Edge-Enabled Digital Integration for Real-Time Monitoring and Analytics in CCUS Surface Operations

P. Saini *
Product Leader, Baker Hughes, Delft, Netherlands

U. Biradar
Technology Leader, Baker Hughes, Mumbai, India

K. Sonawane
Product Manager, Baker Hughes, Mumbai, India

A. Mehta
Software Architect, Baker Hughes, Mumbai, India

D. Chauhan
Software Architect, Baker Hughes, Mumbai, India

S. Bordoloi
Sr. Director, Baker Hughes, London, United Kingdom

Abstract

Objective: The objective of this work is to design and demonstrate a digital integration framework that enhances CCUS surface operations through seamless interoperability, edge-based real-time analytics, and web-enabled visualization. The framework aims to:

1. Integrate SCADA, DCS, and Historian systems using standardized protocols.
2. Enable low-latency anomaly detection and closed-loop control at the edge.
3. Provide intuitive, secure, and scalable decision-support tools via a web interface.
4. Improve operational efficiency, safety, and predictive maintenance capabilities across CCUS sites.

Methodology: The proposed architecture consists of three layers: Integration, Edge, and Web Application.

Integration Layer: Industrial systems are connected using OPC Unified Architecture (OPC UA), enabling secure and interoperable data exchange without significant retrofitting. Historian systems contribute long-term datasets for model training, trend analysis, and maintenance planning.

Edge Layer: Edge nodes deployed near field devices execute real-time analytics, anomaly detection, and event-driven logic. Hosting lightweight machine learning models, the edge layer minimizes latency and supports closed-loop control by sending corrective commands back to SCADA or DCS systems. This design reduces reliance on centralized processing, enabling autonomous or operator-approved interventions such as compressor load adjustments or protective shutdowns.

Web Application Layer: Processed data from the edge is visualized through dashboards, alerts, and historical trend views. The web interface supports encrypted communication and role-based access for cybersecurity compliance. Hybrid deployment models enable cloud-hosted visualization while preserving on-premises control integrity.

Results: Implementation of the proposed framework demonstrates significant improvements in operational responsiveness and decision-making. Real-time edge analytics reduce anomaly detection latency, while closed-loop communication enables rapid corrective actions, minimizing equipment failure risks and unplanned downtime. Operators benefit from unified visibility into real-time and historical data, improving situational awareness and maintenance planning. The hybrid deployment model supports multi-site scalability and centralized monitoring while retaining local autonomy for critical operations.

Novelty and Contribution: The novelty of this framework lies in its integration of legacy industrial systems, edge computing, closed-loop control, and modern web visualization into a unified architecture tailored for CCUS operations. Unlike traditional monitoring systems, the proposed solution transforms data collection into proactive optimization, leveraging both real-time and historical insights. The architecture aligns with ISA/IEC 62443 cybersecurity principles and provides a scalable foundation for future enhancements such as advanced machine learning, digital twins, and subsurface integration.