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Conceptual Framework for Condition-Based Maintenance as a Utility Reliability Program

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ABSTRACT: The increasing complexity and demand pressures on modern power systems underscore the urgent need for reliability-centered strategies that move beyond traditional reactive and time-based maintenance models. Condition-Based Maintenance (CBM) offers a proactive, data-driven approach that enables utilities to optimize asset performance, extend equipment life, and reduce unplanned downtime. This presents a conceptual framework for establishing CBM as a core component of utility reliability programs, integrating technological, organizational, and policy dimensions into a coherent model. The framework emphasizes real-time data acquisition and monitoring through Internet of Things (IoT) sensors, Supervisory Control and Data Acquisition (SCADA) systems, thermal imaging, and vibration diagnostics. These data streams are analyzed using advanced tools such as machine learning algorithms, digital twins, and predictive analytics to identify early signs of degradation and optimize intervention timing. Decision-support systems are central to this framework, providing utility operators with actionable insights for prioritizing maintenance activities and balancing cost, risk, and performance. Enabling factors include a supportive organizational culture that prioritizes reliability and safety, continuous workforce training in advanced diagnostics, and strategic investment in IT infrastructure and cybersecurity. The framework also aligns with international reliability and asset management standards such as ISO 55000 and IEC 60300, while encouraging policy support through incentives, compliance mechanisms, and regulatory integration. Expected outcomes include reduced failures and downtime, optimized maintenance expenditures, improved compliance with reliability benchmarks, and enhanced trust among stakeholders. Continuous feedback mechanisms—anchored in performance monitoring, benchmarking, and adaptive strategies—ensure that the CBM program evolves with emerging risks such as climate impacts and cyber threats. Overall, the conceptual framework demonstrates how condition-based maintenance can serve as a cornerstone for utility reliability, advancing resilience, sustainability, and operational excellence in the energy sector.

KEYWORDS: Condition-based maintenance, Predictive maintenance, Utility reliability, Equipment monitoring, IoT sensors, SCADA systems, Performance metrics, Risk assessment, Failure prediction, Asset management

1.0 INTRODUCTION

The reliability of electricity distribution and transmission systems has become an increasingly critical priority in modern societies where energy underpins economic development, social well-being, and technological advancement (Sidney, 2024; Okiye *et al*., 2024). With the rapid growth in electricity demand, coupled with the integration of renewable energy sources, digital technologies, and distributed generation, utilities face unprecedented challenges in ensuring uninterrupted power delivery (Alade *et al*., 2024; Faiz *et al*., 2024). Reliability is not merely a technical goal but also a policy and societal imperative, as frequent outages or system failures can disrupt industries, compromise public safety, and erode consumer trust (Ilufoye *et al*., 2024; Nwanko *et al*., 2024). In this context, utilities must move beyond conventional approaches to asset management and adopt innovative strategies that align with the dynamic requirements of 21st-century power systems.

Traditional maintenance models, particularly reactive and time-based approaches, present significant limitations in achieving the desired levels of reliability and cost-effectiveness (Okereke *et al*., 2024; Ogedengbe *et al*., 2024). Reactive maintenance, often referred to as "run-to-failure," allows assets to operate until breakdown occurs, leading to unplanned outages, safety risks, and high emergency repair costs. While this approach minimizes upfront expenditures, it results in unpredictable system performance and elevated life cycle costs. Similarly, time-based or scheduled maintenance applies standardized service intervals regardless of asset condition. Though more structured than reactive maintenance, this strategy often results in either over-maintenance, wasting valuable resources, or under-maintenance, exposing systems to premature failures (Nwokocha *et al*., 2024; Etukudoh *et al*., 2024). Both approaches are increasingly inadequate for modern utilities, especially as critical infrastructure ages and is exposed to external stressors such as climate change, cyber threats, and growing demand variability (Nwokediegwu *et al*., 2024; Alahira *et al*., 2024).

Condition-Based Maintenance (CBM) has emerged as a transformative solution to address these gaps, offering a proactive and data-driven approach to utility reliability. By leveraging real-time monitoring technologies such as IoT sensors, Supervisory Control and Data Acquisition (SCADA) systems, and advanced diagnostic tools, CBM continuously evaluates the actual condition of assets (Evans-Uzosike *et al*., 2024; Alao *et al*., 2024). This enables utilities to detect early signs of degradation, predict failure modes, and schedule maintenance interventions precisely when needed. Unlike time-based systems, CBM ensures that maintenance resources are directed efficiently, reducing unnecessary activities while minimizing the risk of catastrophic failures. Furthermore, the integration of machine learning, digital twins, and predictive analytics enhances CBM's predictive accuracy, making it a cornerstone of reliability-centered asset management in the energy sector (Nwokocha, 2024; Faiz *et al*., 2024).

The relevance of CBM extends beyond operational efficiency; it represents a paradigm shift in utility management by aligning technical processes with broader goals of safety, sustainability, and stakeholder confidence. CBM supports regulatory compliance with reliability indices such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI), while also contributing to international standards in asset management. Its ability to optimize costs, extend asset lifecycles, and enhance resilience against systemic risks makes it indispensable in contemporary energy policy and practice (Ogedengbe *et al*, 2024; Nwokocha, 2024).

The objective of this, is to establish Condition-Based Maintenance as a core reliability program for utilities by presenting a conceptual framework that integrates technical, organizational, and policy dimensions. This framework aims to demonstrate how CBM can be systematically embedded into utility operations, creating a structured pathway for improved reliability, efficiency, and resilience (Balogun *et al*., 2024; Nwokediegwu *et al*., 2024). By addressing the limitations of traditional approaches and harnessing the potential of emerging technologies, the CBM framework positions utilities to meet current and future challenges while advancing toward sustainable, reliable, and consumer-centric power systems.

2.0 METHODOLOGY

The PRISMA methodology was adopted to ensure a transparent and systematic process in developing the conceptual framework for Condition-Based Maintenance (CBM) as a utility reliability program. The review process began with the identification of relevant literature through extensive searches in Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. Search strings combined key terms such as "Condition-Based Maintenance," "utility reliability," "electricity distribution," "transmission systems," "predictive analytics," and "asset management frameworks." Additional policy and regulatory documents were sourced from the International Energy Agency (IEA), International Electrotechnical Commission (IEC), ISO standards, and regional utility regulatory authorities to capture practice-oriented and compliance-focused perspectives.

The inclusion criteria required that studies directly addressed CBM practices, reliability engineering, utility maintenance strategies, or frameworks linking data-driven approaches to reliability outcomes. Empirical research, technical reports, policy papers, and conceptual models published between 2000 and 2025 were considered to capture both foundational developments and contemporary applications. Exclusion criteria removed studies focused exclusively on non-utility sectors without transferable insights, as well as works lacking methodological transparency or peer-reviewed credibility.

The initial search produced 1,286 records. After removal of 412 duplicates, 874 articles were screened by title and abstract. Of these, 321 articles were selected for full-text review. Following application of the inclusion and exclusion criteria, 127 studies were deemed relevant and synthesized for this framework. In addition, 18 policy documents and 12 industrial reports were included to strengthen practical insights and ensure alignment with regulatory and operational contexts.

The synthesis process followed a thematic coding approach, organizing findings into domains of CBM technical processes, organizational enablers, data infrastructure, regulatory compliance, and performance outcomes. This enabled the identification of conceptual linkages between monitoring technologies, predictive modeling, decision-support tools, and reliability indices such as SAIDI, SAIFI, and CAIDI. The PRISMA flow ensured methodological rigor, reducing bias by applying consistent inclusion parameters and documenting the progression from identification to inclusion. The final conceptual framework was derived by triangulating evidence across academic, regulatory, and industrial domains, ensuring both theoretical robustness and practical applicability. Through this structured approach, the PRISMA methodology validated CBM as a viable and scalable reliability program for utilities, offering a foundation for further empirical testing and policy adoption.

2.1 Essential Elements of the CBM Framework

Condition-Based Maintenance (CBM) represents a transformative shift in utility maintenance philosophy by moving from reactive or fixed-interval interventions to predictive, data-driven strategies. For electricity distribution and transmission utilities, CBM serves as a cornerstone of reliability-centered operations, enabling early fault detection, risk-informed decision-making, and compliance with stringent performance standards as shown in figure 1(Ibekwe *et al*., 2024; Obadimu *et al*., 2024). The conceptual framework for CBM can be articulated through four interrelated components: data acquisition and monitoring, diagnostic and analytical tools, decision-making mechanisms, and policy and governance integration. Together, these pillars ensure that CBM is not merely a technical exercise but a comprehensive reliability program aligned with organizational and regulatory imperatives.

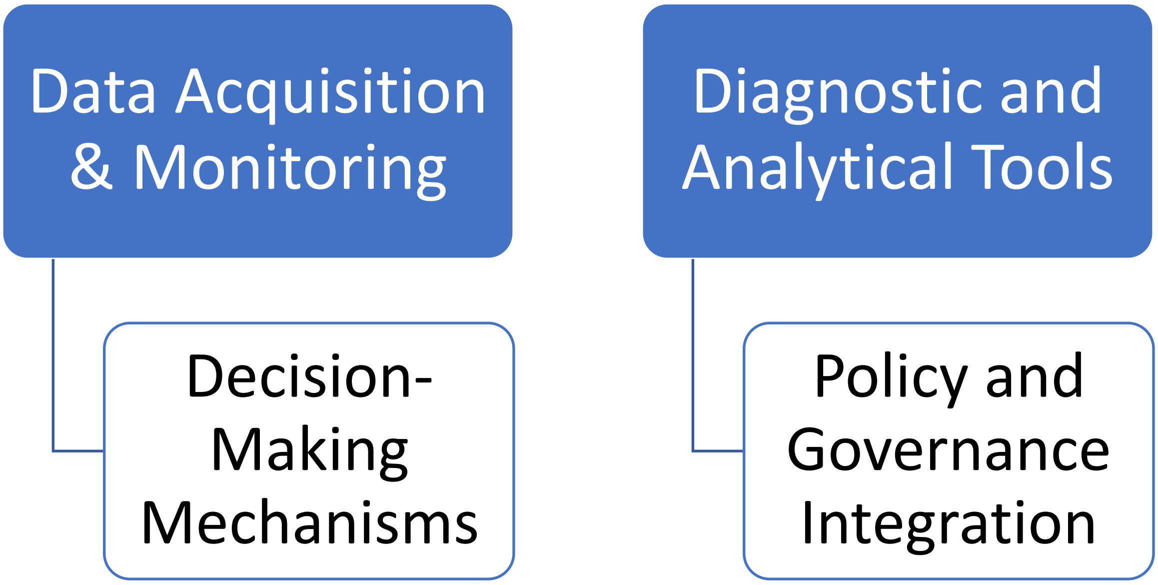

Figure 1: Essential Elements of the CBM Framework

The foundation of CBM lies in the systematic collection of real-time data from critical assets. Utilities increasingly deploy Internet of Things (IoT) sensors to monitor parameters such as temperature, voltage fluctuations, current flows, and environmental conditions that affect equipment performance. Supervisory Control and Data Acquisition (SCADA) systems and smart meters provide continuous monitoring across distribution networks, offering valuable insights into load profiles, power quality, and outage patterns. Advanced technologies such as thermal imaging and vibration monitoring are vital for identifying early-stage anomalies in transformers, cables, and rotating equipment before they escalate into costly failures (Umoren *et al*., 2024; Nwokediegwu *et al*., 2024). To maximize effectiveness, these inputs are integrated with asset management platforms, creating centralized repositories where operational, maintenance, and reliability data converge. This integration ensures traceability, interoperability, and readiness for analytical processing.

Once collected, data must be transformed into actionable insights through advanced diagnostic and analytical tools. Predictive analytics plays a central role, leveraging historical and real-time information to forecast potential equipment degradation and failure modes. Machine learning algorithms enhance this capacity by identifying hidden patterns and correlations that traditional approaches might miss. For example, anomaly detection models can differentiate between normal fluctuations and conditions indicative of impending failures, thereby reducing false alarms and improving diagnostic accuracy. Digital twin technologies further extend analytical capabilities by creating virtual replicas of assets or entire grid sections, allowing utilities to simulate operational scenarios, test intervention strategies, and anticipate long-term performance trends (Asata *et al*., 2023; Okiye *et al*., 2025). Tools for degradation trend analysis provide critical insights into the gradual decline of asset health, enabling utilities to design preventive interventions with precision. Collectively, these tools ensure that diagnostic processes are proactive, accurate, and scalable across complex utility networks.

The real strength of CBM emerges when diagnostic outputs are translated into optimized maintenance actions. Decision-making mechanisms within the CBM framework are designed to prioritize interventions based on risk, consequence, and real-time condition indicators. A risk-based prioritization approach ensures that assets critical to system reliability and customer safety receive higher attention, while non-critical components are maintained more flexibly. Condition indicators guide the timing and scope of maintenance activities, shifting utilities from rigid schedules to adaptive planning models. Maintenance scheduling, informed by predictive analytics, allows utilities to allocate resources effectively, minimizing unnecessary interventions while preventing catastrophic failures (Filani *et al*., 2023; Oluoha *et al*., 2023). Furthermore, decision-support platforms integrate these mechanisms into intuitive dashboards, giving utility managers and field teams real-time visibility into asset health and enabling cross-departmental coordination. By embedding risk awareness into everyday decisions, utilities can balance reliability goals with cost-efficiency.

No CBM framework can achieve long-term sustainability without alignment with policy and governance structures. Embedding CBM objectives into reliability and compliance frameworks ensures that utilities are accountable not only to their internal performance targets but also to external regulatory benchmarks. International standards such as ISO 55000 (asset management) and IEC 60300 (dependability management) provide structured guidelines for integrating CBM into organizational practices, promoting consistency and transparency. Regulatory authorities increasingly emphasize reliability indices such as SAIDI, SAIFI, and CAIDI, requiring utilities to demonstrate measurable improvements in service delivery. By aligning CBM practices with these requirements, utilities strengthen both compliance and stakeholder trust. Governance integration also involves policy support for innovation adoption, such as incentives for digital technology deployment and penalties for failure to meet reliability benchmarks (Okiye *et al*., 2023; Oladimeji *et al*., 2023). This creates a regulatory environment that rewards proactive maintenance while holding utilities accountable for systemic reliability outcomes.

The core components of the CBM framework—data acquisition and monitoring, diagnostic and analytical tools, decision-making mechanisms, and policy and governance integration—form a cohesive architecture that transforms maintenance from a cost center into a strategic enabler of utility reliability. Data-driven monitoring ensures a granular understanding of asset conditions; diagnostic tools convert these insights into actionable forecasts; decision-making mechanisms prioritize interventions for maximum impact; and governance structures institutionalize CBM as a regulatory and organizational mandate. Together, these components establish a robust foundation for utilities striving to meet the dual imperatives of operational efficiency and service reliability in an era of rising demand and technological change. By embedding CBM into their reliability programs, utilities not only enhance system performance but also build resilience, compliance, and customer confidence for the long term (Essien *et al*., 2024; Taiwo *et al*., 2025).

2.2 Enablers of CBM Success

Condition-Based Maintenance (CBM) represents a paradigm shift in how utilities approach reliability and asset management. Rather than relying on reactive repairs or rigid time-based schedules, CBM leverages real-time condition monitoring, predictive analytics, and proactive interventions to reduce failures and extend asset life. However, the success of CBM as a utility reliability program depends not only on technological tools but also on enabling conditions across organizational, technical, policy, and collaborative domains (Ozobu *et al*., 2025; Umoren, 2025). A supportive organizational culture, skilled workforce, advanced IT infrastructure, regulatory and financial support, and cross-sector collaboration collectively form the backbone of effective CBM implementation.

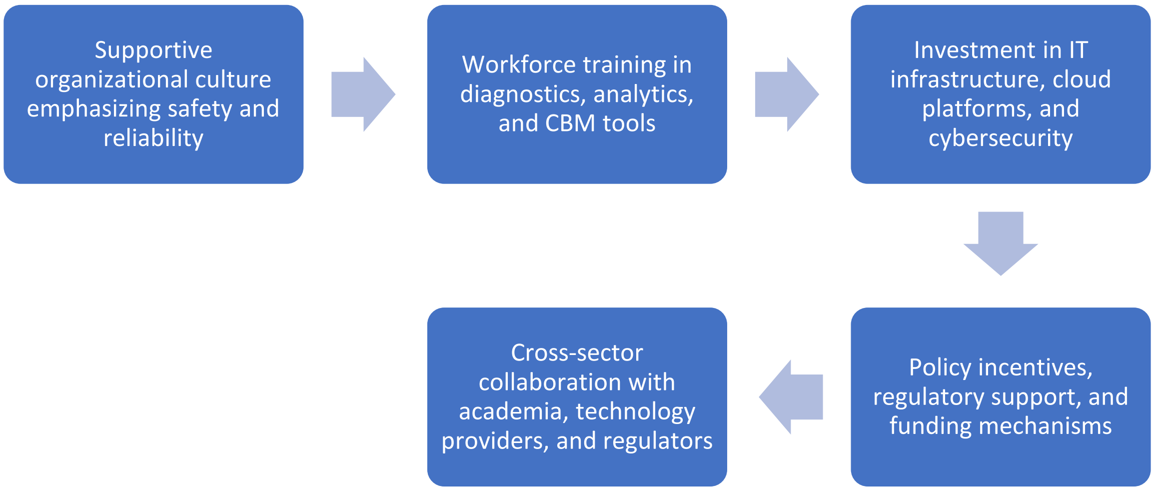

Figure 2: Facilitators of CBM Achievement

At the core of CBM success lies an organizational culture that prioritizes safety, reliability, and proactive asset management. A culture shift is necessary to move from traditional "fix after failure" mindsets toward data-driven, preventive practices. Leadership commitment is vital to embedding reliability as a strategic objective and ensuring that maintenance decisions are not constrained solely by short-term cost considerations. This includes fostering an environment where safety is non-negotiable, where lessons learned from failures are systematically shared, and where reliability metrics such as Mean Time Between Failures (MTBF) or outage frequency are integrated into performance evaluations (Ogundeji *et al*., 2025; Sanusi, 2025). A reliability-centered culture motivates employees to embrace CBM tools, trust data-driven insights, and contribute to continuous improvement initiatives.

Even the most advanced CBM technologies cannot succeed without skilled personnel capable of operating, interpreting, and acting on diagnostic information. Workforce training is therefore a key enabler, ensuring staff at all levels—from engineers to technicians—are proficient in using IoT sensors, SCADA systems, predictive analytics software, and digital twins. Training should also extend to soft skills such as critical thinking, decision-making under uncertainty, and cross-disciplinary collaboration, enabling teams to respond effectively to complex grid conditions (Ukamaka *et al*., 2025; Nwaigbo *et al*., 2025). Structured programs such as certifications in reliability engineering, workshops on failure mode analysis, and simulation-based learning strengthen workforce readiness. In addition, cultivating champions or "CBM leaders" within organizations helps to institutionalize expertise and promote knowledge sharing across departments.

CBM is inherently data-intensive, requiring robust IT infrastructure to manage the collection, integration, and analysis of vast datasets from distributed assets. Investments in cloud-based platforms enable utilities to store, process, and visualize condition data at scale, while ensuring accessibility across departments and geographic locations. Advanced computational tools, including machine learning algorithms, demand scalable infrastructure capable of handling real-time streams from IoT sensors, drones, and monitoring systems. Cybersecurity is equally critical, as CBM relies on interconnected networks vulnerable to cyber threats. Utilities must adopt robust cybersecurity frameworks to safeguard sensitive

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operational data, protect against intrusions, and ensure system resilience. Reliable IT and secure data environments not only support CBM functionality but also build trust among stakeholders, regulators, and customers (Asere *et al*., 2025; Sanusi *et al*., 2025).

Policy and regulatory frameworks play an indispensable role in enabling CBM success. Governments and regulators can accelerate adoption by embedding CBM practices into reliability compliance requirements, linking them to key performance indices such as SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), and CAIDI (Customer Average Interruption Duration Index). Incentives such as tax credits, grants, and performance-based rewards encourage utilities to invest in CBM infrastructure, while penalties for non-compliance create accountability. Funding mechanisms, whether through public-private partnerships or dedicated regulatory allowances, help utilities overcome high upfront costs associated with digital platforms, workforce training, and advanced sensors. By providing a supportive policy ecosystem, regulators ensure that CBM transitions from an optional practice to an institutionalized standard for reliability management.

CBM success also depends on knowledge-sharing ecosystems that bridge utilities, academia, regulators, and technology providers. Collaboration with universities and research institutions enables the continuous refinement of diagnostic algorithms, the development of novel failure models, and the training of the next generation of reliability engineers. Partnerships with technology providers ensure access to cutting-edge tools such as drones for asset inspections, augmented reality for technician support, and AI-driven analytics for fault prediction (OBADIMU *et al*., 2025; Umoren *et al*., 2025). Regulators, on the other hand, provide governance, benchmarking frameworks, and platforms for transparency. Cross-sector collaboration not only enhances technical and organizational capacity but also accelerates innovation diffusion, ensuring utilities remain aligned with global best practices.

The enablers of CBM success extend far beyond technology deployment. They involve embedding a reliability-focused culture within organizations, equipping the workforce with advanced skills, investing in IT infrastructure and cybersecurity, securing supportive policy and financial frameworks, and fostering cross-sector collaboration. Together, these conditions ensure that CBM evolves from a conceptual framework into a practical, sustainable, and transformative reliability program (Evans-Uzosike *et al*., 2025; Oluoha *et al*., 2025). By addressing these enablers holistically, utilities can unlock the full potential of CBM, achieving reductions in downtime, cost efficiencies, and compliance with regulatory benchmarks while strengthening resilience in an era of rising demand, climate risks, and technological complexity.

2.3 Expected Outcomes

Condition-Based Maintenance (CBM) is increasingly recognized as a transformative strategy for ensuring the reliability of electricity transmission and distribution systems. By shifting utilities away from reactive or time-based maintenance toward proactive, data-driven approaches, CBM offers a pathway to greater operational efficiency, asset optimization, and customer satisfaction. The expected outcomes of implementing CBM as a utility reliability program are multifaceted, spanning technical, economic, regulatory, and societal dimensions (Odinaka and Wash–Anigboro, 2025; Taiwo *et al*., 2025). These outcomes include reduced system failures and unplanned downtime, improved asset reliability and lifespan, enhanced compliance with safety regulations, strengthened investor confidence, and a meaningful contribution to sustainability and resilience goals.

One of the most immediate and tangible outcomes of CBM is the reduction in unplanned outages and system failures. By leveraging diagnostic tools, IoT sensors, and predictive analytics, CBM enables utilities to detect anomalies before they escalate into costly breakdowns. For example, early identification of transformer overheating or cable insulation degradation allows timely intervention that prevents cascading failures. The reduction of unplanned downtime directly improves system availability and reduces the burden of emergency repairs, which are often more resource-intensive than scheduled maintenance. In addition, CBM optimizes the allocation of maintenance resources, ensuring that interventions are performed only when necessary, thereby reducing unnecessary labor and spare parts costs. This targeted approach not only drives cost efficiency but also frees resources for reinvestment in grid modernization initiatives.

CBM fundamentally enhances the performance and longevity of critical grid assets. Traditional time-based maintenance often results in under- or over-servicing, which can either leave risks unmitigated or accelerate equipment wear through unnecessary interventions. CBM, by contrast, tailors maintenance actions to the actual condition of assets, reducing wear and extending service life. For instance, vibration monitoring of rotating machinery and thermal imaging of substations provide real-time insights into equipment stress, enabling interventions that maximize reliability. Over time, this results in fewer catastrophic failures, greater energy delivery efficiency, and optimal utilization of capital-intensive infrastructure (Alao *et al*., 2025; Taiwo *et al*., 2025). By maximizing asset lifespan, CBM reduces the frequency of replacements and capital expenditures, ultimately contributing to long-term financial sustainability for utilities.

As utilities operate in highly regulated environments, compliance with reliability, safety, and performance standards is non-negotiable. CBM provides a structured and evidence-based pathway for meeting and even surpassing these requirements. By embedding condition monitoring and predictive diagnostics into maintenance frameworks, utilities can demonstrate adherence to international standards such as ISO 55000 (asset management) and IEC 60300 (dependability management). Furthermore, CBM improves reporting accuracy for key performance indicators such as SAIDI, SAIFI, and CAIDI, which are closely monitored by regulators. Enhanced compliance also translates to improved safety outcomes for both utility workers and consumers, as CBM reduces the likelihood of hazardous equipment failures such as transformer explosions or line faults. In the broader context, regulatory compliance supported by CBM fosters trust between utilities, regulators, and customers, reinforcing the legitimacy of the reliability program.

Another critical outcome of CBM adoption is the strengthening of investor and stakeholder confidence. Utilities are capital-intensive enterprises that depend heavily on investor trust to secure funding for grid modernization, renewable integration, and digitalization projects. Demonstrating the ability to reduce failures, improve asset reliability, and ensure compliance enhances the utility's risk profile, making it more attractive to investors. Stakeholders, including governments, regulators, and consumers, also gain confidence in the utility's ability to deliver reliable and affordable electricity. Transparent CBM-driven performance reporting further reassures stakeholders that utilities are proactively managing risks, ensuring sustainability, and safeguarding long-term value (Ojika *et al*., 2023; Okiye *et al*., 2025). This confidence not only supports capital inflows but also fosters cooperative relationships with regulators and policymakers.

CBM aligns directly with broader sustainability and resilience objectives in the energy sector. By extending asset lifespans, reducing waste from premature replacements, and minimizing energy losses due to inefficient equipment, CBM supports the decarbonization and resource-efficiency agendas. In addition, CBM strengthens grid resilience against climate risks, cyber threats, and rising demand by enabling adaptive and proactive responses. For example, predictive models can help utilities prepare for heatwave-induced equipment stress or storm-related vulnerabilities. Furthermore, the reduced frequency of emergency repairs lowers the carbon footprint associated with rapid dispatch of crews and replacement logistics. As global energy systems transition toward renewable integration and decentralized networks, CBM contributes to ensuring that reliability and sustainability are not compromised but instead enhanced through smarter maintenance practices.

The expected outcomes of implementing CBM as a utility reliability program highlight its transformative potential across technical, economic, regulatory, and societal domains. By reducing unplanned downtime and costs, improving asset performance, ensuring compliance, and strengthening stakeholder confidence, CBM addresses the most pressing challenges faced by modern utilities. Beyond operational efficiency, CBM also contributes to long-term sustainability and resilience, making it a cornerstone of future-ready electricity systems (Ozobu *et al*., 2025; Umoren, 2025). These outcomes position CBM not merely as a maintenance strategy but as a strategic enabler of reliable, sustainable, and trusted utility operations in an era of growing demand, technological disruption, and climate uncertainty.

2.4 Feedback and Continuous Improvement

Condition-Based Maintenance (CBM) is not a static intervention but a dynamic and evolving approach that thrives on feedback loops and adaptive learning. As electricity utilities confront growing reliability challenges from aging infrastructure, digitalization, climate change, and increasing load demands, the ability to continuously refine CBM strategies becomes essential (Essien *et al*., 2025; Odinaka *et al*., 2025). Feedback and continuous improvement mechanisms ensure that CBM frameworks do not merely deliver short-term performance gains but remain resilient, cost-effective, and aligned with long-term utility reliability objectives. The key dimensions of this process include regular evaluation of CBM performance using reliability indices, updating analytical models with field data and emerging risks, benchmarking against global best practices, and adopting adaptive strategies to confront evolving threats.

Effective feedback mechanisms begin with structured performance evaluation. Utilities rely on reliability indices such as the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Mean Time Between Failures (MTBF) to measure the success of CBM initiatives. These indices provide standardized benchmarks for tracking customer-facing outcomes, grid performance, and asset reliability. For example, reductions in SAIDI and SAIFI reflect fewer and shorter outages for customers, indicating that CBM interventions are successfully preventing failures. MTBF trends, on the other hand, reveal whether assets are achieving longer operational cycles between failures. By systematically tracking these indicators, utilities can identify areas where CBM strategies are effective and pinpoint weaknesses that require adjustment. Importantly, performance monitoring also strengthens transparency and accountability, ensuring that utilities can demonstrate the value of CBM to regulators, stakeholders, and investors.

The predictive strength of CBM lies in its reliance on data-driven models, including predictive analytics, machine learning, and digital twins. However, these models must evolve in response to real-world experience and emerging risks. Lessons from field data—such as unexpected failure patterns, anomalous sensor readings, or unforeseen degradation processes—are critical inputs for refining analytical algorithms. For instance, failures triggered by extreme weather events may not align with traditional wear-and-tear models but can be integrated into updated predictive frameworks to improve future accuracy. Similarly, as cybersecurity threats increasingly target digital utility infrastructure, analytical models must incorporate cyber-risk indicators to predict vulnerabilities. Updating models ensures that CBM remains not only accurate in predicting failures but also robust against an evolving risk landscape (Umoren, 2025; OBADIMU *et al*., 2025). This iterative learning process exemplifies the adaptive nature of CBM, where each maintenance cycle improves the system's predictive intelligence and reliability outcomes.

Another critical component of feedback and continuous improvement is benchmarking against global best practices. Utilities worldwide are at different stages of CBM maturity, providing a diverse set of case studies and performance standards that can inform improvement. Benchmarking exercises enable utilities to compare their performance indices, technology adoption, and governance models against those of industry leaders. For example, utilities in advanced markets that have successfully integrated digital twins and AI-driven condition monitoring provide valuable insights into optimizing asset performance under complex grid conditions. Benchmarking not only fosters competitiveness but also encourages knowledge transfer across regions, enabling utilities to adopt proven practices rather than reinvent solutions. Participation in international standards initiatives and industry consortia further reinforces alignment with best practices, ensuring that CBM frameworks remain globally relevant and competitive.

Adaptive Improvements to Address Climate Risks, Cyber Threats, and Evolving Load Demands

The energy landscape is increasingly shaped by disruptive risks, including climate change, cyber threats, and shifting consumption patterns. Continuous improvement in CBM frameworks requires adaptive strategies that proactively address these evolving challenges. Climate risks such as heatwaves, storms, and floods accelerate asset degradation and increase the likelihood of outages. Incorporating climate-resilient design parameters into CBM models helps utilities anticipate and mitigate these threats. Cybersecurity has also emerged as a critical reliability issue, particularly as CBM relies on interconnected sensors, cloud platforms, and real-time analytics (Adebowale, 2025; Dogho, M.O. and Ojoawo, 2025). Continuous updating of cybersecurity protocols and monitoring systems is vital for protecting the integrity of CBM operations. Additionally, evolving load demands driven by electrification, distributed energy resources, and electric vehicles introduce new stresses on grid infrastructure. Adaptive CBM strategies must integrate load forecasting, demand-side management data, and distributed generation monitoring to ensure that maintenance programs remain responsive to rapidly changing energy systems.

Feedback and continuous improvement are the cornerstone of effective CBM implementation in utility reliability programs. By regularly evaluating performance through reliability indices, updating models with field data and emerging risks, benchmarking against global best practices, and adapting to climate, cyber, and demand-related challenges, utilities can ensure that CBM remains robust, relevant, and transformative. This dynamic process elevates CBM beyond a maintenance strategy into a continuously evolving reliability program that supports long-term operational efficiency, sustainability, and customer satisfaction (Annan, 2025). In an era where utilities must balance efficiency with resilience and innovation, feedback-driven CBM provides a framework for learning, adaptation, and enduring reliability.

CONCLUSION

Condition-Based Maintenance (CBM) has emerged as a cornerstone of modern utility reliability programs, providing a transformative shift from reactive and time-based maintenance toward a proactive, predictive, and data-driven paradigm. By continuously monitoring asset health and integrating advanced analytics into decision-making, CBM allows utilities to anticipate failures before they occur, minimize unplanned downtime, and extend the operational lifespan of critical infrastructure. In an era of growing energy demand, aging assets, and increasing exposure to climate and cyber risks, CBM represents not just a technical enhancement but a strategic imperative for power utilities committed to ensuring reliable and sustainable electricity supply.

The strength of CBM lies in its structured, data-driven, and adaptive framework. Through the integration of IoT sensors, SCADA systems, predictive models, and digital twins, utilities can generate actionable insights that optimize maintenance scheduling and resource allocation. Equally important is the alignment of CBM with regulatory standards, governance frameworks, and global best practices, ensuring both compliance and competitiveness. Workforce training, organizational culture, and policy support further enable utilities to realize the full potential of CBM while fostering a safety-first, reliability-focused ethos across operations.

In the long term, CBM delivers far-reaching benefits that extend beyond maintenance optimization. Utilities adopting CBM can achieve enhanced efficiency by reducing maintenance costs, improving energy system performance, and ensuring operational continuity. The approach also strengthens sustainability through the efficient use of resources and contributes to safety by mitigating risks associated with catastrophic equipment failures. Ultimately, CBM enhances the resilience of power infrastructure, instills greater confidence among stakeholders, and positions utilities as leaders in innovation and reliability. By embedding CBM as a central pillar of reliability programs, utilities secure not only immediate performance gains but also the strategic capacity to thrive in a rapidly evolving energy landscape.

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