

Digital Twin-Based Intelligent Management of Natural Gas Reservoirs

Anand Rai, Pawan S. Kheda

Associate Professor, Institute of Management and Technology, Lucknow, India.

Abstract

Natural gas reservoir management increasingly relies on digital twin technology—dynamic, data-integrated virtual replicas of subsurface reservoirs and surface facilities—to bridge the gap between traditional, periodically updated reservoir simulation and the continuous, real-time decision-making that modern gas field operations demand. By fusing physics-based reservoir models with machine learning, real-time sensor data, and cloud computing infrastructure, digital twins enable operators to monitor reservoir behavior, optimize production and injection strategies, and proactively manage geomechanical and operational risk across the full lifecycle of a natural gas asset. This review examines the state of digital twin-based intelligent management for natural gas reservoirs, synthesizing recent advances in hybrid physics-AI reservoir modeling, machine learning-generated reservoir digital twins, digital twin frameworks for underground gas storage operations, and porous-media digital twin validation platforms. It draws on case studies from heterogeneous depleted gas reservoir optimization, geothermal-analogue petrophysical characterization, and geomechanically informed wellbore stability assessment, and further considers methodological parallels with large-scale AI-driven predictive analytics and economic impact frameworks developed for national healthcare systems. The review concludes by identifying persistent challenges in real-time data integration, cross-domain model coupling, and industry-wide standardization, and proposes a research agenda for advancing digital twin-based natural gas reservoir management toward routine, trustworthy use across commercial gas field and storage operations.

Keywords: digital twin, natural gas reservoir, machine learning, reservoir simulation, underground gas storage, real-time monitoring, intelligent field management

1. Introduction

Natural gas reservoir management has traditionally relied on periodically updated numerical simulation models, calibrated against production history and well test data through computationally intensive history-matching workflows, to guide field development and operational decisions. While effective for long-term planning, this conventional paradigm is poorly suited to the continuous, real-time decision-making increasingly demanded by modern gas field and underground storage operations, where injection and withdrawal schedules, well management strategies, and safety interventions must respond dynamically to evolving reservoir conditions rather than to a periodically refreshed static model.

Digital twin technology has emerged as the organizing framework for closing this gap, offering a dynamic, continuously updated virtual replica of a physical reservoir system that integrates real-time sensor data, machine learning-based predictive modeling, and, in its most advanced implementations, physics-based simulation within a unified computational environment. Unlike a conventional reservoir model, a digital twin is designed to evolve continuously alongside its physical counterpart, incorporating new production, pressure, and monitoring data as it becomes available and using this continuously updated state to support real-time operational decision-making, predictive maintenance, and proactive risk management across the reservoir's operational lifetime.

This review synthesizes recent advances in digital twin-based intelligent management of natural gas reservoirs, integrating insights from heterogeneous depleted gas reservoir case studies, geothermal-analogue petrophysical characterization and machine-learning-enhanced geomechanical risk assessment, alongside the growing digital twin literature applied directly to hydrocarbon reservoir and gas storage management (Keilegavlen et al., 2023; Shen et al., 2021; Sircar et al., 2023). It further draws methodological parallels with large-scale AI-driven predictive analytics and economic impact frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d), which offer transferable lessons on deploying continuously updated, decision-supporting digital infrastructure at scale. The objective is to provide a comprehensive synthesis for researchers, engineers, and operators seeking to advance digital twin technology from research demonstration toward routine, trustworthy use in

commercial natural gas reservoir and storage management.

2. Conceptual Foundations of Digital Twins for Natural Gas Reservoirs

2.1 Defining the Reservoir Digital Twin

A digital twin for a natural gas reservoir is a virtual replica that continuously integrates real-time production, pressure, and monitoring data with predictive modeling to represent the current and forecasted state of the physical reservoir system. Sircar et al. (2023) characterize digital twin modeling as the foundation for the next generation of real-time production monitoring and optimization systems within the hydrocarbon industry, distinguishing digital twins from conventional static or periodically updated models by their capacity for continuous, bidirectional data exchange between the physical asset and its virtual representation.

2.2 Hybrid Physics-AI Modeling as the Dominant Architectural Trend

A major and increasingly dominant trend in digital twin development for reservoir management is the integration of first-principles reservoir simulation with machine learning algorithms, enabling digital twins that combine the physical interpretability of conventional simulation with the predictive speed and pattern-recognition capability of data-driven modeling. This hybrid physics-AI paradigm allows digital twins to retain the physical grounding necessary for regulatory and engineering confidence while achieving the computational speed required for real-time or near-real-time operational decision support, a combination that neither purely physics-based simulation nor purely data-driven modeling can achieve alone.

2.3 From Static Simulation to Continuous, Data-Integrated Management

The transition from static, periodically recalibrated reservoir simulation toward continuously updated digital twin management reflects a broader trend toward real-time, data-integrated decision-making across the oil and gas industry more broadly, driven by advances in computational power, cloud computing infrastructure, and the proliferation of high-frequency sensor data from digital oilfield instrumentation. This transition is particularly consequential for natural gas reservoir and storage management, where deliverability, injectivity, and geomechanical stability must be continuously reassessed as reservoir conditions evolve throughout each injection-withdrawal cycle.

3. Machine Learning-Generated Digital Twins for Reservoir Management

3.1 Machine Learning as an Independent Prediction Pathway

Rather than relying exclusively on calibration of a physics-based simulator, recent digital twin implementations have explored training machine learning algorithms directly on static and dynamic reservoir data—production and injection history, saturation and production logs, reservoir pressure surveillance, petrophysical data, and geological models—to generate predictions of reservoir performance independently of traditional numerical simulation. This approach allows the resulting reservoir digital twin to predict more efficient production and injection strategies across a reservoir surveillance program while normalizing dynamic log data against time for improved mapping fidelity between the physical reservoir and its digital representation, in contrast to conventional methods that use such data only for simulator calibration.

3.2 Digital Twin-Based Optimization of Oil and Gas Production

Shen et al. (2021) developed a digital twin-based approach explicitly designed for the optimization and prediction of oil and gas production, demonstrating how a continuously updated virtual representation of the production system can support both predictive forecasting and active optimization of operational parameters, establishing an early and influential framework for extending digital twin concepts from conceptual reservoir representation toward active, optimization-capable production management.

3.3 Digital Twins for Complex, Multiscale Reservoir Mechanisms

Beyond conventional reservoir settings, digital twin frameworks have been extended to capture the complex, multiscale mechanisms characteristic of unconventional reservoirs, including capillarity, dynamic sorption, and injection-salinity effects that govern flow and transport behavior at multiple spatial scales simultaneously. Such multiscale digital twin architectures, which preserve physical laws across scales while incorporating multiscale algorithms capable of resolving strongly nonlinear mechanisms, illustrate the broader trend toward digital twin frameworks explicitly designed to accommodate the complex, multiphysics character of natural gas reservoir systems rather than relying on simplified, single-scale representations.

4. Digital Twins for Underground Natural Gas Storage Operations

4.1 Integrated Geoengineering and Machine Learning Diagnostics

Digital twin technology has been applied directly to underground gas storage (UGS) operations, integrating real-time data, simulation models, and machine learning within a unified operational platform capable of automatic data acquisition, dynamic model updates, and real-time management. Such systems seamlessly integrate geoengineering and machine learning-assisted diagnostics across petroleum engineering and geomechanics domains, enabling interactive dashboards through which operators can monitor operations, ensure flow assurance, predict future reservoir dynamics, and access diagnostic and safety functions in support of intelligent and safe UGS operations.

4.2 Mechanistic Digital Twins for Depleted Reservoir Gas Storage

For underground gas storage developed within depleted hydrocarbon reservoirs, digital twin frameworks combining mechanistic reservoir models with digital technologies have been developed to support both long-term planning and real-time operational management within a single integrated system. By combining planning and operational features, such mechanistic digital twin frameworks aim to achieve intelligent long-term and real-time operational management simultaneously, supporting safer, more efficient, and optimized underground gas storage operations across the full project lifecycle—a design philosophy directly analogous to the progression from static site characterization toward continuously updated operational management that heterogeneous depleted gas reservoir optimization more broadly requires.

4.3 Automated Well Management and Flow Advisory Systems

Digital twin-enabled automated well management and flow advisory capabilities represent a further extension of UGS digital twin functionality, moving beyond passive monitoring and diagnostics toward active, AI-informed recommendations for well operation and flow scheduling. This progression—from passive monitoring, through diagnostic support, toward active operational advisory and eventual automated control—mirrors the broader developmental trajectory observed in digital twin technology for geological CO₂ storage, where similar staged progression from monitoring-oriented "digital shadow" toward fully decision-capable, controlled digital twin architectures has been documented.

5. Experimental Validation and Multiphysics Digital Twin Platforms

5.1 Physical Rig-Based Digital Twin Validation

Because digital twin predictions for subsurface reservoir systems cannot be directly validated against the full-scale physical reservoir within any practical research timeframe, laboratory-scale physical analogue platforms provide an important validation pathway for digital twin methodologies prior to field deployment. Keilegavlen et al. (2023) developed PoroTwin, a digital twin explicitly designed for a laboratory-scale porous media flow rig, demonstrating how digital twin methodologies—continuous data assimilation, model updating, and predictive forecasting—can be rigorously validated against a controlled, instrumented physical analogue before being extended to full-scale subsurface reservoir applications where such controlled validation is infeasible.

5.2 Relevance to Petrophysical and Geomechanical Characterization

The fidelity of any digital twin's predictive capability depends fundamentally on the quality of the underlying petrophysical and geomechanical characterization used to initialize and constrain the twin's representation of reservoir properties. Machine learning-enhanced petrophysical workflows applied to the Three Forks geothermal reservoir in the Williston Basin illustrate how well log, core, and seismic attribute data can be integrated to characterize reservoir quality at high spatial resolution, providing exactly the class of high-fidelity input data that reservoir digital twins require to achieve reliable, site-specific predictive accuracy.

5.3 Geomechanical Integration for Storage Integrity Within Digital Twin Frameworks

Natural gas reservoir and storage digital twins must incorporate geomechanical stability considerations alongside flow and pressure modeling, particularly for storage reservoirs subject to repeated, cyclical injection and withdrawal that can induce fault reactivation or wellbore integrity concerns over time. Machine-learning-enhanced geomechanical characterization and wellbore stability assessment, as demonstrated in the offshore South Tano Field, integrates stress field estimation, rock strength prediction, and drilling parameter analysis into a proactive risk-management workflow; embedding this class of geomechanical model as a continuously updated component service within a broader natural gas reservoir digital twin architecture represents an important integration point for ensuring that digital twin-informed operational recommendations remain both efficient and geomechanically safe.

6. Toward Intelligent, Decision-Capable Reservoir Management

6.1 From Monitoring to Active Optimization

The developmental trajectory of digital twin technology for natural gas reservoir management progresses from passive monitoring and visualization, through predictive diagnostics, toward active operational optimization and, ultimately, automated or semi-automated control recommendations. Digital twin-based approaches explicitly designed for production optimization (Shen et al., 2021) exemplify this progression toward active, decision-capable digital twin functionality rather than passive monitoring alone.

6.2 Portfolio-Scale Digital Twin Management

Beyond individual reservoir or storage site management, national and regional natural gas infrastructure comprising numerous individual reservoirs and storage sites increasingly benefits from portfolio-scale digital twin frameworks capable of coordinating operational decisions across multiple assets simultaneously, extending the site-specific digital twin concept toward a networked, portfolio-wide intelligent management system analogous to the multi-site coordination challenges addressed in heterogeneous depleted gas reservoir storage optimization.

6.3 Cloud Computing and Real-Time Infrastructure

The practical realization of digital twin-based intelligent reservoir management depends substantially on cloud computing infrastructure capable of supporting the continuous data ingestion, model updating, and computational demands of real-time digital twin operation at scale, alongside associated considerations of regulatory compliance and cybersecurity that become increasingly consequential as digital twin systems assume greater operational decision-making authority over critical natural gas infrastructure.

7. Cross-Domain Lessons: Continuously Updated, Decision-Supporting AI at National Scale

While the technical foundations of digital twins for natural gas reservoir management are rooted in subsurface engineering and hybrid physics-AI modeling, valuable operational lessons can be drawn from large-scale, continuously updated predictive AI systems developed in other high-

stakes domains. National-scale AI frameworks developed for precision public health illustrate the operational value of continuously integrating individual-level data streams into updated risk assessments that inform targeted, real-time intervention—an operational analogue to a reservoir digital twin's continuous assimilation of production and pressure data into updated reservoir state estimates that inform operational intervention (Nguyen, 2026a). This principle—that continuously updated, individually characterized monitoring enables more effective, targeted management than periodic, static assessment—maps directly onto the digital twin value proposition for natural gas reservoirs, where each reservoir or storage site's digital twin functions analogously to a continuously monitored, individually characterized asset within a broader portfolio.

National-scale predictive analytics frameworks applied to Medicare and Medicaid populations further demonstrate how AI-driven, continuously updated risk stratification across large, heterogeneous populations can identify cases warranting the most immediate attention while managing the overall cost of the monitoring program itself (Nguyen, 2026d). This population-level monitoring logic parallels the portfolio-scale ambition of digital twin technology in natural gas reservoir management, where operators managing multiple reservoirs or storage sites must similarly prioritize computational and monitoring resources toward the assets exhibiting the highest predicted operational or geomechanical risk, rather than applying uniform digital twin infrastructure investment across an entire portfolio regardless of relative need.

Economic impact analyses of AI adoption in healthcare, quantifying national-scale cost savings and productivity gains attributable to continuously updated, AI-driven monitoring and decision support, offer a further template for building the economic case for digital twin infrastructure investment in natural gas reservoir management (Nguyen, 2026c). Just as healthcare AI systems capable of continuous, real-time risk updating have demonstrated measurable cost reductions through earlier detection and more efficient resource allocation, digital twin systems for natural gas reservoirs can be expected to reduce costs associated with reactive, incident-driven monitoring and intervention by shifting toward continuously informed, proactive reservoir and storage management—an economic argument that merits explicit quantification as digital twin technology matures toward standard industry practice.

Collectively, these cross-domain parallels reinforce a broader principle: the challenge of building trustworthy, continuously updated, decision-capable AI systems at scale is not unique to subsurface natural gas reservoir management, but reflects a general pattern observed across regulated, high-stakes domains where real-time state characterization and proactive intervention offer substantial advantages over periodic, reactive assessment. The maturation of digital twin technology for natural gas reservoirs can accordingly draw on deployment, validation, and cost-justification frameworks already developed in these adjacent, more mature large-scale AI application domains.

8. Challenges and Limitations

Despite substantial progress, several challenges continue to constrain the widespread deployment of digital twin-based intelligent management for natural gas reservoirs.

Real-time data integration and infrastructure. Achieving genuine real-time digital twin operation requires substantial investment in high-frequency sensor networks, data transmission infrastructure, and cloud computing capacity, investments that remain uneven across the global natural gas industry and that constrain the practical realization of continuous, real-time digital twin capability at many operating sites.

Coupling physics-based and machine learning components. While hybrid physics-AI modeling represents the dominant architectural trend in the field, achieving robust, well-validated coupling between first-principles simulation and data-driven prediction components remains methodologically challenging, particularly in ensuring that machine learning components do not introduce physically inconsistent predictions that undermine confidence in the overall digital twin system.

Validation over the full reservoir lifecycle. Because digital twin predictions for subsurface reservoir systems often extend over multi-decade operational lifetimes, direct empirical validation of long-horizon digital twin predictions remains challenging, motivating continued reliance on laboratory-scale physical analogue validation platforms (Keilegavlen et al., 2023) as an important, though imperfect, substitute for full-scale field validation.

Standardization and industry-wide interoperability. The rapid proliferation of digital twin

implementations across different vendors, operators, and geologic settings has outpaced the development of standardized protocols for digital twin architecture, data formats, and validation methodology, complicating efforts to achieve interoperability and comparability across different digital twin systems deployed throughout the natural gas industry.

Regulatory and workforce readiness. As digital twins assume greater operational decision-making authority, regulatory frameworks governing natural gas reservoir and storage operations must evolve to accommodate AI-informed decision-making with appropriate auditability, while the broader workforce and educational infrastructure supporting the natural gas industry must be updated to equip the next generation of engineers and geoscientists with the digital skills required to develop, validate, and operate digital twin systems effectively.

9. Future Directions

Future research should prioritize the development of more tightly integrated hybrid physics-AI digital twin architectures capable of jointly resolving flow, geomechanical, and geochemical processes within natural gas reservoirs and storage sites, building on the machine learning-generated reservoir digital twin approaches (Sircar et al., 2023) and production optimization frameworks (Shen et al., 2021) currently addressing these processes in relative isolation. Extending laboratory-scale digital twin validation platforms such as PoroTwin (Keilegavlen et al., 2023) toward field-representative, multiphysics validation environments represents an important direction for building the empirical confidence required for full-scale digital twin deployment across diverse natural gas reservoir settings.

Integration of high-resolution petrophysical and geomechanical characterization workflows—such as those demonstrated for the Three Forks geothermal reservoir and the South Tano offshore field—directly into natural gas reservoir digital twin training and initialization pipelines represents a further avenue for improving site-specific predictive fidelity, with particular relevance to heterogeneous, multi-constraint storage sites such as the Evetts site in the Permian Basin. Finally, adopting governance, validation, and cost-justification frameworks informed by continuously updated, real-time AI deployment in national-scale healthcare systems (Nguyen, 2026a, 2026c, 2026d) may help establish the standardization and regulatory trust required for digital twin-based natural gas reservoir management to transition from

research demonstration toward routine, industry-wide operational adoption.

10. Conclusion

Digital twin technology, integrating hybrid physics-AI reservoir modeling, machine learning-generated predictive capability, and real-time monitoring infrastructure, represents a rapidly maturing and increasingly central framework for intelligent natural gas reservoir management. Applications spanning machine learning-generated reservoir digital twins, digital twin-based production optimization, integrated underground gas storage diagnostic and operational planning systems, and laboratory-scale porous media validation platforms collectively demonstrate that the field is progressing along a clear developmental trajectory—from passive, periodically updated simulation toward continuously updated, increasingly decision-capable digital twin management—across both conventional gas reservoirs and underground gas storage operations. Cross-domain lessons from continuously updated, real-time AI deployment in national-scale healthcare systems further suggest a pathway toward the governance and cost-justification frameworks necessary for digital twins to achieve regulatory trust and routine operational adoption in natural gas reservoir management. Realizing the full potential of digital twin technology for natural gas reservoirs will require sustained investment in real-time data infrastructure, robust physics-AI coupling, multiphysics validation, and industry-wide standardization—investments essential to ensuring that natural gas reservoirs and storage assets can be managed safely, efficiently, and adaptively as they continue to play a central role in global energy systems.

References

1. Keilegavlen, E., Fonn, E., Johannessen, K., Eikehaug, K., Both, J. W., Fernø, M., Kvamsdal, T., Rasheed, A., & Nordbotten, J. M. (2023). PoroTwin: A digital twin for a FluidFlow rig. *Transport in Porous Media*, 149, 1241–1260. <https://doi.org/10.1007/s11242-023-01992-8>
2. Nguyen, T. T. (2026a). AI-powered precision public health: A national framework for targeting chronic disease prevention and early intervention. *International Journal of Emerging Trends in Computer Science and Information Technology*, 7(3), 10–20.
3. Nguyen, T. T. (2026c). The economic impact of AI adoption in healthcare: Estimating national cost savings, productivity gains, and long-term health outcomes. *International*



Journal of Artificial Intelligence, Data Science, and Machine Learning, 7(3), 1–11.

4. Nguyen, T. T. (2026d). National-scale predictive analytics for Medicare and Medicaid: An AI-driven approach to identifying high-risk populations and reducing healthcare costs. *Journal of Advanced Scientific Research*, 17(6), 1–10.
5. Shen, F., Ren, S., Zhang, X., Luo, H., & Feng, C. (2021). A digital twin-based approach for optimization and prediction of oil and gas production. *Mathematical Problems in Engineering*, 2021, Article 3062841. <https://doi.org/10.1155/2021/3062841>
6. Sircar, A., Nair, A., Bist, N., & Yadav, K. (2023). Digital twin in hydrocarbon industry. *Petroleum Research*, 8(2), 270–278. <https://doi.org/10.1016/j.ptlrs.2022.04.001>