



Mitigating UXO Risks: The Importance of Underwater Surveys in Windfarm Development

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Article Info

ISSN (Online): 2582-7138

Impact Factor (RSIF): 7.98

Volume: 04

Issue: 02

March - April 2023

Received: 12-03-2023

Accepted: 10-04-2023

Published: 23-04-2023

Page No: 915-926

Abstract

The rapid expansion of offshore wind energy has intensified the demand for large-scale marine infrastructure projects in regions historically affected by warfare and military activities. One of the most critical challenges in such environments is the presence of unexploded ordnance (UXO), which poses significant risks to safety, environmental sustainability, and project economics. UXO items, including bombs, mines, and shells, remain hazardous decades after deposition, with the potential to detonate during seabed disturbance caused by piling, trenching, or cable-laying operations. These risks necessitate a systematic and proactive approach to site investigation, with underwater surveys emerging as the cornerstone of UXO risk mitigation strategies in windfarm development. Underwater surveys, employing advanced geophysical tools such as side-scan sonar, magnetometers, and sub-bottom profilers, enable the detection, characterization, and mapping of potential UXO hazards. The integration of remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and geographic information systems (GIS) further enhances the accuracy and reliability of survey outcomes. By identifying anomalies and informing clearance operations, such surveys not only protect human lives but also reduce costly delays, ensure compliance with regulatory frameworks, and safeguard marine ecosystems from unintended ordnance disturbance. Beyond immediate risk reduction, early and comprehensive UXO survey programs contribute to stakeholder confidence, financial predictability, and streamlined project execution. The adoption of standardized methodologies and regulatory guidance across jurisdictions reinforces their role in responsible and sustainable offshore development. Looking forward, the incorporation of artificial intelligence, machine learning, and autonomous systems promises to further optimize UXO detection and risk assessment processes. Ultimately, mitigating UXO risks through robust underwater surveys is indispensable for ensuring safe, efficient, and environmentally responsible windfarm development, thereby supporting the global transition to renewable energy while addressing legacy hazards from past conflicts.

DOI: <https://doi.org/10.54660/IJMRGE.2023.4.2.915-926>

Keywords: Mitigating UXO risks, underwater surveys, offshore windfarm development, unexploded ordnance detection, geophysical survey methods, marine safety, environmental protection.

1. Introduction

The global shift toward renewable energy has accelerated the deployment of offshore wind farms as a cornerstone of clean energy transition strategies. Offshore wind power has emerged as one of the most promising technologies for decarbonizing electricity generation, particularly in regions with high wind potential and limited land availability for onshore projects (Ogunyankinnu *et al.*, 2022; Oyeyemi, 2023). Europe, Asia, and North America have witnessed unprecedented growth in installed offshore wind capacity, with projections indicating further expansion in response to rising energy demands and climate commitments. The strategic placement of turbines in marine environments allows for efficient energy capture, reduced visual impacts onshore, and large-scale contributions to national energy grids (Oluoha *et al.*, 2023; Onotole *et al.*, 2023). However, the

expansion of offshore wind energy also introduces complex challenges that extend beyond engineering and environmental concerns. Among these, the presence of unexploded ordnance (UXO) in many coastal and offshore zones represents a significant but often underappreciated risk factor (Ogundipe *et al.*, 2023; Oluoha *et al.*, 2023).

The seabed in numerous regions designated for offshore wind development remains contaminated by UXO as a legacy of past wars, naval operations, and military dumping practices. Decades after their deployment or abandonment, UXO items—including naval mines, aerial bombs, torpedoes, and artillery shells—retain the potential for detonation under certain conditions. Corrosion may render them unstable, while construction activities such as pile driving, dredging, and cable trenching can inadvertently trigger an explosion (Gbabo *et al.*, 2022; Nwaimo *et al.*, 2023). This presents a dual problem: the direct threat to human safety and the potential disruption of marine infrastructure development. In several documented cases, windfarm projects in the North Sea and Baltic Sea have encountered UXO, resulting in costly delays and specialized clearance operations.

The risks associated with UXO in offshore wind farm projects are multifaceted. From a safety perspective, the detonation of ordnance poses life-threatening hazards to construction crews, survey teams, and vessel operators (Gbabo *et al.*, 2022; Ogunyankinnu *et al.*, 2022). Financially, UXO-related delays and clearance costs can escalate project budgets substantially, undermining investor confidence and threatening the economic feasibility of projects. Environmentally, unintended detonation or mishandling of UXO can disturb marine ecosystems, release hazardous substances, and compromise biodiversity conservation goals. Furthermore, reputational risks for developers are considerable, as accidents or environmental incidents linked to inadequate UXO management can erode public trust in renewable energy initiatives (Ejibenam *et al.*, 2021; Halliday, 2023). Thus, UXO risks demand proactive, systematic, and scientifically informed approaches for mitigation.

In this context, underwater surveys constitute the foundation of effective UXO risk management in windfarm development. Advanced survey techniques, ranging from geophysical mapping with side-scan sonar and magnetometers to inspections with remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), enable the detection, classification, and mapping of potential UXO hazards (Eleftherakis and Vicen-Bueno, 2020; Chemisky *et al.*, 2021). These surveys provide the necessary data to inform clearance operations, optimize turbine siting, and ensure regulatory compliance (Osabuohien, 2017; Onibokun *et al.*, 2022). Their importance lies not only in reducing immediate risks but also in ensuring long-term safety, operational efficiency, and environmental protection throughout the lifecycle of offshore wind projects. The purpose of this is to highlight the central role of underwater surveys in mitigating UXO risks and ensuring the safe, efficient, and sustainable expansion of offshore wind energy. By addressing UXO challenges through robust survey practices, the offshore wind sector can continue to advance as a key driver of global clean energy transition while responsibly managing the legacies of past conflicts embedded in the marine environment.

2. Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was applied to systematically synthesize the available evidence on mitigating unexploded ordnance (UXO) risks through underwater surveys in windfarm development. A structured process was followed to ensure transparency, replicability, and rigor in the review. The search strategy involved querying multiple scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, as well as gray literature from industry reports, governmental guidelines, and offshore regulatory agencies. Keywords and Boolean operators were used in varying combinations, including “UXO risk mitigation,” “underwater surveys,” “offshore windfarm safety,” “marine geophysics,” and “seabed clearance operations.” The search was restricted to publications in English from 2000 to 2025 to capture the rapid expansion of offshore wind energy development and the concurrent rise in marine survey technologies.

The screening process began with the removal of duplicates, after which titles and abstracts were assessed for relevance to UXO detection, survey methodologies, and offshore windfarm applications. Articles not addressing either UXO or underwater survey relevance to renewable energy development were excluded. A full-text review was then conducted on the remaining studies, applying predefined inclusion criteria such as discussion of geophysical or hydroacoustic survey techniques, application to UXO detection in seabed environments, and evaluation of risk management frameworks in offshore construction. Exclusion criteria encompassed studies focusing exclusively on terrestrial UXO clearance, military-only survey applications, or unrelated offshore hazards such as pipeline corrosion or biological impacts.

Data extraction was carried out using a standardized framework that captured study objectives, methodological approaches, types of survey technologies used (magnetometry, side-scan sonar, sub-bottom profiling, autonomous underwater vehicles), effectiveness in UXO identification, limitations encountered, and integration into project planning. The extracted data were synthesized through a narrative approach supported by thematic grouping to highlight recurring patterns across the literature. Themes included the reliability of survey instruments under varying seabed conditions, the role of data fusion and geospatial mapping, the costs and risks associated with false positives, and the regulatory requirements governing UXO risk management in offshore wind farm licensing.

Quality appraisal of the included studies was conducted by adapting established risk-of-bias tools to assess methodological robustness, with particular emphasis on the precision of survey outcomes, validation methods, and industry applicability. Studies presenting empirical field results were weighed more heavily than conceptual or modeling studies, though both categories were considered essential for comprehensive synthesis.

The PRISMA methodology facilitated the transparent presentation of the evidence base, resulting in the development of a framework for understanding how underwater surveys mitigate UXO risks in windfarm development. This process also revealed knowledge gaps,

including limited comparative analyses of different survey techniques, insufficient long-term data on UXO clearance success, and a lack of standardized international guidelines. The systematic review underscores the centrality of underwater survey integration into offshore wind farm project design, ensuring both operational safety and environmental compliance while minimizing costly project delays.

2.1. Understanding UXO Risks in Offshore Environments

Unexploded ordnance (UXO) refers to military munitions that were armed, launched, or deployed but failed to detonate as intended. Despite their inactivity, these devices retain the potential for explosion, posing long-term hazards in terrestrial and marine environments (Aduwo *et al.*, 2019; Ogundipe *et al.*, 2023). Offshore, UXO is especially problematic due to the prevalence of naval battles, aerial bombardments, and deliberate dumping during the twentieth century. In the context of offshore wind farm development, understanding the nature, sources, and implications of UXO risks is vital to ensuring safe, efficient, and sustainable project execution.

UXO encompasses a wide variety of explosive remnants of war (ERW). Common categories include: Aerial bombs, dropped during military campaigns, particularly in World War I and World War II, many of which failed to detonate on impact and settled on the seabed. Naval mines, both moored and bottom mines, deployed extensively to disrupt shipping lanes, remain scattered across oceans and coastal regions. Artillery shells and projectiles, fired from warships or coastal batteries, remain embedded in sediments or exposed on the seabed. Torpedoes, launched from submarines or aircraft, many did not detonate upon impact and continue to pose risks. Other hazardous materials include depth charges, cluster munitions, and chemical weapons, some of which have been corroding in marine environments for decades.

The prevalence of UXO in marine environments is closely tied to the history of global conflicts. European waters such as the North Sea, the English Channel, and the Baltic Sea are some of the most contaminated, owing to intensive naval campaigns during both World Wars. The Baltic Sea, in particular, became a dumping ground for large quantities of munitions and chemical weapons after World War II, creating an enduring legacy of risk.

In the Asia-Pacific region, large-scale naval battles during World War II left significant deposits of ordnance. The Pacific Islands, the South China Sea, and the waters around Japan are heavily affected. Many regions in Southeast Asia also contain UXO from conflicts such as the Vietnam War, where aerial bombardments and naval activities dispersed explosive materials across vast marine areas.

Other former conflict zones, including parts of the Mediterranean, Black Sea, and the Korean Peninsula, remain at risk due to past wars and Cold War military exercises. The global distribution of UXO is thus widespread, overlapping with many areas now prioritized for offshore renewable energy development.

The construction and operation of offshore wind farms involve intensive seabed interaction, which significantly elevates the risk of disturbing UXO. Common risk scenarios include: Driving turbine foundations into the seabed can strike buried ordnance, causing detonation. Trenching and plowing for subsea power cables can expose or damage UXO items. Clearing sediments for foundations or ports may

inadvertently recover or disturb ordnance. Temporary and permanent infrastructure can interact with previously undisturbed UXO.

These activities generate high-energy vibrations, direct physical contact, or pressure changes—all of which can trigger unstable ordnance.

The consequences of encountering UXO during offshore windfarm development are multifaceted, spanning safety, financial, and environmental domains as shown in Figure 1. The most immediate and severe implication is the threat to human life. Construction workers, vessel operators, and divers are directly at risk of injury or death if UXO detonates during handling or disturbance. Even non-explosive interactions can generate fear and stress among personnel, affecting morale and operational efficiency. Safety considerations alone underscore the necessity of comprehensive UXO risk assessment and mitigation strategies. UXO risks can have profound financial implications for offshore wind projects. The discovery of ordnance often leads to delays while clearance operations are conducted. Specialized equipment, skilled explosive ordnance disposal (EOD) teams, and stringent safety protocols are required, all of which contribute to rising costs. Inadequate early-stage surveys can result in unexpected encounters with UXO, forcing project redesigns or halting operations altogether. For developers, such disruptions translate into cost overruns, loss of investor confidence, and potentially reduced competitiveness in the renewable energy market. Beyond human and financial concerns, UXO poses significant environmental threats (Abdulkareem *et al.*, 2023). Accidental detonation can damage seabed habitats, disrupt marine biodiversity, and generate acoustic impacts harmful to marine mammals and fish populations (Marques, 2020; Ganchrow, 2021). Furthermore, corroded ordnance may leak toxic chemicals, including heavy metals and explosive compounds, into marine ecosystems. In cases involving dumped chemical weapons, such as mustard gas or nerve agents in the Baltic Sea, the ecological consequences are particularly severe. These risks challenge the environmental sustainability goals that underpin offshore wind development, necessitating careful UXO management to prevent unintended harm.

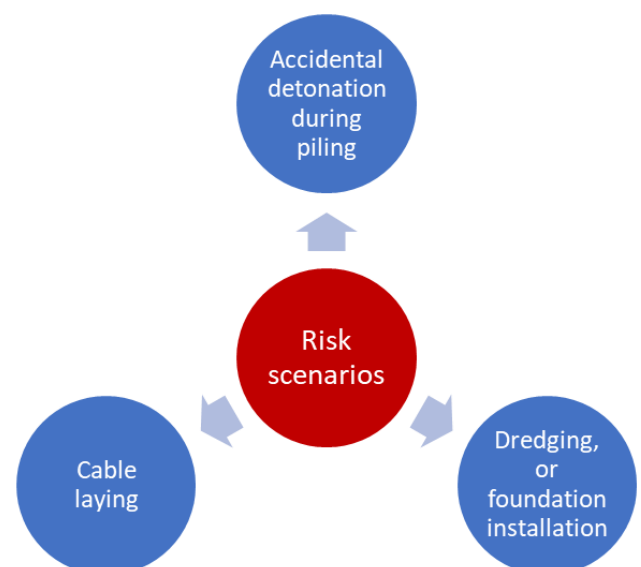


Fig 1: Risk scenarios

UXO risks in offshore environments are deeply rooted in historical conflicts but remain highly relevant to modern renewable energy development. Offshore windfarms, which represent a crucial component of the global energy transition, are uniquely vulnerable to UXO-related hazards due to the intensive seabed interaction required for their construction and operation. The presence of aerial bombs, naval mines, torpedoes, and other ordnance creates tangible safety, financial, and environmental risks. Understanding these risks in detail is the first step toward designing effective mitigation measures, particularly through underwater surveys and clearance strategies. By recognizing the scale and complexity of the problem, stakeholders can prioritize safety and sustainability while advancing offshore wind as a cornerstone of clean energy infrastructure.

2.2. The Role of Underwater Surveys in UXO Mitigation

The rapid expansion of offshore wind energy projects in regions with a history of military activity has brought the issue of unexploded ordnance (UXO) to the forefront of marine infrastructure development. UXOs, remnants of past wars and military training exercises, pose significant risks to construction operations, personnel safety, and long-term environmental stability. To mitigate these risks effectively, underwater surveys have become essential in wind farm development projects. By combining detection, mapping, risk assessment, and clearance planning, these surveys create a structured pathway to address the challenges posed by UXO contamination on the seabed (Price, 2021; Kampmeier *et al.*, 2021).

The primary objectives of underwater surveys for UXO mitigation are multifaceted. First, surveys aim to detect

potential UXOs using advanced sensing technologies capable of differentiating ordnance signatures from natural or anthropogenic seabed anomalies. Once detected, precise mapping is conducted to establish the spatial distribution of potential threats, forming the foundation for subsequent risk assessments (Abdulkareem *et al.*, 2023). Risk assessment involves evaluating the probability of UXO presence, the likelihood of detonation during construction, and the potential consequences for workers, equipment, and the environment. Finally, survey data support clearance planning by prioritizing high-risk zones, guiding safe intervention strategies, and ensuring compliance with regulatory frameworks. Together, these objectives create a systematic approach to reduce uncertainty and enhance the safety and efficiency of offshore wind farm development.

Geophysical surveys form the cornerstone of UXO detection. Side-scan sonar is widely used to produce high-resolution images of the seabed surface, allowing identification of anomalies with shapes or textures consistent with ordnance. This technology is particularly effective in distinguishing surface-laid UXOs from natural seabed features, though its utility diminishes in areas of complex seabed morphology. Complementing sonar, magnetometers detect anomalies in the Earth's magnetic field caused by ferrous materials. Magnetometer data is critical for identifying buried ordnance that would remain undetected through visual or acoustic methods. Sub-bottom profilers, on the other hand, penetrate the seabed sediment to reveal objects buried beneath the surface layers, expanding the detection envelope to greater depths. Together, these geophysical instruments provide a layered methodology that increases detection confidence and reduces the likelihood of false negatives.

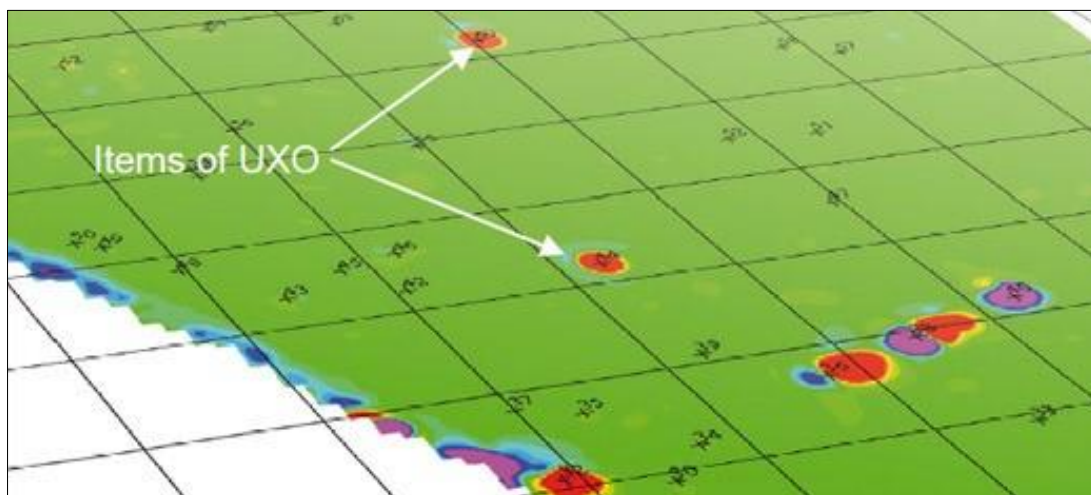


Fig 2: Items of UXO identified during geophysical survey.

In addition to geophysical sensors, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) play a pivotal role in UXO mitigation surveys. ROVs, tethered to surface vessels, allow for precise, operator-guided inspections of suspected UXOs, capturing visual confirmation through high-definition cameras. AUVs, operating independently with preprogrammed missions, enable efficient large-area surveys with advanced payloads including multi-beam echo sounders, synthetic aperture sonar, and magnetometer arrays (Ridolfi *et al.*, 2021; Goswami, 2022). Their ability to operate in deeper waters and challenging conditions makes them indispensable for

covering expansive offshore wind farm sites.

Diver-based surveys remain relevant in shallow zones where geophysical equipment may be less effective or where direct human intervention is required. Divers equipped with handheld magnetometers and imaging tools can confirm UXO presence, conduct detailed inspections, and assist in clearance operations. While diver surveys present higher safety risks and are limited by depth and environmental conditions, they provide an irreplaceable human perspective in complex nearshore environments.

The effectiveness of underwater surveys relies heavily on the accuracy and sophistication of data analysis. Raw

geophysical and visual data undergo systematic processing to filter noise, classify anomalies, and prioritize targets based on UXO-likelihood criteria. Machine learning techniques are increasingly being employed to enhance anomaly classification, enabling the differentiation between ordnance, scrap metal, and natural seabed features. Statistical risk evaluation frameworks integrate survey data with historical records of military activity and environmental factors to produce probabilistic risk assessments. These evaluations inform stakeholders on the level of clearance required, balancing operational safety with cost and environmental considerations. By ensuring that interpretations are both precise and evidence-based, data analysis transforms raw sensor output into actionable knowledge for UXO risk mitigation.

The integration of survey outputs into geographic information systems (GIS) has revolutionized UXO risk management in wind farm development. GIS platforms enable the spatial visualization of survey data, combining layers such as seabed morphology, detected anomalies, and construction layouts. This integration allows planners to model potential hazard zones, optimize turbine placement, and design cable routes that minimize UXO-related risks. Beyond GIS, the emerging use of digital twin technology offers a dynamic framework for project planning. Digital twins, virtual replicas of the physical environment, incorporate survey data, operational simulations, and real-time monitoring inputs to create a continuously updated risk model. This digital ecosystem not only enhances predictive capacity but also supports adaptive decision-making during construction and maintenance phases, ensuring long-term safety and efficiency (Panori *et al.*, 2021; Adepoju *et al.*, 2022).

Underwater surveys play a central role in UXO mitigation by combining detection, mapping, risk assessment, and clearance planning with advanced methodologies. Geophysical instruments, ROVs, AUVs, and diver-based approaches collectively provide the means to detect and confirm UXOs across diverse seabed conditions. Through sophisticated data analysis, anomalies are transformed into actionable risk evaluations, guiding safe and cost-effective clearance strategies. Integration with GIS and digital twins further strengthens the capacity of offshore wind farm developers to anticipate and manage UXO risks proactively. As the offshore renewable energy sector expands, underwater surveys will remain indispensable in ensuring that safety, environmental stewardship, and project timelines are maintained despite the challenges posed by legacy ordnance on the seabed.

2.3. Regulatory and Industry Frameworks

The development of offshore windfarms in areas potentially contaminated by unexploded ordnance (UXO) requires adherence to a complex web of international, regional, and industry-specific regulations (Price, 2021; Hannay and Zykov, 2022). These frameworks are designed to ensure that developers adopt systematic approaches to risk management, prioritize health and safety, and safeguard marine ecosystems. A clear understanding of these regulatory and industry frameworks is therefore critical for project planning, permitting, and execution.

At the international level, several conventions and organizations provide overarching guidelines relevant to UXO risk in offshore environments. The International

Maritime Organization (IMO), as the United Nations body responsible for maritime safety and environmental protection, sets standards that indirectly govern UXO-related practices. Instruments such as the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL) require member states and operators to adopt measures that prevent marine hazards, which encompass UXO clearance and disposal. The London Convention and Protocol on the dumping of wastes and other matter also regulates how UXO may be safely relocated or destroyed at sea.

In European waters, regulatory frameworks are particularly advanced, reflecting both the intensity of offshore wind development and the high prevalence of UXO contamination. The European Union Marine Strategy Framework Directive (MSFD) obligates member states to achieve good environmental status in their marine waters, requiring thorough risk assessments of seabed disturbances. Similarly, the EU Habitats Directive and the Environmental Impact Assessment (EIA) Directive ensure that UXO management is considered within broader environmental protection obligations. At the national level, maritime safety bodies such as the UK Maritime and Coastguard Agency (MCA), Germany's Federal Maritime and Hydrographic Agency (BSH), and the Danish Energy Agency provide additional regulatory oversight. These agencies often require developers to conduct UXO desk-based assessments and geophysical surveys before construction, with clearance operations overseen by certified explosive ordnance disposal (EOD) teams.

In the Asia-Pacific region, countries including Japan, South Korea, and Taiwan have begun formalizing UXO risk management protocols as offshore wind development accelerates. Although regulatory structures are less harmonized than in Europe, ministries of defense, transport, and environment are increasingly issuing project-specific requirements. This reflects growing recognition of UXO as both a safety and environmental concern in marine energy planning.

In addition to government regulations, the offshore wind industry adheres to a suite of technical standards and best-practice guidelines developed by professional organizations and certification bodies. DNV (Det Norske Veritas), one of the leading providers of assurance and risk management services, has issued several standards that address UXO risk within the broader framework of offshore wind farm construction. These include guidelines for risk assessment, geophysical survey methodology, and clearance operations, which help ensure consistent practices across international projects.

The Carbon Trust, through its Offshore Wind Accelerator (OWA) program, has developed practical guidance for developers on UXO risk management, including strategies for survey design, contractor selection, and data interpretation. This guidance has been widely adopted in Europe and informs early project planning phases. Similarly, the International Marine Contractors Association (IMCA) publishes operational guidelines on UXO surveys and clearance, covering safety protocols, competence requirements, and recommended technologies for detection. IMCA's standards are particularly influential for contractors and survey companies engaged in offshore operations.

Together, these industry standards provide a consistent

framework for developers, regulators, and contractors to manage UXO risks effectively. They complement legal requirements by translating broad regulatory principles into actionable methodologies.

UXO risk management is also embedded within broader environmental and safety governance frameworks. Environmental Impact Assessments (EIAs) are mandatory for offshore wind projects in most jurisdictions, requiring developers to evaluate potential impacts of UXO-related activities such as clearance detonations or seabed disturbance. EIAs typically assess ecological consequences, including noise pollution, sediment disruption, and chemical contamination, and propose mitigation measures such as controlled detonation or relocation strategies under strict environmental safeguards (Abdolkhaninezhad *et al.*, 2022; Kamaruddin *et al.*, 2022).

Parallel to environmental obligations, Health, Safety, and Environment (HSE) compliance forms a cornerstone of UXO risk management. Offshore wind projects must meet stringent HSE standards to protect workers, contractors, and surrounding communities. This entails comprehensive risk assessments, safety training, and contingency planning for UXO incidents. Regulators often require developers to

submit UXO risk mitigation plans as part of HSE documentation, ensuring that personnel are shielded from undue hazards during construction and maintenance. Compliance with frameworks such as the UK's Health and Safety at Work Act or international standards like ISO 45001 further reinforces safety culture within the industry.

The regulatory and industry frameworks governing UXO risk in offshore wind farm development reflect the intersection of international maritime law, regional directives, national oversight, and sector-specific standards. While international organizations such as the IMO establish broad principles, regional and national bodies provide more targeted requirements tailored to local environmental and historical conditions. Industry standards from organizations like DNV, Carbon Trust, and IMCA operationalize these principles into practical guidance for developers and contractors, as shown in Figure 2. Finally, EIAs and HSE compliance ensure that UXO management aligns with broader commitments to environmental sustainability and workforce safety. Together, these frameworks provide the foundation for responsible offshore wind expansion, enabling the sector to navigate legacy hazards while delivering on the promise of renewable energy.

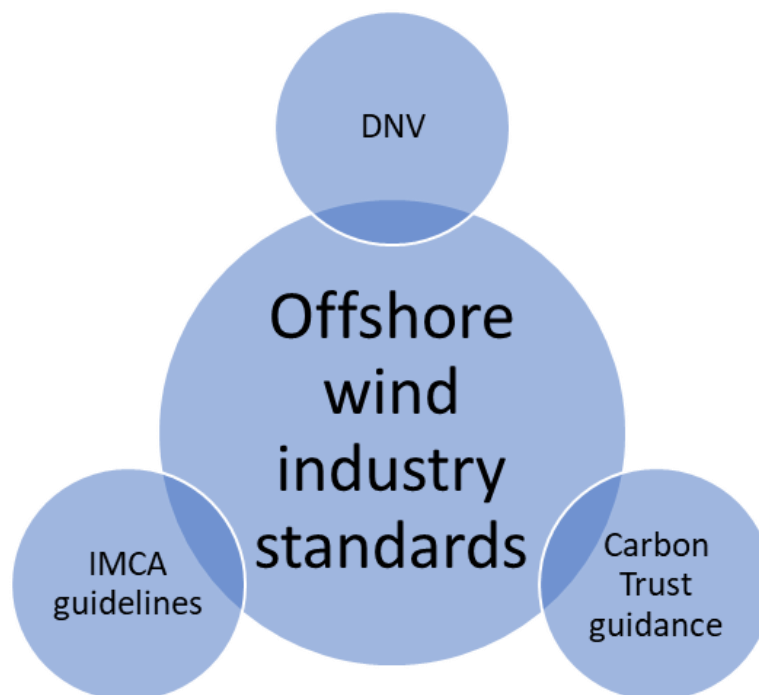


Fig 3: Offshore wind industry standards

2.4. Cost-Benefit Perspective

The development of offshore windfarms involves complex technical, environmental, and financial challenges, among which the presence of unexploded ordnance (UXO) constitutes one of the most critical risk factors. UXO, often remnants of past conflicts, can cause severe safety hazards, operational delays, and unanticipated costs if not adequately managed. Underwater UXO surveys have therefore become a standard component of offshore windfarm planning, yet their financial implications are often debated. From a cost-benefit perspective, investing in comprehensive UXO surveys yields substantial long-term advantages compared to the potential financial and operational losses associated with incidents, accidents, or delays (Johnston *et al.*, 2021;

Meindersma, 2022). Additionally, evolving risk-sharing models between developers, insurers, and contractors further highlight the strategic value of UXO mitigation.

Conducting a comprehensive UXO survey at the early stages of windfarm development requires a significant upfront investment. Depending on the scale of the site, environmental conditions, and the survey technologies employed, costs can range from several million to tens of millions of dollars. These expenses include mobilization of survey vessels, deployment of geophysical equipment such as side-scan sonar, magnetometers, and sub-bottom profilers, as well as specialized personnel for data collection and analysis (Río Fernandez, 2021; Tsai and Lin, 2022; Xu *et al.*, 2022). On top of this, confirmatory inspections by remotely operated

vehicles (ROVs) or divers add further financial requirements. However, the financial risks of bypassing or underfunding surveys are far greater. A single UXO detonation during construction can cause catastrophic damage to equipment, endanger lives, and halt operations indefinitely. Such incidents lead not only to immediate repair or replacement costs but also to prolonged project delays, loss of investor confidence, and potential legal liabilities. Furthermore, regulatory penalties may be imposed for failing to meet safety compliance standards. Even without accidents, discovering UXOs during late construction stages forces unplanned stoppages and costly rerouting of cables or turbine foundations, creating cascading delays that disrupt supply chains and inflate project costs. Thus, while the upfront expenditure for UXO surveys may appear high, it represents a relatively small fraction of total project investment compared to the financial and reputational losses associated with unmanaged UXO risks (Bukhari *et al.*, 2020; Wernert *et al.*, 2021).

The inherent risks associated with UXO in offshore wind farm projects have led to the development of risk-sharing frameworks that distribute responsibilities and liabilities among developers, insurers, and contractors. Developers typically bear the responsibility for commissioning UXO surveys to meet regulatory requirements and secure project financing. However, insurers play a crucial role by offering coverage for residual risks not eliminated through surveys, including unexpected discoveries or incidents during construction. This insurance coverage is contingent on evidence of thorough risk mitigation, meaning that without high-quality surveys, developers may struggle to obtain affordable or comprehensive insurance policies (Abubakar *et al.*, 2022; Mai *et al.*, 2022).

Contractors, particularly those involved in seabed preparation and cable installation, are also integrated into risk-sharing agreements. Many contracts specify that developers must provide verified UXO survey data before work commencement, transferring liability for undetected UXOs to the developer. Conversely, if contractors assume partial risk, they demand higher fees to offset potential hazards. Collaborative frameworks where all parties share both the costs and benefits of UXO risk management create more balanced financial outcomes, ensuring that the burden does not rest solely on one stakeholder (Douangphachanh *et al.*, 2022). In this way, survey investments are both a technical and contractual necessity for risk distribution in large-scale offshore energy projects.

Beyond immediate financial comparisons, the long-term benefits of UXO surveys significantly enhance the economic sustainability of offshore wind projects. One of the most critical advantages is improved project certainty. By detecting and addressing UXOs early, developers minimize unforeseen disruptions during construction and ensure that project timelines remain realistic and achievable. This certainty directly translates into lower contingency budgets, improved cost forecasting, and streamlined supply chain management.

Stakeholder confidence is another long-term outcome of UXO surveys. Investors, regulators, and local communities view robust UXO risk management as a reflection of responsible governance and commitment to safety. In an industry where delays and accidents can severely affect public perception and investment flows, demonstrating proactive mitigation fosters trust and facilitates regulatory

approvals. Moreover, insurers are more willing to provide comprehensive coverage at favorable rates when projects are backed by credible UXO survey data, further enhancing financial resilience (Feng, 2021; Kousky, 2022).

Finally, safety assurance represents a non-quantifiable yet vital benefit. The prevention of accidents not only protects human lives and marine ecosystems but also safeguards the reputation of the offshore renewable energy sector. Each successful project that integrates UXO surveys reinforces industry best practices, creating a cycle of continuous improvement and standardization. Over time, the adoption of advanced survey technologies and integration with digital tools such as GIS and digital twins further strengthens risk mitigation while reducing overall costs.

From a cost-benefit perspective, the initial investment in underwater UXO surveys is outweighed many times over by the financial, operational, and reputational risks of unmanaged ordnance hazards. Risk-sharing frameworks between developers, insurers, and contractors highlight the role of surveys as both a safety requirement and a financial safeguard. Beyond cost savings, the long-term benefits of improved project certainty, enhanced stakeholder confidence, and safety assurance establish UXO surveys as an indispensable component of offshore wind farm development. By framing survey investments not as optional expenditures but as integral risk management strategies, the offshore wind industry ensures that projects remain economically viable, socially responsible, and operationally safe (Kubacka *et al.*, 2021; Mohamed, 2021).

2.5. Best Practices for Developers

The presence of unexploded ordnance (UXO) in offshore environments presents a unique set of risks to the safe and cost-effective development of windfarms (Velenturf *et al.*, 2021; Thomsen *et al.*, 2021). Developers must therefore adopt proactive, systematic, and evidence-based practices to mitigate these risks while aligning with international regulations, industry standards, and sustainability goals. Best practices encompass the early integration of UXO risk assessment into project planning, the use of a multi-tiered survey strategy, collaboration with specialized institutions, and the application of continuous monitoring throughout the project lifecycle. Together, these measures ensure that UXO hazards are managed comprehensively, minimizing potential delays, cost overruns, and safety incidents.

Incorporating UXO considerations from the earliest stages of project development is critical for reducing uncertainty and preventing costly redesigns. During site selection and project design, developers should conduct preliminary assessments of historical conflict activity, naval operations, and military dumping practices in the proposed project area. This early-stage analysis helps determine the likelihood of UXO presence and allows developers to weigh UXO risk alongside other siting factors such as wind resource potential, grid connectivity, and environmental sensitivity. By embedding UXO risk into the initial feasibility studies, developers can design projects with optimized layouts that minimize the probability of encountering ordnance during construction activities.

A best-practice framework for UXO detection follows a multi-tiered survey methodology, which builds progressively from broad-scale research to detailed seabed mapping. This first stage involves reviewing historical records, naval archives, hydrographic charts, and prior survey data to

identify potential UXO contamination zones. It provides a strategic overview that guides subsequent field investigations. Using geophysical techniques such as side-scan sonar, magnetometers, and sub-bottom profilers, reconnaissance surveys cover large areas to detect anomalies consistent with UXO. While not exhaustive, they help refine priority zones for detailed inspection. This final stage applies high-resolution instruments and targeted inspections, often involving remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs). Detailed surveys provide precise data on the location, type, and burial depth of suspected items, supporting safe clearance operations.

This tiered approach ensures cost efficiency while maintaining high detection accuracy, allowing developers to focus resources on areas of greatest risk.

Effective UXO risk management requires collaboration beyond individual project teams. Military archives often contain invaluable information on historical battles, minefields, or dumping grounds, which can inform initial risk assessments. Hydrographic institutes, such as national hydrographic offices, provide seabed mapping data and sediment information that support UXO detection strategies. Additionally, UXO specialists—including explosive ordnance disposal (EOD) companies—bring technical expertise in risk assessment, survey interpretation, and clearance operations. Engaging with these institutions fosters data sharing, enhances survey accuracy, and ensures compliance with regulatory requirements. In many jurisdictions, regulators mandate consultation with certified EOD specialists before construction permits are granted, underscoring the importance of collaborative approaches (Berbrick *et al.*, 2020; VAVOULA *et al.*, 2020).

UXO risk does not end once clearance operations are complete; instead, developers must adopt continuous monitoring and adaptive management strategies throughout the lifecycle of the windfarm. Construction activities such as piling, dredging, or anchor deployment may reveal ordnance missed during surveys, requiring rapid response protocols. During the operational phase, periodic inspections ensure that seabed shifts or sediment erosion have not exposed previously buried items. Adaptive management frameworks allow developers to update risk assessments and mitigation measures as new information emerges, thereby maintaining safety and compliance over time. Importantly, continuous monitoring also reassures stakeholders—including insurers, regulators, and local communities—that UXO risks are being managed responsibly throughout the project's duration.

Best practices for developers in managing UXO risks are anchored in early planning, rigorous survey design, inter-institutional collaboration, and long-term risk monitoring. By integrating UXO assessments during site selection and project design, developers can prevent future delays and safety incidents. A multi-tiered survey approach ensures that risks are identified with precision and addressed efficiently, while collaboration with archives, hydrographic institutes, and UXO experts strengthens the knowledge base and operational capacity of projects. Finally, continuous monitoring and adaptive management safeguard both human safety and environmental sustainability across the project lifecycle. As offshore wind energy continues to expand globally, adherence to these best practices will be vital in securing safe, cost-effective, and environmentally responsible development while addressing the legacy hazards of past conflicts (Amaechi *et al.*, 2022; Androniceanu and

Sabie, 2022).

2.6. Future Directions

The global expansion of offshore wind energy presents unique opportunities and challenges, with unexploded ordnance (UXO) mitigation remaining a significant concern in project planning and execution (Feng, 2021; Thomsen *et al.*, 2021). While underwater surveys currently provide robust frameworks for risk identification and clearance, emerging technological, regulatory, and collaborative pathways are poised to reshape the landscape of UXO management. Future directions in this field are increasingly centered on the integration of artificial intelligence (AI), automation, international governance, and cross-sector partnerships as shown in Figure 3. Together, these developments will enhance detection efficiency, reduce risks, and ensure that UXO mitigation supports the safe and sustainable growth of renewable energy infrastructure.

One of the most promising future directions for UXO risk mitigation lies in the application of machine learning (ML) and AI-driven algorithms for anomaly detection. Current geophysical surveys generate vast datasets from side-scan sonar, magnetometers, and sub-bottom profilers, requiring extensive manual interpretation by specialists. This process is time-consuming, costly, and susceptible to human error. Emerging AI models trained on large datasets of known UXO signatures and non-hazardous seabed anomalies can significantly enhance detection accuracy (Akande *et al.*, 2023). Machine learning can be applied to automate classification, reduce false positives, and prioritize targets with the highest likelihood of being UXOs (Adeshina *et al.*, 2020; Lee and Shin, 2020). Beyond detection, AI-powered predictive models could integrate historical records, environmental conditions, and survey outputs to estimate the spatial probability of UXO presence across unexplored seabed zones. As these technologies mature, they will reduce reliance on manual interpretation, streamline risk assessments, and support faster decision-making in offshore wind farm planning.

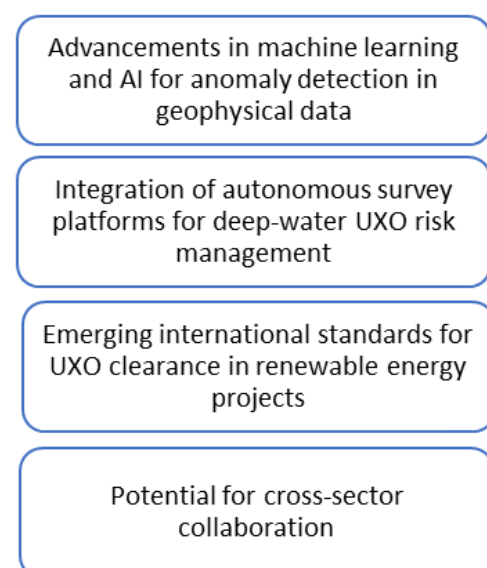


Fig 4: Future Directions

Another transformative development is the integration of autonomous survey platforms for UXO detection in deep-water environments. While remotely operated vehicles

(ROVs) remain indispensable, autonomous underwater vehicles (AUVs) are increasingly proving their value in large-area surveys, particularly in challenging or remote offshore zones. Future advancements will see AUVs equipped with multi-sensor payloads, including synthetic aperture sonar, magnetometer arrays, and high-resolution optical cameras, enabling them to perform simultaneous detection and classification tasks. Furthermore, the convergence of AI with autonomy will allow AUVs to adapt their search strategies in real-time, focusing on areas of higher UXO probability without constant human intervention (Teng and Zhao, 2020; Laird, 2021). This self-learning capability not only reduces operational costs but also improves safety by limiting the need for human presence in hazardous areas. With offshore windfarms moving further into deep-water locations, autonomous survey systems will become indispensable for efficient and scalable UXO risk management.

Regulatory harmonization represents another critical future direction. At present, UXO survey and clearance practices vary across jurisdictions, with some countries lacking detailed guidelines or standardized protocols. This inconsistency poses challenges for developers operating across multiple regions and undermines global best practices. However, international organizations and regulatory bodies are beginning to establish common standards for UXO risk management in renewable energy projects. These include harmonized methodologies for survey execution, data interpretation, clearance thresholds, and post-clearance verification. Emerging standards will not only enhance safety but also provide clarity for developers and insurers, reducing uncertainties and financial risks. Standardization may also drive innovation, as technology developers design survey tools and data processing systems tailored to comply with global requirements (Blind *et al.*, 2020; Viardot *et al.*, 2021). Over time, unified international standards will foster consistency, transparency, and accountability in UXO mitigation practices across the offshore renewable energy sector.

Future progress in UXO risk management will also depend heavily on cross-sector collaboration. The defense sector, which has extensive experience in UXO clearance, can contribute advanced detection technologies, ordnance expertise, and training resources. Marine science institutions, meanwhile, provide critical knowledge of seabed geology and ecological dynamics, ensuring that UXO mitigation strategies are environmentally sensitive. Collaboration with the renewable energy industry itself ensures that detection and clearance technologies are adapted to the specific needs of windfarm development, including scalability, cost-efficiency, and integration with digital planning tools. Such partnerships can lead to shared research programs, joint technology development, and open-access databases of UXO survey data. Importantly, cross-sector collaboration may also accelerate the adoption of dual-use technologies, such as defense-grade sensors adapted for commercial survey operations. By combining expertise from defense, marine science, and renewable energy, future UXO mitigation efforts will achieve greater accuracy, efficiency, and sustainability (Shum *et al.*, 2021; Rennie and Brandt, 2021).

The future of UXO mitigation in offshore wind farm

development will be defined by technological innovation, regulatory harmonization, and collaborative approaches. Machine learning and AI promise to revolutionize anomaly detection by automating classification and enhancing predictive modeling. Autonomous survey platforms, particularly AUVs, will expand the capacity for efficient and safe UXO detection in deep-water environments (Akanke *et al.*, 2023). At the same time, emerging international standards will provide consistency, improving safety and financial certainty for developers and insurers alike (Bains *et al.*, 2022; Shetty *et al.*, 2022). Finally, cross-sector collaboration will leverage expertise from defense, marine science, and renewable energy to create integrated, sustainable solutions. Together, these future directions will transform UXO mitigation from a reactive necessity into a proactive enabler of safe, efficient, and globally scalable offshore renewable energy projects.

3. Conclusion

The expansion of offshore wind energy represents a pivotal step in the global transition toward sustainable and low-carbon energy systems. Yet, this progress is challenged by the persistent legacy of unexploded ordnance (UXO) in marine environments, which continues to threaten safety, disrupt project timelines, and pose environmental hazards. Underwater surveys have emerged as the cornerstone of UXO risk mitigation, providing developers with the tools and data needed to detect, characterize, and manage ordnance hazards effectively. By integrating advanced survey methodologies such as geophysical mapping, remotely operated vehicles, and autonomous platforms, developers can significantly reduce the likelihood of accidents while enhancing the overall reliability of project planning and execution.

Ensuring safety, regulatory compliance, and sustainability must remain central to offshore wind farm development. Comprehensive underwater surveys not only protect workers and contractors from life-threatening risks but also ensure adherence to international and regional regulations governing maritime safety, environmental protection, and project accountability. From a sustainability perspective, careful UXO management prevents ecological disruption and reinforces the environmental integrity of renewable energy initiatives, thereby aligning clean energy production with broader conservation goals.

Looking forward, the sector must embrace proactive, technology-driven, and collaborative strategies to secure future offshore energy infrastructure. Advances in artificial intelligence, machine learning, and autonomous survey systems will improve the accuracy and efficiency of UXO detection, while partnerships with military archives, hydrographic institutes, and ordnance disposal experts will enhance the robustness of risk assessments. Collaboration across regulators, developers, and industry bodies is equally vital to establish standardized practices and reducing uncertainty. By embedding UXO risk mitigation into every stage of project development, the offshore wind sector can overcome legacy challenges and deliver safe, efficient, and environmentally responsible energy solutions that underpin the global clean energy transition.

4. Appendix

UXO ASSESSMENT PROCESS



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How to Cite This Article

Wegner DC, Ayansiji K. Mitigating UXO Risks: The Importance of Underwater Surveys in Windfarm Development. *International Journal of Multidisciplinary Research and Growth Evaluation.* 2023;4(2):915–926. doi:10.54660/IJMRGE.2023.4.2.915-926

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