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Ship collision and offshore renewable energy: Challenges and innovations for structural resilience

Bai-Qiao Chen [a,b,*], Kun Liu [b], Hao Rong [c], Jonas W. Ringsberg [d]

[a] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisbon, Portugal
[b] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212003, China
[c] Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, Liverpool, UK
[d] Division of Marine Technology, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, 412 96, Gothenburg, Sweden

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ABSTRACT

The rapid expansion of offshore renewable energy installations, such as wind farms, tidal turbines, and wave energy converters, has increased concerns regarding ship collision risks. As maritime traffic intensifies, understanding the impact of vessel collisions on these structures is crucial for ensuring operational safety and structural resilience. This review thoroughly analyses ship collisions with offshore renewable structures, concentrating on risk assessment methodologies, structural response mechanisms, and mitigation strategies. Various numerical and experimental approaches for impact modelling are examined, alongside advanced materials and design innovations aimed at improving collision resistance. Furthermore, current regulatory frameworks and emerging technologies, including artificial intelligence (AI)-driven collision avoidance systems, are discussed. The review identifies key challenges and future research directions, emphasising the need for integrated monitoring systems and predictive modelling to enhance offshore energy infrastructure safety. This study provides a foundation for engineers, policymakers, and researchers to develop more resilient offshore renewable energy solutions in response to increasing maritime activity.

1. Introduction

Offshore renewable energy has emerged as a critical component of global efforts to transition toward sustainable energy sources. Among the key offshore renewable energy technologies are the offshore wind farm (OWF) [1–3], tidal energy converter (TEC) [4–6], wave energy converter (WEC) [7–9], ocean thermal energy conversion (OTEC) [10–12], and salinity gradient technologies, among others. Offshore renewable energy has the potential to advance Sustainable Development Goal (SDG) 14, which aims to conserve and sustainably use oceans by combining energy production with blue economy activities such as fisheries, shipping, and tourism. A blue economy driven by offshore renewables would help islands and coastal nations achieve their national objectives, aligning with the Paris Agreement, their Nationally Determined Contributions (NDCs), and the Sustainable Development Agenda for 2030 [13].

Despite its potential, offshore renewable energy faces several challenges: (1) high initial costs. The installation and maintenance of offshore energy systems require significant investment due to the harsh marine environment [14–16]; (2) structural and environmental risks. Offshore installations are exposed to extreme weather conditions, strong currents, and potential ship collisions, which pose risks to their structural integrity [17–19]; (3) grid integration and energy storage. The variability of wind and wave energy necessitates advancements in grid infrastructure, energy storage technologies, and smart energy management systems [20,21]; and (4) regulatory and maritime safety considerations. As offshore energy farms expand, potential conflicts with shipping routes, fisheries, and marine ecosystems must be addressed through improved regulatory frameworks and navigation safety measures [22,23].

As these offshore energy installations become more widespread, they increasingly interact with maritime traffic, including commercial vessels, fishing boats, and offshore service ships. Unlike traditional offshore oil and gas platforms, many renewable energy structures are designed to be lighter and more cost-effective, making them potentially more vulnerable to high-energy impacts [24]. Ship collisions can result in

* Corresponding author. Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisbon, Portugal.
E-mail address: baiqiao.chen@tecnico.ulisboa.pt (B.-Q. Chen).

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substantial damage, leading to structural failures, energy production losses, environmental hazards, and costly repairs [25,26]. In the event of a collision, not only could the energy infrastructure be damaged, but the vessel involved may also sustain structural failures, potentially leading to oil spills, hazardous material leaks, or even loss of life. Given their locations in busy coastal zones or shipping routes, the risk of ship collisions poses a significant challenge to their structural integrity and operational reliability. Therefore, it is imperative to evaluate the resilience of these structures against potential impacts and develop strategies to mitigate collision risks.

In this regard, understanding their structural response to collisions is crucial for long-term durability. Various international and national organizations, such as Det Norske Veritas (DNV) [27–29], the American Bureau of Shipping (ABS) [30,31], Bureau Veritas (BV) [32–34], and the International Electrotechnical Commission (IEC) [35,36], have established guidelines for offshore energy structures. A thorough collision risk assessment is essential to ensure compliance with safety regulations and certification requirements.

Despite the growing deployment of offshore renewable energy installations, research on ship collisions with these structures remains limited. This gap in knowledge poses significant challenges for ensuring the structural resilience and safety of offshore renewable energy devices. Addressing this gap is crucial for developing effective strategies to mitigate collision risks and enhance the durability of these installations.

This review aims to bridge the knowledge gap by providing a comprehensive analysis of ship collisions with offshore renewable energy structures. It explores various aspects, including summarising existing research on collision risks involving offshore wind turbines and other offshore structures. Additionally, it analyses structural response mechanisms and impact resistance strategies for different offshore renewable energy devices. The review evaluates current risk assessment methodologies and proposes integrated approaches that combine numerical modelling, experimental testing, and real-time monitoring. Furthermore, it examines regulatory frameworks and mitigation strategies, identifying gaps in current international guidelines and suggesting improvements. Finally, the review identifies future research directions to enhance the safety and resilience of offshore renewable energy infrastructure.

2. Background

Renewable energy harnesses naturally replenished resources such as sunlight, wind, water, and geothermal heat to generate electricity, offering a sustainable alternative to fossil fuels. As technological advancements improve efficiency and reduce costs, renewables are expected to become the backbone of global energy systems, driving the transition toward a low-carbon future. The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) are both aligned on the latest Net Zero scenarios of tripling renewable capacity to more than 11 GW by 2030 [37,38]. According to IRENA [39], 585 GW of renewable capacity was added in 2024 (see Fig. 1), representing a 15.1 % annual growth rate. The share of renewables in total capacity expansion increased significantly in 2024 and reached 92.5 %. The majority of the renewable energy increase occurred in China, followed by Europe and the United States.

The development of offshore renewable energy is driven by the global transition toward sustainable energy sources and the increasing demand for low-carbon electricity generation. Traditional offshore energy exploitation has been dominated by oil and gas platforms, but advancements in technology and policy incentives have enabled the rapid growth of renewable energy solutions in offshore environments. The origins of offshore renewable energy can be traced back to the 1970s energy crisis, which prompted research into alternative energy sources [40]. The first offshore wind turbines were deployed in Denmark in the 1990s, in shallow water with a depth of less than 6 m, marking the beginning of large-scale offshore wind development [41–43]. In the early 2000s, research into wave and tidal energy gained momentum, with the establishment of test sites and pilot projects in Europe and North America [44,45]. The development of floating wind turbines, which began in the 2010s, further expanded the potential for offshore renewable energy by enabling installations in deeper waters beyond continental shelves [46].

Fig. 2 shows different types of offshore renewable energy devices. The offshore wind farms include fixed-bottom wind turbines in shallow waters and floating offshore wind turbines (FOWTs) deployed in deep-sea environments [47–51]. Offshore wind energy has seen rapid growth, with large-scale installations in Europe, Asia, and North America [46,52–55]. Tidal turbines harness the kinetic energy of ocean currents, typically placed in narrow straits or estuaries where water flow is strong and predictable [45,56]. WECs capture energy from surface waves and are often positioned in areas with high wave activity. They include various types such as Point Absorbers (PA), Attenuators, Terminators, Oscillating Water Columns (OWC), and Oscillating Wave Surge Converters (OWSC) [57–59], each utilising different mechanisms to harness energy from ocean waves. Though less common, OTEC systems use temperature differences between surface and deep water to generate power [10,11,60–62].

Fig. 3 illustrates the number of documents related to Offshore

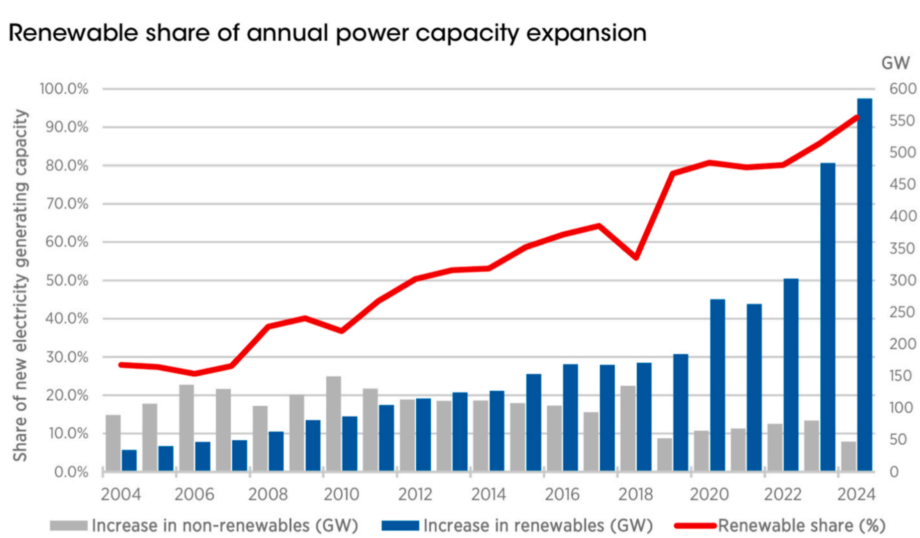

Fig. 1. The renewable share of annual power capacity expansion in the past 20 years, published by IRENA [39].

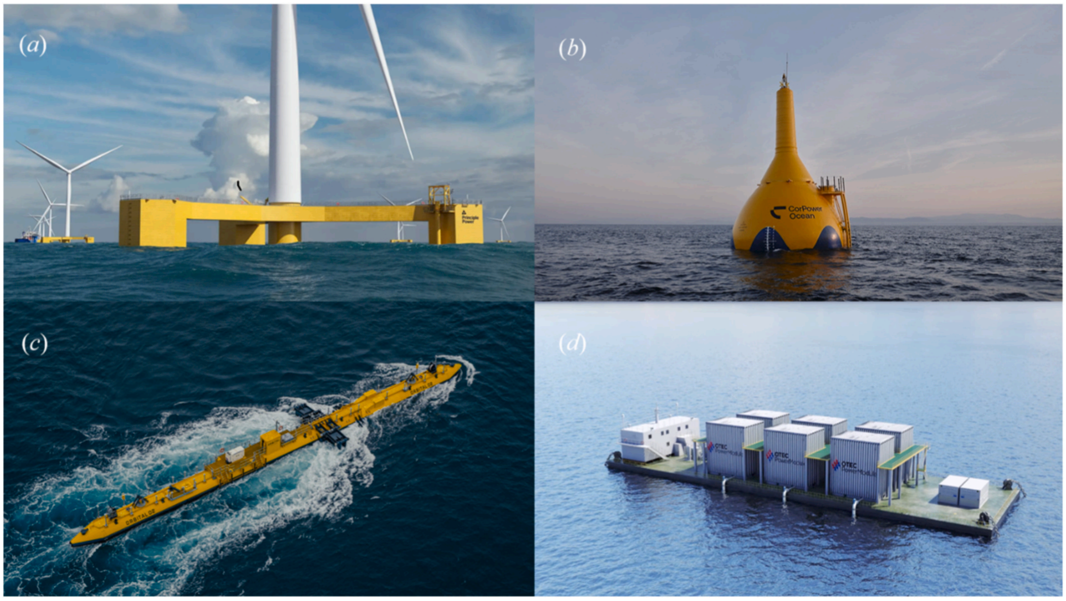

Fig. 2. Offshore renewable energy applications: (a) FOWTs - WindFloat FC [63], (b) WEC - CorPower Ocean C4 [64], (c) TEC – Orbital O2 [65], and (d) Global OTEC [66].

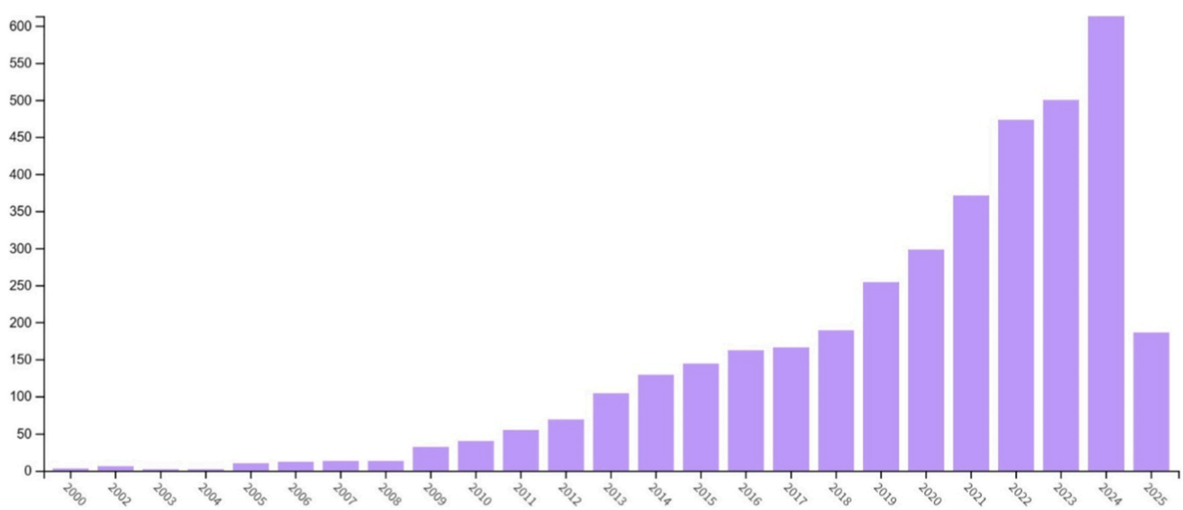

Fig. 3. Documents over time graph for Offshore Renewable Energy from WoS, from 2020 to March 2025.

Renewable Energy indexed in the Web of Science (WoS) database over time, spanning from 2020 to March 2025. The graph shows a clear upward trend in the number of documents, indicating a growing interest and research activity in the field of Offshore Renewable Energy. This could lead to more innovations, improved technologies, and better strategies for integrating renewable energy into the global energy mix.

Offshore renewable energy is expected to play a critical role in achieving global carbon neutrality goals and reducing dependence on fossil fuels. Although it accounts for a relatively small share of the overall renewable energy mix, it has significant growth potential and plays a crucial role in the global energy transition. To ensure the world follows a climate-safe pathway, IRENA's 1.5 °C scenario envisions a substantial expansion in offshore wind, ocean energy, and floating photovoltaic systems over the next few decades [39]. Fig. 4 presents a visual representation that illustrates the distribution of publications related to various types of offshore renewable energy and underscores the diverse interests and ongoing research efforts in the field.

The chart highlights the significant focus on offshore wind energy, which accounts for the majority of the publications. The International

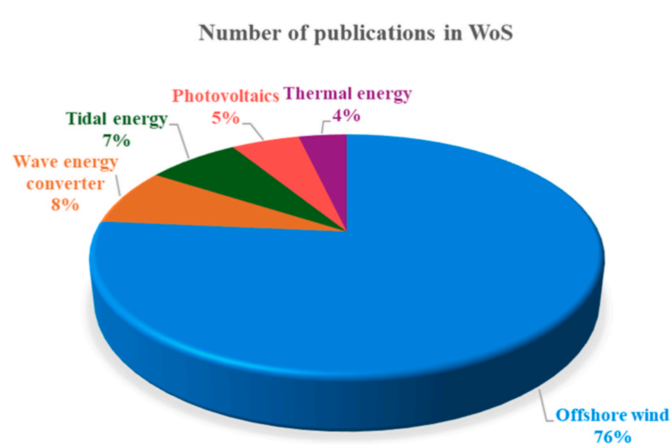

Fig. 4. Distribution of offshore renewable energy-related publications from WoS, from 2020 to March 2025.

Energy Agency (IEA) and the European Union (EU) have set ambitious targets for offshore wind expansion, with projections indicating that offshore wind alone could generate over 1400 GW by 2050. More specifically, offshore wind capacity is expected to grow from 34 GW in 2020 to 380 GW by 2030 and surpass 2 TW by 2050 [13].

Meanwhile, wave energy converters, tidal energy, photovoltaics, and thermal energy also contribute to the research landscape, albeit to a lesser extent. According to IRENA, ocean energy is projected to add 350 GW to offshore renewable generation capacity by 2050 [13]. Wave and tidal energy are still in the demonstration and early commercial phases, but they hold immense potential for coastal and island communities that require stable and localised energy sources. Hybrid WEC systems represent a promising direction for future offshore renewable energy development. By combining multiple energy harvesting principles or integrating wave energy with other marine structures such as wind platforms [67], aquaculture cages [68,69], and floating breakwaters [70], these hybrid configurations can offer enhanced energy yield and operational stability. Recent studies employing advanced numerical and experimental methods, including computational fluid dynamics (CFD) and nonlinear finite element (FE) models, have demonstrated notable improvements in energy conversion efficiency and wave attenuation. Emerging research also highlights the potential of co-located and multi-mode systems to address intermittency and improve structural resilience under variable marine conditions [71–73].

The large-scale deployment of offshore renewable energy technologies, such as FOWTs, WECs, and floating photovoltaics (FPVs), will not take place in isolation, but rather in the form of arrays or energy parks occupying extensive marine space. For example, the Hywind Tampen project in Norway includes 11 8-MW floating wind turbines [62,74], while the planned South Korean Ulsan floating wind farm is expected to host over 80 units [75]. Similarly, wave or tidal energy test sites such as EMEC in the UK and Mutriku in Spain already demonstrate clustered deployments [53,56]. As these installations expand, they will increasingly intersect with existing maritime traffic routes, fisheries, and other sea uses, thereby amplifying the importance of understanding and mitigating collision risks. The present study is therefore both timely and essential for informing spatial planning, safety regulations, and design practices before large-scale deployment becomes the norm.

3. Collision scenarios and risk analysis

As wind farms are increasingly located near navigable sea lanes, the risk of ship collisions with offshore energy structures has become a significant safety and engineering concern. Such collisions not only pose a threat to the structural integrity of wind turbines and associated platforms but also to vessel safety, environmental protection, and the continuity of energy production. Understanding the nature of these collisions, particularly their typology, frequency, and consequences, is essential for informing risk assessments, regulatory frameworks, and structural design standards.

3.1. Historical incidents of ships colliding with offshore structures

Offshore energy farms require significant capital investments, and unplanned outages resulting from collision damage can result in substantial financial losses. Fig. 5 presents the annual statistics of collision accidents involving offshore installations caused by both passing and visiting vessels from 1970 to 2014 [76]. The study identified an annual collision frequency of 8.3×10^{-4} per platform-year, based on 32 recorded vessel collisions between 2005 and 2014 [76]. The challenge of obtaining more recent data arises from limited availability and access restrictions to updated databases and records regarding offshore installation collisions. Despite this limitation, historical data provides valuable insights into collision trends and underscores the importance of ongoing research and updated data to ensure the safety and resilience of offshore renewable energy structures.

Table 1 provides a summary of reported ship collision incidents involving offshore structures, primarily focusing on offshore renewable energy installations. The table lists the date, location, vessel and structure involved, along with a brief description and consequences of each incident. The primary causes of ship collisions with offshore structures include human errors such as navigation mistakes, misjudgement of distances, and fatigue-related errors. Adverse weather conditions like fog, storms, and extreme wave heights can reduce visibility and manoeuvrability, increasing the risk of collisions. Technical failures, including loss of ship propulsion or steering control, can lead to unintended drift and accidents. Additionally, traffic density near major shipping lanes or fishing zones poses increased risks for offshore farms.

For comparison and completeness, a few notable cases involving oil and gas platforms are also included. This is particularly relevant given

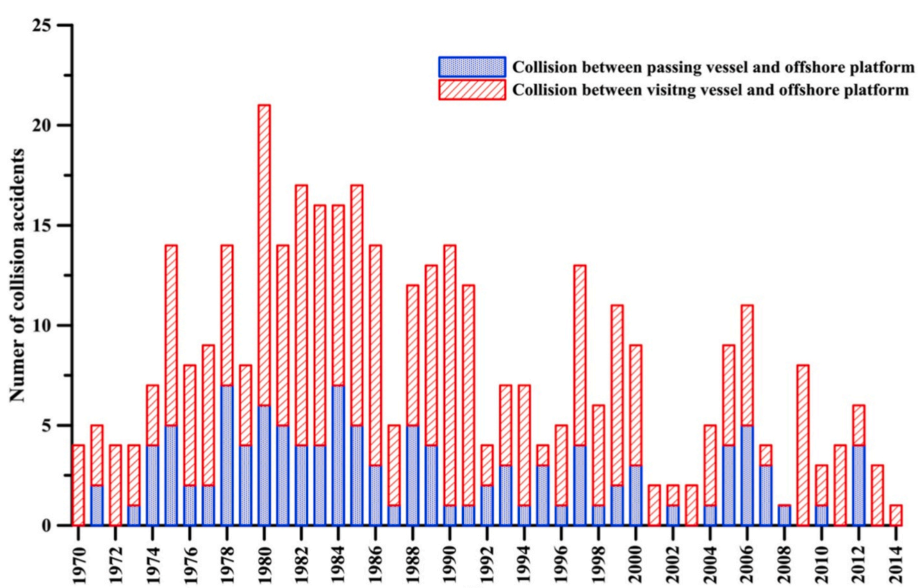

Fig. 5. Worldwide accidents of ship–offshore installation collisions [76].

Table 1
Major incidents between ships and offshore structures.

Date	Location	Vessel	Offshore Structure	Outcome	Source
Nov. 1966	Gulf of Mexico	Smith Lloyd 8	Ocean Traveller (semi-sub)	47 personnel evacuated, no fatalities	[76]
2004	North Sea	Far Symphony	West Venture (semi-sub)	Structural damage, no major casualties	[77]
2005	North Sea	Ocean Carrier	Ekofisk 2/4-P (jacket platform)	Local structural damage	[77,78]
2006	Norwegian Sea	Navion Hispania	Njord Bravo FSU	Minor damage, operations affected	[78]
2007	North Sea	Bourbon Surf	Grane jacket (fixed platform)	Structural assessment required	[79,80]
June 2009	North Sea	Big Orange XVIII	Ekofisk 2/4-W tripod jacket	Significant platform and vessel damage	[80]
2010	North Sea	Far Grimshader	Songa Dee (semi-submersible)	Minor structural damage	[81]
Nov. 2012	UK	Island Panther	Wind turbine I-6	Damaged vessel, no serious injuries	[82]
April 2018	Baltic Sea	Vos Stone	Wind Turbine	Vessel and turbine damaged	[83]
April 2020	Southern North Sea	Njord Forseti	Borkum Riffgrund Wind Farm	Serious vessel damage and crew injuries	[84]
July 2021	South China Sea	Sheng Ping 001	CGN Wind Farm	Vessel partially sank, crew missing	[85,86]
January 2022	North Sea (Netherlands)	Julietta D	Hollandse Kust Zuid Wind Farm	Damage to monopile foundation	[86,87]
April 2023	North Sea (Germany)	Petra L	Monopile in Gode Wind 1 Wind Farm	Vessel damaged, turbine offline for inspection	[88]

the increasing interest in fixed-bottom solutions such as jacket and jack-up structures for offshore wind deployment in medium water depths [89]. In the Big Orange XVIII incident, the multipurpose vessel lost control and collided with the Ekofisk 2/4 W platform at the Ekofisk oil field in the North Sea (see Fig. 6a). The collision caused significant structural damage to the platform and the vessel itself. Investigations revealed that the autopilot had not been disengaged, contributing to the loss of control.

Fig. 6 illustrates the damaged structures from some of the incidents. In April 2020, the wind farm support vessel Njord Forseti collided with a wind turbine tower at the Borkum Riffgrund wind farm in the Southern North Sea while transiting between wind farms at approximately 20 knots. The impact caused severe damage to the vessel (see Fig. 6b) and resulted in injuries to crew members, who were evacuated for medical treatment. Investigations highlighted that a proper lookout was not maintained, leading to the collision. In January 2022, the bulk carrier Julietta D became adrift after a collision with another vessel and subsequently drifted through the Hollandse Kust Zuid wind farm in the Netherlands, colliding with one of the monopile foundations (see Fig. 6c). An aerial inspection revealed damage to the foundation, necessitating further assessments. In April 2023, the cargo ship Petra L struck a wind turbine at Ørsted's Gode Wind 1 offshore wind farm in the North Sea, resulting in a significant hole in its hull (see Fig. 6d). The vessel managed to reach the port of Emden, Germany, for damage assessment. The wind turbine involved was taken out of operation for further investigation.

Furthermore, research also exists on collisions between marine life, such as fish and marine mammals, and floating renewable energy structures like tidal turbines. However, this topic falls outside the scope of this review.

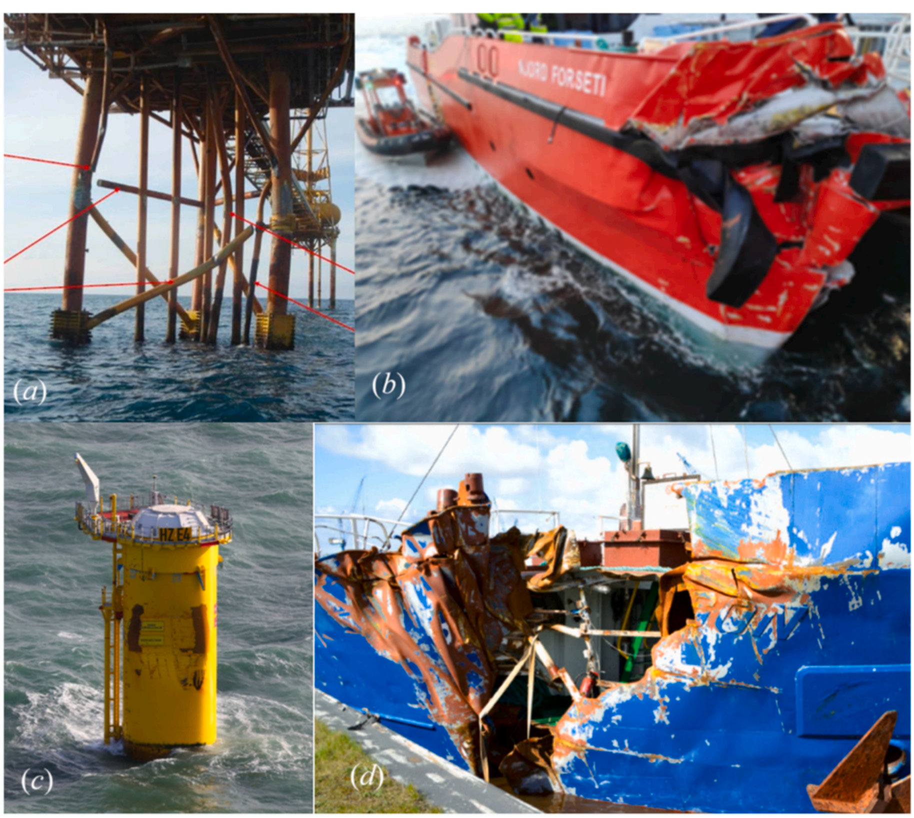

Fig. 6. Examples of damaged structures after ship-offshore structure collisions: (a) Ekofisk 2/4 W platform [90], (b) wind farm support vessel Njord Forseti [84], (c) damaged wind turbine monopile foundation [91], and (d) Petra L after colliding with a wind turbine [88].

3.2. Common types of collisions involving ships and offshore energy structures

Collisions involving ships and offshore energy structures can be summarized by categorizing them based on the vessel's operational state and its activity relative to the installation [92,93].

3.2.1. Based on vessel operational state

Among the various collision scenarios, powered and drifting ship collisions represent two fundamentally distinct mechanisms, each with unique operational causes, impact dynamics, and risk profiles.

Powered collisions occur when a vessel under active propulsion impacts an offshore wind energy structure. These incidents typically result from failures in navigation, human error, mechanical malfunction, or environmental interference during ship operations [81]. The vessel's engine and steering systems are functional at the time of the accident, which means the kinetic energy involved can be substantial due to the vessel's forward momentum and mass. In the powered scenario, the in-field vessel tends to impact the installation at speed and, therefore, there is the potential for significant damage [94]. A key concern with powered collisions is their potential to produce high-energy impacts, especially when large commercial vessels such as container ships, bulk carriers, or tankers are involved. These ships often travel at relatively high speeds and possess significant mass, leading to collision energies that may exceed the structural design capacity of monopiles, jackets, or floating platforms. Studies have shown that in powered passing vessel collisions, the navigator is often unaware of the platform's presence [95] and passing merchant vessels pose the highest threat in powered collision scenarios, particularly when safety zones are infringed or not adequately enforced [87]. These ships frequently operate close to offshore wind turbines during installation or servicing activities.

Drifting collisions occur when a vessel loses propulsion and/or steering control and is carried toward offshore structures by environmental forces such as wind, waves, and current [81,84]. Unlike powered collisions, drifting events are characterised by lower speeds and impact energies [96]. Nevertheless, they remain a significant safety concern, particularly in scenarios involving prolonged drift paths and delayed emergency response. The causes of drifting include engine failure, electrical system blackout, mechanical breakdown, or onboard incidents such as fire or flooding [97,98]. In such cases, vessels lose navigational control and become vulnerable to environmental drift. If such drift paths intersect with offshore wind farm areas, the risk of collision with turbines, substations, or mooring systems becomes non-negligible. Drifting incidents are particularly concerning for vessels engaged in support operations around wind farms [99].

3.2.2. Based on activity relative to the installation

Visiting vessels, also referred to as attendant, field-related, or service vessels, are ships that regularly approach or berth at offshore installations to perform a range of operational tasks. These include delivering supplies, conducting maintenance and inspection work, facilitating crew changes, performing underwater interventions, and supporting installation or construction activities [76]. Examples include supply vessels, shuttle tankers (during offloading), diver support vessels, multi-purpose service vessels, emergency response and rescue vessels (ERRVs), wind turbine installation vessels (WTIVs) and so on. According to a statistical study, supply vessels are the most frequent colliding vessel type in the offshore oil/gas and wind turbine industries [92]. Due to their frequent and close proximity to offshore structures, visiting vessels are associated with a relatively high frequency of collision incidents, particularly during approach, positioning, and cargo transfer operations [76]. While many such collisions occur at low velocities, the risk is still significant, as the impacts from visiting vessels can cause structural damage to wind turbine foundations and ladders [100]. In addition, Maintenance-related activities by maintenance ship vessels are associated with collision risks with offshore wind turbines, particularly during replacement tasks [98].

Passing vessels, also known as external or route vessels, are ships that transit through maritime corridors near offshore installations without operational interaction. These vessels include large merchant ships, cargo carriers, tankers, passenger ships, fishing vessels, and trawlers [81]. Although collisions involving passing vessels are statistically less frequent than those involving visiting vessels [93], they pose a disproportionally higher risk due to the typically larger mass and higher speeds of these ships [96]. This type of collision is especially critical in the context of offshore wind farms located near busy shipping lanes, where high traffic density increases the probability of human or technical error. Thus, even though passing vessel collisions are low in frequency, they represent high-consequence events that require robust prevention and monitoring strategies [95,101].

3.3. Risk assessment of ship-offshore installation collisions

The expansion of offshore renewable energy zones coincides with rising global maritime activity. A clear understanding of the probability and consequences of ship-structure collisions enables informed decision-making in site selection, structural design, and navigation safety measures. Considering these factors, it is crucial to develop robust methodologies for collision risk assessment that integrate probabilistic modelling, numerical simulations, and real-world data analysis to enhance the resilience and sustainability of offshore renewable energy projects.

Generally, collision scenarios are selected using either deterministic or probabilistic methods. The deterministic approach often involves selecting a worst-case collision scenario from past accidents combined with expert judgments. In most cases, this approach becomes conservative when platforms are designed based on the selection of the most prominent accident. Conversely, the probabilistic approach utilises more advanced statistical and probabilistic techniques to determine the scenarios, making it a more viable option despite its extensive computational requirements [102].

In the domain of offshore platform safety, risk assessment methodologies for ship collisions can be broadly categorised into qualitative, semi-quantitative, and quantitative approaches, each offering unique strengths and limitations in identifying hazards, evaluating risks, and supporting decision-making [95]. Qualitative methods rely mainly on expert judgment, experience and descriptive analysis to identify hazards, analyse potential causes, and estimate the likelihood and severity of consequences [103]. This approach is less dependent on detailed statistical data and is useful when precise numerical data is scarce or in the early stages of risk identification [104]. Rather than producing exact figures, qualitative assessments categorise risk using linguistic descriptors such as "probable" or "severe". In terms of qualitative risk assessment, typical tools include expert panels [103], hazard logs [104], and narrative consequence assessments [105].

Bayesian Networks (BNs) represent a powerful semi-quantitative tool, especially when probabilities are derived from expert knowledge. It was developed in Ref. [106] a semi-qualitative collision risk assessment model to assess the vessel-turbine collision risks by incorporating Bayesian networks (BN) with evidential reasoning (ER) approaches.

Quantitative risk assessment aims to numerically calculate the level of risk, typically defined as a combination of the frequency (probability) of an event and the magnitude of its consequences [95,102]. This approach requires more detailed data (historical, statistical, simulation, analytical) and sophisticated modelling techniques to produce numerical risk values [92]. Quantitative approaches encompass a range of advanced modelling techniques. For example, Monte Carlo Simulation (MCS) is widely used to generate collision scenarios and estimate probabilistic outcomes [107]. Combined with Automatic Identification System (AIS) data and ship manoeuvring simulators, the model can simulate traffic dynamics, assess collision frequencies, and quantify impact energies on offshore structures.

Fig. 7 illustrates the overall flowchart of the tasks involved in a collision risk assessment. It begins with defining the collision event by considering operational conditions, structural characteristics, and environmental parameters. Statistical methods are then used to select the best-fit probability density functions (PDFs) and identify credible collision scenarios. Historical data and frequency analysis help calculate the risk, which is determined by multiplying the frequency of collisions (F) by their consequences (C). Consequence analysis involves detailed simulations and structural assessments to understand the impact and repair costs. Finally, risk evaluation categorises the risk levels and establishes criteria for acceptance, supplemented by mitigation measures and cost-benefit analysis to ensure the redesign or implementation of effective safety measures.

The accidents are identified in Fig. 8. These factors include (1) the geographical location, type, and age of the platform, (2) the density and operational mode of the colliding ship, (3) key factors involved in ship-to-platform collision mitigation measures on platforms such as automatic radar plotting aids (ARPA), vessel traffic services (VTS), and standby vessels (SBV), (4) external environmental conditions like wind, waves, currents, tides, and visibility, and (5) navigational control failures such as human error or mechanical/watchkeeping failures. These parameters are often interrelated. For example, a collision might result from a communication error between the platform and the crew, combined with poor visibility [95].

Many offshore wind farms, for example, are located near major shipping lanes. The construction of a new OWF will disrupt vessel traffic flows, and its subsequent operations and maintenance will add to the navigational complexity. This increased complexity raises the risk of collisions between vessels and OWFs, potentially leading to damage to vessels and turbine structures [97]. Due to limited historical data on such collisions, other sources like automatic identification system (AIS) data and expert judgment have been utilised to supplement maritime risk analysis [105,106,108–111]. These sources help estimate collision probabilities, assess the impact of OWF installations on shipping routes,

Fig. 8. Key elements in collisions between ships and offshore structures [95].

and evaluate the severity of collisions using subjective risk models.

A novel hybrid approach to develop a multi-data-driven Bayesian network (BN) risk model based on AIS data and subjective judgments was proposed in Ref. [106]. A target-free data learning approach was introduced to train data-driven BNs using AIS data. The modelling approach combined AIS and subjective data to aid vessel-turbine collision-avoidance decisions. The Bayesian searching approach (BSA) was used to visualise traffic flow characteristics, while the evidential reasoning (ER) method aggregated expert judgments to obtain

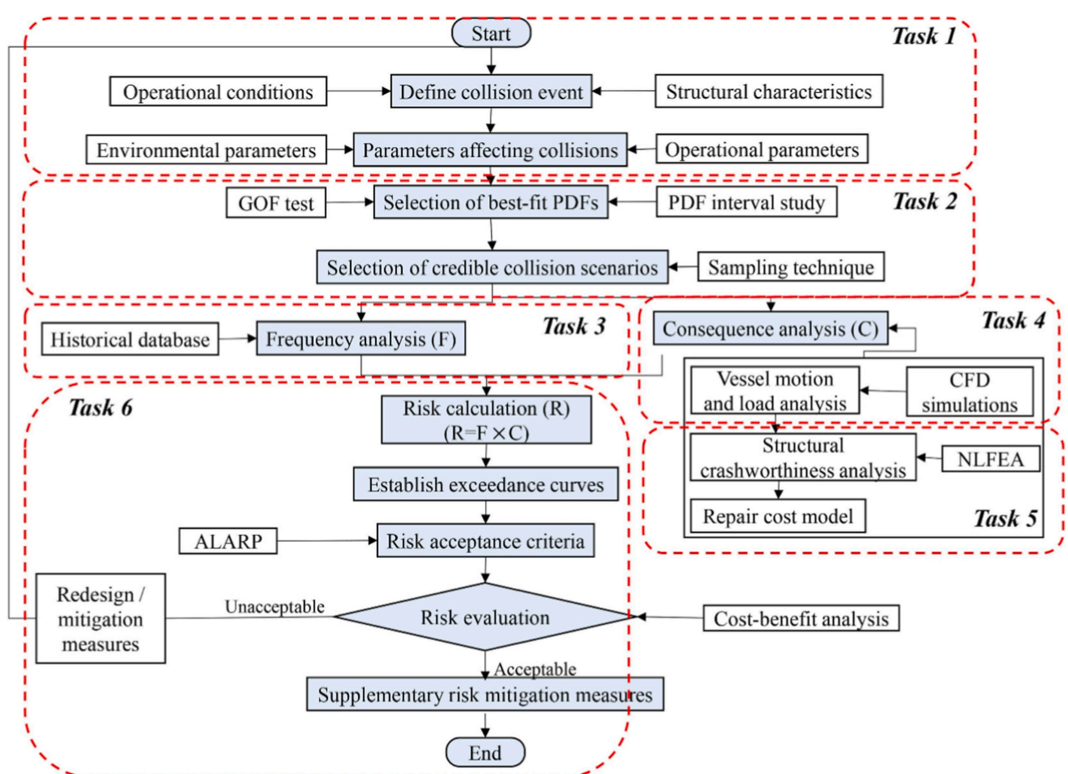

Fig. 7. Procedure for a quantitative risk analysis of collisions between ships and offshore structures [102].

subjective information for risk evaluations. Finally, IF-THEN rules were established to convert subjective information into conditional probability tables (CPTs), resulting in a multiple-data-driven and BN-based risk model.

Fig. 9 illustrates a methodology for risk analysis of ship collisions with stationary infrastructure. The methodology presented in Ref. [107] involved three steps: the collection of AIS data, the analysis of AIS data for event definition and modelling, and the modelling and simulation of events in a ship manoeuvre simulator. AIS data were used to gather both event-specific and general traffic statistics. Based on these statistics, various event models were proposed for input into the simulator, where the evolution of events was simulated and analysed. The Monte Carlo method was used to calculate accident probabilities in marine traffic.

One of the major challenges in ship collision risk assessment lies in the realistic modelling of human errors and technical faults, which are often the root causes of collision incidents. These aspects are difficult to quantify using conventional deterministic or purely statistical approaches. In this regard, Bayesian inference methods and event-based simulations, such as the framework used in Ref. [107], are crucial for incorporating uncertainty, operator behaviour, and system failures in a structured way. By updating the probability distributions based on observed data and simulating rare but critical scenarios, these methods can improve the reliability of risk estimates and support the design of effective mitigation strategies [97,106].

4. Structural response and impact mechanics

Although this chapter primarily focuses on large-scale offshore structures such as offshore wind turbines (OWT) foundations, it is worth noting that many emerging offshore renewable technologies, including floating WECs, floating solar photovoltaics (PVs), and tidal energy devices, are still in the early stages of development. Due to the limited availability of commercial deployments and standardised design practices for these systems, their impact response and structural behaviour under collision scenarios are not yet fully understood. Nevertheless, as their deployment increases in the coming years, further research will be essential to assess their unique collision vulnerabilities and protective design strategies.

4.1. Energy absorption mechanisms

Offshore structures, particularly those used in renewable energy applications, are increasingly designed to endure accidental impacts, including ship collisions. One of the most critical aspects of such design is understanding and enhancing the mechanisms by which these structures absorb impact energy. Upon collision, a portion of the kinetic energy from the vessel is transferred into the offshore structure, which then dissipates this energy through various mechanisms such as plastic deformation, local buckling, and damping due to hydrodynamic interaction.

The collision scenarios of ships to OWTs with fixed and floating foundations are depicted in Fig. 10. For fixed-bottom structures, such as monopile or jacket foundations, energy absorption predominantly occurs through localised plastic deformation and stress redistribution along the impacted region. The rigid connection to the seabed limits the structure's overall movement, leading to significant localised stresses and potential failure if not properly designed. Reinforced zones and sacrificial components are often integrated into the structure to absorb energy and mitigate damage. In contrast, floating offshore structures, such as semi-submersibles and spar-type floating wind turbines (FWTs), exhibit different energy absorption characteristics due to their mooring systems and inherent flexibility. These structures can move and rotate to a certain extent, which helps dissipate part of the impact energy through global motion and hydrodynamic drag.

As illustrated in Fig. 11, the dissipation of strain energy during a collision event can be determined through strength analysis by constructing force-displacement curves for both the striking and impacted structures [112]. These curves may be obtained either analytically or through experimental testing. For a specified level of impact loading, the total energy absorbed, denoted as E_a, corresponds to the combined area under the force-displacement curves of the two interacting bodies. Specifically, E_s represents the energy absorbed by the ship, while E_p denotes the energy dissipated by the offshore platform. In scenarios where a fendering or buffering system is installed, the energy absorption contribution of this system should also be accounted for in the overall dissipation assessment.

In the context of ship collisions with offshore structures, energy absorption can be analysed through the interplay of external dynamics and internal mechanics. External dynamics govern the global motion of the colliding bodies, while internal mechanics describe how the materials and structural components deform and dissipate energy under impact loads.

By using the conservation of momentum principle, the general formulation for a ship-OWT impact can be expressed by Ref. [112]:

$$M_s V_s + M_{OWT} V_{OWT} = (M_s + M_{OWT}) V_c \tag{1}$$

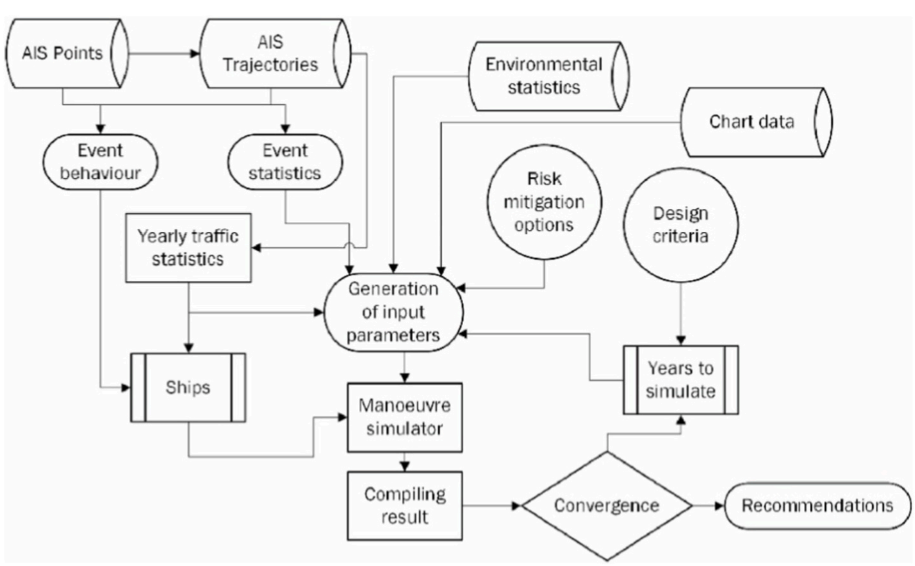

Fig. 9. The procedure of a risk analysis of ship collisions with stationary infrastructure using AIS data and a ship manoeuvring simulator [107].

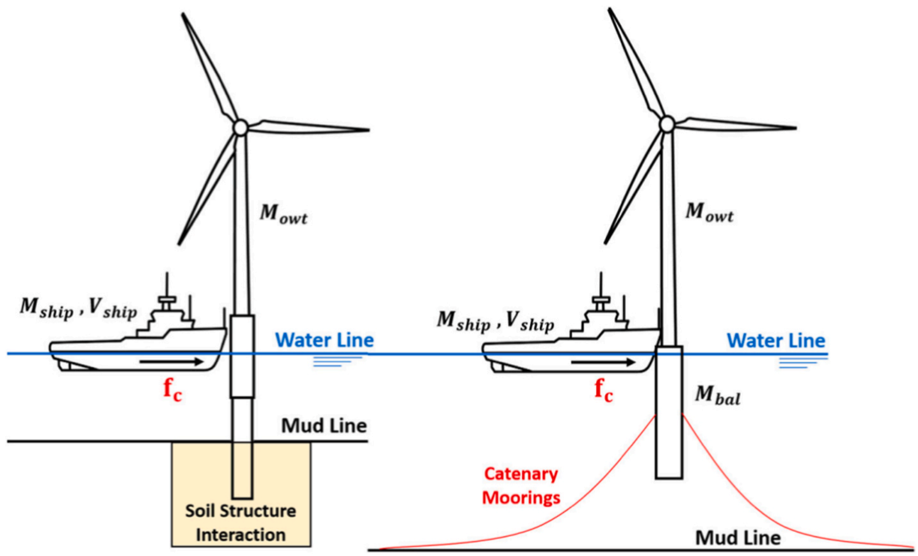

Fig. 10. Collision scenarios involving a fixed wind turbine supported by a monopile (left) and a floating wind turbine with catenary moorings (right) [18].

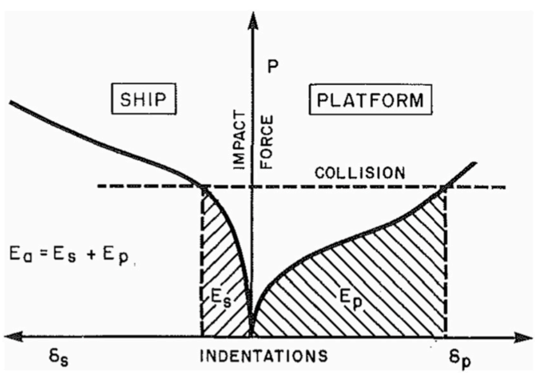

Fig. 11. Typical energy absorption characteristics during ship-platform collision [112].

where M_s and M_{OWT} are the masses of the ship and the OWT, V_s and V_{OWT} are the initial velocities of the ship and the OWT, respectively, and V_c is the common velocity after impact.

When considering the added mass and different velocities after the impact, the formulation is given by Ref. [113]:

$$(M_s + M_{a,s})V_s + (M_{OWT} + M_{a,OWT})V_{OWT} = (M_s + M_{a,s})V_{f,s} + (M_{OWT} + M_{a,OWT})V_{f,OWT} \quad (2)$$

where $M_{a,s}$ and $M_{a,OWT}$ are the added masses of the ship and the OWT, and $V_{f,s}$ and $V_{f,OWT}$ are the final velocities of the ship and the OWT after the impact, respectively.

In terms of internal mechanics, the material behaviour, such as yield strength, strain rate sensitivity, and energy dissipation capacity, plays a crucial role in governing how energy is distributed and absorbed. Assuming a perfectly plastic collision, the total energy dissipation during the collision is given by:

$$E_a = \frac{1}{2}(M_s + M_{a,s})V_s^2 \cdot (1 - V_{OWT}/V_s)^2 \bigg/ \left(1 + \frac{M_s + M_{a,s}}{M_{OWT} + M_{a,OWT}}\right) \quad (3)$$

The structural response of offshore renewable energy platforms to ship collisions involves multiple energy dissipation mechanisms, whose relative importance varies with foundation type. Table 2 provides a comparative overview of how plastic deformation, local buckling, hydrodynamic interaction, and mooring damping contribute to energy absorption in fixed-bottom versus floating platforms. For example, jacket structures are highly susceptible to local buckling in slender braces, while semi-submersibles rely heavily on mooring damping and hydrodynamic interaction to dissipate collision energy.

Table 2
Comparative energy dissipation mechanisms across structural typologies.

Energy Dissipation Mechanism	Fixed-Bottom Structures (e.g., Monopile, Jacket)	Floating Structures (e.g., Spar, TLP, Semi-sub)
Plastic deformation	High (in impacted zone, especially monopiles)	Moderate (localized in topside or pontoon)
Local buckling	High (especially in slender jacket braces)	Low to Moderate (depends on structural layout)
Hydrodynamic interaction	Moderate (wave slamming, added mass)	High (platform motion, wave-structure coupling)
Mooring system damping	Not applicable	High (critical for energy dissipation and restoring stability)

4.2. Material selection and collision protection

The stiffness and geometry of local structural components, such as ship bows, platform columns, or bracing systems, significantly affect the energy dissipation process. Advanced material models and detailed local stress-strain analyses are therefore essential to accurately capture the energy absorption mechanisms during ship and offshore structure collisions. In addition, the long-term effects of corrosion, particularly in steel-based offshore structures, can reduce material strength and ductility, thereby compromising the structural integrity and collision resistance [55,114–116]. Corrosion protection measures and degradation-aware material modelling are therefore critical components in structural design.

Material selection plays a central role in the impact resistance of offshore renewable energy structures. The ideal material must strike a balance between strength, ductility, corrosion resistance, and fatigue performance under complex marine loading conditions. For steel-based structures, high-strength low-alloy (HSLA) steels are commonly used due to their excellent strength-to-weight ratios and good performance under plastic deformation, which is essential for energy absorption during collisions [117].

Steel is the predominant material used for the support structures of offshore wind turbines. However, recent research has emphasised the advantages of employing concrete as an alternative material for offshore applications [118,119], including wind turbine substructures [74,120]. Concrete offers several potential benefits, such as reduced production costs, improved durability, and superior fatigue resistance. Moreover, the cost of concrete-based structures tends to be more stable and predictable, especially in contrast to the high volatility of steel prices, which often exhibit fluctuations several times greater than those observed in cement markets [18]. Despite these advantages, the numerical analysis of collisions involving reinforced concrete offshore structures presents additional challenges. Unlike steel, concrete requires more complex constitutive models with a greater number of input parameters to accurately capture its nonlinear and damage-prone behaviour under impact loading. This complexity makes the simulation of collision events involving concrete structures significantly more intricate [74].

For components more likely to undergo localised impact, such as the lower part of turbine towers or fendering systems, materials with high fracture toughness and ductility, such as marine-grade aluminium alloys [114] or composite laminates [121,122], are being investigated. Composites, in particular, offer weight savings and tailored energy absorption capabilities, though their performance under repeated impacts and environmental degradation remains a topic of ongoing research. In the research of [123], an interesting study was presented about the application of composite materials in impact scenarios, showing that the spiral structure of laminated panels significantly improves impact resistance. A novel floating composite honeycomb collision protection structure was proposed to mitigate damage resulting from high-energy ship-OWT collisions [121]. The structure contains two steel layers with a core of ultra high performance concrete (UHPC), as shown in Fig. 12. In the study, elasto-plastic analyses of the sandwich wall honeycomb core were performed, the energy dissipation mechanism was investigated, and equivalent material parameters for the honeycomb unit were derived.

Recent studies have demonstrated significant improvements in

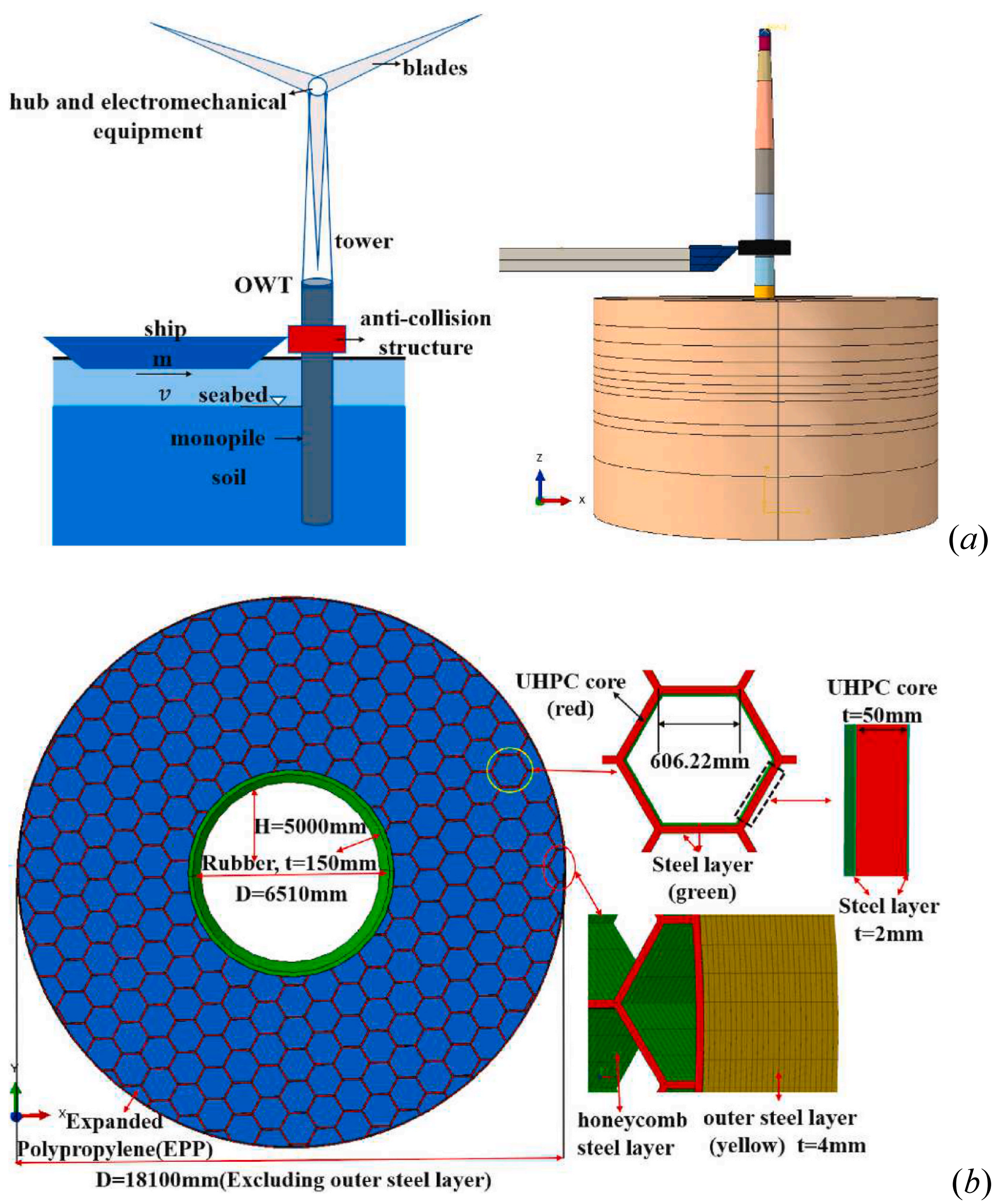

Fig. 12. A developed composite honeycomb collision protection structure for OWT monopiles: (a) the anti-collision system, and (b) UHPC-steel-EPP floating composite anti-collision structure [121].

impact resistance through the use of advanced materials and hybrid configurations. For example, in experimental and simulation-based evaluations of fiber–metal hybrid composite laminates, it was revealed that energy absorption increased by over 35 % compared to conventional GFRP layers under low-velocity impact scenarios [124]. Similarly, in the investigation on the post-impact shear buckling behavior in hybrid laminates, it was found that tailored stacking sequences could delay failure onset and improve residual strength [125]. In the context of offshore applications, thermoplastic polyurethan (TPU) based hybrid sandwich structures incorporating metal mesh and rubber layers have shown promising results under quasi-static perforation and dynamic impact loading, with enhanced damage tolerance and energy dissipation capacity [126]. These findings support the adoption of multi-material strategies for critical zones in OWT foundations.

Structural optimisation complements material selection by ensuring that the layout and thickness distribution of components are configured to channel and dissipate impact energy effectively [123,127,128]. Common optimisation strategies include topology optimisation, shape optimisation, and multi-objective optimisation that simultaneously consider strength, mass, and cost [129,130].

For floating structures such as WEC [131], fish cages [132], OWT [133], FPSO [134] and floating solar systems [135], optimisation must also consider the interaction between mooring system loads and global motions. Materials used in mooring lines, such as synthetic fibre ropes or chain-wire combinations, must be selected based on their shock absorption capacity, fatigue resistance, and compatibility with dynamic tension loads caused by impact-induced vessel motions.

Recent advances in additive manufacturing and hybrid material systems offer new opportunities for customising material properties and structural geometries to enhance impact resistance [136,137]. These developments open up possibilities for incorporating functionally graded materials and internal lattice structures that are capable of localised deformation without catastrophic failure.

4.3. Numerical simulation techniques

Numerical simulations play a vital role in evaluating the impact resistance of offshore renewable energy structures, especially when physical testing is limited by scale, cost, or safety concerns [138]. The finite element method (FEM) is the most widely adopted method for simulating structural responses under collision scenarios [100,139–154]. It allows for a detailed analysis of stress distribution, deformation patterns, and failure modes under various impact energies and angles.

High-fidelity FEM tools, such as LS-DYNA, ABAQUS, and USFOS, are commonly used to model both the vessel and the impacted structure, incorporating non-linear material behaviour, contact mechanics, and large deformations. A list of simulations regarding the collision scenarios is presented in Table 3, including information about vessel types, offshore structures, solvers, element types, collision speeds, and more. These simulations enable the assessment of localised damage, such as denting, buckling, and tearing of structural elements, as well as global responses like vibration and displacement. Special attention is given to mesh refinement in contact zones and the application of appropriate boundary conditions representing fixed or floating foundations.

For floating offshore structures, it is necessary to couple structural models with hydrodynamic simulations to accurately capture the dynamic response to impact. Coupled simulations integrate potential flow theory (by using SESAM HydroD [135,148] or ANSYS AQWA [102]), panel methods (e.g. using WAMIT [127,142]), or CFD with structural solvers [148,155,156]. The inclusion of realistic environmental loads, such as wind, wave, and current actions, is essential for accurate assessment, as highlighted in recent studies [157–159]. HydroD and AQWA are particularly effective for frequency-domain analysis of wave–structure interactions, whereas FAST and OpenFAST [127,133,148,157], developed by the National Renewable Energy Laboratory (NREL), offer comprehensive time-domain simulation capabilities for floating wind turbines, integrating aerodynamic, hydrodynamic, and structural dynamics in a modular framework. These tools are increasingly used in collision risk assessments for floating offshore wind systems and semi-submersible platforms under combined environmental and accidental loads.

Fig. 13 shows the steps of a coupled algorithm of hydro-aero-mooring loads and structural analysis. The methodology involves preparing text files with hydrodynamic coefficients from HydroD and FORTRAN module files for load calculations. LOADUD subroutine reads nodal information for each time step, storing velocity history to calculate radiation potential damping. Hydrodynamic coefficients are processed to generate matrices for added mass, hydrostatic forces, and retardation functions. Aero-hydro-mooring loads are evaluated using current nodal information.

A problem with nodal force application on deformable bodies was solved by reading nodal acceleration from a 'nodout' file. LS-DYNA structural analysis uses updated user loads every 100 steps. Results include user load history and coupled simulation outcomes like 6 degrees of freedom (DOF) motion, structural deformation, impact force, and energy dissipation.

4.4. Experiments and field data

Validating the impact resistance of offshore renewable energy structures necessitates a combination of experimental testing and field observations. These methods are crucial for corroborating numerical models and ensuring the structural integrity of installations under collision scenarios. Validation of numerical results through experiments, such as scaled impact tests or drop-weight experiments, remains crucial [25,26,134,136]. Hybrid modelling approaches combining FEM with experimental calibration help reduce uncertainty and improve

Table 3
Summary of finite element analyses on the ship–offshore structure collisions.

Reference	Vessel	Offshore Structure	FE solver	Element type	Collision speed	Calculation time
[100]	Offshore accommodation barge	OWT + monopile/jacket	ABAQUS	SR4 shell	1, 2, 4 m/s	–
[121]	Bulk carrier	OWT + monopile	ABAQUS	C3D8R, S4	1, 4 m/s	2 s
[140]	4600-ton multipurpose vessel	5 MW OWT + monopile	Patran + LS-DYNA	Belytchko-Tsay shell	1, 2, 3 m/s	1.44 s
[141]	5000DWT container ship	3 MW OWT + monopile	LS-DYNA	Belytschko-Lin-Tsay shell	2 m/s	1s
[142]	Supply vessel, shuttle tanker	DTU 10 MW FOWT	USFOS	Belytschko-Lin-Tsay shell	2 m/s	4.5 s, 2.5 s
[143]	Tanker/bulker/container	OWT + monopile/jacket/tripod	LS-DYNA	–	2, 3, 4 m/s	–
[144]	7500-ton supply vessel	10 MW OWT + monopile	USFOS	–	1 m/s	3 s
[145]	6237t bulk carrier	OWT + monopile/tripod/jacket	LS-DYNA	Shell + solid elements	2 m/s	3 s
[146,147]	2000t ship	3 MW OWT + monopile	LS-DYNA	–	2, 5 m/s	3 s
[148]	Offshore service vessel	FOWT	LS-DYNA, FAST	Belytchko-Tsay shell	1, 2, 3, 4, 5 m/s	4 s
[149]	Offshore service vessel	OC3 HYWIND Spar	LS-DYNA	Belytchko-Tsay shell	2, 5 m/s	4 s
[150]	Ro-Pax vessel	DTU 10 MW OWT	ABAQUS	S4R shell, R3D4	1, 3, 5 m/s	4,10 s
[151]	Supply vessel UT 745	DTU 10 MW monopile	SIMA	Beam, spring	1, 2, 3 m/s	2.2 s

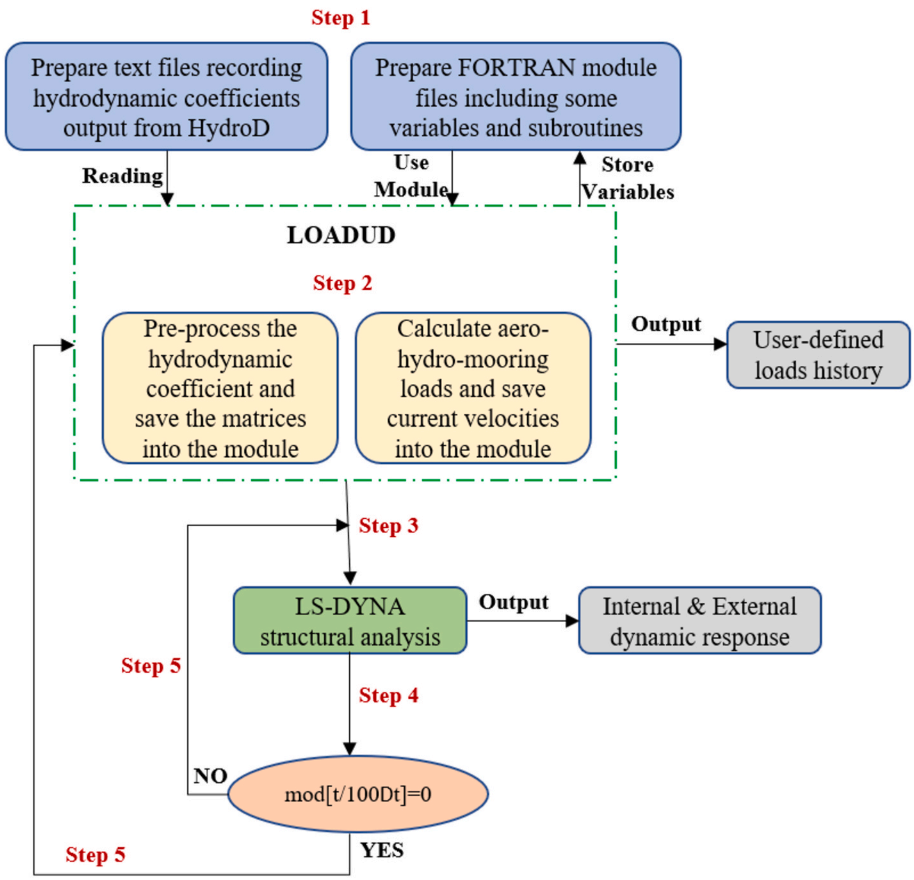

Fig. 13. An aero-hydro coupled method for ship-FOWT collisions [148].

prediction accuracy [160,161].

Laboratory-scale experiments have been instrumental in understanding the dynamic response of offshore structures to ship impacts. For instance, experimental studies were conducted on the dynamic response of a 4 MW monopile wind turbine, with a scale ratio of 1:50, subjected to vessel collisions [162]. The research highlighted the effectiveness of crashworthy devices in enhancing the anti-collision performance of wind turbines, demonstrating significant reductions in nacelle acceleration and impact forces.

Field data can provide invaluable insights into real-world collision incidents [9]. The risk of collisions between service vessels and offshore wind turbines was assessed in Ref. [97], emphasising that substantial structural damage can be caused even by low-speed impacts. The need for improved risk assessment frameworks and design considerations to mitigate such risks was underscored by their study. On the other hand, due to insufficient historical data, estimating the probability and consequences of collision scenarios from data alone is unfeasible. Instead, a Bayesian approach, interpreting collision probability as our degree of belief based on all available knowledge, is recommended.

Combining experimental and field data enhances the accuracy of numerical simulations. For example, the influence of shape design on FOWT was evaluated in Ref. [163], and experimental findings were integrated to refine their models. Such integrative approaches ensure that simulations accurately reflect real-world behaviours, leading to more resilient structural designs.

Experimental work on ship collisions with offshore renewable energy structures is limited. Consequently, error quantification for the most simplified methods relies on past experimental data from ship-ship collisions or high-fidelity non-linear finite element models, which depend heavily on the analyst's skills and the simulation tool's capabilities. Further experimental research is crucial to better understand the response of such offshore structures to ship collisions, improve and validate analytical and numerical models, and quantify their accuracy versus computational effort. This is especially important for floating structures due to the high coupling between structural, hydrostatic, hydrodynamic, wind, and mooring forces.

Despite advancements, challenges remain in replicating complex collision scenarios in controlled environments and acquiring comprehensive field data. Future research should focus on developing standardised testing protocols and enhancing monitoring systems to capture detailed impact events. Collaborative efforts between industry and academia can facilitate the sharing of data and best practices, fostering the development of more robust offshore energy structures.

5. Mitigation strategies and regulatory frameworks

5.1. Designs to enhance collision resistance

Design improvements aimed at enhancing the collision resistance of offshore renewable energy structures include strengthening key structural components and incorporating energy-absorbing features. For fixed structures such as monopiles and jackets, thickening the wall at the waterline level, reinforcing transition pieces, and using high-ductility steels can improve resistance to local impact damage [122,129,130]. Floating structures, on the other hand, can benefit from distributed buoyancy systems, reinforced pontoons, and watertight compartmentalisation to reduce the risk of capsizing or progressive flooding after impact [19,127,128].

To mitigate damage from ship collisions, a variety of structural design modifications and protective measures have been developed for offshore renewable energy installations. A key approach involves the integration of passive energy dissipation components that deform or absorb energy upon impact, thereby protecting the primary structure. Common solutions include crushable elements, such as foam-filled panels, honeycomb composites and sandwich-structured impact panels [121,137], which can be strategically installed at vulnerable zones like splash zones, boat landings, or the base of turbine towers.

Sacrificial structures are also employed on platforms like semi-submersibles and monopile foundations, offering additional protection against low-to moderate-energy impacts. These elements are designed to absorb kinetic energy through controlled deformation, often using materials such as rubber, aluminium foam, or inflatable membranes. For example, research has proposed innovative crashworthy devices such as adaptive inflatable barriers [164], steel-sphere shell–aluminium foam pads [146], and rubber fender assemblies [165] as effective collision mitigation tools.

A novel rotational composite rotational guiding anti-collision device made of polyurethane foam-glass fibre reinforced polymer (PU-GFRP) was proposed in Ref. [166], aiming to reduce the damage caused by ship impacts on monopile foundations for OWTs. As illustrated in Fig. 14, the direction of a moving ship can be altered by the rotational guiding device, thereby reducing the impact force acting normally on the structure. Furthermore, enhanced collision protection is achieved through the integration of a GFRP structure with foam filler. It should be noted that this study is limited by the lack of full-scale experimental validation under real sea conditions, simplifications in ship and foundation modelling, and the need for further investigation into device geometry, structural damage, and practical implementation factors such as cost and maintenance.

In parallel, reinforcement of critical structural zones is commonly applied. This includes increasing the wall thickness at high-risk regions, introducing internal stiffeners, or embedding energy-absorbing inserts. These modifications must be carefully optimised to maintain structural integrity without compromising hydrodynamic performance, weight balance, or economic feasibility [163].

In recent efforts to develop physical mitigation measures, MARIN has proposed the concept of “Crash Barriers”, which are dedicated offshore buffer structures designed to absorb and dissipate the energy of ship collisions before impact with critical installations such as wind turbines [167]. These barriers aim to provide passive protection and can be deployed as a surrounding layer or along strategic zones of offshore energy parks. Though still in the experimental stage, early tests suggest they could be a cost-effective and scalable solution to enhance safety in high-traffic areas.

5.2. Technological innovations in collision avoidance

It was concluded in Ref. [115] that ship collisions and submarine cable accidents are among the main navigation risks associated with OWFs. Fig. 15 illustrates a Fault Tree Analysis (FTA) model used to systematically assess the causes of collision risks in these environments. It breaks down the top-level event (collision) into underlying causes such as collision tendency and the absence of anti-collision measures. These are further divided into specific scenarios like collision with propulsion, drifting, improper anti-collision facilities, and arbitrary sailing within the farm. Key contributing factors identified include collision avoidance failure, bad weather, and habitual use of routes passing through wind farms. At the most detailed level, the model highlights issues such as a lack of lookout, navigation equipment failure, and even electromagnetic interference from turbines. This structured approach helps clarify how operational, environmental, and technical failures combine to elevate collision risks, guiding the development of targeted mitigation strategies.

Advancements in real-time monitoring and decision-support systems have opened new possibilities for collision avoidance in offshore renewable energy zones. One major development is the use of AI-based navigation systems that integrate machine learning (ML) algorithms to detect and predict ship movement patterns [75,168]. These systems can

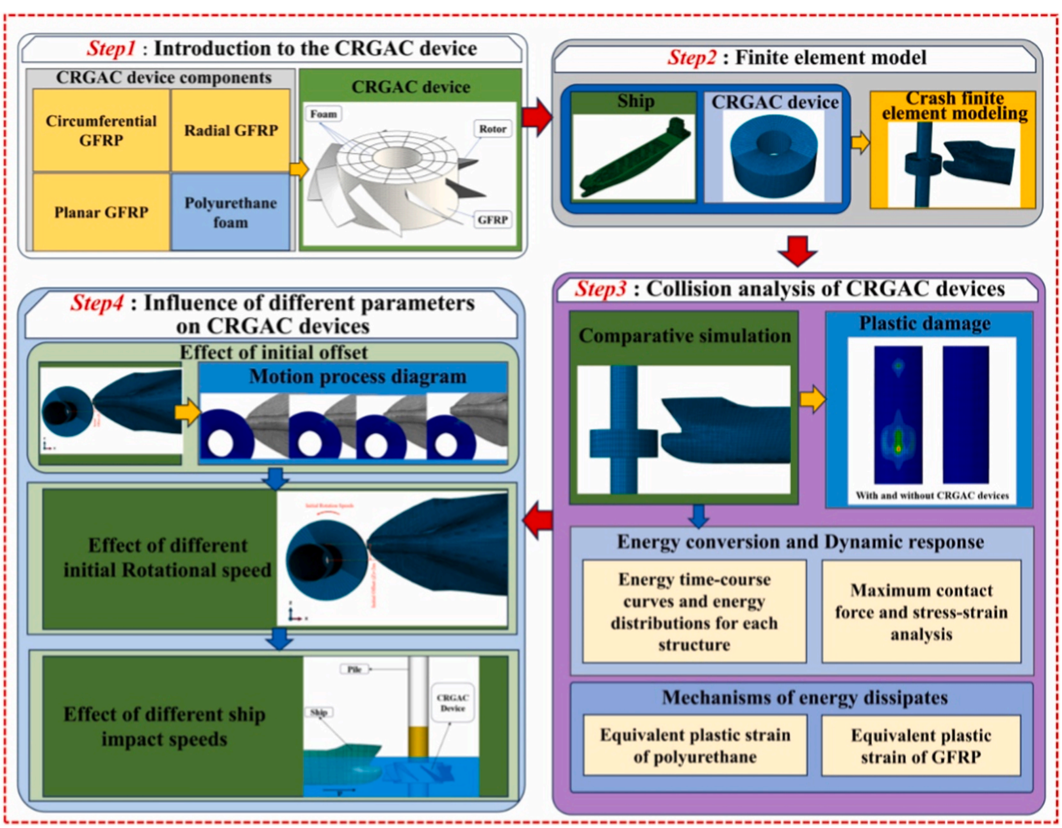

Fig. 14. Procedures in the analysis of crashworthiness and energy dissipation of an anti-collision device using GFRP [166].

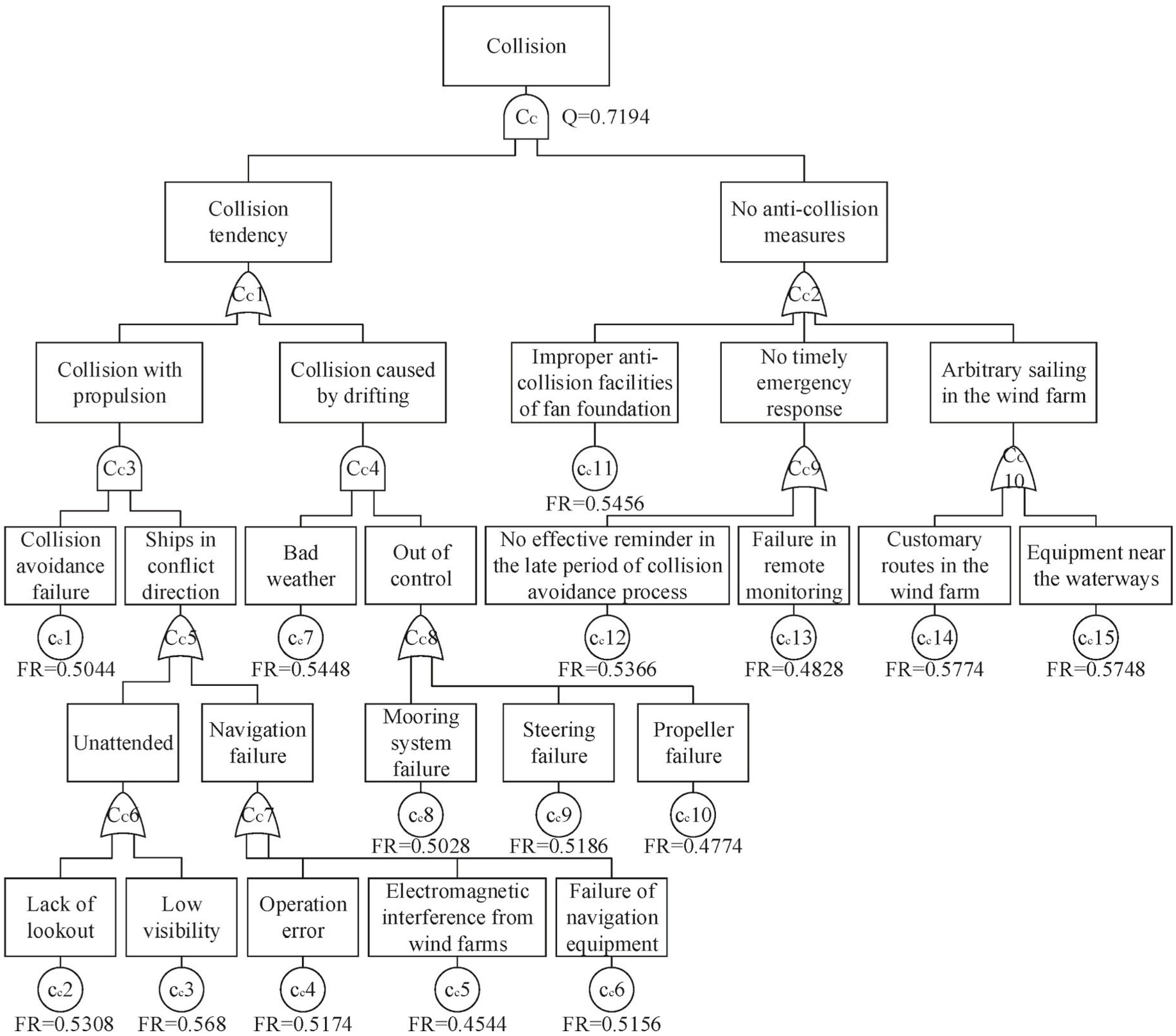

Fig. 15. FTA on collision risk of OWTs [115].

analyse traffic density, vessel behaviour, and weather inputs to provide early warnings and suggest evasive manoeuvres.

In a recent research [75], ship collision risks around the Ulsan floating offshore wind farm in Korea were assessed using AIS data and probabilistic traffic modelling. Maritime traffic distribution and ship dimensions were analysed, and an optimal route width of 8943 m was determined under a 90 % confidence interval to reduce the likelihood of collisions. The proposed method was developed to support decision-making for safe separation distances between ships and offshore wind farms, particularly in regions with dense maritime traffic. An intelligent ship collision avoidance mechanism was developed in Ref. [168] based on an improved swarm intelligence algorithm. An adaptive brain storm optimisation (ABSO) technique, enhanced by variational inference-based expectation-maximisation for Mean-shift, was applied to expedite the decision-making in collision scenarios. The fitness function was defined using turning amplitude and deviation from the original route, and the algorithm was tested under various ship encounter situations such as crossing, head-on, and overtaking. One of the constraints included avoiding manoeuvres toward offshore wind farms. The method was demonstrated to enable effective and safe navigation near offshore wind farms through scenario-based validation.

Smart sensors such as LiDAR, radar, and thermal imaging cameras are being deployed on offshore structures and vessels to enhance situational awareness, especially in poor visibility conditions. Integration of these sensors with AIS allows for automated tracking, classification, and alarm generation in the event of unsafe proximity [169,170]. The AIS transponders in large ships are used to significantly improve vessel traffic monitoring and enhance the safety of offshore wind farms. Fig. 16 outlines possible improvements to AIS use: in addition to basic Coast Guard monitoring, wind farms could be equipped with AIS receivers to detect and warn ships on potential collision courses or even integrated as AIS base stations to broadcast their boundaries as closed areas. To fully implement these enhancements, cooperation with maritime authorities is essential, especially in addressing current limitations such as the exclusion of fishing vessels from AIS requirements.

As shipping becomes increasingly autonomous, there is a growing need for integrated systems that not only detect surrounding traffic but also feed behavioural data into collision avoidance algorithms. This shift requires sensor and AIS data to support real-time, automated decision-making in autonomous vessels. One relevant example is the AUTO-Barge project, which focuses on developing autonomous barges for inland waterways. Although primarily targeted at inland navigation, the technologies, such as autonomous navigation, object detection, and situational awareness, are equally applicable to offshore ship traffic and could greatly enhance the safety of offshore renewable installations in the future [171].

Further innovation includes digital twins of offshore wind farms [116,172,173], where real-time sensor data and simulations are combined to model physical behaviours under various conditions, including collision scenarios. These digital platforms support proactive risk

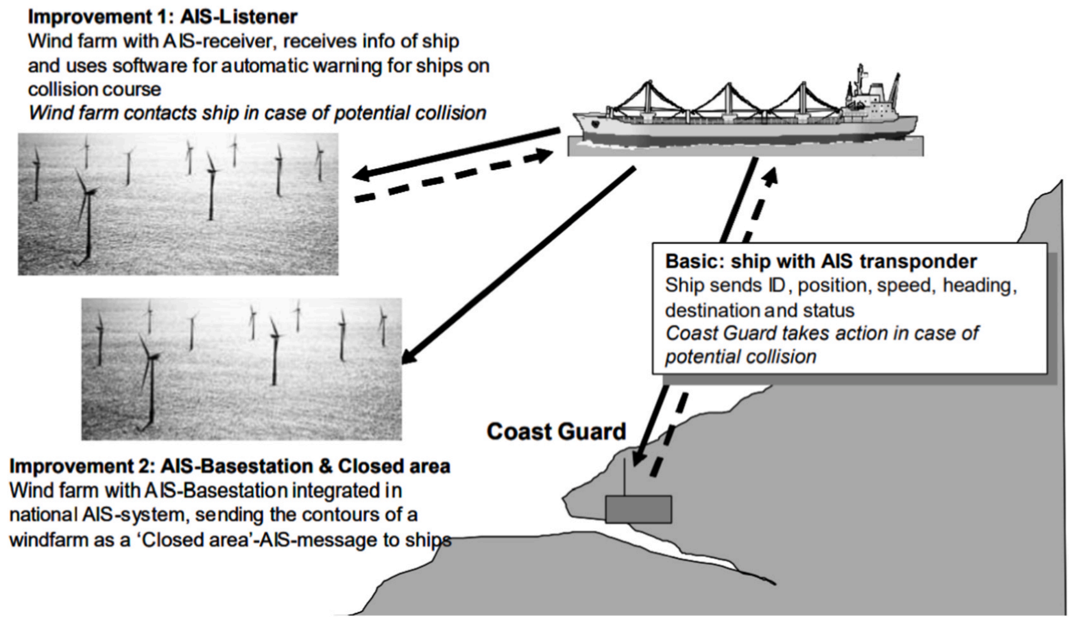

Fig. 16. Use of AIS to reduce risks of ship-OWF collisions [170].

management and can guide future infrastructure design and emergency response planning.

5.3. International regulations and classification society guidelines

A variety of international regulations and classification society guidelines provide the regulatory framework for collision risk management. Although most existing standards were initially developed for oil and gas platforms, they are increasingly referenced for offshore renewable energy applications [22]. While IMO's COLREGS apply at sea for general navigation, they do not directly address structural response. Therefore, design engineers often rely on classification society recommendations and regional maritime authority policies when assessing impact resistance and required mitigations for offshore structures.

DNV has developed a range of standards and recommended practices covering various types of offshore renewable energy structures, including tidal turbines [27], floating wind turbine structures [28], and floating solar photovoltaic systems [29]. In addition, they offer the DNV-ST-0126 [174] and DNV-RP-C204 [175], which cover design principles and accidental limit state (ALS) considerations for offshore wind turbine support structures. DNV-ST-0126 [174] provides structural design requirements for offshore wind turbine support structures, including monopiles and jackets. It outlines minimum safety levels, load combinations, and impact resistance criteria, identifies collision impact as a type of accidental loads, but does not yet offer detailed provisions for ship collision scenarios involving floating or hybrid platforms. DNV-ST-0437 [176] provides guidance for assessing abnormal design load cases involving unintended vessel collisions with offshore wind turbines. Key provisions include.

- Scope Limitation: Supply vessels operating within the wind farm but not approaching turbines are excluded from collision scenarios.
- Design Collision Scenario: The impact energy should be based on an unintended lateral collision by the maximum authorised service vessel, assumed to drift at a minimum speed of 2.0 m/s.
- Hydrodynamic Considerations: The added mass effect must be included in the energy calculation.
- Fendering Effects: The energy absorption capacity of the vessel's fendering system should be considered.
- Structural Design Strategy: It is acceptable for secondary structural components to be sacrificial (e.g., designed to tear off or yield) to protect primary supporting structures from excessive damage.

ABS has also released bulletins for floating offshore wind concepts, emphasising mooring integrity and impact scenarios [30,31]. Bureau Veritas (BV) provides guidelines on environmental loads and ship impact assessments for floating structures, as found in their NR572 [32], NI 631 [33] and NI 682 [34] rules and notes. International Standard IEC specifies TS 62600-100 for wave, tidal and other water current converters [35]. IEC 61400-3 outlines design requirements for offshore wind turbines, including collision loads, environmental factors, and safety zones [36]. A detailed comparison of these standards and guidelines can be found in Table 4.

Despite the existence of international regulations and classification society guidelines, current frameworks often lack specificity for novel offshore renewable structures and dynamic collision scenarios, highlighting the need for more targeted standards and clearer implementation strategies tailored to emerging technologies and site-specific risks. Moreover, in many emerging offshore renewable energy markets, such as in parts of Asia, Africa, and South America, region-specific regulatory frameworks are still underdeveloped, underscoring the need for localised guidelines that address unique operational and environmental conditions [22].

6. Future research directions and challenges

6.1. Policy recommendations for safer offshore energy infrastructure

To ensure the safety and resilience of offshore renewable energy infrastructure, it is essential to develop comprehensive policy frameworks that address the unique challenges posed by ship collisions and other maritime risks. Policymakers should consider implementing stricter regulations for vessel traffic management in proximity to offshore installations, including mandatory AIS usage for all vessels, enhanced navigational aids, and designated safe zones around wind farms and other structures.

Marine spatial planning (MSP) should be a core component of policy frameworks, ensuring that offshore renewable energy installations are optimally sited to avoid overlap with major shipping lanes or fishing zones [3,46,54,105,111]. An effective MSP can significantly reduce

Table 4
Overview of standards and guidelines by classification societies and international organizations.

Organization	Key Documents & Standards	Covered Structures	Focus Areas	Noted Gaps or Limitations
DNV	DNV-ST-0164 [27], DNV-ST-0119 [28], DNV-RP-0584 [29], DNV-ST-0126 [174], DNV-RP-C204 [175]	Tidal turbines, floating wind, floating PV	Design principles, ALS considerations, mooring systems, floating solar	Less specific guidance for WECs
ABS	Floating Offshore Wind Bulletins [30,31]	Floating wind concepts	Mooring integrity, structural impacts, collision scenarios	Limited standardisation for WECs and PVs
BV	NR572 [32], NI 631 [33], NI 682 [34]	Floating structures	Environmental loading, ship impact assessment	Less focus on fixed-bottom wind turbines
IEC	TS 62600-100 [35], IEC 61400-3 [36]	Wave, tidal, offshore wind	Design requirements, safety zones, environmental and collision loads	TS 62600 series still evolving; implementation varies

potential conflict areas and serve as a collision risk mitigation first layer. Each country has a strategic MSP that should contribute to long-term sustainable development by guiding how the sea should be used. It can guide how the sea and its use should be managed through various regulations and measures.

Additionally, international collaboration is crucial for harmonising standards and sharing best practices across different regions. Future policies should also promote the adoption of innovative technologies, such as digital twins and AI-driven collision avoidance systems, to enhance the monitoring and management of offshore energy assets. By fostering a regulatory environment that supports technological innovation and prioritises safety, policymakers can help mitigate the risks associated with the growing interaction between maritime traffic and offshore renewable energy installations.

6.2. The role of AI and big data in predictive collision analysis

With the growing availability of sensor data from operating wind farms and offshore facilities, data-driven modelling using AI and big data analytics is emerging as a promising complement to traditional simulation techniques. AI algorithms can analyse vast amounts of AIS data, weather conditions, and vessel movement patterns to predict potential collision scenarios and assess risks in real-time. Machine learning models can be trained to recognise patterns and anomalies in maritime traffic, providing early warnings and recommendations for collision avoidance.

Additionally, big data analytics can enhance the accuracy of risk assessments by incorporating historical data, expert judgments, and real-time information. Future research should explore the development of advanced AI-driven decision support systems that can dynamically adapt to changing conditions and provide actionable insights for improving the safety and efficiency of offshore renewable energy operations.

Nevertheless, AI and big data techniques should not only be used to analyse historical collision events but also to identify high-risk scenarios before they occur. By integrating AIS data, weather forecasts, and vessel behaviour patterns, predictive models can trigger alerts or recommend real-time mitigation actions (e.g., traffic rerouting, preemptive speed reduction) to reduce the probability of collision. Such proactive applications are essential for the safe operation of offshore renewable energy parks.

6.3. Integrating real-time monitoring and digital twin technologies

The integration of real-time monitoring systems and digital twin (DT)technologies represents a significant advancement in the management and safety of offshore renewable energy installations [62]. Digital twins, which are virtual replicas of physical assets, enable continuous monitoring and simulation of offshore structures under various operational and environmental conditions. By incorporating real-time data from sensors installed on wind turbines, tidal turbines, and other offshore devices, digital twins can provide valuable insights into the structural health and performance of these installations [177–179]. This approach allows for proactive maintenance, early detection of potential issues, and optimisation of operational strategies to enhance resilience against ship collisions and other hazards.

Future research should focus on developing more sophisticated digital twin models that can accurately simulate complex interactions between offshore structures and maritime traffic, as well as integrating AI and machine learning algorithms to improve predictive capabilities. A proactive use of digital twin technologies enables not only real-time tracking of structural responses but also the prediction of degradation trends over time. This is crucial to ensure sufficient structural strength as components age, especially under continuous wave loading and corrosion exposure, thus preventing long-term fatigue-related failures.

6.4. Limitations and further concerns

A review of existing literature reveals that most studies on ship collisions with offshore renewable energy structures focus primarily on FWTs, while research on WECs, tidal energy devices, and other offshore renewable installations remains scarce. This discrepancy does not necessarily imply that these structures face negligible collision risks. Instead, several factors may contribute to the research gap.

(1) Technological maturity and deployment scale: Floating wind farms have experienced rapid commercial expansion, particularly in Europe and Asia, driving increased research interest in their collision risks. In contrast, wave and tidal energy technologies are still in the early stages of commercialisation, leading to limited safety-related studies.
(2) Structural visibility and placement: FWTs are tall and highly visible, often equipped with collision warning systems. In contrast, WECs and tidal energy devices tend to be lower in profile or even submerged, making them less visible to ships, particularly small fishing or leisure vessels.
(3) Data availability and incident reporting: Research on collision risks relies heavily on AIS data and recorded incidents, which primarily track large commercial vessels. However, small vessels, which may pose a higher risk to wave energy devices, are often underrepresented in these datasets.
(4) Geographical and operational factors: Many wave and tidal energy devices are deployed in areas with strong currents or high wave activity, often outside major shipping routes. This may lead to an underestimation of their exposure to vessel collisions. However, ongoing research and development of multi-purpose platforms and integrated offshore energy solutions suggest that future installations may be significantly larger in scale and spatial footprint, increasing the likelihood of interaction with maritime traffic.

This research gap raises several concerns.

(1) Limited understanding of collision risks beyond wind turbines. The unique structural and operational characteristics of WECs, tidal energy converters, and hybrid offshore platforms require specific risk assessments that differ from those developed for floating wind farms. The lack of research in this area may lead to an underestimation of potential hazards. Moreover, large-scale deployment of such systems is only just beginning. Since we currently lack real-world experience from commercial arrays of WECs, floating PVs, and tidal devices, now is a critical moment to conduct proactive research and establish risk mitigation strategies before these installations become widespread.
(2) Insufficient data on small vessel collisions. While most risk assessments focus on large commercial ships, small vessels such as fishing boats, service ships, and recreational vessels are more likely to interact with wave and tidal energy installations. These smaller crafts pose a non-negligible risk, yet their impact remains poorly quantified.
(3) Lack of integrated simulation and monitoring approaches. Current collision studies often rely on either numerical simulations or historical data, but rarely integrate real-time monitoring, AI-based prediction models, and experimental validation. A more comprehensive methodology is needed to improve the accuracy of impact risk assessments.
(4) Regulatory and design challenges. Existing international regulations (e.g., IMO, DNV, IEC standards) primarily address offshore wind structures, with limited guidelines for wave and tidal energy installations. A lack of standardised collision mitigation strategies could hinder the large-scale deployment of these technologies.

To consolidate the review's practical insights, Table 5 summarises the key technical and regulatory challenges, corresponding innovative solutions, recommended validation methods, and the stakeholders responsible for the implementation.

Table 5
Summary of identified challenge to the corresponding innovative solution.

Identified Challenge	Innovative Solution	Validation Method	Responsible Stakeholder
Ship collision risk near offshore renewable installations	AI-driven collision avoidance, designated safety zones, crashworthy structures	Numerical simulation, field monitoring	Designer, Operator, Regulator
Lack of real-time predictive capabilities	DT platforms, big data analytics, ML-based risk forecasting	Real-time monitoring, AI model validation	Operator, Designer
Insufficient collision protection for fixed-bottom structures	Reinforced monopile/jacket zones, sacrificial elements, composite crash panels	Experimental testing, FEM simulation	Designer
Limited understanding of small vessel collision risks	Inclusion of fishing/service vessels in AIS-based models, subjective risk analysis	Bayesian inference, expert judgment	Regulator, Operator
Inadequate material resilience under impact and corrosion	Use of HSLA steel, UHPC composites, PU-GFRP devices, corrosion-aware design	Material testing, nonlinear FEM	Designer
Lack of integrated simulation and monitoring frameworks	Coupled aero-hydro-mooring-structural models, hybrid validation approaches	Numerical simulation, experimental calibration	Designer, Researcher
Absence of standardised testing protocols for novel offshore structures	Development of benchmark experiments and hybrid modelling frameworks	Experimental testing, simulation benchmarking	Researcher, Regulator
Regulatory gaps for WECs, tidal, and floating PV systems	Extension of DNV/IEC/ABS guidelines, regional policy development	Expert review, policy audit	Regulator
Collision risk from autonomous and small vessels	Enhanced AIS coverage, smart sensors, adaptive route planning algorithms	Field trials, scenario-based validation	Operator, Maritime Authority
Poor integration of marine spatial planning with offshore energy siting	Strategic MSP frameworks, traffic separation schemes	GIS analysis, stakeholder consultation	Regulator, Planner
Limited data on collision incidents beyond wind turbines	Expansion of incident databases, inclusion of WEC/tidal/floating PV cases	Data mining, field reporting	Operator, Researcher

7. Conclusions

This review has highlighted the critical challenges and innovative solutions related to ship collisions with offshore renewable energy structures. Key findings include the importance of understanding structural response mechanisms and energy absorption during collisions, the role of advanced materials and design optimisations in enhancing impact resistance, and the need for robust risk assessment methodologies that integrate numerical simulations, experimental testing, and real-time data analysis.

The study of structural response and impact mechanics is crucial for understanding how offshore renewable energy structures behave under dynamic loads, such as ship collisions. When a vessel impacts these structures, the kinetic energy is transferred and dissipated through mechanisms like plastic deformation, local buckling, and hydrodynamic interaction. Fixed-bottom structures, such as monopile or jacket foundations, primarily absorb energy through localised plastic deformation and stress redistribution, while floating structures, like semi-submersibles and spar-type floating wind turbines, dissipate energy through global motion and hydrodynamic drag due to their inherent flexibility and mooring systems.

Advanced numerical simulations, including FEMs and coupled hydrodynamic-structural models, are essential for accurately predicting the impact resistance and structural response of these installations. Experimental validation and real-world data further enhance the reliability of these models, ensuring that the designs can withstand accidental impacts and maintain operational integrity. Additionally, the emergence of new simulation methods and technologies holds promise for further advancements in this field.

To improve the resilience of offshore renewable energy structures, it is recommended to incorporate case studies of real-world applications to illustrate practical implications. Highlighting recent advancements in materials and methods used in impact mechanics can provide insights into the latest developments in the field.

The review also emphasised the significance of regulatory frameworks and technological innovations, such as AI-driven collision avoidance systems and digital twin technologies, in improving the safety and resilience of offshore renewable energy installations. Looking ahead, the integration of real-time monitoring systems and digital twin technologies will play a pivotal role in advancing the safety and efficiency of offshore renewable energy operations. The application of AI and big data analytics will further enhance predictive collision analysis and risk management.

While this review advocates for an integrated risk-assessment framework combining numerical simulations, experimental testing, and real-time data analysis, it is important to acknowledge the practical challenges of coupling these heterogeneous data streams. Issues such as sensor fidelity in harsh marine environments, high computational demands of coupled simulations, and iterative validation cycles between models and field data remain significant barriers to implementation. Policymakers must develop comprehensive regulatory frameworks that support technological innovation and address the unique challenges of offshore renewable energy. Continued research and collaboration between industry, academia, and regulatory bodies are essential to ensure the sustainable growth and resilience of offshore renewable energy infrastructure in the face of increasing maritime activity.

It is important to note that while efforts were made to provide a comprehensive overview, not every aspect of collision-related offshore renewable energy structures may have been covered within the scope of the current review. Further research is encouraged to explore specific limitations and future directions in this rapidly evolving field.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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