES development have been navigated according to the local needs for safety improvement of the ORES units and increasing the feasibility of health monitoring regulations in return. The importance of addressing regulatory gaps has been highlighted to foster innovation and investment in the offshore renewable energy sector. The key regulatory and standards highlights include.

- Existing standards do not predominantly address energy infrastructure. There is a critical need for industry-specific guidelines to effectively monitor and maintain ORES.
- Establishing specific regulations and standards for ORES is essential to ensure the safety, performance, and reliability of these projects in Australia's unique environmental and operational context.
- Australian standards can be extended to address extreme environmental conditions and to provide guidance on designing ORES structures for resilience.
- Regulations should also include recommendations for integrating new technologies and materials to support innovation and enhance ORES performance.
- Developing detailed risk management guidelines tailored to ORES is crucial for mitigating project-specific risks.
- Decommissioning standards should be revised to include various end-of-life scenarios and ensure that decommissioning practices are economically viable and environmentally sustainable.
- ORES project successes face challenges associated with structural reliability, particularly as they operate beyond their design life, where the likelihood of failures substantially increases. Condition monitoring technologies can help bridge this gap but are underutilized in Australia.
- Deeper waters and floating structures introduce unique challenges to system reliability and maintenance, necessitating advanced diagnostics and maintenance strategies to address size-related and environmental issues.
- Effective SHM can enhance safety, decision-making, predictive maintenance, and risk management in ORES. The development and adoption of systematic SHM standards, including accurate and high-quality data measurement, is crucial.
- Effective use of sensory technologies including strain gauges, acoustic sensors, and weather buoys, is crucial for detecting early signs of degradation and failures in various components.
- Integrating SHM with inspection processes and standardizing data measurement, processing, and interpretation are essential for improving ORES reliability.

In addition, the significance of understanding failure modes and their associated uncertainties in ORES development has also been emphasized, as this knowledge can inform risk management strategies and improve the safety and reliability of offshore renewable energy productions. The key highlights include.

- OWTs face high failure rates in critical components such as the tower, rotor blades, and generator due to harsh marine environments and extreme weather, with issues like cracks and corrosion.
- FOWTs experience high failure rates in components like the mooring system, tower, and floating foundation, primarily due to material corrosion and fatigue damage.
- A comprehensive understanding of FOWTs failures is lacking, particularly regarding biofouling, seawater chemistry changes, and corrosion-fatigue damage, underscoring the need for standardized protection and improved preventive measures.

- Major risk factors include environmental conditions, extreme weather, and technical equipment failures. The emphasis on limit state design (ALS) is crucial for ensuring safety, especially given the lack of ALS standards for offshore renewable energy farms.
- In WECs, mechanical components like mooring lines and hydraulic parts are most vulnerable, with failures linked to fatigue, wear, and environmental conditions. Design improvements must balance resilience to extreme conditions with hydrodynamic performance, and high-risk components should be prioritized for inspection and maintenance.
- Short-term and limited real operational data complicates failure analysis, highlighting the importance of integrating climate change impacts into failure predictions and risk assessments. Machine learning models can enhance reliability predictions by accounting for changes in climate variables.
- Combining offshore wind and aquaculture systems introduces complex risks, including structural impacts and increased biofouling. Detailed early-phase assessments and innovative designs are essential to manage these risks effectively.
- Decommissioning ORES involves safety-critical operations with significant risks, such as crane failures and structural corrosion. Comprehensive structural assessments and risk evaluations are vital to prevent safety accidents and operational failures during decommissioning.

Overall, unlocking ORES potential in Australia requires enhancing site-specific knowledge, establishing robust regulations, addressing vulnerabilities, fostering knowledge sharing, and leveraging existing monitoring practices. This multifaceted approach ensures a sustainable and responsible future for ORES in the country.

CRediT authorship contribution statement

Mohammad Mahdi Abaei: Writing – original draft, Resources, Methodology, Conceptualization. **Sumit Kumar:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ehsan Arzaghi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Nima Golestani:** Writing – original draft, Validation, Conceptualization. **Nagi Abdussamie:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Vikram Garaniya:** Writing – review & editing, Supervision, Conceptualization. **Fatemeh Salehi:** Writing – review & editing, Funding acquisition, Conceptualization. **Mohsen Asadnia:** Writing – review & editing, Funding acquisition, Conceptualization. **Tina Soliman Hunter:** Writing – review & editing, Funding acquisition, Conceptualization. **Alexandre Pichard:** Writing – review & editing, Funding acquisition, Conceptualization. **Rouzbeh Abbassi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

All required data are available within the paper.

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