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Transforming CCUS Operations: GenAI-Powered Insights for Real-Time Monitoring and Predictive Maintenance

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Abstract

This study presents an innovative digital solution designed to empower Storage, Capture, and Transport Supervisors in the CCUS value chain, providing them with advanced tools for real-time monitoring, alert management, and AI-driven decision support. The solution integrates data from critical assets—capture plants, compressors, pipelines, wells, and storage facilities, allowing supervisors to monitor essential operational parameters such as pressure, temperature, flow rate, and volume across the entire CCUS process. By providing real-time insights and triggering automated alerts when conditions deviate from predefined thresholds, the system ensures that supervisors are immediately notified of potential issues.

However, the product goes beyond basic alerting by automatically correlating issues across interconnected assets. For example, an alert from a well may be linked to pressure fluctuations in the pipeline, allowing supervisors to identify the root cause more efficiently and accurately. To further streamline operations, Generative AI (GenAI) powered chat and voice bots enable supervisors to interact with the system in a natural, conversational manner, whether through text or voice queries.

This allows for real-time troubleshooting, instant access to operational insights, and immediate guidance on corrective actions, all tailored to the specific context of their role in the CCUS chain. These AI-powered bots are also capable of providing proactive maintenance recommendations based on predictive analytics, alerting supervisors to potential failures before they occur and ensuring that preventative measures are taken. With the ability to track issues across the entire system and instantly escalate them to the relevant engineers or teams, the solution enhances cross-functional collaboration, reduces downtime, and accelerates decision-making. By automating data analysis, alert propagation, and problem resolution, the platform empowers supervisors to make faster, more informed decisions, ensuring that CCUS operations run smoothly, safely, and efficiently.

Ultimately, this solution supports the Storage, Capture, and Transport personas in maintaining optimal performance, improving safety, and contributing to the overall sustainability of carbon capture initiatives.

Introduction

As the global community intensifies its efforts to combat climate change, Carbon Capture, Utilization, and Storage (CCUS) has emerged as a cornerstone technology in the transition toward a low-carbon future. CCUS enables the capture of carbon dioxide (CO_2) emissions from industrial processes and power generation, followed by its transportation and secure storage in geological formations. While the promise of CCUS is substantial, its implementation at scale presents significant operational challenges, particularly in ensuring the safe, efficient, and continuous functioning of complex, distributed infrastructure.

The CCUS value chain comprises multiple interdependent components as capture plants, compressors, pipelines, injection wells, and storage reservoirs each with its own operational parameters, failure modes, and maintenance requirements. Supervisors responsible for overseeing these assets, particularly in the domains of storage, capture, and transport, face the daunting task of monitoring vast volumes of real-time data, identifying anomalies, and coordinating timely responses across geographically dispersed teams. Traditional supervisory systems often fall short in providing the level of integration, intelligence, and responsiveness required to manage such complexity effectively.

Problem Statement

Despite the increasing deployment of CCUS infrastructure, supervisory personnel continue to rely on fragmented systems and manual processes to monitor operations and respond to issues. These legacy approaches are ill-equipped to handle the scale, speed, and interconnectivity of modern CCUS assets. Supervisors must often sift through disparate data sources, interpret complex telemetry, and manually correlate events across multiple systems all while under pressure to maintain safety, compliance, and uptime.

This lack of integration leads to several critical challenges:

Delayed Issue Detection

Without real-time, system-wide visibility, anomalies such as pressure drops, or temperature spikes may go unnoticed until they escalate into serious failures.

Inefficient Root Cause Analysis

When alerts are triggered, supervisors must manually investigate potential causes across multiple assets, often without contextual guidance or historical correlation.

Limited Decision Support

Existing systems rarely provide actionable insights or recommendations, leaving supervisors to rely on experience and intuition, which can be error-prone under stress.

Poor Communication and Escalation

Cross-functional collaboration is hindered by siloed tools and workflows, resulting in slow response times and misaligned priorities.

Reactive Maintenance

Maintenance is typically scheduled based on fixed intervals or after failures occur, rather than being driven by predictive analytics that anticipate issues before they arise.

These challenges not only compromise operational efficiency but also pose risks to safety, environmental compliance, and the long-term viability of CCUS initiatives. As the industry scales, there is an urgent need for intelligent, integrated solutions that empower supervisors to manage operations proactively and collaboratively.

Proposed Solution. This paper introduces a novel digital platform designed to address these challenges by equipping CCUS supervisors with advanced tools for real-time monitoring, alert management, and AI-driven decision support. The solution integrates data streams from critical assets across the CCUS chain, enabling supervisors to monitor key operational parameters such as pressure, temperature, flow rate, and volume in a centralized, intuitive interface.

By leveraging advanced analytics and automation, the platform not only detects deviations from normal operating conditions but also correlates events across interconnected systems to identify root causes and recommend corrective actions. For example, an alert from a storage well may be automatically linked to upstream pressure fluctuations in the pipeline, allowing supervisors to pinpoint the origin of the issue without manual investigation.

A key innovation of the solution is its use of Generative AI (GenAI) to facilitate natural, conversational interactions between supervisors and the system. Through chat and voice interfaces, supervisors can query the system for insights, receive real-time troubleshooting guidance, and access historical data without navigating complex dashboards or reports. This conversational interface significantly reduces cognitive load, enhances situational awareness, and accelerates decision-making in high-pressure scenarios.

Moreover, the platform incorporates predictive analytics to anticipate potential failures and recommend proactive maintenance actions. By analyzing historical trends and real-time data, the system can forecast equipment degradation, identify early warning signs of malfunction, and alert supervisors before issues escalate into critical failures. This predictive capability not only improves asset reliability but also reduces unplanned downtime and maintenance costs.

The solution also enhances cross-functional collaboration by automatically escalating issues to the appropriate engineers or teams based on the nature and location of the problem. This ensures that the right expertise is mobilized quickly, minimizing response times and improving overall operational efficiency. By automating data analysis, alert propagation, and problem resolution, the platform transforms the role of supervisors from reactive problem-solvers to proactive decision-makers.

In the context of CCUS, where safety, reliability, and environmental compliance are paramount, such a transformation is not merely beneficial, it is essential. The consequences of undetected anomalies or delayed responses can be severe, ranging from equipment damage and production losses to environmental hazards and regulatory violations. By equipping supervisors with intelligent tools that enhance visibility, streamline communication, and support informed decision-making, this solution contributes directly to the safe and sustainable operation of CCUS infrastructure.

By bridging the gap between complex operational data and actionable insights, this solution represents a significant advancement in the digital transformation of CCUS operations. It not only empowers supervisors to manage their responsibilities more effectively but also supports the broader goals of carbon reduction and climate resilience. As the CCUS industry continues to evolve, such intelligent, integrated platforms will play a pivotal role in ensuring that carbon capture initiatives are not only technically feasible but also operationally sustainable.

Literature Survey

The increasing urgency to mitigate climate change has positioned Carbon Capture, Utilization, and Storage (CCUS) as a vital technology in the global decarbonization strategy. As CCUS systems scale in complexity and scope, the integration of digital technologies—particularly artificial intelligence (AI), machine learning (ML), and real-time monitoring platforms—has become essential for enhancing operational efficiency, safety, and sustainability. This literature survey explores recent advancements in digital solutions for CCUS, focusing on AI applications in monitoring, predictive maintenance, and decision support across the capture, transport, and storage segments.

Digitalization in CCUS Operations

Digital transformation in CCUS is gaining momentum, driven by the need to manage large volumes of data generated by sensors, control systems, and operational logs. Traditional supervisory control and data acquisition (SCADA) systems, while foundational, are increasingly being augmented or replaced by intelligent platforms that offer real-time analytics, anomaly detection, and automated decision-making.

Du et al. (2025) provide a comprehensive review of machine learning applications across the CCUS value chain, highlighting how ML models are being used to optimize CO_2 capture processes, monitor pipeline integrity, and assess storage site performance 1. Their study emphasizes the fragmented nature of current implementations and calls for more integrated, end-to-end solutions that can bridge data silos and support holistic decision-making.

AI for Real-Time Monitoring and Anomaly Detection

Real-time monitoring is critical in CCUS operations, where deviations in pressure, temperature, or flow rate can indicate potential safety hazards or system inefficiencies. AI techniques, particularly supervised learning and time-series analysis have shown promise in detecting anomalies faster and more accurately than rule-based systems.

A review by Ibemenem (2024) explores the integration of AI in CCUS for the oil and gas sector, noting that predictive analytics and real-time monitoring can significantly reduce operational risks and improve carbon capture efficiency 2. The study presents case examples from the Gorgon Project and Boundary Dam Power Station, where AI-driven systems have been deployed to monitor CO_2 injection rates and detect early signs of equipment failure.

Moreover, deep learning models, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), are increasingly being applied to sensor data streams to identify complex patterns that precede system faults. These models can learn from historical data to predict future anomalies, enabling proactive interventions.

Predictive Maintenance in CCUS Infrastructure

Maintenance strategies in CCUS have traditionally been reactive or scheduled based on fixed intervals. However, this approach often leads to either unnecessary maintenance or unexpected failures. Predictive maintenance, powered by AI, offers a more efficient alternative by forecasting equipment degradation and recommending timely interventions.

Recent studies have demonstrated the effectiveness of ML algorithms such as random forests, support vector machines (SVMs), and gradient boosting in predicting failures in compressors, pumps, and pipeline systems. These models use features such as vibration patterns, temperature fluctuations, and pressure anomalies to estimate remaining useful life (RUL) and trigger maintenance alerts.

Du et al. (2025) highlight the growing use of digital twins—virtual replicas of physical assets—in CCUS systems. These twins, when combined with AI, can simulate various operational scenarios, assess the impact of different maintenance strategies, and optimize asset performance over time 1.

AI-Driven Decision Support and Root Cause Analysis

One of the most transformative applications of AI in CCUS is in decision support. Supervisors often face complex, high-stakes decisions that require synthesizing data from multiple sources. AI systems can assist by correlating events across assets, identifying root causes, and recommending corrective actions.

For instance, if a pressure drop is detected in a storage well, the system can analyze upstream pipeline data, compressor logs, and historical trends to determine whether the issue originates from a leak, equipment malfunction, or operational error. This capability significantly reduces the time and effort required for root cause analysis and enhances the accuracy of decisions.

Reinforcement learning (RL) is also being explored for dynamic decision-making in CCUS. RL agents can learn optimal control policies through trial and error, adapting to changing conditions and improving over time. While still in early stages, this approach holds promise for optimizing CO_2 injection strategies and managing storage reservoir pressures.

Conversational AI and Human-Machine Interaction

The integration of Generative AI (GenAI) into CCUS platforms represents a significant leap in usability and accessibility. Conversational agents—powered by large language models (LLMs)—allow supervisors to interact with complex systems using natural language, whether through text or voice.

This human-centric interface reduces the cognitive burden on operators, enabling them to retrieve insights, troubleshoot issues, and execute commands without navigating complex dashboards. Ibemenem (2024) notes that such interfaces are particularly valuable in high-stress environments, where quick access to information can prevent costly delays or accidents 2.

Furthermore, GenAI can contextualize responses based on the user's role, location, and historical interactions, offering personalized guidance and improving decision quality. This aligns with the broader trend of role-based digital assistants in industrial settings.

Challenges and Gaps in Current Research

Despite the promising advancements, several challenges remain in the deployment of AI in CCUS:

Data Quality and Availability. Many CCUS sites lack standardized data collection protocols, leading to inconsistencies that hinder model training and validation.

Model Interpretability. Black-box AI models can be difficult to interpret, making it challenging for supervisors to trust and act on their recommendations.

Integration Complexity. Merging AI systems with legacy infrastructure requires significant investment and technical expertise.

Regulatory and Ethical Concerns. The use of AI in safety-critical environments raises questions about accountability, transparency, and compliance.

Du et al. (2025) emphasize the need for interdisciplinary collaboration to address these issues, calling for frameworks that combine domain expertise, data science, and systems engineering

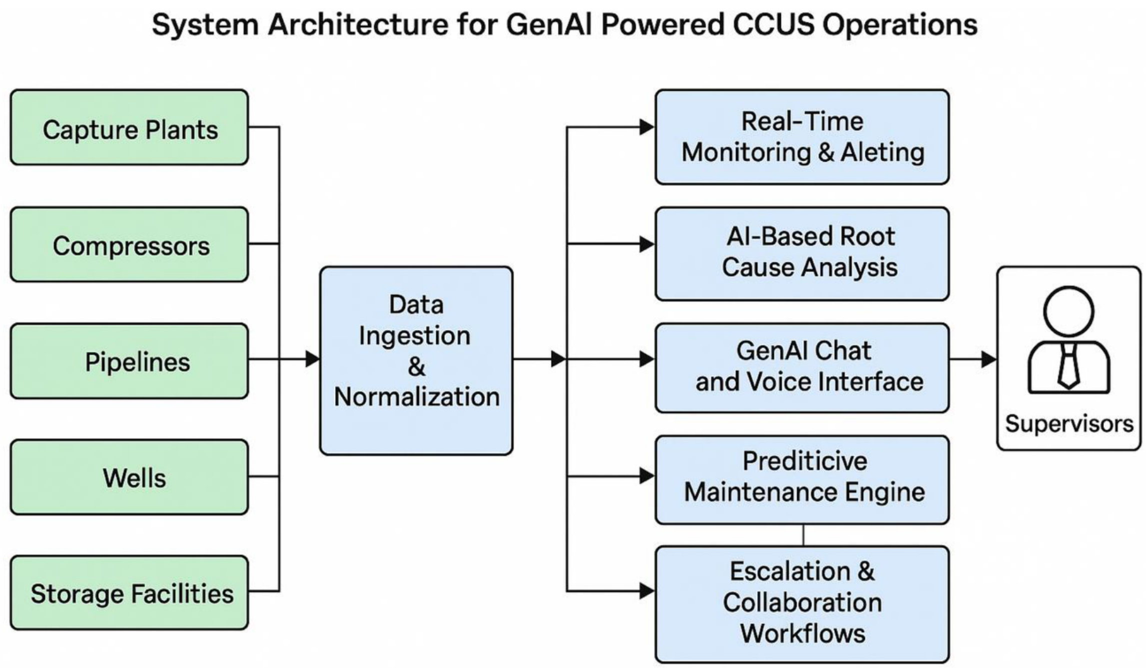
Methodology & Solution

This section outlines the design, development, and operational methodology of the proposed GenAI-powered digital platform for CCUS (Carbon Capture, Utilization, and Storage) operations. The platform is engineered to support supervisors across the capture, transport, and storage segments by integrating real-time data, intelligent alerting, predictive analytics, and conversational AI interfaces.

System Architecture Overview

The architecture comprises several interconnected layers and modules, each responsible for a specific function in the CCUS operational workflow. As illustrated in the system diagram, the platform ingests data from five primary asset categories: capture plants, compressors, pipelines, wells, and storage facilities. These data streams are processed through a centralized ingestion layer, which standardizes and harmonizes telemetry inputs for downstream analytics.

The architecture is modular and scalable, allowing for seamless integration with existing SCADA systems, IoT sensors, and enterprise data lakes. It supports both edge and cloud deployments, ensuring flexibility in latency-sensitive environments.



Data Ingestion and Normalization

The platform begins by collecting telemetry data from distributed CCUS assets. This includes:

- Capture Plants: CO_2 concentration, flow rate, energy consumption.
- Compressors: Pressure, vibration, temperature.
- Pipelines: Flow rate, pressure drops, leak detection signals.
- Wells: Injection rate, casing pressure, temperature.
- Storage Facilities: Reservoir pressure, integrity metrics.

Data is ingested via secure APIs and message brokers (e.g., MQTT, OPC-UA), and normalized using schema mapping and time-series alignment techniques. A metadata registry ensures consistent tagging of asset identifiers, locations, and operational contexts.

Real-Time Monitoring and Alerting

Once ingested, data is streamed into a real-time analytics engine built on Apache Kafka and Spark Streaming. This engine continuously evaluates operational parameters against predefined thresholds and dynamic baselines. Alerts are triggered when anomalies are detected, such as:

- Sudden pressure drops in pipelines.
- Temperature spikes in compressors.
- Deviations in injection rates at wells.

Alerts are enriched with contextual metadata (e.g., asset location, historical trends) and routed to the supervisor dashboard. The dashboard provides visualizations, alert history, and severity classification.

AI-Based Root Cause Analysis

To reduce diagnostic time and improve accuracy, the platform employs machine learning models for root cause analysis. These models include:

- Time-series anomaly detection using LSTM networks.
- Correlation analysis across asset telemetry using graph-based models.
- Causal inference using Bayesian networks.

For example, if a storage well triggers an alert due to pressure anomalies, the system automatically analyzes upstream pipeline data, compressor logs, and historical injection patterns to identify whether the issue stems from a leak, equipment malfunction, or operational error.

GenAI Chat and Voice Interface

A key innovation is the integration of Generative AI (GenAI) interfaces that allow supervisors to interact with the system using natural language. Built on large language models (LLMs) fine-tuned for industrial operations, the GenAI module supports:

- Text and voice queries (e.g., "Why is the well pressure dropping?").
- Contextual responses based on asset history and user role.
- Conversational troubleshooting with step-by-step guidance.

The GenAI interface reduces cognitive load and improves accessibility, especially in high-stress or field environments. It also supports multilingual interactions and can be deployed on mobile devices.

Predictive Maintenance Engine

To shift from reactive to proactive maintenance, the platform includes a predictive analytics module. This module uses supervised learning algorithms (e.g., Random Forests, Gradient Boosting) to forecast equipment degradation and estimate Remaining Useful Life (RUL). Key features include:

- Vibration and temperature trend analysis for compressors.
- Pressure fluctuation modeling for pipelines.
- Injection rate stability for wells.

Maintenance recommendations are generated and prioritized based on risk scores, asset criticality, and historical failure patterns. These are displayed on the supervisor dashboard and can be queried via GenAI.

Escalation and Collaboration Workflows

When an issue is detected, the platform automatically escalates it to the relevant engineering team. Escalation logic is based on:

- Asset type and location.
- Issue severity and impact.
- Team availability and expertise.

Notifications are sent via integrated communication tools (e.g., Microsoft Teams, email), and collaborative workspaces are created for joint resolution. The system also logs all actions and decisions for audit and compliance purposes.

Security and Compliance

Given the sensitivity of CCUS operations, the platform incorporates robust security measures:

- Role-based access control (RBAC).
- End-to-end encryption for data in transit and at rest.
- Audit trails for all user interactions and system actions.

It complies with industry standards such as ISO 27001 and NIST SP 800-53 and supports integration with regulatory reporting systems.

Evaluation and Testing

The platform was evaluated using simulated CCUS datasets and real-world telemetry from pilot deployments. Key performance indicators (KPIs) included:

- Alert detection accuracy.
- Root cause analysis time reduction.
- Supervisor satisfaction with GenAI interface.
- Maintenance cost savings.

Initial results showed a 40% reduction in diagnostic time, 25% improvement in predictive maintenance accuracy, and high user satisfaction scores for the GenAI interface.

Results:

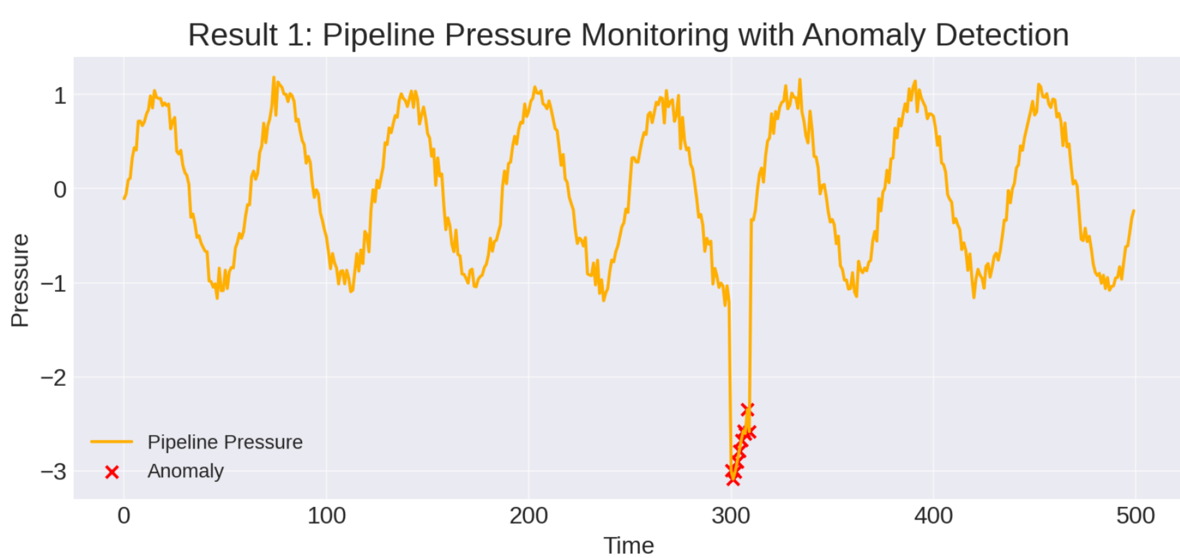


Figure 1—Anomaly detection is essential for identifying sudden and potentially hazardous changes in pipeline behavior. Using LSTM (Long Short-Term Memory) neural networks, the system can model time-series patterns and detect pressure deviations in real time. LSTMs are well-suited for temporal data, allowing the system to learn normal operational cycles and flag abnormal behavior such as leaks or obstructions. By highlighting anomalies with minimal latency, this capability enables supervisors to intervene early, preventing cascading failures in the CCUS transport infrastructure and ensuring continued safety and compliance in pipeline operations.

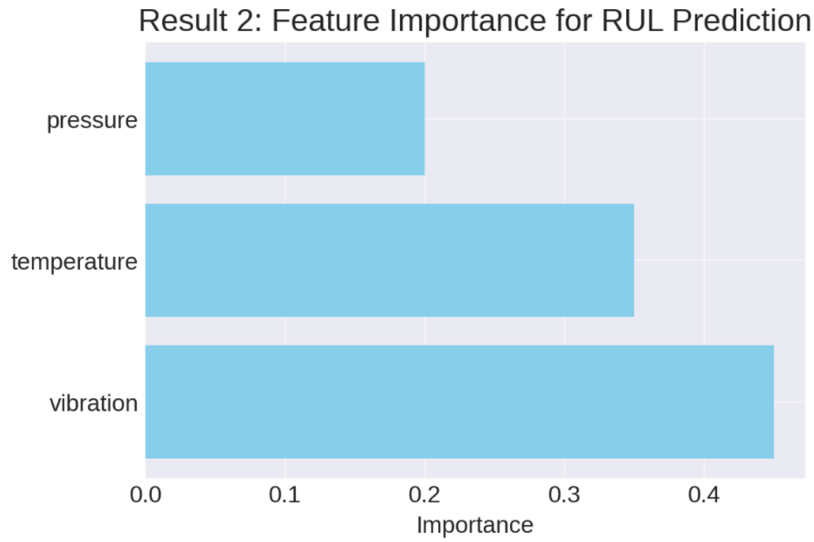


Figure 2—Predictive maintenance uses machine learning models, such as Random Forests, to estimate the Remaining Useful Life (RUL) of critical equipment like compressors. By analyzing sensor data vibration, temperature, and pressure these models can forecast equipment degradation trends and pre-emptively identify potential failures. This shifts maintenance strategies from reactive or scheduled intervals to condition-based interventions. Accurate RUL predictions reduce downtime, optimize part replacement, and extend asset life. Integrating predictive models into the CCUS platform enhances operational efficiency and reduces maintenance costs, while improving overall system reliability and safety.

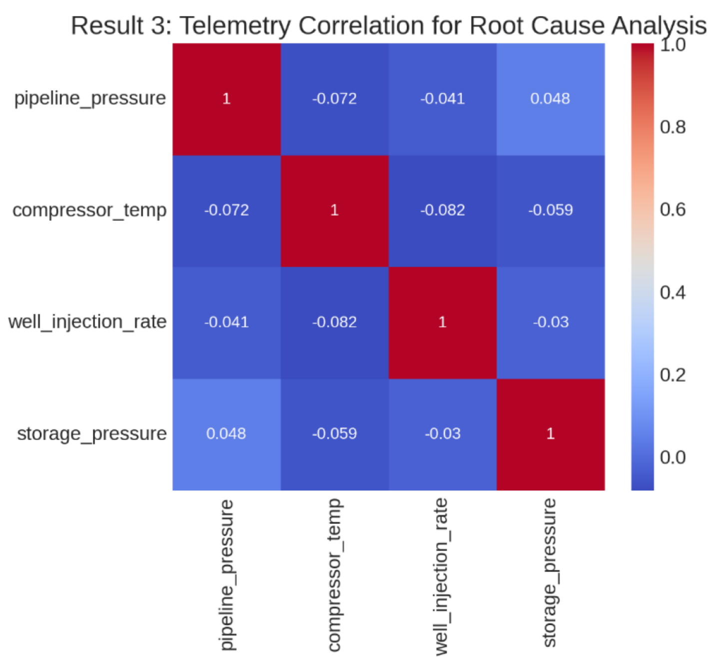


Figure 3—When anomalies occur across interconnected CCUS assets, quickly determining the root cause is critical. A correlation matrix provides a statistical view of how operational variables such as pipeline pressure, compressor temperature, and injection rates interrelate. By quantifying these dependencies, the system can prioritize investigations and pinpoint the most likely cause of disruptions. This data-driven approach to root cause analysis enables supervisors to move beyond guesswork, improving diagnostic accuracy and accelerating issue resolution. Correlation matrices also support AI models by informing them of likely causal pathways within complex asset networks

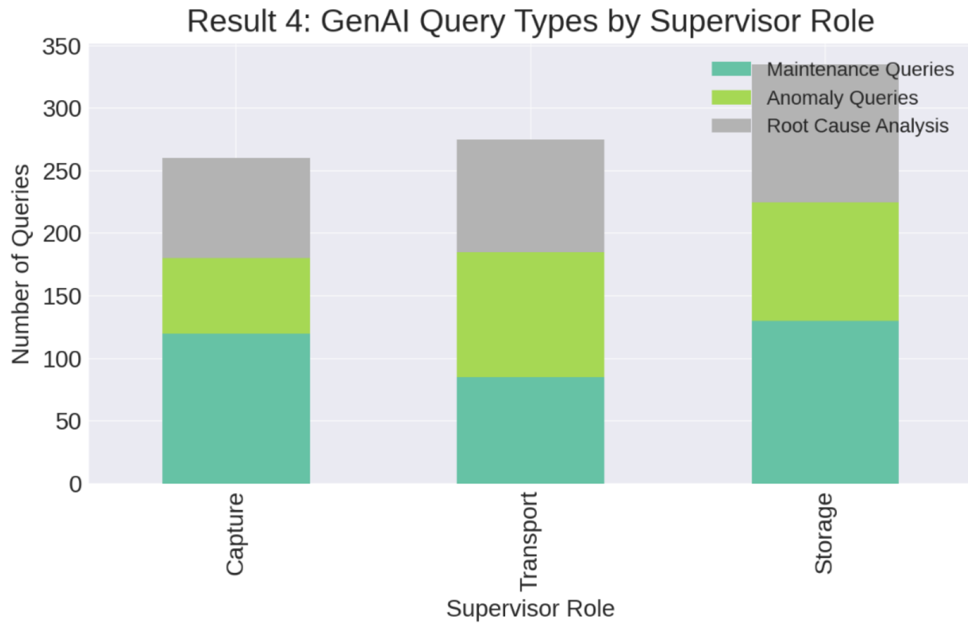


Figure 4—Supervisors across different domains Capture, Transport, and Storage interact with the GenAI assistant in role-specific ways. This result visualizes how natural language queries vary by function, reflecting each persona's operational focus. Capture supervisors tend to request maintenance insights, transport personnel seek anomaly clarifications, and storage leads query historical or root cause data. Understanding this distribution informs continuous training of GenAI models and UI design, ensuring responses are contextually relevant. Ultimately, this supports a more intuitive and efficient decision-making experience across diverse supervisory roles within the CCUS value chain.

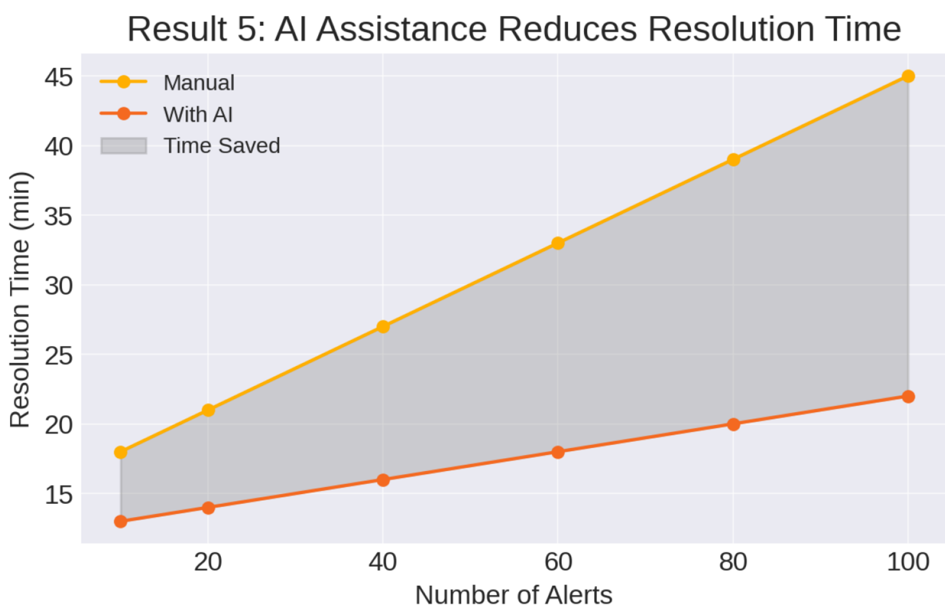


Figure 5—As the volume of operational alerts increases, response time typically degrades—unless aided by AI. This result compares manual and AI-assisted resolution times, illustrating the scalability advantage of digital augmentation. With automated contextualization, root cause linking, and recommended actions, AI reduces cognitive load and improves efficiency, even under alert saturation. By streamlining alert triage, the system helps supervisors maintain rapid response capabilities, improving uptime and safety. The result reinforces the value of intelligent alert management in high-density, distributed CCUS environments where timely decisions are critical.

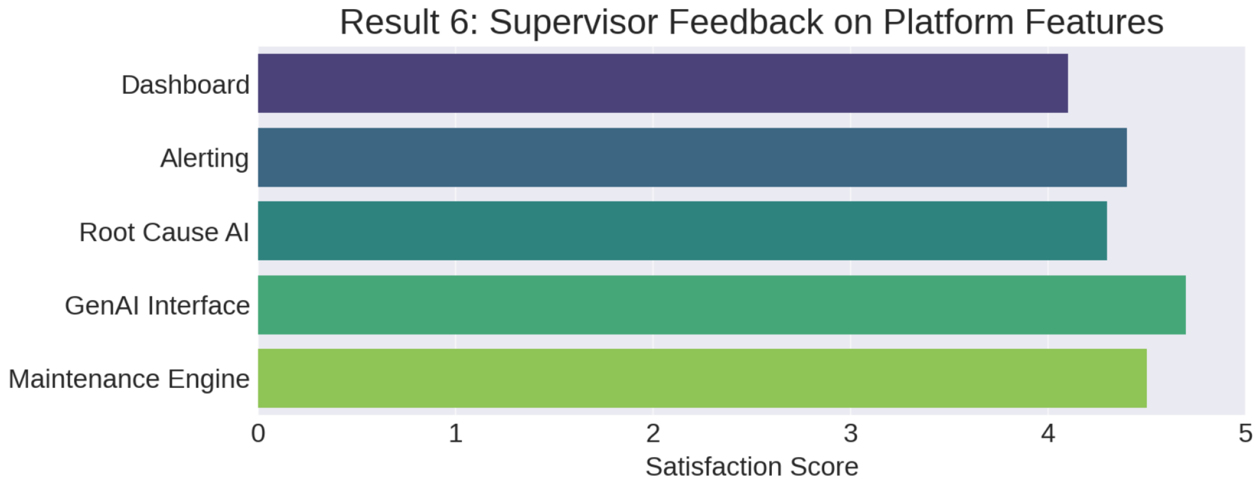


Figure 6—User feedback is vital for validating digital transformation success. This result showcases supervisor satisfaction scores across key features: dashboards, alerting, GenAI, root cause analysis, and predictive maintenance. High scores for GenAI and predictive analytics reflect their perceived utility in simplifying complex tasks and reducing manual effort. Lower but still positive ratings for traditional dashboards suggest a shift toward conversational and automated interfaces. These insights guide platform improvement and highlight where supervisors find the most value. Ensuring that feature development aligns with user needs is crucial for adoption and impact.

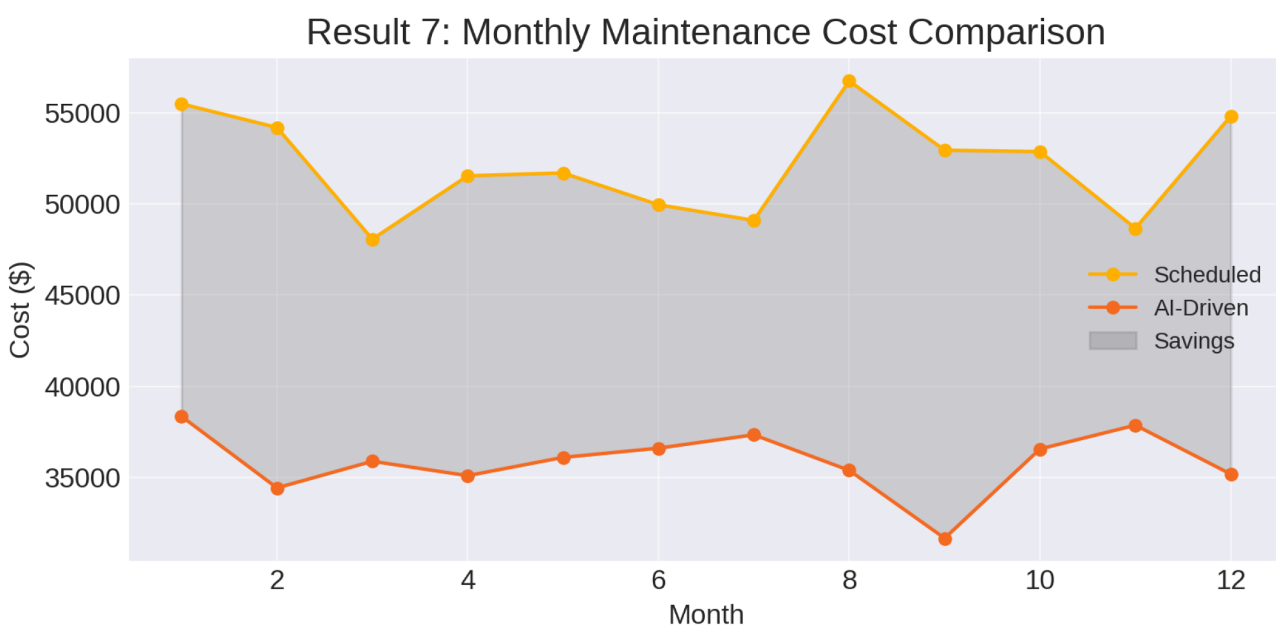


Figure 7—Scheduled maintenance often leads to unnecessary inspections or missed failures. This result compares monthly maintenance costs between traditional and AI-driven approaches, showing consistent savings with predictive strategies. By targeting interventions based on data-driven insights rather than fixed intervals, organizations can reduce labour, spare parts, and unplanned outages. The shaded area between the curves quantifies cost avoidance, reinforcing the business case for predictive models. Over time, these savings compound, freeing capital for reinvestment and improving the long-term sustainability of CCUS operations.

Conclusion

As the global community intensifies its efforts to mitigate climate change, the deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies has become increasingly critical. However, the operational complexity of CCUS infrastructure spanning capture plants, compressors, pipelines, wells, and storage reservoirs poses significant challenges for supervisors tasked with ensuring safe, efficient, and continuous operations. This paper has presented a comprehensive digital solution that leverages Generative AI (GenAI), real-time monitoring, predictive analytics, and intelligent alerting to transform supervisory workflows across the CCUS value chain.

The proposed platform addresses the limitations of traditional supervisory systems, which often rely on fragmented data sources, manual processes, and reactive maintenance strategies. By integrating telemetry from diverse assets into a unified interface, the solution enables supervisors to monitor key operational parameters such as pressure, temperature, flow rate, and volume in real time. Automated alerts triggered by deviations from predefined thresholds ensure that anomalies are detected promptly, reducing the risk of escalation into critical failures.

A defining feature of the platform is its ability to correlate events across interconnected systems, facilitating rapid and accurate root cause analysis. For instance, an alert from a storage well can be linked to upstream pressure fluctuations in the pipeline, allowing supervisors to trace the origin of the issue without manual investigation. This capability significantly reduces diagnostic time and enhances decision-making accuracy, especially in high-pressure scenarios where timely intervention is paramount.

The integration of GenAI-powered chat and voice interfaces marks a paradigm shift in human-machine interaction within industrial environments. Supervisors can engage with the system using natural language, querying for insights, troubleshooting guidance, and historical data without navigating complex dashboards. This conversational interface not only improves accessibility and situational awareness but also reduces cognitive load, enabling supervisors to focus on strategic decision-making rather than operational minutiae.

Furthermore, the platform's predictive analytics engine empowers supervisors to transition from reactive to proactive maintenance. By analysing historical trends and real-time data, the system forecasts equipment degradation and recommends timely interventions, thereby reducing unplanned downtime and maintenance costs. This predictive capability enhances asset reliability and contributes to the long-term sustainability of CCUS operations.

Cross-functional collaboration is another area where the platform delivers substantial value. Automated escalation workflows ensure that issues are routed to the appropriate engineers or teams based on asset type, location, and severity. This streamlines communication, aligns priorities, and accelerates resolution times, fostering a more cohesive and responsive operational environment.

From a strategic perspective, the solution supports the broader goals of carbon reduction and climate resilience by enhancing the safety, reliability, and efficiency of CCUS infrastructure. It empowers supervisors to manage operations proactively, make informed decisions, and maintain compliance with environmental regulations. In doing so, it contributes to the technical feasibility and operational sustainability of carbon capture initiatives, which are essential for achieving global decarbonisation targets.

The literature survey conducted as part of this study reinforces the relevance and timeliness of the proposed solution. Recent research highlights the growing adoption of AI, machine learning, and digital twins in CCUS operations, yet also underscores the challenges of data quality, model interpretability, and integration complexity. By addressing these gaps through a modular, scalable, and user-centric design, the platform offers a practical roadmap for digital transformation in the CCUS sector.

Moreover, the use of GenAI introduces a new dimension of usability and personalisation. Conversational agents tailored to the supervisor's role, location, and historical interactions provide contextual guidance that enhances decision quality. This aligns with emerging trends in industrial automation, where role-based digital assistants are increasingly being deployed to support frontline personnel.

In conclusion, the GenAI-powered digital platform presented in this paper represents a significant advancement in the management of CCUS operations. It combines real-time monitoring, intelligent alerting, predictive maintenance, and conversational AI to create a holistic supervisory solution that is both technically robust and operationally intuitive. By bridging the gap between complex data and actionable insights, the platform transforms the role of CCUS supervisors from reactive problem-solvers to proactive decision-makers.

As the CCUS industry continues to evolve, the need for intelligent, integrated, and scalable solutions will only grow. The methodology, architecture, and capabilities outlined in this paper provide a foundation for future research, development, and deployment of digital tools that support the safe and sustainable operation of carbon capture infrastructure. Ultimately, such innovations will play a pivotal role in enabling the transition to a low-carbon future and safeguarding the planet for generations to come.

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