Journal of Frontiers in Multidisciplinary Research

Sustainability and Low-Carbon Transitions in Offshore Energy Systems: A Review of Inspection and Monitoring Challenges

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Article Info

E-ISSN: 3050-9726
P-ISSN: 3050-9718
Volume: 04
Issue: 02
July – December 2023
Received: 15-08-2023
Accepted: 18-09-2023
Published: 21-10-2023
Page No: 273-285

Abstract
The advancement of offshore and ocean energy technologies is shifting focus towards sustainable energy systems integration while balancing the net-zero GHG emissions. These developments of offshore wind, tidal, and wave technologies serves as either a complement to, or a substitute for, traditional oil and gas systems. With the integration of offshore renewable energy technologies, there has been a rise in the development of operational inspection and monitoring, impact assessment, carbon-neutral operational performance, and the resilience and longevity of assets. Renewable technologies, such as those advancing offshore wind, tidal, and wave systems, contrast with traditional offshore systems, which operate in dynamic marine environments. In contrast, mature hydrocarbon offshore platforms often face data deserts. The integration of the external systems' photogrammetry, remote sensing, digital twinning, and AVs creates a versatile solution for inspection. However, poor data quality, lack of data standardization, and lack of standard interoperability frameworks pose key challenges to monitoring. The carbon emission monitoring due to net-zero policy ship emissions, in addition to the operational energy usage, poses regrettable emissions, undermining the operational sustainability goal. The shifts in operational energy usage and vessel carbon emissions impact reliability as well. Offshore assets are highly exposed to extreme climate events, biofouling, and other climate impacts. Predictive analytics, through Machine Learning, is being sought to estimate the failures to optimize the inspection intervals while aligning with DOE and DHS frameworks. It remains difficult to merge conventional oil and gas inspection techniques with new low-carbon, data-driven approaches suited for renewable infrastructures. This review underscores the necessity for internationally unified monitoring protocols, carbon-neutral inspection processes, and complementary lifecycle assessments to preserve the technical dependability and sustainability of renewable offshore systems. The offshore energy industry, for example, would be able to fully offset any operational emissions, become more resilient, and meet global net-zero targets faster. They would achieve this faster if the challenges related to sustainability and dependability were addressed simultaneously.

DOI: https://doi.org/10.54660/.JFMR.2023.4.2.273-285

Keywords: Sustainability, Low-Carbon Transitions, Offshore Energy Systems, Inspection Challenges, Monitoring Challenges

1. Introduction

Nations are formulating approaches aimed at reducing emissions, minimizing climate change consequences, and implementing strategies for sustainable development, all of which are accompanied by significant shifts within the frame of energy systems globally (Zohuri, 2023; Gan *et al.*, 2023). Steps taken toward achieving net-zero emissions, coupled with the commitments adopted by the Paris Agreement, have shifted the focus toward energy systems devoid of fossil fuels, while simultaneously decarbonizing the energy systems (Pye *et al.*, 2021; Balgehshiri and Zohuri, 2023). Such change(s) are needed, as the altered industrial value chains, energy markets, and the governance of the natural environment have had impacts that reach further than technological advancements. In this regard, the newly recognized offshore energy systems, which were configured to accommodate the oil and gas industry, are viewed as important sites for the development of large-scale renewable energy systems such as offshore wind, wave, and tidal energy (Carleton *et al*., 2021; Zimmer *et al*., 2023). In regard to the ongoing global energy transitions, the systems in consideration are critical due to their locations, ease of access to the powerful and continuous natural energy resources, and their ability to connect with the existing marine infrastructure (Eales *et al*., 2021; Teniwut *et al*., 2022).

Systems for offshore energy are increasingly acknowledged for their potential contribution toward the attainment of net-zero targets. For instance, offshore wind farms are developing at a rapid pace throughout Europe, Asia, and North America, and greatly assist with national decarbonization strategies as well as policies. In the same way, although less developed, tidal and wave energy systems offer exceptional potential as intermittent and dependable renewable energy sources (Khare and Bhuiyan, 2022; Gidiagbaa *et al*., 2023). These systems create hybrid opportunities, wherein renewable technologies are configured with the currently deployed offshore oil and gas infrastructure, reducing the operational carbon footprint through joint logistics. However, the offshore renewables potential is still limited for numerous reasons, including the technical, operational, and geopolitical realities tied to surveillance, monitoring, and long-term reliability (Salvador and Ribeiro, 2023; Giannopoulos, 2023).

Just like any other processes that happen offshore, reliable and sustainable offshore operations require consistent monitoring and inspections. Compared to onshore systems, "offshore assets function under more challenging and extreme conditions, including the effects of saltwater, corrosion, and weather, extreme currents and biofouling" (Googan, 2022; Mannino *et al*, 2023). Clearly, the aforementioned conditions lead to accelerated material degradation, operational risks, and structural failures. Because of the scuba diver surveys, the rest of the monitoring methods being examined seem more cost-effective and less resource-intensive. "Digital technologies (ROVs, AUVs, drones, and digital twin frameworks) enable constant and data-driven monitoring of offshore assets" (Chen *et al*., 2023; Wibisono *et al*., 2023). While new technology like ROVs and AUVs has eased the processes of data collection, many new issues have been introduced, including data systematization, vulnerability that comes with cybersecurity, and the complexity of giving meaningful interpretation to complex data sets. "To bridge the gap in the low-carbon context, monitoring and inspection frameworks should integrate technology and balance it with supportive policies towards the environment" (Banihabib and Assadi, 2023; Fasasi *et al*., 2023).

This review exists at the crossroad of expanding offshore energy and the acute need for low-carbon transitions. It seeks to analyze the rationales for the renewable energy offshore systems and the challenges of inspection, resilience, and the strive for carbon-neutrality. In particular, it explains the emphasis on how inspection techniques have to change to meet the particular structural and operational attributes of offshore wind, tidal, and wave systems. Also, it deals with the resilience of these systems to climate change impacts, in particular, rising seas and more frequent and intense storms, and how predictive analytics might assist in that preparedness. In addition, it addresses the active carbon emissions of the current inspection and monitoring activities and emissions reduction pathways that include renewable energy-powered inspection platforms, life cycle sustainability assessment, and rationalized global policies and standards (Asif *et al*., 2022; Arul *et al*., 2023).

Positioning inspection and monitoring as pivotal to the successful transition of offshore energy to low-carbon sources reinforces the need to integrate oil and gas legacy practices with new data-centric approaches to renewable infrastructures (Ofoedu *et al*., 2022; Bassey, 2022). This includes the technological dimension, but also the regulatory, environmental, and operational aspects, thus offering a synthesized understanding of the next relations. This approach enhances the technological dependability and resilience of offshore energy systems, while also aligning with the sustainability and net-zero targets of the international community.

2. Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was applied to ensure a transparent, reproducible, and structured review of literature on sustainability and low-carbon transitions in offshore energy systems, with a focus on inspection and monitoring challenges. The review began with the identification of relevant databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and SpringerLink, as these platforms host peer-reviewed research on renewable energy integration, offshore operations, inspection technologies, and low-carbon frameworks. Keywords and Boolean operators were combined to capture the scope of the study, such as "offshore energy," "renewable integration," "low-carbon transition," "inspection challenges," "monitoring systems," "sustainability," "wind energy," "tidal energy," and "carbon-neutral operations." The initial search produced 1,243 records.

After removal of duplicates, 876 articles remained and were screened by titles and abstracts. Studies unrelated to offshore systems, purely theoretical discussions with no inspection or monitoring relevance, or those focused exclusively on onshore energy infrastructure were excluded. This step reduced the pool to 324 articles. The eligibility stage involved full-text assessment, guided by inclusion criteria that required studies to address at least one of the following: integration of renewable offshore energy systems, inspection technologies for offshore structures, sustainability frameworks, or monitoring strategies to support carbon reduction. Exclusion criteria included conference abstracts without full data, opinion pieces, and studies older than 20 years unless deemed seminal. Following this process, 142 articles were shortlisted for final synthesis.

Data extraction was carried out systematically, capturing study objectives, methodologies, key findings, and identified challenges. Particular attention was given to reported limitations in inspection and monitoring systems, high costs of advanced sensor deployment, interoperability and standardization barriers, and resilience requirements in offshore operations under low-carbon frameworks. Cross-comparison enabled the identification of recurring themes, including the increasing demand for real-time monitoring, reliance on AI-driven analytics, and the difficulty of scaling technologies across wind and tidal infrastructures.

The final review synthesized evidence across these studies, highlighting both technological opportunities and unresolved challenges. Using the PRISMA approach ensured that the evidence base was comprehensive and robust, while minimizing selection bias and ensuring reproducibility. The methodology provided a structured foundation for critically examining inspection and monitoring as essential enablers of sustainability and low-carbon transitions in offshore energy systems.

2.1. Integrating Renewable Energy into Offshore Systems

The shift to low-carbon offshore energy systems is a key element in tackling the global climate emergency while providing new sustainable energy systems. Leading the way are technologies associated with the offshore exploitation of wind, tidal, and wave energy, all of which are associated with the huge, yet largely untapped, promise of marine resources, as shown in Figure 1(Saha *et al*., 2023; Oliver, 2023). The integration of these paired renewable sources and offshore structures is especially problematic in the areas of inspection, monitoring, and long-term resiliency. This is compounded by the harsh conditions of marine environments, the hybrid integration with the oil and gas existing platforms, and the offshore systems' renewable and sustainable systems. This attempts to outline the inspection and monitoring of hybrid systems with offshore wind, tidal, and wave energy, as well as the evolving offshore energy hybrid systems toward sustainability (Greaves *et al*., 2022; Hosseinzadeh *et al*., 2023).

The expansion of offshore wind has been the focus of renewables integration in the offshore domain, with large-scale farms deployed in Europe, Asia, and increasingly North America. The scalability of offshore wind, especially in deep-water locations, offers large benefits in helping achieve decarbonization goals. This expansion, however, comes with significant engineering challenges, for which reliable inspection and monitoring systems are essential.

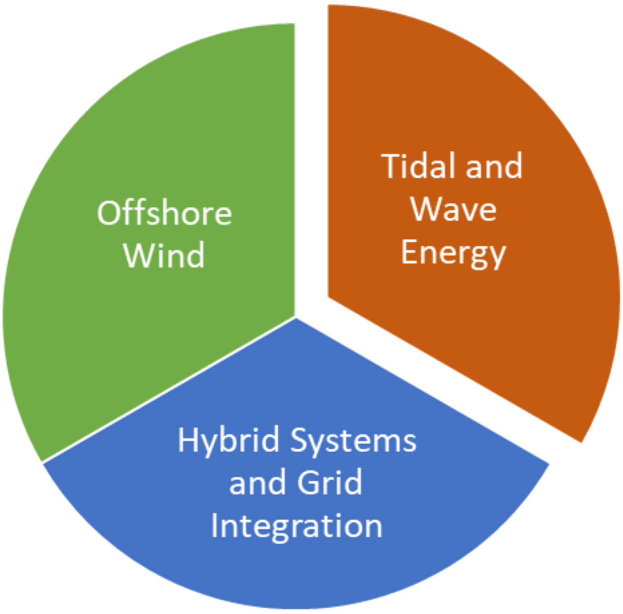

Fig 1: Integrating Renewable Energy into Offshore Systems

The various types of foundations pose different types of challenges for inspectors. Pole-mounted monopiles, the most widely used means of support for given structures, bear pulp-like and bone-like mechanical structures simultaneously due to wind, wave, and current loading. This can lead to the formation of cracks and fatigue damage, requiring regular non-destructive testing (NDT) and remote visual inspection (RVI) to monitor. Floating platforms and structures, more commonly used for deeper water installations, add to the complexity of the situation. Unlike static foundations, floating platforms undergo dynamic motions and therefore have a high risk of fatigue failure in the mooring lines, anchors, and joints of the platform (Amiri *et al*, 2021; Zhang *et al*, 2024). Of equal importance is the monitoring of the integrity of submarine cables, as they constitute the backbone for energy transmission from the turbines to the shoreline. Submerged cables are some of the most expensive pieces of infrastructure due to the cost and risk of damage associated with their repair and the difficulty of accessing them when they are punctured or damaged.

Such inspection challenges are intensified by environmental stressors. Saltwater corrosion continues to degrade titanium structures, while biofouling decreases hydrodynamic performance and accelerates hydrodynamic structure wear. Structures' fatigue loading also increases the complexity of predicting long-term performance, with cyclic wind, wave, and turbine operation activities. There is still difficulty with the use of advanced sensors, digital twins, and autonomous underwater vehicles (AUVs) for detection due to the high costs of implementation. There are also gaps in the global standard protocols, which further set back general use. The offshore wind farms scaling in capacity and geographic, this further increases the need to address these inspection and monitoring demands to sustain operations (Kou *et al*., 2022; Adekanmbi *et al*., 2024) indicate that with).

Offshore wind technologies are still relatively mature, while tidal and wave energy technologies still tend to lag in operations and dataset availability. Due to the vast quantities, these two resources are highly predictable and abundant, yet offer unique challenges for integration into offshore systems. The inspection framework reliability data keeps adapting to real-time unplanned degradation modes (Tzachor *et al*., 2022; Reza *et al*., 2024).

"Amongst the most critical problems to address in dynamic inspection technology, and a class of multi-faceted problems, focus on the submerged portion of the structure. Tidal turbines, for instance, possess rotor blades, gearboxes, and bearings that function in turbulent marine waters under extreme hydrodynamic streaming. These devices are concealed and require the services of divers, ROVs, and purpose-built AUVs to make the required assessments. A similar problem occurs for oscillating water column devices and certain types of wave energy converters employing point absorbers and attenuators. These devices possess components that are continuously impacted by oscillating stressors. Predictive analytics tools accounting for the above-water surface in-situ loading patterns (Zhu *et al*., 2022; Ahmada, 2024) are required.

In the adjacent document, multi-mode wave energy converters are classified by certain marine condition attributes and service underway. In contrast to the offshore wind regime, which is subject to the relatively regular marine conditions, the offshore service patterns, i.e., tidal and wave resources, are governed by a lattice of hydrodynamic adjustable settings formed by morphologies of sea bottoms, tidal capacities, and storm frequencies. This level of disorder places a bounding surface on operating ranges of the tidal device and wave device, establishing envelope constraints for inspection and service intervals. Submerged devices are less subject to the enviro stressors of bio corrosion and bio fouling; inspection devices should possess serviceable attributes for wave condition prediction (Ubina and Cheng, 2022; Kakolu and Faheem, 2023).

Even with the barriers, the opportunities for innovation brought about by monitoring and inspection for tidal and wave energy are significant (Adanta *et al*., 2024; Simbolon *et al*., 2024). The reliability of modular device architectures, condition monitoring systems, and integrated sensor arrays can be improved as systems become more modular. However, the current size of tidal and wave energy deployments greatly constrains the resources available for monitoring standardization. This makes collaboration between industry, academic institutions, and government regulators crucial in advancing these technologies.

Recent offshore territories encounter new types of energy integration by the installation of new renewable wind energy systems on traditionally used oil and gas rigs. This integration allows better construction and functional spatial efficiency of infrastructural (Greaves *et al*., 2022; Jonasson *et al*., 2024). These new wind or tidal energy hybrid systems will create complex grid systems and shared structures with older oil rigs while enabling streamlined upkeep and operation networks, as shown in Figure 2. This advanced method has the potential to shift the offshore power economy and the infrastructure, moving toward greener ecosystems by reducing the reliance on dominantly used fossil fuels in Table 1.

Monitoring and inspections in the offshore energy sector are greatly transformed under the new circumstances of multi-renewable hydrodynamics systems networks. Customary oil and gas installations require advanced, skilled inspectors and nominate boundaries due to their profound risk of safety and damage to nature. The newest enhancement with renewable energy systems creates new complexities with structural interfaces, cable networks, and power systems under the integrated frameworks of (Deveci *et al*., 2022; Fan *et al*., 2023). An example of monitoring in the hybrid offshore system is monitoring the vibration and rust components, which interlink the domino structures. The connection of the wind power components to oil and gas grid components relies on advanced monitoring systems, which provide deep domain complex patterns of electrical, mechanical, and structural subsystems.

Integrating grids remains a key obstacle. This involves balancing the operational needs of the offshore platforms and the onshore grids with the variable nature of renewable energy sources. This also involves the real-time assessment of power grids, power quality, and cybersecurity of the grid. Predictive analytics, energy digital twins, and resilience models can also be used for forecasting grids, diagnosing grids, and ensuring grid resilience. However, the inter-domain, cross-border regulations and standardized data hamper their effectiveness (Bazmohammadi *et al*., 2021; Wu *et al*., 2023). These systems also lack cohesive offshore codes, which, together with cross-border regulations, detrimentally impact the integration of hybrid offshore systems.

While this remains problematic, considering existing infrastructure can offer a basis for hybrid energy integration systems. This reduces the carbon emissions, increases the life span of the asset, and lowers the operational costs. However, hybrid offshore systems should be inspected and monitored for operational safety, reliability, and sustainability to guarantee economic attractiveness.

The incorporation of renewable energy into offshore structures is pivotal toward reaching global decarbonization and sustainability aims. Each offshore wind, tidal, and wave energy has its own prospects and issue field, especially in terms of inspection and monitoring (Rinaldi *et al*., 2021; Ali *et al*., 2021). Offshore wind energy platforms face unique structural fatigue, corrosion, and internal cable inspection limitations that will require novel monitoring and management solutions. Tidal and wave energy systems require submerged dynamic component monitoring while wave systems operate under variable and uncontrolled conditions. Moreover, hybrid systems emphasize the challenges associated with multiple renewable energy source infrastructures and the constant and seamless integration into the grid that will be required for net-zero emissions.

Overcoming these issues will come from the use of digitally twinned systems, hybrid autonomous and AI vehicles for inspection, and cross-border, tacit, and collaborative eco-regulatory treaties for aligned governance and standardization of data and processes (Mihai *et al*., 2022; Samuel *et al*., 2023). Integration of renewables offshore and the inspection and monitoring systems that will be developed in order to maintain efficiencies and safeguards during the automation all hinge on technological advancements.

2.2 Inspection Demands in Low-Carbon Offshore Operations

The transition to low-carbon offshore energy systems requires a change to the methodology for inspection and monitoring of asset reliability and safety practices, and their sustainable use. Offshore environments are inherently harsh, and attack the physical assets with fatigue, corrosion, and marine growth, and with mechanical and climate stressors (Chirdeep *et al*., 2023; Letcher, 2023). These problems are even worse with novel and dynamic offshore renewable energy systems, such as wind farms and tidal turbines, where the structure of the systems is new and the energy is hydrodynamic, as shown in Figure 2. Proper and rapid inspection of the structures is important as it supports maintenance, minimizes emissions, and extends the life of the asset in Table 1. This focuses on the inspection challenges and the evolving dimensions of inspection technologies, relentless issues of data centralization, standardization, and the evolving safety compliance issues within the sustainable offshore operational framework.

In the past, the only means to inspect offshore structures and machinery was the use of human divers who performed visual and manual evaluations of subsea structures and machinery. Although effective during the initial stages of offshore oil and gas activities, the use of diver inspections was limited by the maximum possible depth of diving, safety concerns along with operational costs and safety. Diving support vessels used to deploy divers also had high carbon emissions which further conflicted with the new need for sustainable operations and support vessels (Srivastava *et al*., 2022, Barnes *et al*., 2023).

Fig 2: Inspection Demands in Low-Carbon Offshore Operations

The use of remotely operated vehicles (ROVs) marked a major shift, as they were the first vehicles to enable safer and more efficient operations by extending the operational range. ROVs equipped with high-resolution imaging and sonar mapping, along with manipulator arms capable of performing complex tasks, were able to inspect a wide range of depths. Inspection practices have advanced to another level with autonomous underwater vehicles (AUVs), which can carry out inspections alongside other activities on untethered, pre-programmed missions that cover larger areas with reduced logistics. More recently, the use of aerial drones, which allow for fast inspection of offshore structures like wind turbine blades, flare stacks, and substation with minimum human presence (Courbis *et al*., 2023; Svensson, 2023).

Automated image recognition, defect classification, and anomaly detection are capabilities enabled by accompanying artificial intelligence (AI) and machine learning for these robotic platforms (Javaid *et al*., 2022; Vermesan *et al*., 2022). These systems greatly lessen the need for human analysis and, in the process, speed up reliability while reducing human interaction and consequently human error. AI-backed analytics in renewable energy systems with repetitive, modular components, such as arrays of wind turbine towers, can improve uniformity of inspection quality across massive fleets.

Inspection technologies get further advanced by the use of digital twins. Assets in offshore locations can be virtually modeled and monitored in real-time alongside other predictive data to test degradation, performance, and failure of components. This paradigm shift moves inspection away from the outdated periodic and reactive paradigm and toward proactive, condition-based management that eliminates unplanned downtime and aligns with carbon-neutral objectives. Digital twins also allow testing of impacts such as increased storm intensity and sea-level rise, reinforcing the strategic value of inspection in relation to sustainability transitions. This demonstrates how digital twins assist with climate resilience by integrating inspection data with predictive models to strengthen the framework of sustainability transitions (Henriksen *et al*., 2022; Zhen, 2023).

Table 1: Safety and Regulatory Compliance

Focus Area	Key Points	Implications for Offshore Inspection and Operations
Stricter environmental and safety requirements for sustainable operations	Offshore industries face increasingly stringent environmental protection rules (e.g., emissions limits, biodiversity safeguards) alongside traditional safety standards.	Requires adoption of greener inspection technologies, compliance with multi-jurisdictional frameworks, and integration of safety with sustainability metrics.
Challenges of balancing carbon-neutral inspection methods	Transition to low-emission support vessels, renewable-powered drones, and hybrid inspection logistics is still constrained by costs, infrastructure availability, and regulatory uncertainty.	Operators must balance regulatory compliance, operational efficiency, and carbon-reduction targets, while avoiding risks of non-compliance or increased inspection costs.

Regardless of the advancements in inspection technologies, problems still arise in the management of offshore systems as well as the standardization of inspection data. One of the major problems stems from the differences in inspection datasets of fossil fuel infrastructures versus renewable energy infrastructures. Inspection data for oil and gas platforms date back decades, and oil and gas platforms have well-established methodologies regarding defect classification and risk prioritization (Ma *et al*., 2021; Tong *et al*., 2023). This is in contrast with offshore wind, tidal, and wave systems, which still lack long-term operational data as well as established inspection protocols. This lack of symmetry makes it exceedingly difficult to use data from the oil and gas sector to apply risk-based reliability models to renewable infrastructures, due to the fact that there is no easy method for developed systems to cater to developing systems.

Even more problematic is the fact that there are no globally accepted standards for monitoring renewable assets. While there are frameworks constructed by classification societies and regulatory bodies for oil and gas operations, these frameworks are absent for renewable energy operations. For instance, the methodology used for inspecting the blades of offshore wind turbines differs in Europe and Asia, creating gaps in cohesion for data compatibility and performance benchmarking for assets. These conflicts, poor cohesion, and lack of established relationships create gaps that prevent the construction of unified databases that support predictive analytics and enhance the sharing of knowledge to help other regions (Shukla *et al*., 2023; Bühler *et al*., 2023).

The use of different types of inspection platforms creates issues related to data quality and interoperability. ROVs, AUVs, and drones, as well as digital twins, simultaneously produce and acquire data of diverse kinds, from high-resolution images to sonic recordings and real-time sensor data. The absence of common standards and integration frameworks makes combining these datasets into meaningful analytics an unresolved technical and administrative problem (Agboola *et al*., 2023; Somasundaram, 2023). In addition, the cybersecurity challenges of sending and archiving sensitive inspection data augment the problem of building an interoperable framework for monitoring.

There is an urgent need to develop global standards for inspection data of renewable energy systems. These standards would improve comparability and reliability, as well as facilitate the construction of common predictive models for resilience and sustainability. Efforts to unify inspection protocols should also consider the renewable assets lifecycle, ensuring data-based decision-making for installation, operation, and decommissioning is aligned with carbon-neutral goals.

While the industry transitions offshore energy systems to a low-carbon future, it is a requirement to incorporate safety and inspection practices, compliance regulations, and lower carbon emissions. To ensure the safety of the workers and marine life, offshore infrastructures need to meet sustainability goals. In the wake of meeting the sustainability regulations set, there have been increased measures enforced that require even lower emissions and more thorough inspection and verification processes, for decarbonization and compliance to goals set on structural integrity and minimized ecosystem risks (Eyinade *et al*., 2021; Khanam *et al*., 2023)

One of the most important challenges is the need to balance all of these requirements while minimizing emissions that result from inspection operations. Traditional inspection logistics use a diesel-powered system to and from the offshore sites, thus contributing to the inspection campaigns' carbon footprint, resulting in the potential of violating the purpose of renewable energy added (McMillan *et al*., 2023; Kar *et al*., 2023). The most useful solution has proven to be the most constrained in terms of cost, scalability, availability, and emissions- supplementing fewer emissions or hybrid inspection vessels, renewable energy-powered monitoring platforms, and solar buoys and wind-assisted drones.

Regulatory compliance also involves integrating automated inspection IP. As A.I analytics for digital twins advance and integrate themselves with decision-making in inspections, regulatory compliance must ensure algorithmic auditability, data integrity, and cyber resilience. This has special importance for offshore critical energy infrastructure systems where failure has a disproportionate and cascading economic and environmental impact (Mohammed *et al*., 2022; Pal *et al*., 2023). Innovation and compliance are not self-sufficient and require joint tools from the private sector, the public sector and international governance structures to sustain innovation while ensuring compliance to safety and environmental standards.

Finally, the scope of safety goes beyond systems and technology to the people in the organization. Automating most manual inspections does reduce a lot of risk but doesn't eliminate the need for people particularly when complex systems need some verification from human operators and when AI ingested outputs need some approval (Yaseen, 2021; Falco *et al*., 2021). This means that having a workforce free from the new socially accepted forms of exploitation and capable of operating the advanced platforms for inspection, while also abiding to low-carbon practices is a regulatory and operational requirement.

The need for inspections in offshore low-carbon operations stem from a combination of technological barriers, difficulties in data management, and compliance obligations. The transition from a diver's constituent inspections to digitally-connected, AI-enabled systems has revolutionized the ability to monitor offshore assets. However, issues of data variance, absence of international norms, and the inspections' logistics carbon footprint significantly impede the alignment of inspection operations with sustainability goals. Additionally, the increasing concern for safety and environmental protection demands a paradigm shift in inspection systems to incorporate reliable, resilient, and carbon-neutral methodologies (He *et al*., 2023; Liang *et al*., 2023). Well-planned and effective monitoring systems are equilibrium for the offshore energy industry for the fulfilment of dual objectives of low-carbon economic transition and dependable energy provision.

2.3 Resilience in Offshore Low-Carbon Systems

The global risk landscape in energy transition continues to evolve with the further development of offshore wind, tidal, and wave power, and their hybrid energy systems. The use of such low-carbon technologies in hybrid systems is a significant development. At the same time, these operations and systems face challenges in their performance stability. Extremely harsh offshore conditions expose structures and associated assets to a range of mechanical, chemical, and physical energies. The use of digital technologies also introduces issues of data, analytics, and collaboration silos around the protective and predictive systems (Liu *et al*., 2023;

Chen *et al*., 2023). The low carbon resilience systems offshore seamlessly combine engineering robust assets with the adaptive inspection and modeling, along with the use of predictive systems to lessons derived from the oil and gas industry.

Climate and environmental components have a critical impact on the robustness of offshore low-carbon systems. Due to climate change, heightened storm activity has already impacted offshore wind farms and subsea cable networks, resulting in interruptions to the energy supply and expensive repairs. Severe storm surges and extreme wave loads inflict considerable damage to the foundations, mooring systems, and turbine towers, increasing the risk of structural fatigue and critical system failure. Coupled with rising sea levels, which modify the dynamic load boundaries, the complex interactions within the wave-surge-saturated zone alter the bottom conditions, the ratio of superstructure to wave height, and the exposure threshold defined by structural silencing. Additionally, these conditions change the long-term wave pattern and hydrodynamics of the region, which affect the reliability and operation of tidal and wave energy converters, ultimately resulting in more frequent shutdowns during low wave intensity periods (Baloch *et al*., 2021; Wang *et al*., 2023).

The climate stressors directly impact both inspection scheduling and resilience planning. Any inspection planning using traditional frameworks as a baseline, which often utilize rigid, set timelines, will no longer be feasible in a world filled with growing uncertainty and diversity. What is needed instead is a more adaptive method to inspection planning, where changes in the forecasts and real-time data of the monitored structure's health will determine the level of inspection and supply needed. For instance, within turbine blades, subsea cables, and floating platforms, advanced sensors raise alarms when there is accelerated wear, enabling corrective measures to be taken before damage is sustained. More to the point, in resilience planning, compound events should be more thoroughly examined, such as the synchronized exposure to high winds, waves, and corrosive seawater, which has a high probability of precipitating unexpected failure modes (Lu *et al*., 2022; Moeini and Memari, 2023). These offenses, as part of the inspection and monitoring frameworks, will enable lower emission systems to offshore more sophisticated capabilities to accommodate the elements of uncertainty brought about by climate change.

For offshore low-carbon systems, protective maintenance is an integral part of resilience strategies. As opposed to time-based maintenance or corrective maintenance approaches, predictive maintenance works by analyzing data streams in real-time to make predictions of faults before critical failures. Particularly in this area, Machine Learning employs algorithms that help pinpoint and track degradation signs in vibrations, structural loads, acoustic emissions, and many more. Offshore predictive models are trained by ML on extensive datasets, which helps in forecasting corrosion, cable failures, fatigue, and more. Unplanned downtimes are avoided this way. (Lazakis *et al*, 2022, Yang *et al*, 2023)

It is equally important to integrate resilience metrics. Predictive analytics should extend beyond simply enumerating failures to consider the resilience of offshore systems, their ability to recover, and sustain essential operations through significant stress. Organizations like the U.S. Department of Energy (DOE) and the Department of Homeland Security (DHS) have established resilience as a national priority, focusing on metrics like recovery time, redundancy, adaptability, and robustness. Incorporating these metrics into offshore systems monitoring aligns with the overarching smart infrastructure resilience goals (Argyroudis *et al*., 2022; Makhoul *et al*., 2023). For example, digital twin platforms—virtual models of offshore assets—can depict structure responses to storms or component failures, helping operators fine-tune inspection schedules and resilience spending.

In addition, predictive maintenance reduces costs and carbon emissions, which is positive for the environment. By executing strictly the inspections that are necessary, the operational costs are lower and the longevity of the assets is longer because the vessels that produce emissions are travelling less. Therefore, predictive maintenance analytics is improving the technical resilience as well as bolstering the predictive analytics sustainability of offshore low-carbon systems. There are still gaps to address with data interoperability, cybersecurity, and the lack of personnel to explain the output of AI systems. These predictive maintenance gaps still need to be solved to fulfill the predictive maintenance promise as the cornerstone of resilience.

Low-carbon systems can also be informed by reliance on renewable offshore oil and gas systems, which are abundant. For many decades now, oil and gas platforms have developed frameworks that operate under extreme conditions, performing sophisticated inspections due to the reliability necessary. These frameworks are also applicable to offshore renewable energy systems (Prodhan *et al*., 2022; Futai *et al*., 2022). For example, ROVs and AUVs carry out inspections for subsea pipelines and can be repurposed to also inspect tidal turbine blades, anchors of floating wind, and buried power cables.

Implementing these innovations requires evaluation of both commonalities and divergences. Offshore renewables and oil and gas infrastructure share exposure to corrosive seawater, hydrodynamic forces, and structural fatigue. Though renewables assets usually consist of smaller, modular components deployed at much greater spatial scales, requiring more economically viable and scaled inspection techniques. Oil and gas infrastructures will provide the foundational methods, and renewables will require their lighter, more automated, and more data-centric translations.

Converging traditional inspection approaches with more sustainable and automated data-informed techniques is one of the first and most critical steps. Manuscript inspection logs, in the form of "run sheets", provide real value—however tend to lack the "hawk-eye" systematic approach of analytical thinking. The blending of historical oil and gas inspection databases with operational databases of renewables has the potential to expedite the development of resilient predictive models (Adebisi *et al*., 2021; Mahmood *et al*., 2023). Furthermore, the cross-collaboration approach fosters "thinking-out-of-the-box" with respect to the innovation of sensors, data, personnel, and even training approaches. For example, specialized personnel in offshore renewable infrastructure, such as welding inspection or corrosion monitoring, can shift their skill set to assist with renewables infrastructure and greatly reduce the burden of training.

At the end of the day, the resilience of offshore low-carbon systems is embedded in the fusion of traditional oil and gas inspection practices and the flexible, sustainable, and data-centric approaches of renewables. This fusion enhances the freedom and flexibility for the operators to use their proven techniques and strategies integrated with more progressive technologies focused on the low-carbon agenda.

The feasibility of offshore low-carbon systems hinges on resilience; offshore low-carbon systems are also poised to contribute to global decarbonization goals. Weather-related stressors such as storms, sea-level rise, and shifting waves require adaptive inspection methods that go beyond rigid timelines. Anything labeled maintenance scheduled at a certain time should be avoided. If possible, passive inspection systems should be replaced with more intelligent systems that can be driven remotely, ideally using machine learning and digital twins. Predictive maintenance and machine learning driven analytics can be powerful tools for shaping resilience metrics aligned with DOE and DHS guidelines. Aur, arguing from first principles, provides insights to derive renewables uniqueness from fossil era systems. Innovation should not be cloistered to blind tradition. Bridging of a fossil era and a renewables system is more robust (Shil and Eusufzai 2022; Dhali *et al*., 2023).

Any offshore low-carbon system, as near and distant primary sources of energy, could be more than circumstantial if not resilient. Strategic alignment of value and supply chains to create global and regional systems of systems can strengthen any offshore low-carbon system. This leadership should be from the point of classical environmental guidelines towards a multi-layered predictive framework for environmental resilience republics. Synergized and systems Koether synthesis can quickly strengthen offshore renewables environments to satisfactory levels of reliability and sustainability. Reliable systems also bolster global objectives such as systemic carbon reduction, energy sufficiency, and climate-adaptive responses. Sustainable development gets an additional advantage through the predictable neutrality and resilience of climate systems.

2.4. Toward Carbon-Neutral Offshore Operations

The shift towards the deployment of low-carbon offshore energy systems does not rest solely on producing renewable electricity. It equally rests on the supportive operations like inspection and monitoring, which also need to meet the defined carbon neutrality goals. The offshore wind, tidal, and wave technologies play a significant role in the decarbonization of the global energy supply. However, the inspection and maintenance infrastructure that supports the safe and reliable operation of these technologies has the potential to add a significant amount of greenhouse gas emissions itself (Andersson *et al*., 2022; Ning *et al*., 2023). Thus, the offshore operations need to be carbon neutral, and this can only be achieved through robust policies that integrate inspection, lifecycle sustainability of operations, and a dictated roadmap that the industry needs to follow, as shown in Figure 3. The fusion of these elements guarantees that the offshore energy sector not only harvests the energy and produces it clean, but it also upholds global sustainable development by fully transforming the emissions into the operational footprint of the energy.

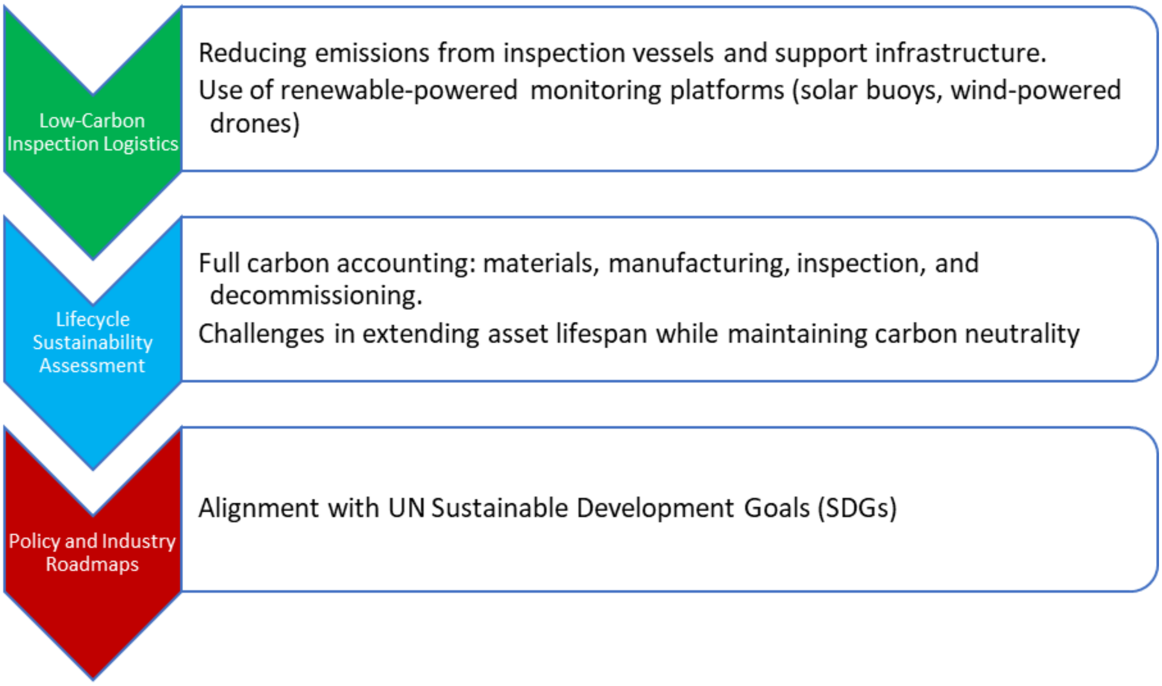

Fig 3: Low-Carbon Inspection Logistics

For crew, ROVs, and a multitude of heavy equipment vessels, inspection and maintenance methods that are termed as primary in the offshore sector, have always been regarded as low-cost and self-sufficient of carbon emission-free. Broadly defined as inspection, the absence of these renewable energy systems has been favorably referred to as clean energy in the wake of global climate change. However, as the utility of offshore renewable energy increases and the span of hundreds of turbines or tidal devices stretches across large oceanic territories, it has the potential to undermine the vision of clean energy.

Inspection logistics' emissions reduction includes both modest refinements and radical optimizations." E. Adopting hybrid and fully electric vessels mitigates the carbon payoff of inspection campaigns." D. "A reduction of hybrid propulsion systems that integrates alternative fuels such as hydrogen or ammonia can sustain maritime inspection support."

Vessel efficiency is complemented by the use of renewable-powered monitoring stations, which provide effective long-term solutions. Solar buoys that use sensors can conduct structural and environmental monitoring without a line of sight, limiting the vessel's requirements. Wind-powered drones and autonomous systems can also conduct turbine blade inspections. These renewable-powered systems enable way more emissions reduction and support condition-based maintenance and structure periodic inspection schedules.

The use of autonomous underwater vehicles (AUVs) also aids in the sustainability of logistics because they can disengage from surface vessels for a long period of time. AUVs can be launched from the shore or from substations offshore that are equipped with renewable energy. They can perform subsea foundation and cable inspections without emitting the pollutants associated with vessel-based operations (Khalid *et al*. 2022, Hariharan 2023). Along with the rest of these advances in technology, these AUVs also greatly improve the carbon neutrality of offshore operations. Their use and the accompanying decarbonization strategy for asset management justify the improved approach to supply and inspections.

The ability to capture complete carbon neutrality depends fully upon understanding emissions with respect to the entire lifecycle of offshore energy assets. Lifecycle sustainability assessment (LCA) is a set of activities that captures operational emissions and, in addition, materials, manufacturing, transportation, and, in the end, decommissioning, including installation, inspection, and maintenance. The offshore wind and tidal energy systems are clear cases where low-carbon electricity is created while being operated, but have a major construction and maintenance phase that results in high emissions due to the intensive use of steel, composite materials, and the heavy transportation associated with installation vessels and/or construction.

Lifecycle emissions include a wide variety of activities, including inspection, which is often overlooked. Each vessel mobilization, drone deployment, and sensor change contributes, however incrementally, to the system's overall carbon emissions. Capturing inspection within the carbon lifecycle accounting perimeter supports the premise that emissions reduction policies should cover the operational ecosystem needed to maintain offshore assets, not only energy production. For example, replacing periodic vessel-based inspections with predictive monitoring enabled by digital twins will reduce lifecycle emissions associated with unnecessary site visits while sustaining asset integrity.

One of the main problems to tackle is achieving carbon neutrality while increasing the operational life of offshore renewable assets. This will indeed have an added advantage of reducing installation, therefore extending the operational life will enable new systems to be set up while reducing the overall carbon cost associated with the materials and construction. On the other hand, aging assets can lead to higher operational emissions when using conventional methods. Meeting the dual targets of extending life while achieving carbon neutrality will require novel approaches, such as modular replacements, renewable-powered inspection systems, and turbine material recycling and reuse within a circular economy framework (Velenturf, 2021; Ahuja, 2023).

Moreover, decommissioning is an important consideration for an asset at its end-of-life, particularly sustainable decommissioning. Unsustainable decommissioning practices, particularly associated with offshore energy operations, can undermine efforts to achieve carbon neutrality. Instead of current practices of decommissioning that entail high carbon emissions, waste, and circular economy neglect, more steel structures should be recycled, foundations reused, and rare materials from turbines recovered. If decommissioning is integrated into the life cycle assessment, entire life cycle carbon neutrality for offshore assets can be achieved during the periods of minimal asset activity during operational decommissioning.

Shifts to carbon-neutral offshore operations demand collaborative innovation across the offshore industry, as well as from national and regional policymakers. Employing the United Nations Sustainable Development Goals (SDGs) as frameworks enables more integrated approaches that advance offshore energy while considering environmental and social governance. SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 13 (Climate Action), and SDG 14 (Life Below Water) form the basis of the offshore energy development discourse to adopt and implement decarbonization pathways. Anchoring these goals to inspection and monitoring activities at all stages ensures that advancements in the offshore sector result in tangible environmental sustainability (Olugu *et al*., 2022).

Industry standards in industrial emission control and reduction technologically have also sought to 'green' evolving inspection technologies in outline emission reduction policies. Standard-setting bodies like the International Maritime Organization (IMO) and International Electrotechnical Commission (IEC) have begun to develop policies that boundary the reduction of emissions during the conduct of offshore operations. For example, ISO standards for offshore wind energy systems have increasingly begun to include criteria for sustainable practices and their active use, supported by maritime decarbonization initiatives-such as, the use and promotion of low-emission support vessels. These policies and practices not only act as 'sustainability' technical and operational cornerstones, but also act as a monopoly, garnering industry actors to develop and utilize carbon-neutral inspection technologies.

In the offshore energy sector, policies like emissions reporting and carbon pricing, along with carbon-neutral inspection and monitoring practices, green financing tools, are also designed to promote the use of policies like low-emission zone (LEZ) emission reporting. Funding R&D for self-sufficient renewable energy inspection technologies, supporting deployable pilots and policies for hybrid vessels, along with life cycle carbon emission reporting for offshore projects, are ways in which governments can remove barriers to LEZ (Koutoudjian *et al*., 2021; Lee and Saygin, 2023). Public legend partnerships as a level of the industry globally advance through self-committed targets and the policies of their own governments, effectively combining regulatory and 'light-subsidized collaboration to concentrate on sustainable pathways while diversifying the financial and tech support gaps.

Interoperability and global harmonization must be at the core of all Industry Roadmaps. Offshore renewable energy covers myriad locations and governments. Shared inspection standards and lifecycle carbon databases help shift the balance towards more efficient knowledge, carbon-neutral practice cross-adoption. Governance and Industry Roadmaps, on the other hand, place great value on policy by crystallizing cross-border cooperation. Structural changes leading towards carbon-neutral policy and practice for offshore renewable energy, which combine logistics, lifecycle, and policy and legal, are entangled. Reduced inspection emissions from low-carbon logistics and remote monitoring powered by renewable vessels with emission-less spectra, autonomous offshore platforms, and rhum emits powered. Policies and Industry Roadmaps aligned with the SDGs and Elarc standards, from an Industry Roadmap on these offshore spaces, enable emigration-free domains of practice to go cross-border (Horry *et al*., 2022; Berrone *et al*., 2023).

The dual goal of producing renewable electricity in the offshore support operations renewable energy sector lies in addressing the dimensions between the operations themselves… Offshore operations move through the notion of carbon-neutral technology in a manner that serves as a constructive approach… that emphasizes the interrelationships of energy security, carbon goals, and environmental service. In this manner, the periphery vision of the operational components of inspection and monitoring gets converted to the core vision of the operational components as sustainable and resilient strategies of the global energy transition.

3. Conclusion

The incorporation of renewable energy into offshore systems presents a deeply exciting opportunity; yet a daunting challenge remains. The offshore wind, tidal, and wave technologies, which lie on the periphery, could accelerate CO2 reductions globally, yet their use raises cancellation of servicing aircraft and other critical inspection and monitoring needs. The technical challenge of reliability of the work done is seen in the structural fatigue of the monopile and the steady drift of the floating platform, the fragile submarine cables, and the unknowns of the wave and tidal devices. All of which suffer the degradation of inspection and scrutiny. Offshore, these challenges become saltwater corrosion, biofouling, storm surges, and variable wave conditions. These challenges serve to complicate inspection programs and accelerate schedules. The offshore, renewable, low-carbon systems remain unsolved, and the many questions on their sustainability and profitability remain unattended in achieving these goals.

Developing low-carbon inspection methods could be key to resolving these issues. Shift models and frameworks of predictive maintenance relying on machine learning, digital twins, and autonomous inspection technologies are critical to asset management paradigm shifts from reactive to proactive. The offshore operators augmenting their monitoring policies to promote non-intrusive asset protection, positive environmental support, and the maintenance of a net-zero carbon vision, as policy frameworks, give operators the opportunity to embed the resilient metrics coherence with other infrastructure systems to achieve the overall goals. Unified metrics and collaborative standards on resilient infrastructure integrated with global cross-jurisdictional data allow boundary harmonization on diverse technologies. Such integrated standards enable the amplification of the overarching protocols on net-zero carbon shifts and position cross-node harmonization on diverse technologies.

The future visionary concept of offshore operations is fully sustainable, monitored digitally, and has Energy infrastructures that are climate resilient. In this concept, autonomous systems, hybrid systems, and subsea networks are controlled and assisted by global regulatory frameworks, Predictive analytics, and machine learning. Predictive analytics drove systems managed by autonomous machines to mitigate system downtimes and enhance overall climate safety. Achieving this requires global strategies on technology, policy, cross-industry collaboration, and technological advancement. The collaborative approach will greatly enhance cross-sector offshore renewable systems and thus will be pivotal in the global low-carbon energy transition.

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