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Invited review

Artificial intelligence methods adapted to the CO_2-assisted oil and gas resource endowment of the Middle East

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Abstract:
The Middle East, as the world's most resource-rich region for oil and gas, features complex reservoir geology, a long development history, and massive production systems, facing multiple challenges such as enhancing recovery, reducing development costs, and achieving a green transition. Artificial Intelligence (AI) technologies provide revolutionary tools to address these challenges. This paper systematically reviews AI methods adapted to the specific oil and gas resource endowment of the Middle East, covering the entire industry chain including geological exploration, reservoir characterization, production optimization, equipment operation and maintenance, and energy transition. It analyzes the specific AI application requirements for scenarios prevalent in the region, such as high-temperature, high-pressure carbonate reservoirs, fractured-vuggy reservoirs, and secondary development of mature fields. Key technological pathways, including data-physics integration, multi-scale modeling, digital twins, and theory-guided machine learning, are outlined. Combined with the strategic practices of Middle Eastern National Oil Companies, the challenges and future directions for AI implementation are discussed. The research indicates that building a synergistic innovation system integrating "domain knowledge + big data + high-performance computing" is crucial for unlocking the potential of Middle Eastern hydrocarbon resources and driving the industry's intelligent transformation.

1. Introduction

The Middle East holds approximately 48% of the world's proven oil reserves and 38% of its natural gas reserves (Bhattarai and Yousef, 2025; Middle East, 2026). These resources are primarily hosted within thick carbonate sequences. These reservoirs are often characterized by high temperature, high pressure, high salinity, and strong heterogeneity (Al-Hashmi et al., 2016; Xu et al., 2020). After decades of development, many major fields have entered a "dual-high" stage of high water cut and high recovery factor, making production stabilization and enhancement increasingly difficult (Xue et al., 2023). Concurrently, driven by the global energy transition and "carbon neutrality" goals, major oil-producing countries in the region have proposed national strategies like "Vision 2030," aiming to diversify their economies while developing new energy technologies such as hydrogen and Carbon Capture, Utilization, and Storage (CCUS) (Lim, 2025), alongside maintaining the core role of hydrocarbons. The integration of machine learning into oil and gas development represents a transformative paradigm shift for resource-rich regions such as the Middle East. Amid the dual pressures of energy transition and declining conventional reserves, machine learning offers unprecedented capabilities to address longstanding challenges in reservoir characterization, production optimization, and operational risk management. By unlocking insights from multi-source heterogeneous data, including seismic surveys, well logs, and real-time sensor streams. Such digital models enable precise prediction of reservoir properties, proactive detection of pipeline leaks, and optimization of drilling parameters, thereby enhancing recovery efficiency while reducing operational costs and carbon footprints.

Against this backdrop, national oil companies in the Middle East are strategically investing in digital transformation and AI-driven innovation to maintain competitive advantages.

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This research underscores the critical importance of adapting ML methodologies to regional geological complexities and energy transition goals, providing a structured framework for integrating physical domain knowledge with data-driven techniques. Ultimately, advancing ML in O & G development not only bolsters energy security but also accelerates the transition toward sustainable, low-carbon energy systems, offering valuable lessons for global O & G operations and energy transition practices.

Artificial Intelligence, particularly Machine Learning (ML), Deep Learning (DL), and data science (Tariq et al., 2021; Srivastava et al., 2023), offers a new paradigm to address these challenges. AI can process vast, high-dimensional, and multi-source oil and gas data (e.g., seismic, well logs, production history, equipment sensor data), uncover hidden patterns, build high-fidelity predictive models, and enable real-time optimization and autonomous decision-making for complex systems. However, the region's unique resource endowment imposes specific requirements on AI methods: Models must effectively capture the strong heterogeneity of carbonates, adapt to the complex phase behavior of fluids under high temperature and pressure, handle the massive, multi-source historical data accumulated over long development periods, and balance the dual objectives of traditional hydrocarbon enhancement and coupled new energy development.

This paper aims to systematically review and critique the progress and application of AI methods adapted to the characteristics of Middle Eastern oil and gas resources. It first analyzes the core technical demands of development in the region, then reviews the state of AI applications across different domains, summarizes key enabling technologies, and finally discusses challenges and future trends.

2. Core demands and AI application scenarios in Middle Eastern oil & gas development

2.1 Geological exploration and reservoir characterization

Major Middle Eastern fields are often located in deep carbonate formations where storage space is dominated by pores, vugs, and fractures with extremely complex spatial distribution (Abdullatif, 2010). Traditional geophysical methods face bottlenecks in accurately describing fracture-vug systems and predicting "sweet spots (Wang et al., 2024)."

Utilizing deep learning, including Convolutional Neural Networks, also known as CNN, for automatic fault detection, intelligent identification of fracture-vug bodies, and lithofacies classification, significantly improving interpretation efficiency and accuracy. For instance, using 3D CNNs to directly predict porosity and fracture density from seismic volumes. Intelligent Well Log Prediction and Interpretation: Addressing challenges of missing or costly log data by applying ML (e.g., XGBoost, Random Forest) or DL models to predict key information like shear wave velocity and rock mechanical parameters from conventional logs, supporting reservoir evaluation and fracturing design. Integrating seismic, log, geological, and dynamic production data to construct high-resolution, geologically realistic reservoir models using Generative Adversarial Networks (GANs), Graph Neural Networks (GNNs), etc. For example, the Pore-GNN framework for permeability prediction from micro-CT images can be extended to macro-scale reservoir property modeling.

2.2 Reservoir dynamic prediction and production optimization

Water flooding is common in mature Middle Eastern fields, often suffering from uneven flood front advancement and severe ineffective circulation, necessitating precise dynamic prediction and injection-production optimization.

Training deep learning surrogate models (e.g., DNN, Recurrent Neural Networks - RNN) on large sample sets generated from reservoir numerical simulation to replace computationally expensive physical simulators, enabling rapid production forecasting, parameter sensitivity analysis, and automated history matching. This is particularly important for large Middle Eastern fields with numerous wells and long production histories. Combining Reinforcement Learning (RL), intelligent optimization algorithms (e.g., Particle Swarm Optimization - PSO, Genetic Algorithms) with surrogate models to real-time optimize injection rates for injectors, production rates for producers, and well pattern adjustments, maximizing recovery or net present value. Data-driven intelligent optimization can handle complex multi-objective, multi-constraint production problems. Constructing field-scale digital twin systems that integrate geological, wellbore, and surface facility models, utilizing AI for bidirectional calibration between physical models and real-time data, dynamic forecasting, and proactive optimization. This is central to achieving closed-loop management of intelligent fields.

2.3 Drilling and completion engineering

Drilling in the Middle East involves great depths and complex formations, leading to high costs. Improving drilling efficiency and ensuring wellbore safety are critical. Utilizing real-time drilling data through ML models, for example, Long Short-Term Memory, LSTM networks to predict Rate of Penetration (ROP) and optimize parameter combinations. Simultaneously, AI can be used for early detection of risks like lost circulation or stuck pipe. Fracturing Design Optimization: For acid fracturing in carbonate reservoirs, AI can optimize acid formulations, injection schedules, and diverting agent parameters to enhance fracture complexity and conductivity. ML can be used to simulate and predict fracture propagation geometry.

2.4 Oil & gas transportation and facility management

The region possesses vast pipeline networks and gathering/processing facilities. Ensuring their safe, efficient, and low-carbon operation is paramount.

Integrating multi-source sensor data (acoustic, pressure, flow) and applying pattern recognition and anomaly detection algorithms (e.g., Isolation Forest, Autoencoders) for early warning and precise localization of minor pipeline leaks.

Frameworks combining model-based and data-driven methods represent a development trend.Predictive Maintenance for Equipment: For critical equipment like compressors and pumps, constructing health indicators from sensor time-series data and using ML to predict remaining useful life and failure probability, enabling a shift from scheduled to predictive maintenance. In scenarios like field microgrids or central processing facilities, AI can optimize the coordinated dispatch of power generation, storage, and consumption, increasing the share of renewable energy integration and reducing overall energy consumption and carbon emissions.

2.5 Energy transition and CCUS/hydrogen

Middle Eastern countries are actively developing hydrogen industries and CCUS projects to reduce the carbon intensity of hydrocarbon production and create new growth avenues.

For CO_2 Enhanced Oil Recovery and Storage (CO_2-EOR), AI can accelerate multi-component, multi-phase thermodynamic phase equilibrium calculations (flash calculations), optimize CO_2 injection strategies (e.g., Water-Alternating-Gas), and monitor CO_2 plume migration in real-time to ensure storage security. Deep learning-assisted phase equilibrium frameworks can significantly improve simulation efficiency. Utilizing depleted hydrocarbon reservoirs for hydrogen storage is a promising direction. AI can simulate hydrogen migration in porous media, its interaction with residual fluids, optimize injection-withdrawal strategies, and predict storage efficiency and safety risks. AI can assist in planning integrated energy systems coupling oil/gas fields with solar, wind, and other renewables, achieving complementary multi-energy utilization and maximizing economic benefits.

3. Key AI technological pathways adapted to the Middle Eastern context

The complexity and specificity of Middle Eastern oil and gas problems necessitate that AI methods move beyond pure “black-box” data-driven approaches towards deep integration with domain knowledge.

3.1 Physics-informed and theory-guided machine learning

Purely data-driven models suffer from limitations in extrapolation and physical consistency. Physics-Informed Neural Networks (PINNs) and Theory-Guided Machine Learning (TGML) have emerged as crucial directions. These methods embed governing equations (e.g., Darcy’s law, mass conservation), physical constraints (e.g., thermodynamic consistency), and expert rules as regularization terms into the loss function, ensuring model predictions adhere to physical laws. For instance, thermodynamic consistency constraints are vital when simulating CO_2 storage or high-pressure-high-temperature fluid phase behavior. Frameworks like Lagrangian Dual-based TGNN (TGNN-LD) can automatically balance the weights between data and physical constraints, enhancing accuracy and efficiency.

3.2 Multi-scale intelligent modeling and computational acceleration

Middle Eastern carbonate reservoirs exhibit pronounced multi-scale characteristics from pore to reservoir scale. The integration of AI with multi-scale methods is an inevitable trend. Cross-scale Information Transfer: Using deep learning (e.g., style transfer networks) to upscale equivalent properties (e.g., relative permeability) obtained from pore-scale simulations to the reservoir model. Multi-scale Reduced-Order Modeling (ROM): Combining methods like Proper Orthogonal Decomposition (POD) with deep learning to reduce the dimensionality of high-dimensional complex systems, constructing high-fidelity, fast-computing reduced-order models for real-time simulation and optimization.

For bottleneck processes like flash calculations, using Deep Neural Networks as surrogate models can achieve speed-ups of hundreds to thousands of times, making large-scale compositional simulation feasible.

3.3 Data governance and fusion

Data from Middle Eastern fields is characterized by large volume, long history, diverse sources (structured and unstructured), and variable quality. Effective data governance is foundational for AI success. Applying methods like K-Nearest Neighbors imputation and DBSCAN clustering to handle missing values and outliers. Using Generative Adversarial Networks (GANs) (Lian et al., 2023) to synthesize high-quality training data, addressing sample imbalance. Constructing unified AI frameworks (e.g., multimodal large models) capable of simultaneously processing seismic images, well logs, textual reports (geological descriptions), production curves, and other multi-modal data for a more comprehensive geological and engineering understanding.

3.4 Digital twins and hybrid modeling

Digital Twins for entire fields or production systems represent the culmination of AI application. They are not single AI models but hybrid ecosystems integrating “physical models + data-driven models + real-time data + AI algorithms.” Physical models provide the mechanistic skeleton, data-driven models (surrogates) offer local corrections and fast predictions, and AI algorithms (e.g., RL, optimization) are responsible for real-time decision-making and optimization. This hybrid modeling approach combines physical interpretability with data adaptability, making it highly suitable for the full lifecycle management of large, complex Middle Eastern hydrocarbon assets.

4. AI strategies and practices of Middle Eastern national oil companies

Middle Eastern NOCs such as Saudi Aramco and the Abu Dhabi National Oil Company (ADNOC) are active promoters and leading practitioners of AI technology.

5. Challenges and future outlook

Table 1. Middle Eastern NOCs such as Saudi Aramco and the Abu Dhabi National Oil Company (ADNOC) are active promoters and leading practitioners of AI technology.

Company	Country	AI policy/strategy	Key outcomes/effects	Reference
ADNOC (Abu Dhabi National Oil Company)	UAE	"AI-Enabled Energy" & 2030 AI Leadership: Strategy to become the world's most AI-enabled energy company by 2030. This involves deploying over 200 AI tools across operations, extensive partnerships (Microsoft, AIQ, Gecko Robotics), operations, extensive partnerships and developing AI agents for process automation.	• 90% improvement in production forecast accuracy. • 50% reduction in unplanned downtime. • Deployment of AiPSO platform across 25 oilfields by 2027, enabling staff to complete complex tasks up to 10x faster.	China Macro Network, 2025
Aramco Saudi	Saudi Arabia	Industrial AI & Digital Sovereignty: Focus on scaling industrial AI through cloud-based solutions (Microsoft Azure) with an emphasis residency. Strategy includes co-developing and commercializing AI solutions for a global energy marketplace.	• Enhanced operational efficiency and global competitiveness. • Establishment of a secure, intelligent digital ecosystem for the energy sector. • Advancement of workforce capabilities in AI engineering, cybersecurity, and data.	Aramco, 2026
QatarEnergy	Qatar	AI-Driven LNG Expansion: demand growth (especially from data centers) to justify and guide the expansion of LNG production. Focus on integrating AI for operational efficiency while maintaining a low carbon footprint through carbon sequestration.	• Positioning as a major player in the global LNG market to meet future demand driven by AI. • Development of LNG projects with the lowest possible carbon	Qatar, 2026
Kuwait Oil Company (KOC)	Kuwait	Digital Transformation & AI Innovation: Strategic partnership with Microsoft to establish an AI Innovation Center and Cloud Center of Excellence. Aims to connect oil field production with AI technologies to support the country's 2035 production capacity target (4 million bpd).	• AI-driven drilling platform scheduling to reduce the number of days needed to drill a well. • Increased operational efficiency and reduced costs through real-time operational data management and predictive analytics, aligned with Kuwait Vision 2035.	KOC , 2025

Company	Country	AI policy/strategy	Key outcomes/effects	Reference
NIOC (National Iranian Oil Company)	Iran	Strategic AI Department & Digitalization: Plans to establish a specialized AI department within its Research and Technology Directorate to overcome sanctions and enhance efficiency. Strategy includes digitizing 15 oi and gas fields and drafting an AI-based governance framework.	• Aim to integrate AI into reservoir studies, seismic data interpretation, and drilling to enhance production and reduce costs. • Goal to rank among the top 10 countries in AI, as per national leadership directives, despite current low investment compared to regional peers.	NIOC, 2025
Sonatrach	Algeria	Smart Infrastructure & IoT Integration: Plans to establish a specialized AI department within its Research and Technology Directorate to overcome sanctions and enhance efficiency.	• High-precision, automated pipeline integrity monitoring. • Enhanced operational safety and efficiency for oil and gas transportation infrastructure.	Sonatrach, 2024
North Oil Company (NOC)	Algeria	Comprehensive Business Operations AI: Implementing a wide-scale digital transformation with SAP solutions (RISE with SAP, Ariba, Signavio) to create an integrated, Focus on standardizing processes and end-to-end automation.	• Consistent standardization and reduced IT complexity across operations. • Creation of a resilient, intelligent, and agile business operation to remain competitive in the evolving energy landscape, with data hosted locally for sovereignty and security.	NOC, 2025

5.1 Major challenges

Data Silos and Quality: Historical data exists in varied formats and scattered storage, creating significant data silos. Acquiring some critical data (e.g., high-frequency downhole data) is costly or unavailable. Effectively encoding complex carbonate geology knowledge and flow mechanisms into AI models remains a technical hurdle. Model interpretability needs urgent improvement to gain engineer trust. Model Generalization and Long-term Reliability: Can models trained on a specific field be generalized to geologically similar but different new fields. How can models self-adapt to dynamic reservoir changes over decades-long development cycles. Computing Infrastructure and Energy Consumption: Large-scale AI training and digital twin operation require substantial computing power. In desert environments, data center energy consumption and cooling pose significant challenges, creating tension with low-carbon goals. A severe shortage exists of professionals proficient in both oil & gas and AI. The relatively conservative culture of the traditional oil and gas industry presents resistance to the adoption of new AI technologies.

5.2 Future outlook

Oil & Gas Industry Large Language Models (Energy-Specific LLMs): Similar to general-purpose LLMs like DeepSeek, future will see the emergence of industry-specific LLMs focused on oil and gas. These will understand geological reports, engineering drawings, academic papers, answer professional queries, and assist in design, serving as "intelligent assistants" for engineers. AI will evolve from assisting decisions to making autonomous decisions. Within safe boundaries, automatic closed-loop optimization from single wells to entire fields will be realized, such as automatically adjusting injection-production ratios in response to market oil price fluctuations.

AI will more deeply enable the green transition. It will not only optimize existing processes for cost reduction and emission cuts but also lead the design, monitoring, and risk management of new energy projects like CCUS, underground hydrogen storage, and geothermal development. Deploying part of the AI inference capability at the edge (wellhead, equipment) for low-latency real-time control, while collaborating with cloud centers for model training and global optimization. With advances in quantum computing, quantum machine learning algorithms hold promise for breakthrough progress in solving ultra-large-scale combinatorial optimization problems prevalent in the oil and gas sector.

6. Conclusion

The unique oil and gas resource endowment of the Middle East, centered on complex carbonate reservoirs, at a high maturity development stage, and bearing the mission of energy transition, provides a vast arena and specific demands for the application of Artificial Intelligence. Successful AI application is not a simple matter of applying generic algorithms but must follow a path of deep integration with domain knowledge. Physics-informed machine learning, multi-scale intelligent modeling, and digital twin hybrid systems represent key technological pathways adapted to the Middle Eastern context.

Leading Middle Eastern oil companies have taken the initiative, promoting AI implementation through strategic investment and industry-academia collaboration, achieving tangible results across exploration, production, and maintenance. Looking forward, overcoming bottlenecks related to data, models, and talent, developing oil & gas industry LLMs and autonomous intelligent systems, and positioning AI as a core engine for the green transition will be critical for the Middle Eastern oil and gas industry to maintain its competitiveness and achieve sustainable development. The region's practices will also provide valuable insights for the intelligent transformation of the global oil and gas industry.

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Conflict of interest

The author declares no competing interest.

References

Al-Hashmi, A. R., Divers, T., Al-Maamari, R. S., et al. Improving polymer flooding efficiency in Oman oil fields. Paper SPE SPE EOR Conference at Oil and Gas West Asia, Muscat, Oman, 21-23 March, 2016.

Abdullatif, O. Geomechanical properties and rock mass quality of the carbonate Rus formation, Dammam dome, Saudi Arabia. Arabian Journal for Science and Engineering, 2010, 35(2): 173-197.

Aramco and Microsoft deepen industrial AI push.

Bhattarai, K., Yousef, M. Petroleum resources and energy transitions in the MENA region: Geopolitical and economic implications, in the Middle East, edited by K. Bhattarai and M. Yousef, Springer, Cham, pp. 137-166, 2025.

Expansion roadmap of AI applications for UAE's energy giant: Calling for trillion-level infrastructure investment and securing partnerships with top-tier enterprises. (in Chinese)

Energy system of Middle East. The International Energy Agency 2026.

Kuwait Oil Company, Microsoft opens AI innovation center.

Lim, Y. Carbon capture, utilization, and storage (CCUS), in Alternative fuels for environmentally-friendly ships: Hydrogen, ammonia, bio-fuels and e-fuels, edited by Y. Lim, Nature Switzerland, Cham, pp. 67-82, 2025.

Lian, Y., Geng, Y., Tian, T. Anomaly detection method for multivariate time series data of oil and gas stations based on digital twin and MTAD-GAN. Applied Sciences, 2023, 13(3): 1891.

National Iranian Oil Company: A key player in Iran's economy and industry. Iranian Brands 2025.

Qatar Energy's AI strategy 2026: Fueling global AI with LNG and securing market dominance.

Srivastava, K., Singh, T. P., Pradhan, M. R., et al. Understanding data analytics and predictive modelling in the oil and gas industry (1st ed). Boca Raton, FL, USA, CRC Press, 2023.

Sonatrach: Fiber optic sensing enables high-precision intelligent oil and gas pipeline inspection. (in Chinese)

SAP expands digital transformation partnership with Qatar's NOC.

Tariq, Z., Aljawad, M. S., Hasan, A., et al. A systematic review of data science and machine learning applications to the oil and gas industry. Journal of Petroleum Exploration and Production Technology, 2021, 11(12): 4339-4374.

Wang, H., Guo, Z., Kong, X., et al. Application of machine learning for shale oil and gas "sweet spots" prediction. Energies, 2024, 17(9): 2191.

Xu, Z., Li, S., Li, B., et al. A review of development methods and EOR technologies for carbonate reservoirs. Petroleum Science, 2020, 17: 990-1013.

Xue, L., Liu, P., Zhang, Y., et al. Status and prospect of improved oil recovery technology of high water cut reservoirs. Water, 2023, 15(7): 1342.