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TECHIES

Official Bulletin 34th Edition - KDN: PQ1780/J/187
www.mbot.org.my

Predictive Maintenance and Reliability Enhancement Using AI-Driven Digital Twin **for PLC-Based Systems in Malaysia's Upstream Oil and Gas Industry**

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Malaysia's upstream oil and gas industry plays a vital role in national energy security and economic development, with operations spanning offshore platforms, pipelines, and production facilities. These environments are inherently complex and hazardous, requiring high levels of system reliability to ensure continuous and safe operations.

At the core of these operations are **Programmable Logic Controller (PLC)-based systems**, which provide robust real-time control for critical processes such as pumping, pressure regulation, and safety interlocking. However, conventional PLC systems are primarily designed for deterministic control rather than predictive intelligence.

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/what's inside

ISSN 0128-1313

/chief editor's note

In the upstream oil and gas industry, exploration and production companies play a critical role in extracting crude oil and natural gas from beneath the earth's surface. Exploration focuses on locating viable reserves, while production involves drilling and extraction to bring these resources to market.

In this edition, we turn our attention to the growing application of artificial intelligence (AI) in production operations. However, while the potential is significant, the actual effectiveness of these technologies remains to be fully established. Questions surrounding cost reduction, loss minimisation, and improvements in safety performance, such as reducing incidents and accidents, require further validation through real-world implementation.

This also raises important considerations for industry stakeholders. Is it worthwhile to install AI-based technologies in ageing facilities? To what extent are operators willing to invest in data sharing, particularly when each site possesses unique characteristics? Furthermore, how sustainable is the maintenance of such systems, and do the long-term benefits justify the associated costs?

These are not merely technical questions, but strategic ones. It is now up to technologists, operators, and decision-makers to critically evaluate these factors to ensure that AI delivers lasting value to the industry.

Assoc. Prof. Dr. Mohamad Asmidzam Ahamat

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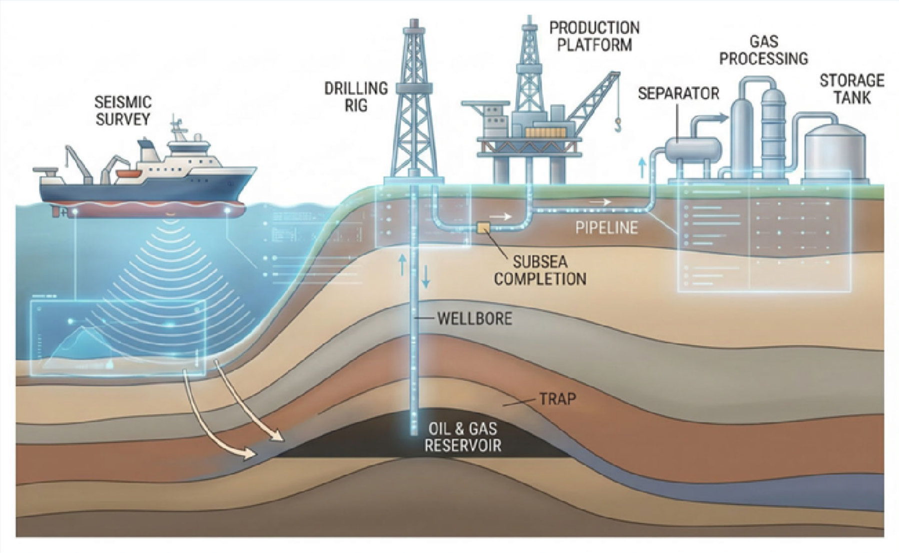
With the increasing demand for operational efficiency and reduced downtime, there is a growing need to shift from reactive maintenance practices to predictive and reliability-centered strategies. The integration of Artificial Intelligence (AI) and digital twin technologies offers a practical and scalable solution to achieve this transformation in Malaysia's upstream oilfields. [1-3].

Reliability Challenges in Malaysia's Upstream Operations

Malaysia's upstream oil and gas sector continues to face significant reliability challenges, particularly in mature offshore assets. A substantial proportion of offshore infrastructure in Southeast Asia has been in operation for over 20 years, increasing the likelihood of equipment degradation and failure. Unplanned downtime remains a major concern, with offshore production losses estimated at USD 100,000 to USD 300,000 per hour, and 5 to 10% of production time lost annually due to unexpected failures. [4-5].

Additionally, harsh operating conditions such as high pressure, elevated temperatures, and corrosive environments contribute to 20 to 30% of equipment failures. Despite the widespread use of PLC-based control systems, most facilities still rely on reactive maintenance approaches, with fewer than 20% adopting advanced predictive analytics. As a result, maintenance costs can account for up to 40% of total operating expenditure, underscoring the need for more intelligent, predictive maintenance strategies. [6-7].



Upstream Processes in the Oil and Gas Industry.

> **"Unplanned downtime remains a major concern, with offshore production losses estimated at USD 100,000 to USD 300,000 per hour, and 5 to 10% of production time lost annually due to unexpected failures.**

Limitations of Conventional PLC-Based Maintenance Approaches

Programmable Logic Controllers (PLCs) are specialized industrial control systems designed to provide reliable, real-time automation of critical processes in upstream oil and gas operations. They are widely used to control and monitor activities such as drilling, fluid handling, pressure regulation, and safety shutdown systems. Their deterministic execution, high reliability, and resilience to harsh environments make them essential for ensuring operational continuity and safety, particularly in offshore and remote facilities. In addition, PLC systems generate large volumes of operational data from connected sensors, offering significant potential for further integration with advanced technologies such as digital twins and artificial intelligence.

Despite these strengths, conventional PLC-based systems have inherent limitations in supporting predictive and reliability-centered maintenance. Their operation is primarily based on predefined logic, enabling real-time control, alarm-based monitoring, and basic fault detection, but lacking the ability to predict future failures or analyze complex multi-variable data patterns. Furthermore, PLC systems are not designed to adapt dynamically to changing operating conditions without manual reprogramming. As a result, maintenance strategies remain largely time-based or reactive, leading to inefficient resource utilization, higher maintenance costs, and an increased risk of unexpected equipment failures that can compromise overall system reliability.

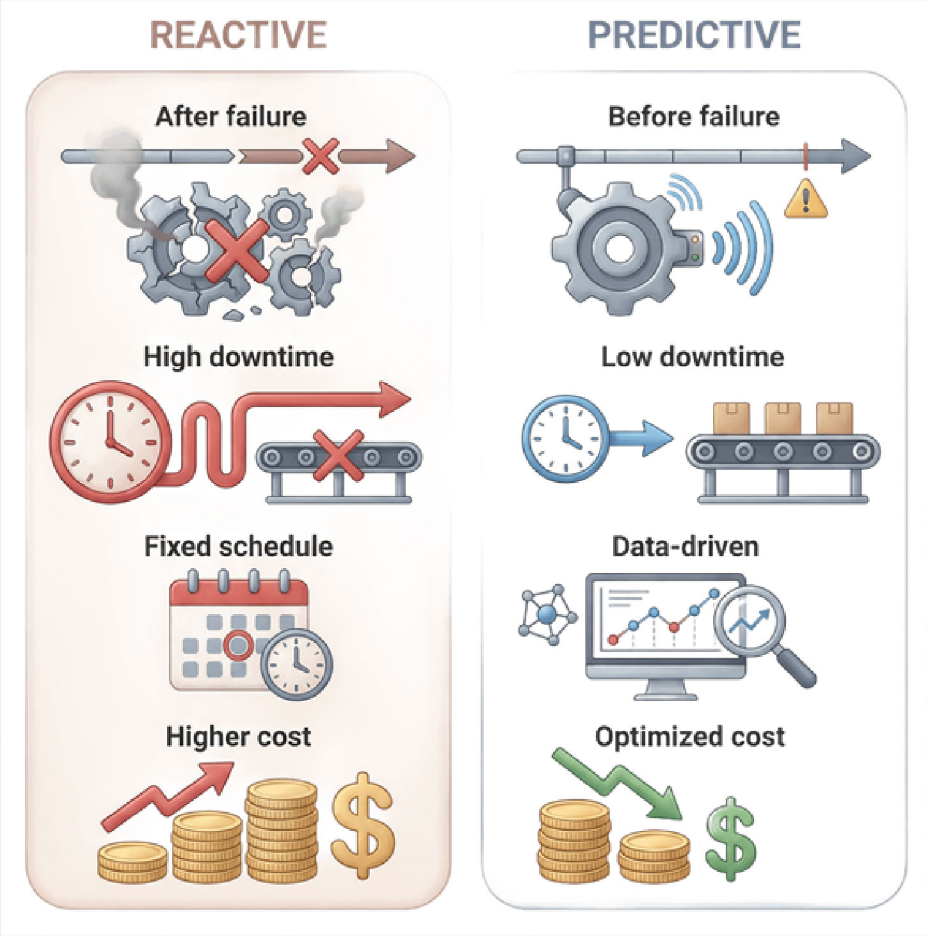
AI-Driven Digital Twin for Predictive Maintenance in Upstream Oil and Gas Operations

An AI-driven digital twin represents an advanced integration of real-time operational data, simulation models, and machine learning algorithms to enable predictive and reliability-centered maintenance in upstream oil and gas systems. In PLC-based environments, the digital twin functions as a virtual representation of physical assets such as pumps, compressors, and pipelines, continuously synchronized with live data obtained from field sensors and control systems [8-9].

This integration enables real-time monitoring, simulation of equipment behavior under varying operating conditions, and continuous assessment of system performance without interrupting actual operations. By leveraging data streams from PLC systems, engineers are equipped with a comprehensive and dynamic understanding of asset health and operational status.

The incorporation of artificial intelligence significantly enhances the capabilities of the digital twin. Machine learning models analyze multi-variable sensor data such as vibration, temperature, and pressure signals to identify hidden patterns and detect early-stage anomalies. These models can predict equipment degradation trends and estimate the Remaining Useful Life (RUL) of critical components, enabling proactive maintenance planning.

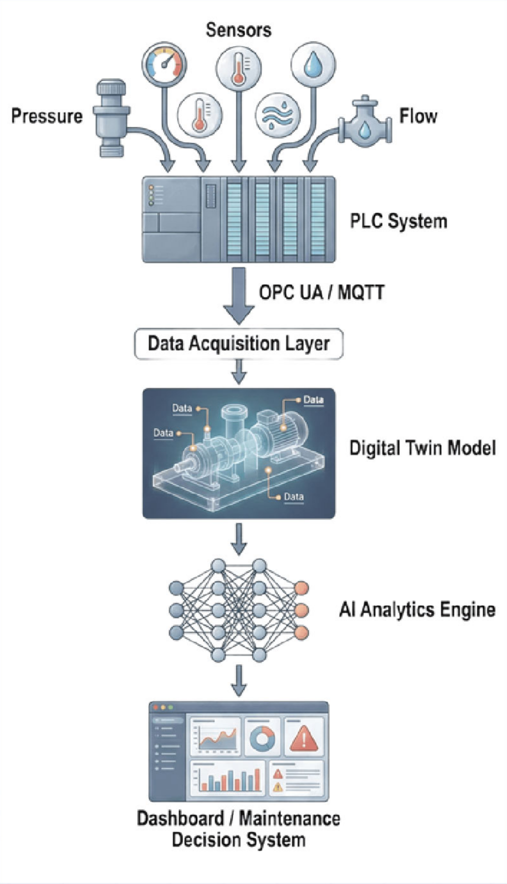
In a typical upstream scenario, sensors connected to PLC systems continuously monitor equipment performance, such as pump operation. The collected data is transmitted to the digital twin platform, where AI algorithms analyze trends and identify deviations from normal behavior. When anomalies are detected, early warnings are generated, allowing maintenance actions to be scheduled before failures occur. This approach transforms maintenance strategies from reactive to predictive and condition-based, significantly improving reliability and operational efficiency.



Comparison of Reactive Maintenance and Predictive Maintenance.

Implementation Framework for AI-Driven Digital Twin in Malaysia's Upstream Oilfields

In the context of Malaysia's upstream oilfields, implementation must consider legacy infrastructure, offshore constraints, and data integration challenges. The successful deployment of AI-driven digital twin systems in Malaysia's upstream oil and gas industry requires a structured and systematic engineering approach. This ensures seamless integration with existing PLC infrastructures while maintaining reliability and operational continuity.



AI-Driven Digital Twin Architecture for PLC-Based Upstream Systems.

The implementation process begins with data acquisition and integration, where real-time data is collected from PLC-connected sensors installed on critical equipment. Industrial communication protocols such as OPC UA and MQTT are employed to facilitate secure and efficient data transmission. Ensuring data quality, consistency, and reliability at this stage is essential for accurate analysis and model performance [10-11].

Following this, a digital twin model is developed to replicate the behavior of key equipment and processes, including pumps, compressors, and pipeline systems. The model simulates system performance under various operating conditions while incorporating PLC control logic to ensure a realistic system representation.

The next stage involves the development of AI models using both historical and real-time operational data. Machine learning algorithms are trained to detect anomalies, predict equipment failures, and assess reliability trends. These models are continuously refined to improve prediction accuracy and adaptability to dynamic operating environments.

Finally, the system is deployed and integrated into real-world operations, where the AI-driven digital twin platform provides continuous monitoring and visualization through user dashboards. These systems enable data-driven decision-making by offering actionable insights for maintenance planning, ultimately reducing downtime, improving asset reliability, and optimizing operational performance.

Conclusion

Predictive maintenance and reliability enhancement using AI-driven digital twin technology represent a significant advancement for Malaysia's upstream oil and gas industry. By integrating PLC-based systems with AI and simulation platforms, engineers can transition from reactive maintenance to proactive and intelligent asset management.

This transformation not only improves operational efficiency and safety but also supports the long-term sustainability and competitiveness of Malaysia's energy sector. As digital transformation accelerates, adopting these technologies is essential to shaping the future of smart, reliable upstream operations.

As Malaysia continues its transition towards digitalized and intelligent oilfield operations, the integration of AI-driven digital twin systems will play a critical role in enhancing reliability, reducing operational risks, and supporting sustainable energy practices. Engineers equipped with expertise in automation, AI, and system integration will be essential in driving this transformation.

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By Capt. Ts. Sujendravel Letchumanan, Qatar Energy

Artificial Intelligence in Upstream Operations: Enhancing Safety, Efficiency, and Decision

The upstream oil and gas industry has always relied on advanced technology to operate safely and efficiently in challenging offshore environments. Artificial intelligence (AI) is rapidly transforming the upstream oil and gas industry. In recent years, AI has emerged as a powerful tool capable of transforming the management of offshore operations. Offshore operations that traditionally rely on human expertise, predictive maintenance, and operational planning and monitoring safety are now benefiting from intelligent data-driven systems that improve safety, efficiency, and operational reliability. AI is progressively becoming an integral part of upstream operations.

In modern offshore fields, large volumes of operational data are generated every second from sensors, satellite communications, and vessel monitoring systems. AI technologies enable operators to convert this vast amount of data into actionable insights that support real-time decision-making. The integration of AI tools is beginning to reshape the daily operations for offshore professionals involved in marine coordination, drilling support, and logistics management.

AI in Daily Offshore Operations

Daily offshore operations involve numerous activities across multiple assets, including production platforms, drilling rigs, floating production and storage offloading (FPSO/FSO) tankers, and supporting marine units such as supply vessels and anchor handling tugboats, all of which must operate in a coordinated and controlled manner. Traditionally, many operational decisions have relied heavily on human experience and manual observations.

AI systems now analyze vast operational data, including vessel movements, weather, equipment status, and logistics, to identify patterns and recommend efficiency improvements. By integrating AIS signals with satellite imagery, radar, and ECDIS, AI-enabled vessel tracking provides real-time monitoring and predictive intelligence, detecting "dark vessels" that traditional AIS systems may miss. This capability enhances navigation safety, reduces congestion around offshore assets, mitigates collision risks, and improves fuel efficiency.

Additionally, AI-based decision support tools can assist marine coordinators in planning vessel movements, cargo, and personnel transfers by evaluating multiple operational factors to enable more reliable decision-making. Moreover, such digital monitoring systems help reduce reliance on manual reporting by enabling a centralized operation monitoring across multiple assets.

"Additionally, AI-based decision support tools can assist marine coordinators in planning vessel movements, cargo, and personnel transfers by evaluating multiple operational factors to enable more reliable decision-making.

Predictive Maintenance and Equipment Reliability

Equipment reliability is critical in offshore operations where unplanned failures can lead to costly downtime and safety risks. One of the most practical and impactful applications of AI in the upstream operation sector is predictive maintenance. Traditionally, equipment maintenance has been performed based on fixed schedules (preventive) or after a failure (breakdown) occurred.

However, with AI-powered predictive maintenance systems, data from sensors installed on equipment such as marine risers, drilling components, engines, and pumps are used to monitor parameters like vibrations, pressure, temperature, and loads. For instance, the IBM Maximo Application Suite, developed by IBM, applies machine learning algorithms to identify patterns in operational parameters. These early warning signals allow the maintenance team to address potential equipment failures before they escalate into operational disruptions. Such early detection of mechanical or hydraulic anomalies can significantly reduce the risk of accidents during lifting operations.

Moreover, the maintenance team can perform targeted inspections and repairs before failures occur by identifying issues early. This significantly reduces downtime, improves equipment lifespan, and enhances operational safety.

Smart Production Monitoring and Optimization

In upstream oil and gas production, efficiency is proportionally linked to monitoring and optimizing production performance. AI-driven systems can

AI-enabled monitoring and optimization of FPSO turret mooring and subsea production systems. The illustration shows how real-time data from turret structures, mooring lines, and subsea infrastructure are integrated into an intelligent analytics platform unit to enhance production, performance, structural integrity, and operational safety.

analyse production data continuously and identify opportunities to improve output. AI-driven smart technologies in Floating Production Storage and Offloading (FPSO) units are shifting offshore operations from reactive, manual monitoring to predictive, autonomous management. Key leaders such as MODEC, SBM Offshore, and SLB are integrating these tools to maximize uptime and safety.

Traditional mooring inspections for Floating Production Storage and Offloading (FPSO) units often rely on intermittent and costly remotely operated vehicle (ROV) surveys that provide only a static "snapshot" of system health. To overcome these limitations, AI-driven models such as the Neural Motion Estimator (NeMo) can be deployed to enable continuous 24/7 monitoring and enhance operational effectiveness. Instead of direct visual checks, the system analyzes the FPSO's dynamic behaviour by processing real-time data from GPS, motion sensors, and environmental inputs like wind and waves. By learning the platform's unique "digital fingerprint", its expected movement patterns under varying conditions, the AI can detect microscopic deviations in equilibrium that signal a mooring line break. This proactive approach prevents "ghost failures", where damaged lines remain undetected during calm weather, thereby avoiding catastrophic drift-off events and allowing for highly targeted, cost-effective repairs.

AI for Safety, Sustainability, and Compliance

Safety is always the priority in offshore operations due to the complex nature of upstream environments. Even small incidents can escalate into major hazards if not properly managed. AI is increasingly being used to enhance safety monitoring and risk detection. Another emerging AI application in upstream facilities is

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computer vision technology. AI-powered video analytics systems can automatically monitor operational areas using cameras installed on offshore platforms. For example, Azure AI Vision, developed by Microsoft, enables computer vision (CV) to upgrade offshore safety by turning existing CCTV networks into intelligent, proactive monitoring systems that operate 24/7 without fatigue. The automation of hazard and non-compliance detection reduces reliance on manual inspections and human oversight, which are susceptible to errors in high-risk, high-stress offshore environments.

Conclusion

Despite the rapid advancement in AI technologies, human expertise remains essential in offshore operations. Offshore professionals provide critical situational awareness, operational judgment, and practical experience that AI cannot fully replicate. AI is an assistant, not a replacement, in offshore operations. While intelligent systems analyze vast datasets and reveal patterns beyond human perception, human expertise provides the situational awareness, judgment, and practical experience that machines cannot replicate. The future of upstream operations lies in collaboration, where AI supports decision-making and experienced professionals ensure safe, effective outcomes.

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By Capt. Ts. Dr. Mohd Awiskarni bin Shamsudin, Dunster Business School Switzerland (DBSS)

AI-Driven Methane Leak Detection Systems for Upstream Operations: SAFER, CLEANER, AND MORE COMPLIANT OPERATIONS

Methane has moved from being a "background loss" in gas operations to a frontline concern for safety, climate policy, and corporate accountability. It is a highly flammable hydrocarbon, capable of forming explosive gas clouds around process equipment, and a potent greenhouse gas with a global warming potential far higher than carbon dioxide over 20 year horizons. For a producer country like Malaysia, upstream methane management now sits directly at the intersection of operational safety, environmental stewardship, and regulatory scrutiny.

Malaysia's upstream sector operates under a dense framework of industrial and environmental law, including the Petroleum (Safety Measures) Act 1984 and the Environmental Quality Act 1974, which require operators to maintain safe installations and minimise harmful emissions. Malaysia's third iteration of its Nationally Determined Contribution commits to peaking economy wide greenhouse gas emissions around 2030 and reducing 15 to 30 metric tons of CO_2 equivalent by 2035, placing renewed focus on methane from oil and gas operations. These developments signal a shift from treating fugitive emissions and routine flaring as operational housekeeping towards treating them as strategic risks.

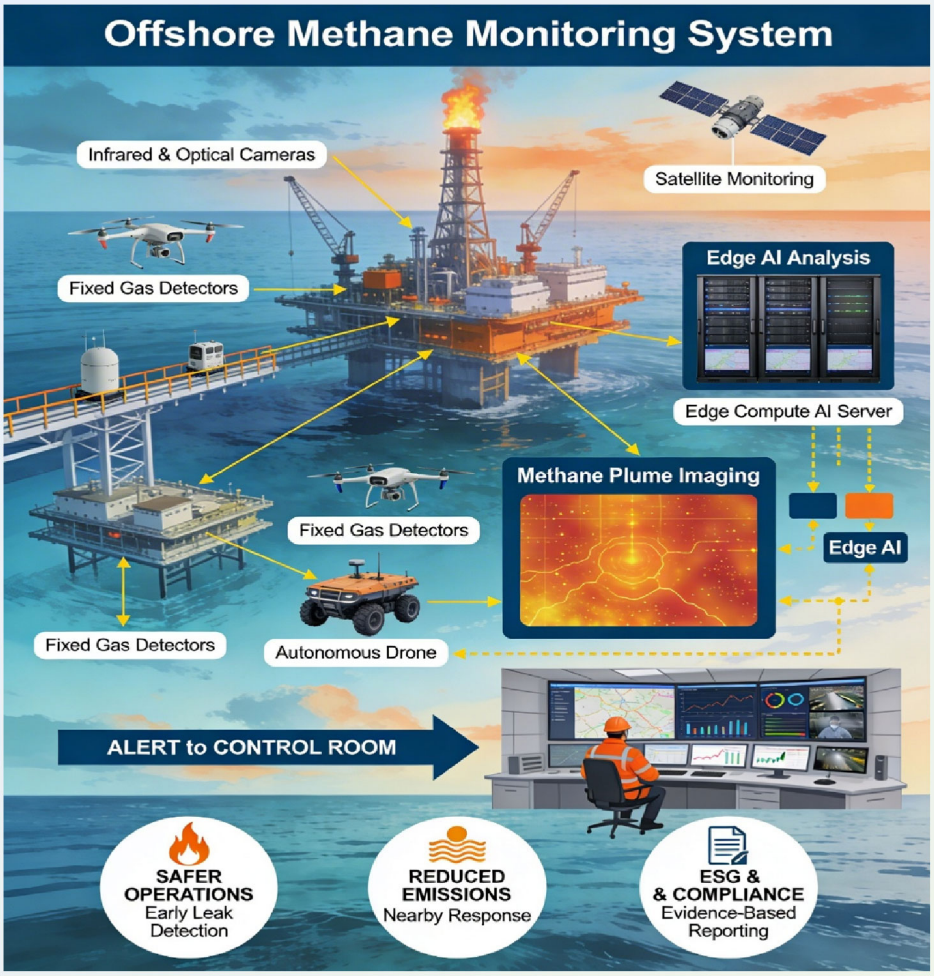
Traditionally, offshore methane leak detection has relied on periodic inspections: handheld gas detectors, manual patrols, and optical gas imaging (OGI) surveys. While indispensable, these methods often identify leaks only after they have persisted for days or weeks, and can miss short duration but high volume events that occur between survey rounds. As infrastructure becomes more complex and ESG expectations intensify, operators are exploring continuous, data driven approaches. A prominent example is the deployment of AI methane leak detection systems, the integrated systems that combine sensor networks, advanced analytics, and automated inspection platforms to detect and characterise emissions in near real time.

How an AI-driven methane leak detection system works

An AI methane-leak detection system functions as an intelligent monitoring layer within a digitalised field architecture rather than as a single device. They fuse inputs from multiple sensing technologies deployed around wells, topside equipment, and flares, and apply machine learning models to distinguish genuine emission signatures from background noise.

Typical data inputs include fixed gas detectors and process instruments (pressure, temperature, and flow), infrared and optical cameras, drone-mounted or robot-mounted gas sensors, and, in some contexts, satellite observations over large basins. These streams are analysed using models trained on historical operating data, labelled leak and non leak events, and meteorological conditions such as wind speed and direction.

When unusual patterns appear, for example, a sharp rise in methane concentration at a particular sensor, combined with a characteristic wind pattern and corroborating camera imagery, the AI-driven methane-leak detection system flags a probable leak event, estimates its magnitude, and proposes a likely source location. Computer vision algorithms applied to infrared footage can also detect methane plumes and recognise abnormal flare behaviour, such as unlit pilots or smoky, high opacity flames that suggest poor combustion. Structured alerts summarising the event location, estimated rate, confidence score, and supporting images are then transmitted to operations and HSE personnel for verification and response.



AI-driven methods and data sources for upstream methane detection

AI-driven Method	Main Data Sources	Typical Deployment	Operational Value
Supervised anomaly detection	Gas detector readings, pressure/flow trends, maintenance logs	Compressors, separators, gas processing units	Learns normal patterns, flags deviations consistent with leaks
Deep learning computer vision	Infrared plume images, optical video feeds	Valves, flanges, pipelines, flare stacks	Detects methane plumes and abnormal flare behaviour in real time
Spatio temporal data fusion	Drone sensors, fixed monitors, wind fields, and site layout	Well pads, offshore topsides, gathering lines	Estimates the source location and leak rate from transient spikes
Satellite assisted screening	Atmospheric methane column measurements, regional inventories	Large onshore basins, remote fields	Identifies “super emitters” and prioritises follow up surveys

Safety, sustainability, and compliance benefits

Early detection of methane emissions delivers tangible safety benefits in upstream operations. Methane clouds accumulating near ignition sources such as hot surfaces, electrical equipment, or open flames can escalate into explosions if not detected and controlled promptly. Continuous monitoring systems, when properly configured, can detect abnormal gas concentrations within minutes to hours rather than days, allowing operators to isolate equipment and vent, depressurise, or shut down safely before conditions deteriorate.

From a climate and resource efficiency perspective, faster detection reduces cumulative emissions and product loss. The controlled release of methane experiments and comparison studies suggest that continuous monitoring solutions can detect a significant share of high volume leakage events much earlier than quarterly OGI surveys, with several commercial systems achieving true positive detection rates above 80% for larger releases while keeping false positive rates below 10% under test conditions. For operators, this translates into fewer "lost gas days" and lower CO_2 equivalent footprints per unit of production.

AI methane leak detection systems also improve compliance and ESG reporting. Because events are time stamped and georeferenced, with pre and post repair evidence, the resulting digital audit trail can feed directly into emissions inventories, environmental reports, and sustainability disclosures. As regulators and investors increasingly request measurement-based methane data rather than purely factor based estimates, such records become a strategic asset, not just a technical log.

Operational gains from AI methane leak detection systems

Dimension	Ai Enabled Benefit	Impact on Upstream Operations
Safety	Early detection and localisation of flammable gas clouds	Reduces ignition and explosion risk and supports safer shutdown and repair
Sustainability	Faster repair and improved flare efficiency	Less methane and carbon emissions
Compliance	Automated, documented monitoring of leaks and flaring	Simplifies regulatory reporting and ESG disclosures
Operational efficiency	Insights into recurring leak points and flare up causes	Enables targeted maintenance, reduces downtime, and product loss

Deployment pathway for Malaysian offshore fields

For offshore operators, the deployment of AI methane detection systems can be approached as a staged enhancement to existing safety and integrity systems rather than a wholesale replacement.

In the first stage, engineers identify high risk zones such as compressor trains, condensate lines, pig launchers, riser bases, and flare systems, and rationalise sensor placement to ensure coverage of likely leak points and potential gas cloud accumulation areas. Historical alarm logs, OGI survey findings, and weather data are consolidated into an initial training and validation dataset.

In the second stage, machine learning models are trained and tested. Supervised anomaly detection models learn baseline patterns from normal operations, while deep learning vision models are fine tuned using infrared and optical footage from controlled releases and typical background

> "AI methane leak detection systems also improve compliance and ESG reporting. Because events are time stamped and georeferenced, with pre and post repair evidence, the resulting digital audit trail can feed directly into emissions inventories, environmental reports, and sustainability disclosures.

conditions, including rain, low light, and hot equipment interference. Model performance is evaluated for both sensitivity and false alarm rates, recognising that individual commercial systems can vary widely in detection and quantification accuracy.

In the third stage, the system is operationalised on the asset. AI models run on edge computing servers on the platform so that detection continues even if communication with shore is temporarily disrupted. Only structured, high confidence alerts are transmitted to onshore control rooms, where operations and HSE teams validate events, initiate inspections or repairs, and log confirmation measurements.

Over time, feedback from real incidents and near misses is used to recalibrate models and refine threshold settings, creating a learning loop that improves performance and builds a robust audit trail for Malaysia's regulators.

Governance and professional responsibilities

The introduction of AI methane leak detection systems does not diminish the need for rigorous engineering judgement; if anything, it intensifies it. Data quality, sensor calibration, and model validation directly influence whether dangerous leaks are missed or whether crews are overwhelmed by nuisance alarms. Clear procedures must define which thresholds trigger which actions, when manual verification is required, and how operators can override AI recommendations while documenting their rationale.

Transparency and explainability matter when AI outputs feed into emissions inventories, safety cases, or ESG disclosures. Engineers and environmental specialists must understand the basic logic and limitations of the AI models and be able to communicate those limits to internal and external reviewers. This demands new competencies in data engineering, model assurance, and digital ethics, layered on top of traditional process safety, integrity, and HSE skills.

For Malaysian professionals, there is an additional responsibility: to ensure that deployments of AI methane detection systems are evaluated primarily on safety and environmental outcomes, not just on efficiency, novelty, or marketing potential. Only by anchoring deployments in measurable risk reduction and genuine emissions abatement can operators maintain trust among regulators, investors, and nearby communities.

A focused pathway to methane stewardship

Artificial intelligence is entering many corners of upstream operations; methane leak detection and flaring management stand out as safety, sustainability, and compliance interests align unusually tightly. Deployed thoughtfully, AI methane leak detection systems can accelerate leak detection and repair, reduce explosion risk, cut greenhouse gas emissions, and generate defensible, measurement based records for regulators and stakeholders.

For Malaysian upstream operators, this is a practical way to demonstrate responsible stewardship of gas resources while aligning with national climate commitments and evolving methane expectations. Rather than treating AI as a buzzword, focusing on targeted applications such as a methane leak detection system shows how digital technologies can translate directly into safer, cleaner, and more transparently compliant offshore operations.

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Strengthening East Coast Development Through Technology, Talent, and Innovation

Kuantan, 25 April 2026 – The Malaysia Board of Technologists (MBOT) organised the MBOT East Coast Symposium themed "Catalysing East Coast Development Through Tech Talent & Innovation". The symposium served as a strategic initiative to strengthen the professional development of technologists and foster closer collaboration among state governments, industries, and academic institutions.

The opening ceremony was officiated by YB Dato' Ir. Razali bin Kassim, Chairman of the Pahang State Committee for Public Works, Transport, and Health. He expressed the state government's commitment to supporting the development of a progressive technology ecosystem. Other prominent figures in attendance included YH Prof. Dato' Dr. Muhammad Fauzi bin Mohd Zain, Vice Chancellor of UCYP University; YBhg. Prof. Dato' Ts. Ir. Dr. Mohamed Ibrahim bin Abdul Mutalib, President of MBOT; and YBhg. Dato' Seri Mustapa Mohamed, Advisor to the Ungku Aziz Centre for Development Studies.

The symposium served as a dynamic platform for knowledge sharing, the exchange of views, and the exploration of strategic collaboration opportunities among participants. Throughout the event, various discussion sessions were held, focusing on the challenges and opportunities in developing a sustainable technology talent ecosystem in the East Coast of Peninsular Malaysia. Participants also took the opportunity to expand their professional networks and explore new initiatives to drive more comprehensive regional technological development.

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Graduate Technologists	Qualified Technicians	Professional Technologists	Certified Technicians	Total MBOT Registrants (As of March 2026)
66,466	15,256	27,829	4,044	113,595

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