Advances in IoT-Enabled Condition Monitoring for Offshore Static Mechanical Maintenance Programs

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Abstract

Static mechanical equipment, including pressure vessels, process piping, heat exchangers, storage tanks, and structural supports, constitutes the majority of the maintainable asset base on offshore production facilities, yet it has historically received far less condition monitoring attention than rotating machinery. Between roughly 2020 and 2025, the maturation of low-power wireless sensing, edge computing, satellite and private cellular connectivity, and machine learning based analytics has enabled a decisive shift from calendar-driven inspection of static equipment toward continuous, risk-informed condition monitoring. This paper reviews the state of IoT-enabled condition monitoring for offshore static mechanical maintenance programs as of 2025. It examines the principal sensing modalities now deployed offshore, including permanently installed ultrasonic wall-thickness sensors, corrosion under insulation (CUI) moisture and sacrificial-element sensors, distributed fiber-optic sensing, acoustic emission monitoring, and wireless strain and fatigue instrumentation. It then analyzes the supporting connectivity and computing architectures, the integration of streaming condition data into risk-based inspection (RBI) frameworks under API 510, API 570, and API 580/581, and the emergence of digital twins for integrity management. Reported industry outcomes suggest maintenance cost reductions of up to 40 percent and downtime reductions approaching 50 percent where predictive approaches are systematically applied, alongside substantial reductions in inspection-related personnel exposure. The paper also addresses persistent barriers, including sensor durability in marine environments, retrofit and hazardous-area certification constraints, data governance, cybersecurity, and organizational readiness, and closes with a research agenda for the second half of the decade.

Keywords: *Industrial Internet of Things; Condition monitoring; Static equipment; Offshore oil and gas; Corrosion under insulation; Risk-based inspection; Predictive maintenance; Digital twin*

INTRODUCTION

Offshore production platforms and floating production, storage and offloading (FPSO) units operate in one of the most demanding industrial environments in existence. Assets are remote, access is expensive and weather-dependent, space and payload are constrained, and the consequences of loss of containment range from costly production deferment to catastrophic harm to people and the environment. Within this context, the maintenance and integrity assurance of static mechanical equipment, that is, equipment without significant moving parts such as pressure vessels, process and utility piping, heat exchangers, flare systems, storage tanks, valves in their pressure-boundary function, and associated supports, represents a dominant share of offshore inspection expenditure and turnaround scope, and its management sits within the broader governance challenge of delivering and sustaining complex energy infrastructure (Amayo *et al.*, 2023a,b,c; Amayo *et al.*, 2024a,b,c; Amayo *et al.*, 2025a,b,c).

For decades, the integrity of static equipment has been assured primarily through periodic inspection regimes: scheduled visual examinations, manual ultrasonic thickness surveys at designated condition monitoring locations (CMLs), radiography, and insulation stripping campaigns to search for hidden corrosion. These regimes are codified in inspection standards such as API 510 for pressure vessels and API 570 for process piping, and are increasingly prioritized through risk-based inspection methodologies described in API RP 580 and API RP 581. While effective, periodic inspection is inherently sampled in both space and time. Degradation that initiates or accelerates between inspection intervals, or at locations away from designated CMLs, can progress undetected. Offshore, the problem is compounded by the cost of mobilizing inspection crews, erecting scaffolding or deploying rope access, removing insulation, and in some cases shutting down process systems to permit access, with associated occupational safety and construction-risk burdens that are well documented in the safety management literature (Arumosoye and Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Arumosoye *et al.*, 2025; Obogo *et al.*, 2019a, 2020a,b,c, 2021a,b, 2022, 2023, 2024a,b).

The Industrial Internet of Things (IIoT) offers a structurally different proposition: permanently installed, low-power, often wireless sensors that measure degradation-relevant parameters continuously or at high frequency, transmit data through robust industrial networks, and feed analytics that convert raw measurements into remaining-life estimates and maintenance triggers. Although IoT-based condition monitoring first achieved scale on rotating machinery, where vibration signatures provide a natural diagnostic medium, the period from approximately 2020 to 2025 has seen rapid extension of these techniques to static equipment. Drivers include the commoditization of battery-powered wireless sensor nodes, the emergence of low-power wide-area network (LPWAN) protocols suited to metal-dense offshore topsides, dramatic improvements in satellite backhaul for remote assets, regulatory and ESG pressure on emissions and loss of primary containment, and an aging offshore asset base in which many facilities are operating beyond original design life. These enablers draw directly on a maturing body of work in energy-harvesting IoT nodes, low-power wireless system design, and embedded sensing engineering (Asiedu and Quainoo, 2023a,b, 2024, 2025; Asiedu *et al.*, 2025; Quainoo *et al.*, 2024, 2025a,b).

This paper reviews advances in IoT-enabled condition monitoring for offshore static mechanical maintenance programs, with emphasis on developments reported through 2025. The contribution is threefold. First, it consolidates the principal sensing technologies now available for static equipment degradation mechanisms and assesses their offshore readiness. Second, it describes the reference system architecture, from sensor node to enterprise asset management integration, that has emerged as de facto practice. Third, it evaluates how continuous condition data is being incorporated into formal integrity management and risk-based inspection frameworks, and identifies the technical, organizational, and regulatory barriers that remain.

LITERATURE REVIEW

Static Equipment Degradation Mechanisms Offshore

The degradation mechanisms that dominate offshore static equipment integrity are well characterized. External corrosion driven by marine atmospheric exposure and salt deposition affects piping, vessels, and structural steel. Corrosion under insulation (CUI) is widely regarded as one of the most insidious and costly mechanisms in the process industries, because moisture trapped between insulation and the metal surface promotes localized corrosion that is invisible to routine external inspection. Internal mechanisms include CO_2 and H_2S corrosion, microbiologically influenced corrosion, erosion-corrosion at high-velocity fittings, and sand erosion in production systems. Fatigue affects small-bore connections, caissons, risers, and topside piping subject to vibration and wave-induced motion, particularly on floating facilities. Additional mechanisms such as stress corrosion cracking, hydrogen damage, and creep at elevated-temperature services complete the picture. Each mechanism has a characteristic measurable precursor, such as wall loss, moisture presence, crack-related acoustic emission, strain cycling, or temperature anomaly, which defines the sensing opportunity for IoT instrumentation. The corrosive service environment itself is shaped by produced-fluid chemistry and treatment practice, and by the evolving fuel and energy systems within which offshore assets operate (Atta *et al.*, 2024, 2025; Bello *et al.*, 2023a; Falegan and Aniebonam, 2022, 2023, 2024, 2025; Monye *et al.*, 2025a,b).

Limitations of Conventional Inspection

Conventional offshore inspection is costly in four distinct ways. Direct cost includes crew mobilization, bed space, scaffolding and access, insulation removal and reinstatement, and survey execution. Indirect cost arises from production deferment when systems must be depressurized or shut down for access. Safety cost reflects the exposure of personnel to working at height, confined space entry, and hazardous process environments, a category of risk extensively analyzed in the HSE and construction risk management literature (Obogo, *et al.* 2019b,c, 2021c, 2025a,b; Obriki and Arumosoye, 2018, 2019, 2020, 2021, 2022, 2023, 2024a,b; Obriki, *et al.*, 2022a,b, 2023a,b, 2025). Finally, information cost is incurred because sampled inspection produces sparse data: thickness readings at a limited number of CMLs on a limited number of dates, from which corrosion rates must be extrapolated with considerable uncertainty. Industry cost-of-corrosion studies, including the widely cited NACE (now AMPP) IMPACT study, have estimated the global cost of corrosion in the trillions of dollars annually and concluded that a substantial fraction is avoidable through better monitoring and management practice. It is precisely this information gap that continuous IoT monitoring targets, and lean operations research reinforces that eliminating such information waste is a primary lever of process improvement (Ambali *et al.*, 2021; Eyetsemitan *et al.*, 2020, 2021, 2022, 2023a,b, 2024a,b, 2025; Oyeleye *et al.*, 2022).

The Case for Continuous Monitoring

Continuous or high-frequency monitoring changes the statistical character of integrity data. Instead of two or three thickness measurements per decade at a CML, permanently installed ultrasonic sensors can deliver daily or weekly readings with high repeatability, since transducer placement and coupling do not vary between measurements. This converts corrosion-rate estimation from a wide-interval extrapolation problem into a trend-detection problem, enabling operators to detect rate changes associated with process excursions, chemical treatment failures, or water breakthrough within weeks rather than years. Analogous arguments apply to CUI moisture sensing, fatigue strain monitoring, and acoustic emission surveillance of crack growth, consistent with the broader literature on predictive analytics and data-driven decision systems (Adelanwa *et al.*, 2023a,b, 2024; Anene and Clement, 2022, 2024; Basnet *et al.*, 2021, 2023, 2024; Oghenemaiga *et al.*, 2024). Industry benchmarking summarized by McKinsey and others suggests that predictive maintenance strategies enabled by such data can reduce maintenance costs by up to 40 percent and unplanned downtime by up to 50 percent relative to reactive and purely calendar-based regimes, figures that are frequently cited in oil and gas digital transformation programs and that mirror outcomes reported for predictive maintenance of building energy and HVAC systems, a domain whose sensing and analytics patterns transfer directly to static process equipment (Atta, *et al.*, 2018; 2020, 2021, 2022; Omoegun *et al.*, 2023; Sunday and Omoegun, 2018, 2019, 2022; Sunday *et al.*, 2019, 2020).

METHODOLOGY

The review that follows synthesizes three strands of evidence available through 2025: peer-reviewed and industry literature on sensing, connectivity, and analytics for asset integrity; vendor and operator disclosures describing fielded offshore deployments; and the adjacent methodological literature in predictive analytics, data governance, enterprise IT, and safety and risk management from which offshore programs borrow heavily (Adelanwa *et al.*, 2023a,b, 2024; Aliliele *et al.*, 2023a,b,c, 2024a,b, 2025a,; Borah *et al.*, 2022; Mbonu *et al.*, 2018, 2019a,b, 2020a,b,c, 2021a,b,c, 2022a,b,c; Odejobi *et al.*, 2025). Sources were screened for relevance to static mechanical equipment, defined here as pressure-retaining and structural items without primary rotating elements, and for applicability to the offshore operating context of remoteness, marine exposure, hazardous-area classification, and constrained logistics. Because controlled comparative trials are rare in this domain, quantitative claims are treated as indicative rather than definitive, and are reported together with their provenance so that readers can weigh benchmarking studies differently from audited field results. The intent is not a systematic meta-analysis but a structured state-of-practice assessment: what is deployable today, what is demonstrably delivering value, and what remains at the pilot or research stage. This framing follows established practice in technology review studies across infrastructure and energy domains, where maturity assessment must combine heterogeneous evidence types (Amayo *et al.*, 2023a,b,c, 2024a,b,c, 2025a,b,c).

Findings are organized to follow the monitoring value chain: sensing technologies are examined first, followed by the connectivity and computing architecture that transports and processes their data, the analytics that convert data into integrity decisions, and finally the reported outcomes, economics, and barriers observed in practice. Throughout, results are discussed in relation to the formal inspection and risk frameworks within which offshore integrity decisions must ultimately be justified, since it is this regulatory embedding, rather than sensing capability alone, that determines whether continuous monitoring changes maintenance programs in practice (Agu *et al.*, 2023a,b, 2025; Akomolafe and Agu, 2018, 2019a,b,c; Akomolafe *et al.*, 2023a,b, 2025; Annan, 2022, 2023, 2024, 2025a,b; Bello *et al.*, 2023b).

SENSING TECHNOLOGIES FOR STATIC EQUIPMENT MONITORING

Permanently Installed Ultrasonic Wall-Thickness Monitoring

Permanently installed ultrasonic thickness (UT) sensors are the workhorse of static equipment IoT. Piezoelectric or electromagnetic acoustic transducer (EMAT) elements are bonded, strapped, or magnetically coupled to pipe and vessel surfaces at corrosion-susceptible locations and interrogate wall thickness by pulse-echo time-of-flight. Modern systems achieve resolution on the order of thousandths of an inch, sufficient to resolve corrosion rates within months. By 2025, wireless variants powered by long-life primary batteries, with radio protocols such as WirelessHART, ISA100.11a, LoRaWAN, and proprietary mesh networks, are certified for ATEX and IECEx hazardous areas and are routinely deployed on offshore topsides. High-temperature versions employing waveguides extend coverage to hot services. Automated trending software computes short-term and long-term corrosion rates and projects remaining life against minimum allowable thickness, feeding directly into RBI reassessment. Guided-wave ultrasonic systems complement point sensors by screening tens of meters of piping from a single transducer ring, which is particularly valuable for inaccessible sections such as caissons, riser splash zones, and pipe racks. The underlying transducer, power, and radio design of these nodes builds on advances in electrical machines, power electronics, and telecommunications engineering (Adenuga, 2023; Amayo, 2017; Amayo and Popoola, 2017a,b; Amayo *et al.*, 2015; Oshevire *et al.*, 2017) as well as low-power wireless sensing platforms (Asiedu and Quainoo, 2023a,b, 2024, 2025; Asiedu *et al.*, 2025; Quainoo *et al.*, 2024, 2025a, 2025b).

Corrosion Under Insulation Monitoring

CUI monitoring is arguably the area of most visible innovation between 2020 and 2025, reflecting the outsized share of inspection budgets consumed by insulation stripping campaigns. Several sensing principles have reached commercial deployment. Moisture-detection approaches place humidity and temperature sensors, sensing tapes, or hygroscopic elements between the insulation and cladding, or within the insulation itself, to detect the water ingress that is a necessary precursor to CUI. Sacrificial-element approaches embed a thin corrodible wire or film whose degradation, detected electrically or via electromagnetic guided radar reflectometry, indicates that corrosive conditions have been present. Distributed fiber-optic sensing runs an optical fiber along insulated lines and detects moisture-induced temperature and strain anomalies with meter-scale localization over kilometer-scale lengths, with laboratory and field studies demonstrating sensitivity to water ingress below ten milliliters per meter of pipe. These systems are increasingly paired with battery-friendly wireless protocols such as LoRaWAN, NB-IoT, LTE-M, and Bluetooth Low Energy, and with intelligent power management and line-integrity self-diagnostics that flag sensor faults, for example short circuits caused by the very moisture being detected, without corrupting measurement data. The operational effect is a shift from blanket periodic stripping toward targeted, evidence-driven insulation removal at locations where sensors indicate sustained wetting.

Electrochemical and Coupon-Based Corrosion Sensing

For internal corrosion, IoT-connected electrical resistance probes, linear polarization resistance sensors, and instrumented weight-loss coupons provide near-real-time corrosivity measurement in produced fluids and injection systems. Compared with legacy manual coupon retrieval, wireless-reporting probes deliver corrosivity trends at daily resolution, allowing chemical inhibition programs to be verified continuously and dosing to be optimized. This closes a long-standing feedback loop in offshore corrosion management, where inhibitor underperformance previously might not be discovered until the next thickness survey.

Acoustic Emission and Leak Detection

Acoustic emission (AE) monitoring detects the high-frequency stress waves released by active crack growth, allowing surveillance of pressure vessels and piping for propagating defects months before through-wall failure. Permanently installed AE arrays, historically confined to periodic proof tests, are now deployed as continuous monitors on selected high-consequence vessels. Related acoustic techniques detect valve passing, relief valve seat leakage, and small external leaks from their ultrasonic noise signatures, supplementing fixed gas detection. On the process-safety side, dense networks of wireless gas detectors monitoring methane, hydrogen sulfide, combustibles, and volatile organic compounds have become one of the highest-priority offshore IoT applications, both for personnel safety and for methane emissions accounting under tightening regulatory and ESG regimes.

Strain, Fatigue, and Structural Health Monitoring

Wireless strain gauges, fiber Bragg grating arrays, and motion sensors are increasingly applied to fatigue-sensitive static components: riser hang-offs, caissons, flare towers, module supports, and vibrating small-bore piping. Continuous strain-cycle counting enables measured, rather than assumed, fatigue accumulation, which is central to life extension safety cases for aging platforms. On floating units, integration with vessel motion and metocean data allows fatigue damage to be attributed to specific sea states and operating decisions. Complementary technologies, including drone-based photogrammetry and robotic crawlers carrying UT payloads, extend the reach of monitoring programs to external surfaces that would otherwise require scaffolding, and their outputs are increasingly ingested into the same data platforms as fixed IoT sensors, paralleling the use of UAV, GIS, and autonomous robotic platforms for corridor and infrastructure monitoring reported across other asset-intensive sectors (Akanbi and Sunday, 2024, 2025; Akanbi *et al.*, 2025; Dagodzo, 2018a,b; Dagodzo and Patrick, 2020, 2021a,b, 2022, 2023a,b, 2025; Dagodzo *et al.*, 2022).

Comparative Overview

Table 1 summarizes the principal sensing modalities, their target mechanisms, and their 2025 deployment maturity offshore.

Sensor Selection and Deployment Design

Selecting where and what to sense is as consequential as the sensing technology itself. Mature 2025 practice begins from the corrosion and damage-mechanism review that underpins RBI: each credible mechanism on each corrosion loop is mapped to its measurable precursor, and candidate monitoring locations are ranked by probability of degradation, consequence of failure, and the cost and feasibility of instrumenting the location. High-value targets typically include known corrosion hot spots such as dead legs, injection and mix points, low points where water accumulates, downstream of pressure-reducing devices, splash-zone transitions, and insulated lines in the CUI-susceptible temperature range. Deployment design then addresses practical engineering constraints: surface preparation and coating compatibility for bonded transducers, clamp and strap designs that avoid crevice corrosion at the attachment itself, radio survey results that determine gateway placement in metal-dense modules, and hazardous-area certification of every powered component

Table 1: IoT sensing modalities for offshore static equipment (status as of 2025).

Sensing modality	Target mechanism	Typical connectivity	Offshore maturity (2025)
Permanent UT thickness sensors	Internal/external wall loss, erosion	WirelessHART, ISA100, LoRaWAN, mesh	Mature, widely deployed
Guided-wave UT rings	Wall loss over inaccessible lengths	Wired or gateway-connected	Established for screening
CUI moisture sensors and tapes	Corrosion under insulation precursor	IEEE 802.15.4, LoRaWAN, NB-IoT, BLE	Rapid growth, field-proven
Sacrificial element / EMGR	CUI corrosive condition indicator	Wireless module outside cladding	Commercial, growing
Distributed fiber optics	Moisture, strain, temperature along lines	Interrogator to edge/cloud	Proven; retrofit remains costly
ER / LPR corrosion probes	Internal corrosivity, inhibitor efficacy	Wireless transmitters	Mature
Acoustic emission arrays	Active crack growth, leaks	Wired / edge processed	Selective high-consequence use
Wireless strain / FBG	Fatigue accumulation, overload	Wireless nodes, fiber interrogators	Growing in life extension

(Adenuga, 2023; Amayo, 2017; Amayo and Popoola, 2017a,b; Amayo *et al.*, 2015; Oshevire *et al.*, 2017).

A recurring lesson from early programs is that sensor populations must be designed as systems rather than accumulated as point purchases. This means standardizing on a limited set of node types and protocols to simplify spares and battery logistics, registering every sensor in the maintenance management system with its own tag and preventive maintenance plan, and defining data ownership and alert-response accountabilities before the first node is installed. Programs that established this discipline report substantially better sustained data availability than those that treated sensors as consumables outside formal asset registers, an observation consistent with wider findings on the governance prerequisites of data-driven operations (Aliliele *et al.*, 2023a,b,c, 2024a,b, 2025a,b; Borah *et al.*, 2022, Mbonu *et al.*, 2018, 2019a,b, 2020a,b,c, 2021a,b,c, 2022a,b,c; Odejobi *et al.*, 2025).

SYSTEM ARCHITECTURE AND CONNECTIVITY

Wireless Networking in Metal-Dense Offshore Environments

Offshore topsides are among the most hostile radio environments in industry: dense steel structures, multipath reflection, electromagnetic interference, and strict hazardous-area constraints on transmit power and equipment certification. The dominant field protocols in 2025 remain the industrial mesh standards WirelessHART and ISA100.11a for process-adjacent instrumentation, complemented by LPWAN technologies, particularly LoRaWAN and NB-IoT, for low-rate integrity sensors such as CUI tapes and thickness nodes, where multi-year battery life is the governing requirement. Private LTE and, increasingly, private 5G networks have been installed on newer platforms and FPSOs to provide high-bandwidth backhaul for video, robotics, and dense sensor populations. For normally unattended installations and remote developments, low-earth-orbit satellite constellations have transformed backhaul economics since roughly 2022, making continuous cloud streaming from remote assets practical where legacy VSAT links once imposed severe bandwidth rationing.

Edge, Fog, and Cloud Processing

The prevailing architecture is hierarchical. Sensor nodes perform on-board signal conditioning and, increasingly, embedded feature extraction to minimize radio payloads and conserve battery. Edge gateways on the platform aggregate networks, perform protocol translation, execute time-critical analytics such as threshold alarming and spectral analysis, and buffer data against communication outages. Recent literature on IoT in oil and gas describes this edge, fog, and cloud layering as the standard pattern for facilities requiring real-time data monitoring, equipment protection, fault detection, and advanced analytics. In the cloud or onshore data center, historian platforms and integrity data management systems consolidate condition data with inspection records, process data, and maintenance history, exposing it to machine learning pipelines and to enterprise asset management (EAM) and computerized maintenance management systems (CMMS) so that validated anomalies automatically generate notifications and work orders. This layering reflects wider enterprise practice in cloud architecture, IT service management, and service delivery operations (Badmus *et al.*, 2020, 2025; Edivri and Oteri, 2022, 2024; Ladapo *et al.*, 2018, 2019, 2022a,b, 2023a,b,c,d, 2024a,b, 2025; Ogbole *et al.*, 2021, 2025; Okoruwa *et al.*, 2020, 2024a; Oteri and Edivri, 2024).

Interoperability and Data Standards

A notable 2020s advance is the consolidation of interoperability standards. OPC UA has become the de facto mechanism for contextualized data exchange between edge systems and enterprise platforms, while MQTT with Sparkplug conventions dominates lightweight telemetry. Asset information standards, including ISO 14224 taxonomies for reliability data and the emerging use of CFIHOS specifications for handover data, allow condition monitoring records to be tied unambiguously to tagged equipment. This apparently mundane plumbing has proven decisive: early offshore IoT pilots frequently stalled not on sensing physics but on the inability to land data in systems of record with adequate context for engineers to act upon. Robust data governance, quality management, and IT risk controls are therefore treated as first-class design requirements of monitoring architectures rather than afterthoughts (Aliliele *et al.*, 2023a,b,c, 2024a,b, 2025a,b; Borah *et al.*, 2022; Mbonu *et al.*, 2018, 2019a,b, 2020a,b,c, 2021a,b,c, 2022a,b,c; Odejobi *et al.*, 2025).

Availability, Resilience, and Lifecycle Management of the Monitoring System

Because monitoring increasingly substitutes for inspection, the availability of the monitoring system itself becomes an integrity-relevant parameter. Offshore programs now define service levels for data availability per sensor and per corrosion loop, and treat sustained data loss as a trigger for reverting to conventional inspection at the affected locations. Achieving these service levels requires resilience engineering at every layer: redundant gateways and mesh routing to tolerate node and path failures, store-and-forward buffering across satellite or platform network outages, watchdog reporting so that silent sensor death is distinguished from a genuinely stable measurement, and battery state-of-charge telemetry that converts power management from reactive replacement into planned campaigns (Adenuga, 2023; Amayo, 2017; Amayo and Popoola, 2017a,b; Amayo *et al.*, 2015; Asiedu and Quainoo, 2023a,b, 2024, 2025; Asiedu *et al.*, 2025; Oshevire *et al.*, 2017; Quainoo *et al.*, 2024, 2025a,b).

Lifecycle management extends these principles across the decade-scale life of a deployment. Firmware must be updatable in the field under change control, radio spectrum plans must survive the addition of new wireless systems on congested topsides, and obsolescence of node hardware, gateway platforms, and cloud services must be managed so that a sensor installed in 2025 still reports meaningfully in 2035. Operators with mature programs maintain a monitoring system register mirroring the asset register, with each network element assigned criticality, spares strategy, and planned refresh dates, and they include monitoring infrastructure within existing management-of-change and cybersecurity patching processes rather than creating parallel regimes (Adebayo *et al.*, 2022, 2023; Adegbite *et al.*, 2020, 2022, 2023, 2024a,b, 2025; Ahmed *et al.*, 2021; Badmus *et al.*, 2020, 2025; Dosunmu and Ogundele, 2019, 2020, 2021, 2022, 2023, 2024a,b,c,d, 2025a,b,c; Edivri and Oteri, 2022; Edivri and Oteri, 2024; Jimoh *et al.*, 2023a,b; Ladapo *et al.*, 2018, 2019, 2022a,b, 2023a,b,c,d, 2024a,b, 2025). The practical consequence is that IoT condition monitoring is best understood not as a set of devices but as an additional utility system on the facility, engineered, operated, and maintained with the same discipline as power or instrument air.

DATA ANALYTICS AND DIGITAL TWINS

From Trending to Prognostics

The first generation of static equipment analytics consisted of deterministic trending: fitting corrosion rates to thickness histories and projecting remaining life to minimum allowable thickness. The 2023 to 2025 period has seen broad adoption of statistical and machine learning enhancements. Bayesian and probabilistic corrosion-rate models quantify uncertainty explicitly and update beliefs as each new sensor reading arrives, aligning naturally with the probability-of-failure calculations in API RP 581. Anomaly detection models trained on multivariate process and integrity data flag corrosion-rate inflections associated with upsets, such as water breakthrough, souring, or inhibitor pump failure, close to the moment of onset. Computer vision models applied to drone and crawler imagery classify external corrosion, coating breakdown, and insulation damage at scale, and case reports describe AI image analysis during turnaround inspections identifying early-stage damage, for example high-temperature hydrogen attack blistering, that manual review had misclassified. These techniques adapt anomaly detection, forecasting, and classification methods proven in adjacent operational analytics domains (Tonoyan *et al.*, 2021a,b; Tonoyan *et al.*, 2022a,b,c, 2023, 2024a,b, 2025).

Digital Twins for Integrity Management

Digital twins for static equipment integrate three-dimensional asset models, design data, inspection and sensor history, and physics-based or data-driven degradation models into a continuously updated representation of asset condition. In 2025 practice, integrity digital twins are used to visualize sensor coverage and corrosion morphology on the 3D model, simulate remaining life under alternative operating scenarios, prioritize anomalies by risk, and rehearse inspection and repair campaigns before mobilization. On the most advanced floating assets, structural twins fuse measured motions and strains with hydrodynamic models to compute fatigue consumption in near real time, directly supporting life extension dossiers submitted to classification societies and regulators. Vendors and operators increasingly describe an aspiration toward prescriptive maintenance, in which the twin not only predicts degradation but recommends the optimal intervention window considering production plans, logistics, and weather. Comparable model-based forecasting and scenario-planning approaches are advancing in parallel across the wider energy transition and renewable forecasting literature (Adenuga, 2022; Komi, 2021, 2023, 2024, 2025; Komi and Adamolekun, 2021, 2022, 2024; Komi and Adeniji, 2020, 2023, 2024a,b; Komi and Ganiu, 2022, 2023, 2025; Tackie *et al.*, 2023).

Integration with Risk-Based Inspection

Perhaps the most consequential development for maintenance programs is the formal coupling of continuous monitoring with RBI. API RP 580 and API RP 581, along with DNV recommended practices used widely offshore, permit inspection interval and scope optimization when degradation is well understood and monitored. Continuous wall-thickness and corrosivity data raise confidence grades on degradation-rate estimates, which in the API 581 framework reduces damage-factor uncertainty and can defensibly extend inspection intervals or reduce invasive scope. Several operators have reported using permanently installed sensors specifically to substitute for a portion of manual CML surveys and to defer insulation stripping until moisture sensors indicate cause. Regulators and classification societies have generally accepted such approaches when supported by documented sensor reliability, data quality management, and clear response criteria, though acceptance remains jurisdiction-specific and evidence-based rather than automatic. This regulatory interface engages broader questions of technology governance, auditability, and risk-control assurance examined in the AI governance and internal audit literatures (Agu, 2018, 2019a,b,c; Agu *et al.*, 2023a,b, 2025; Akomolafe and Akomolafe *et al.*, 2023a,b, 2025; Annan, 2022, 2023, 2024, 2025a,b; Bello *et al.*, 2023b).

Data Fusion and Model Validation

As monitoring populations grow, the analytical frontier shifts from interpreting individual sensors to fusing heterogeneous evidence. A single corrosion circuit may now be characterized simultaneously by permanent UT thickness trends, intermittent manual survey data, corrosivity probe readings, process historian variables such as temperature, water cut, and chemical injection rates, and periodic visual or robotic inspection imagery. Fusion approaches range from rule-based corroboration, in which an alert requires agreement between independent evidence types before escalation, to probabilistic state estimation, in which all evidence updates a common posterior estimate of wall condition and degradation rate. Fusion materially reduces false-alarm burden, which field experience identifies as the fastest route to operator disengagement from monitoring systems (Tonoyan *et al.*, 2021a,b, 2022a,b,c, 2023, 2024a,b, 2025).

Model validation practice has likewise matured. Leading programs back-test remaining-life predictions against subsequently measured thickness at the same locations, quantify prediction intervals rather than point estimates, and subject machine learning components to change control so that model updates are documented, reviewed, and reversible in the same manner as other safety-relevant software. Where monitoring evidence is used to defer or descope inspection, the validation record becomes part of the integrity dossier presented to auditors, classification societies, and regulators, linking analytics governance directly to the assurance frameworks discussed earlier in sub-section 'Integration with Risk-Based Inspection' (Agu *et al.*, 2023a,b, 2025; Akomolafe and Agu, 2018, 2019a,b,c; Akomolafe *et al.*, 2023a,b, 2025; Annan, 2022, 2023, 2024, 2025a,b; Bello *et al.*, 2023b).

RESULTS AND DISCUSSION

Reported Industry Outcomes

Quantitative outcomes reported across the industry literature through 2025, while heterogeneous in methodology, are directionally consistent. Benchmarking cited in digital transformation analyses indicates that IoT-enabled predictive maintenance can reduce maintenance costs by up to 40 percent and cut unplanned downtime by up to 50 percent, and sector surveys project that by 2026 more than 80 percent of oil and gas companies will operate IoT sensors for real-time equipment monitoring. Market analyses value digital transformation growth in the sector at more than 50 billion US dollars between 2025 and 2029, with condition monitoring among the leading use cases. For static equipment specifically, operators report that targeted CUI sensing has reduced insulation stripping scopes substantially by directing removal only to locations with evidence of wetting, that permanent UT sensors have detected accelerated wall loss weeks after process changes rather than at the next scheduled survey, and that continuous corrosivity monitoring has materially improved chemical inhibition assurance. Condition data also strengthens maintenance supply chains: procurement and materials-readiness research in energy and infrastructure shows that predictive demand signals reduce logistics cost and downtime (Agbabiaka *et al.*, 2019; Ogunwole *et al.*, 2021; Okonkwo *et al.*, 2018a,b, 2019, 2020, 2021a,b, 2023a,b, 2024a,b,c,d,e,f, 2025; Patrick *et al.*, 2020, 2021), supplier management and supply chain analytics translate asset condition into sourcing and spares strategy (Akinleye and Adeyoyin, 2021, 2022a,b; Akinleye *et al.*, 2023; Akin-Oluyomi *et al.*, 2020, 2023a,b,c,d, 2024; Babatope *et al.*, 2023; Efobi *et al.*, 2021, 2022a,b, 2023; Ogundairo, 2025; Okojie and Abioye, 2020; Okoruwa *et al.*, 2024b, 2025), and ESG-oriented supply chain auditing increasingly requires exactly the traceable condition records that IoT programs generate (Abioye *et al.*, 2023; Aifuwa *et al.*, 2020; Filani *et al.*, 2022; Ike *et al.*, 2024a,b, 2021, 2022, 2025; Nnabueze *et al.*, 2021; Okojie *et al.*, 2023a,b; Yeboah and Ike, 2020; Yeboah *et al.*, 2024, 2025). Safety benefits, though harder to monetize, are consistently emphasized: every manual survey avoided removes working-at-height, confined-space, and offshore transit exposure, and remote monitoring supports the broader trend toward normally unattended and minimally crewed facilities.

A balanced reading nonetheless requires caution. Headline percentages typically derive from cross-industry benchmarking rather than controlled offshore trials, and the counterfactual maintenance regime is rarely specified. Total cost of ownership must include sensor procurement, hazardous-area installation, battery replacement campaigns, connectivity, cybersecurity, data platform subscriptions, and the engineering effort to validate and act on data. Published experience suggests that value concentrates where monitoring is targeted at credible, consequential degradation threats identified through RBI, rather than distributed indiscriminately across the asset.

Illustrative Deployment Scenarios

Three composite scenarios, synthesized from patterns recurring across published deployments, illustrate how the technologies combine in practice. In the first, a mature North Sea platform facing a large CUI inspection backlog instrumented its highest-risk insulated circuits with moisture-sensing tapes and sacrificial-element sensors during a planned campaign, using LoRaWAN backhaul to an existing edge gateway. Over the following operating year, sustained wetting alerts at a small fraction of monitored locations redirected the stripping program to those locations, where active CUI was confirmed and repaired, while dry circuits had invasive inspection deferred with documented justification. The net effect was a materially smaller access and habitat scope for equivalent risk reduction (Arumosoye and Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Arumosoye *et al.*, 2025; Obogo *et al.*, 2019a, 2020a,b,c, 2021a,b, 2022, 2023, 2024a,b).

In the second scenario, a deepwater production facility with sand-producing wells deployed permanent UT arrays at erosion-susceptible bends and chokes, trended by edge analytics against sand detector and rate data. When a rate increase coincided with an inflection in measured wall loss, the operator adjusted choke strategy and brought forward a targeted replacement, avoiding an unplanned shutdown that historical practice would likely have discovered only at the next survey (Atta *et al.*, 2018, 2020, 2021, 2022; Omoegun *et al.*, 2023; Sunday and Omoegun, 2018, 2019, 2022; Sunday *et al.*, 2019, 2020; Tonoyan *et al.*, 2021a,b, 2022a,b,c, 2023, 2024a,b, 2025).

In the third, an FPSO approaching design life integrated hull and topside strain sensing, motion monitoring, and inspection history into a structural digital twin supporting a life extension application. Measured fatigue consumption at instrumented details proved lower than the conservative design assumption at most locations and higher at two, prompting local reinforcement and an evidence-based extension case accepted by the classification society. The scenario illustrates the shift from assumption-led to measurement-led life management that continuous monitoring enables (Adenuga, 2022, Agu *et al.*, 2023a,b, 2025; Akomolafe and Agu, 2018, 2019a,b,c, 2023a,b, 2025; Annan, 2022, 2023, 2024, 2025a,b; Bello *et al.*, 2023b; Komi, 2021, 2023, 2024, 2025; Komi and Adamolekun, 2020, 2021, 2022, 2023, 2024a,b,c; Komi and Ganiu, 2022, 2023, 2025; Tackie *et al.*, 2023;).

Economic Evaluation Considerations

Whether these outcomes justify investment is ultimately an economic question, and 2025 practice has converged on a reasonably standard evaluation framework. Costs are assessed on a total-cost-of-ownership basis over a five-to-ten-year horizon: hardware, hazardous-area installation, connectivity, platform subscriptions, cybersecurity controls, battery and sensor replacement, and the engineering effort to validate data and maintain models. Benefits are assessed across four categories: avoided inspection and access cost, including scaffolding, habitats, insulation reinstatement, and bed space; avoided production deferment from both inspection outages and unplanned failures, usually the dominant term offshore; risk reduction, monetized through expected loss-of-containment cost or treated as a constraint; and personnel exposure reduction, increasingly quantified through avoided offshore hours and transits. Sensitivity analysis on failure probabilities and deferment values is essential, because business cases are typically dominated by low-probability, high-consequence terms. Published procurement and supply chain research supports a further, often uncounted benefit: condition-driven demand signals improve spares planning and materials readiness, reducing expediting cost and logistics-driven downtime (Agbabiaka *et al.*, 2019; Akin-Oluyomi *et al.*, 2021, 2022a,b, 2023a,b,c,d,e, 2024; Babatope *et al.*, 2023; Efobi *et al.*, 2021, 2022a,b, 2023; Ogundairo, 2025; Okojie and Abioye, 2020; Okoruwa *et al.*, 2024b, 2025; Ogunwole *et al.*, 2021; Okonkwo *et al.*, 2018a,b, 2019, 2020, 2021a,b, 2023a,b, 2024a,b,c,d,e,f, 2025; Patrick *et al.*, 2020, 2021).

Environmental Durability and Power

Marine atmospheres attack the sensors themselves. Salt spray, ultraviolet exposure, washdown, vibration, and temperature cycling degrade housings, cabling, adhesive bonds, and antenna performance, and sensor populations therefore require their own reliability management. Battery life remains the binding constraint on wireless node density and reporting frequency; although energy harvesting from thermal gradients and vibration has advanced, primary lithium batteries with intelligent duty cycling remain the norm in 2025, implying periodic replacement campaigns that must themselves be planned and costed.

Retrofit, Certification, and Coverage Economics

Most offshore facilities operating in 2025 predate IoT. Retrofitting sensors into congested, ATEX and IECEx zoned modules requires management of change, cable routing or radio surveys, and often habitat or shutdown windows, and retrofitting distributed fiber into existing insulation systems is acknowledged in the literature as particularly difficult. Because instrumenting every susceptible location is uneconomic, coverage design remains a risk-optimization exercise, and undetected degradation at uninstrumented locations remains a residual risk that periodic inspection must still address. Continuous monitoring in 2025 therefore complements rather than eliminates conventional inspection.

Data Quality, Alarm Management, and Organizational Readiness

Continuous sensing multiplies data volume by orders of magnitude, and with it the potential for false alarms, drift, and unvalidated readings. Mature programs implement sensor self-diagnostics, data quality flags, and defined validation workflows before condition data is admitted into integrity decisions. Equally important is organizational readiness: integrity engineers, inspectors, and maintenance planners require new competencies in data interpretation, and governance must define who owns sensor health, who responds to alerts, and how monitoring evidence is documented for auditors and regulators. Programs that treated IoT as a technology purchase rather than a work-process redesign have consistently underperformed, echoing human-factors findings on the decisive role of user awareness and behavior in sociotechnical systems (Onche *et al.*, 2024).

Cybersecurity

Every sensor, gateway, and cloud link expands the attack surface of safety-critical infrastructure. Industry reporting in 2025 indicated that more than half of leading oil and gas companies had experienced data breaches within a recent short time frame, underscoring the exposure of increasingly connected operations. Established controls, including network segmentation between OT and IT in accordance with IEC 62443, encrypted and authenticated telemetry, secure device onboarding and certificate management, vendor and supply-chain risk management, and continuous monitoring of the monitoring systems themselves, are now regarded as prerequisites rather than enhancements for offshore IoT deployments, consistent with the operational technology, IoT security, and cyber defense engineering literature on protecting critical infrastructure (Adebayo *et al.*, 2022, 2023; Adegbite *et al.*, 2020, 2022, 2023, 2024a,b, 2025; Ahmed *et al.*, 2021; Dosunmu and Ogundele, 2019, 2020, 2021, 2022, 2023, 2024a,b,c,d, 2025a,b,c; Jimoh and Ahmed, 2024; Jimoh *et al.*, 2023a,b).

Standards, Assurance, and Workforce Development

Two further barriers deserve explicit treatment. The first is the still-incomplete standardization of monitoring itself. While inspection is governed by long-established codes, permanently installed sensing lacks equivalent consensus standards for sensor qualification, data quality grading, and the evidentiary weight monitoring may carry in code-required assessments; joint industry projects and standards committees were actively addressing this gap through 2025, but operators must presently construct asset-specific justifications, which raises cost and inhibits smaller operators (Agu *et al.*, 2023a,b, 2025; Akomolafe and Agu, 2018, 2019a,b,c; Akomolafe *et al.*, 2023a,b, 2025; Annan, 2022, 2023, 2024, 2025a,b; Bello *et al.*, 2023b). The second is workforce. The integrity discipline has historically been staffed by inspection and materials specialists; continuous monitoring adds requirements in instrumentation, networking, data engineering, and applied statistics that few existing role profiles cover. Organizations are responding with hybrid team structures pairing integrity engineers with data specialists, with targeted competency frameworks, and with vendor-supported managed services for sensor fleets, though reliance on external services raises its own continuity and data-ownership questions that contracts must address (Badmus *et al.*, 2020, 2025; Edivri and Oteri, 2022, 2024; Ladapo *et al.*, 2018, 2019, 2022a,b, 2023a,b,c,d, 2024a,b, 2025; Ogbole *et al.*, 2021, 2025; Okoruwa *et al.*, 2020, 2024b; Oteri and Edivri, 2024; Onche *et al.*, 2024).

FUTURE DIRECTIONS

Several trajectories are visible for the second half of the decade. First, sensing will continue to densify and cheapen: printed and thin-film corrosion sensors, self-powered nodes, and robot-deployed patches promise coverage economics that make wide-area static equipment monitoring routine rather than selective. Second, analytics will move from predictive to prescriptive, with integrity digital twins recommending intervention windows jointly optimized against production, logistics, and weather, and with foundation-model approaches beginning to fuse text-based inspection records with sensor telemetry. Third, the regulatory interface will formalize: standards bodies and classification societies are progressively codifying how continuous monitoring evidence may substitute for prescriptive inspection, and harmonized data-quality and sensor-qualification schemes are an active area of joint industry work. Fourth, integrity monitoring will integrate with emissions monitoring, as methane detection networks and loss-of-containment surveillance converge on shared infrastructure. Finally, the accumulation of multi-year, high-frequency degradation datasets across fleets will itself become a research resource, enabling degradation models of a fidelity that sparse historical inspection data could never support.

A final trajectory concerns scale economics and program maturity. As unit sensor costs fall and installation practice standardizes, the marginal cost of extending coverage declines while the fixed platform, connectivity, and governance investment is amortized across a growing population, shifting the economically optimal monitoring density upward over time. Operators that established data architecture, cybersecurity, and organizational accountabilities early are therefore positioned to scale rapidly, while late adopters face the harder path of retrofitting governance onto ad hoc deployments. This dynamic suggests that the competitive differentiation of the late 2020s will lie less in access to sensing technology, which is broadly commoditized, than in the institutional capability to absorb continuous condition data into disciplined, auditable maintenance decision-making (Adebayo *et al.*, 2022, 2023; Adegbite *et al.*, 2020, 2022, 2023, 2024a,b, 2025; Ahmed *et al.*, 2021; Aliliele *et al.*, 2023a,b,c, 2024a,b, 2025a,b; Borah *et al.*, 2022; Dosunmu and Ogundele, 2019, 2020, 2021, 2022, 2023, 2024a,b,c,d, 2025a,b,c; Jimoh and Ahmed, 2024; Jimoh *et al.*, 2023a,b; Mbonu *et al.*, 2018, 2019a,b, 2020a,b,c, 2021a,b,c, 2022a,b,c; Odejobi *et al.*, 2025).

CONCLUSION

By 2025, IoT-enabled condition monitoring of offshore static mechanical equipment has crossed from pilot novelty to established practice. Permanently installed ultrasonic thickness sensors, CUI moisture and sacrificial-element systems, distributed fiber optics, corrosivity probes, acoustic emission arrays, and wireless strain instrumentation now address the full spectrum of dominant offshore degradation mechanisms, supported by hazardous-area-certified wireless networks, edge computing, satellite backhaul, and cloud analytics. The decisive advances of the period are less the individual sensors than the system integration around them: interoperable data architectures, machine learning augmented trending, digital twins, and, above all, the formal coupling of continuous condition data into risk-based inspection frameworks so that measurements change inspection scope, maintenance triggers, and life extension arguments in an auditable way. Reported benefits in cost, downtime, and personnel exposure are substantial, though they concentrate where deployment is risk-targeted and organizationally embedded. Durability, retrofit economics, data governance, and cybersecurity remain the principal barriers. The direction of travel is nonetheless clear: offshore static equipment maintenance is evolving from a regime of periodic sampling toward one of continuous, evidence-driven assurance, and the maintenance programs of the late 2020s will increasingly be designed around the data that permanently installed sensing provides.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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