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Process Optimization Strategies for Unconventional Gas Production in Saudi Arabia

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Abstract-** Since Saudi Arabia initiated unconventional gas exploration program, emphasis moved from reservoir characterization to execution where optimization would play a key role. To identify the optimization levers in tight and shale gas development operations within Saudi Arabia in particular in Jafurah Basin region, this paper reviews the relevant literature in academic sources covering years from 2020 to 2025. The evidence-based approach will be used in which research papers regarding reservoir characterization, fracture stimulation design, production analysis, economic viability, and sustainable development will be considered as means of conducting an analysis of the following five optimization aspects: high-resolution characterization, landing and spacing optimization, completion and hydraulic fracturing optimization, production forecasting, and water, methane, and cost management. Literature indicates that there is no unique way to maximize the project's value. Nonetheless, the relationship between petrophysical analysis, anisotropic fractures' stimulation design, well completion design, forecasting through machine learning, and economic assessment proves to be effective. From the perspective of Saudi Arabia, the main take away message about optimization is that the processes of optimization must evolve beyond individual wells and become the operational system within the field level. Optimization strategy is proposed for Saudi Arabia in terms of unconventional gas development by using an integrated approach covering appraisal, pilot, execution, ramp-up, and optimization phases. Therefore, the future efforts on optimization of gas projects in Saudi Arabia must concentrate on subsurface, completions, production, and environmental workflows rather than optimization itself.

***Keywords:** Saudi Arabia, Unconventional Gas, Jafurah Basin, Process Optimization, Hydraulic Fracturing, Production Forecasting, Review Paper*

I. INTRODUCTION

First of all, unconventional gas is strategically important for Saudi Arabia since it contributes to increasing gas production in Saudi Arabia, providing extra barrels of crude oil for exports or application in higher-value processes, and supporting industrial diversification while keeping carbon intensity low compared to oil-based power generation technologies. The discussion of Jafurah resources, in particular, revealed the importance of probability-based planning and analogy assumption in view of the complexity of resource development with regard to the Tuwaiq Mountain Formation (Weijermars et al., 2021; Jin and Weijermars, 2022).

Field development updates also emphasized the applicability of the asset to Saudi Arabian strategy of increasing its gas production potential and midstream development (Aramco, 2022; Aramco, 2024a; Aramco, 2024b). However, sheer size is not enough to make an unconventional gas development project profitable. Rather, such projects depend on the ability to drill appropriate wells, produce fractures, carry out efficient clean-up, perform draw-down operations, and benefit from insights gained from previous wells.

At the same time, recent research indicates that optimization of the entire process is significantly different from optimization of the specific stages in the course of reservoir development. Unconventional gas wells are characterized by close interactions of geomechanics, fracture complexity, flow-back, draw-down rate, parent-child well interaction, completion, and economic factors (Dheyauldeen et al., 2021; Xue et al., 2021; Wang et al., 2023).

Small changes in such factors as well location, distance between clusters, proppant loading, clean-up approach, and production strategy can affect expected performance and NPV drastically. Additionally, Saudi Arabia should address peculiarities of carbonate targets, high demands for scaling up production, and the need to optimize unconventional gas production processes along with water-saving and emissions reduction strategies. In general, Saudi Arabia should develop approaches to optimizing unconventional gas field development as it does not have to prove its ability to develop these assets but needs to optimize the entire process to allow scaling and sustainability. The purpose of this paper is to investigate approaches to process optimization of unconventional gas production in Saudi Arabia, addressing three research questions in the process.

In particular, it is important to examine what information is currently available regarding domains where optimization can yield positive results most reliably. Moreover, it is essential to analyze how subsurface uncertainty affects interactions between subsurface features, drilling, and production in the course of field development. Finally, what process-related framework can facilitate optimization and integration of economic and technical control over unconventional gas wells in Saudi Arabia? Although many review papers focus on optimization as a purely technical issue, this analysis aims to offer a comprehensive description of multi-disciplinary optimization approaches in relation to unconventional hydrocarbon development in Saudi Arabia.

II. REVIEW METHODOLOGY

The structure of the manuscript will be in accordance with that of the standard literature review and not that of a field case study. Evidence for claims made during the period 2020-2025 will consist of articles published in scholarly journals and at conferences, along with updates from relevant corporations regarding their activities in unconventional gas production in Saudi Arabia. Sources will be selected according to the following five priority criteria of their relevance: studies devoted specifically to the situation in Saudi Arabia or Jafurah; reviews addressing recently published information on efficiency of resource exploitation; studies on fracture design and geomechanics; studies on application of data-based methods for prediction of production and completion optimization; and studies on water usage, emissions, and cost management issues in exploitation of unconventional oil and gas deposits (Huang et al., 2024; Wang et al., 2023; Chen et al., 2025). In terms of rationale for the selected methodological approach, there will be four major stages. First, sources will be grouped depending on their main area: reservoir description, drilling and landing, hydraulic fracturing and completion optimization, production analytics, or sustainability and cost management. Second, decision variables and criteria mentioned in the source will be identified:

reservoir properties, number of stages, fracture spacing, production lift, recovery efficiency, unit costs, water intensity, or emission exposure. Third, results achieved using this source will be verified internally by checking whether they differ from other results in the same area of science.

Fourth, findings will be synthesized using the stage-gate approach for Saudi fields. Therefore, this seems to be an adequate approach to writing about the topic, given the fragmentation of the literature in recent years. There seem to be two limitations with the suggested methodological approach. First, the absence of proprietary corporate data will render analysis possible only on the basis of the published scientific literature.

Second, due to differences across basins, the findings may miss something important for Saudi unconventional reservoirs. However, despite the above-mentioned drawbacks, the literature review seems to provide sufficient practical evidence.

Considering the above, it can be concluded that the body of literature selected gives a good overview that should be enough to develop necessary optimization principles for gas production in Saudi Arabia, especially given the experience gained so far with regard to Jafurah (Weijermars et al., 2021; Shawaf et al., 2023a; Gaduwang et al., 2025).

III. STRATEGIC OPTIMIZATION DOMAINS

The literature converges around one practical conclusion: unconventional-gas performance improves when operators optimize sequences and interfaces, not just isolated technical parameters. In other words, the critical unit of analysis is the production process itself. The following sections synthesize the main optimization domains and explain how they interact in a Saudi context.

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Table 1. Review synthesis of the principal optimization domains relevant to Saudi unconventional gas development.

Optimization domain	Core process levers	Primary performance indicators	Saudi relevance
Reservoir characterization	tiering, TOC, geomechanics, stress mapping, uncertainty ranges	quality ranking, landing confidence, variability reduction	high because the Tuwaiq Mountain interval is mechanically layered and heterogeneous
Well design and spacing	landing depth, lateral placement, stage count, cluster spacing	normalized productivity, interference risk, capital efficiency	high because field-scale development requires repeatable geometry rules
Completion execution	fluid system, pump schedule, diversion, clean-up, flowback	treatment efficiency, cleanup duration, preserved conductivity	high because execution quality determines whether designed fractures become productive fractures
Production analytics	rate-transient analysis, hybrid forecasting, ML ranking, choke control	forecast accuracy, intervention ranking, update speed	high because Saudi developments are moving from appraisal data scarcity to operational data abundance
Water, methane, and cost	reuse strategy, disposal planning, leak detection, portfolio screening	water intensity, emissions exposure, unit development cost	high because large-scale growth must remain operationally and environmentally resilient

3.1 Reservoir characterization and sweet-spot discrimination

High-quality reservoir characterization is the first optimization layer because every downstream decision depends on how accurately operators distinguish productive rock from merely drillable rock. For Jafurah, publicly available work has shown that the Tuwaiq Mountain interval is not a generic shale target but a heterogeneous carbonate mudrock system in which total organic content, porosity, maturity, mineralogy, and tiering strongly influence completion success (Weijermars et al., 2021; Shawaf et al., 2023a).

The implication is operationally important: sweet-spot identification must integrate geoscience and completion design rather than treat geology as a separate, static stage. If the wrong interval is landed or if inter-well spacing ignores stratigraphic quality variations, even sophisticated completion designs will only optimize poor rock.

Recent Saudi-focused studies strengthen this point by linking anisotropy, mechanical layering, and petrophysical differentiation to fracture behavior.

Shawaf et al. (2023a) found that elastic anisotropy and stress orientation materially affect fracture geometry in the Tuwaiq Mountain Formation, implying that generic design templates can misrepresent created fracture dimensions and spacing requirements. Related work on differential effective-medium applications in the same basin also indicates that mechanical-property estimation should be updated with calibrated petrophysical models rather than assumed from broad analog ranges (Shawaf et al., 2023b).

In practical terms, this means that process optimization should begin with a rock-and-stress model capable of supporting landing-window selection, stage spacing, cluster design, and interference assessment. The optimization gain here is not purely scientific; it reduces wasted stimulation intensity in intervals unlikely to sustain high conductive fracture networks.

A second reservoir-characterization lesson is the need to incorporate uncertainty explicitly. Probabilistic resource-estimation workflows for Jafurah were developed precisely because deterministic planning can understate uncertainty in productivity, liquids yield, and economic outcomes (Weijermars et al., 2021; Jin and Weijermars, 2022). For process optimization, this implies that subsurface characterization should feed scenario-based completion design and pilot appraisal. Instead of fixing one "best" development recipe early, operators gain more value by designing pilots that discriminate among competing geologic and geomechanical interpretations. This approach shortens the learning cycle and creates a better basis for later standardization.

3.2 Well placement, spacing, and development geometry

Optimization thus moves beyond reservoir characterization into the realm of contact geometry, including well orientation, spacing, stage design, and completion timing. The critical interdependence of these factors is especially evident in unconventionals, where the wellbore position determines both the contact geometry and the stress regime within which fractures develop.

Current optimization techniques indicate that well placement and fracture design should be considered in tandem. For instance, Xue et al. (2021) found that ensemble-based optimization becomes more valuable when well placement, fracture attributes, and operating conditions are all optimized simultaneously rather than incrementally. Similarly, Wang et al. (2023) assert that unconventional production optimization requires integrated algorithms and models capable of managing numerous design elements and nonlinear interactions.

While most of these techniques were developed elsewhere, the key takeaway is highly transferable. The issue in Saudi unconventional gas production is no longer how long the lateral is or how many stages it has. Instead, the critical decisions involve how to co-optimize design aspects such as landing depth, fracture half-length targets, the number of stages, cluster spacing, and expected parent-child communications within each mechanical tier.

That is the importance of current fracture modeling studies in Jafurah: they reveal that anisotropic fracture geometry changes are expected to alter the stimulated reservoir volume and thereby the economic optimum of spacing and completion intensity (Shawaf et al., 2023a; IPTC-23472-MS, 2024). Any lateral differences in stress contrast or brittleness can render fixed spacing strategies obsolete, leaving behind gas or causing mutual destruction.

Current research literature also suggests that the economic optimum does not necessarily equate the technical maximum. While increasing the number of stages, using more fracturing fluids, or packing the lateral with clusters will increase short-term production, it is uncertain whether that will increase full-cycle value. More and more platform-well and hydraulic fracturing optimization studies now focus on the decision-making framework that weighs production response against costs, uncertainties, and risks (Zhang et al., 2025; Lin et al., 2025).

In Saudi Arabia, where unconventional development is expanding at the field scale, that means that capital efficiency must be a built-in aspect of the optimization process. Design of experiments, pilot spacing tests, and phased development platforms prove more useful than one-time technical achievements.

3.3 Completion execution, hydraulic fracturing, and clean-up

Completion and hydraulically fractured execution represent the practical essence of unconventional gas optimization because they translate geological potential into flow conductivity.

From a scientific point of view, execution rather than design is crucial in this regard. There is a wide range of factors that can undermine the theoretical efficiency of a particular design, such as abnormal treatment conditions, fluid loss, proppant transport, stress shadow generation, fracture clean-up, and wellbore-related problems (Yang et al., 2024; Mao et al., 2024; Nasriani et al., 2025).

Thus, for carbonate-prone or heterogeneous systems, this aspect should not be overlooked, as treatment behavior is unlikely to coincide with predictions from analysis of a homogeneous reservoir.

Several Saudi studies emphasize the role of geomechanical completion design that accounts for rock properties, including heterogeneity, anisotropy, bedding orientation, and stress magnitude.

This implies that process optimization should involve a completion design cycle, which includes pre-job calibration, in-process monitoring, and post-job evaluation of the results.

While treating completion design as static can lead to inefficient repeatable geometry being applied to multiple pads, seeing each treatment as a learning opportunity opens up new possibilities for improvement of stage efficiency, fluid systems, pumping schedule, diversion techniques, and perforation design (Wang et al., 2023; Zhang et al., 2025).

As current trends suggest, this iterative cycle is increasingly recognized in other fields of unconventional gas optimization, where quality assurance during execution is becoming at least as significant as the initial modeling step. Finally, post-fracture clean-up and flowback operations must also receive adequate attention since they determine the degree of conductivity preservation that was achieved during fracturing and stimulation.

As evidenced in recent research, capillary pressure effects and permeability jail behaviors have proven to be highly detrimental to unconventional gas productivity and should be addressed in ultra-tight formations, where they can particularly damage production due to the multiple fracturing of horizontal wells (Nasriani et al., 2024; Nasriani et al., 2025).

Since the field-scale expansion of unconventional drilling in Saudi Arabia poses the temptation to apply uniform flowback techniques without proper rock-fluid sensitivity testing, there is room for improvement in this area.

3.4 Production analytics, forecasting, and closed-loop control

With the well in service, process optimization becomes a challenge of surveillance and decision-making. Literature reviews on shale gas productivity assessments reveal that no one single forecasting technique can serve as a reliable methodology in all cases. The recommended approach includes the integration of decline curve analysis, analytical techniques, numerical simulation, and machine learning depending on data availability and objectives of the operation (Huang et al., 2024).

This is particularly relevant to Saudi shale-gas developments where wells drilled earlier may lack sufficient production history, while those drilled later generate enough production history data for statistical modeling and application of machine learning approaches. Optimization through analytics must be sequential and take into account the development maturity level: physics-informed models are more useful for early appraisal phase, whereas hybrid or purely data-driven workflows offer competitive results at later stages.

In line with the increasing trend of forecasting by applying data-driven models, recent research by Rahmanifard and Gates (2024) revealed that the use of integrated forecasting and optimization of the well completion procedure allowed identifying shale-gas wells with considerable uplift potential. Other recent studies confirmed that interpretable machine learning models, productivity classification procedures, and optimizing neural network algorithms can help to improve prediction of production performance in shales (Peng et al., 2024; Zhang et al., 2025; Rao et al., 2025).

While such approaches do not replace traditional engineering knowledge, they make it possible to decrease the time needed for the identification of underperforming wells, assessment of completion quality, and prioritization of wells requiring interventions.

It follows that, in Saudi Arabia, process optimization through analytics must be considered as a part of the operational infrastructure rather than merely an analytics project. Reliable forecasting techniques require the standardization of data collection processes across several aspects: drilling, completion, production, pressure management, and water management.

Besides, maximum benefits can be achieved only if data-based surveillance is associated with decision-making actions like choke management, selection of wells suitable for refracturing, sequencing of pads, and updating the design of the next well. In the unconventional setting, the distinction between raw data collection and data management and governance is crucial: uncalibrated high-frequency data and insufficient metadata lead to noise rather than new insights.

3.5 Water, methane, and cost optimization

It is becoming clear that optimization of unconventional gas development is inherently linked to water considerations, emissions, and costs. While previous research tended to see these factors as constraints that need to be managed following the development of the solution itself, the literature now argues that optimization problems must incorporate water, emission, and cost targets explicitly.

Water demand, flowback management, opportunities to reuse produced water, methane leakage risks, and infrastructure limitations affect the economic and social viability of various completion and production solutions (Arciniega-Esparza et al., 2022; Li et al., 2025). A technically successful treatment process that results in excessive water-related complexity may not be the optimal process design in water-scarce or infrastructure-constrained settings. There are multiple reasons why these lessons apply to Saudi Arabia specifically. First, large-scale unconventional development necessarily involves many successive fracturing treatments, complex logistics, and high water demands for treatment operations. Second, the development is taking place within a policy environment that expects the growth of unconventional gas output to contribute to the larger objective of the energy transition, with increased domestic use of natural gas to fuel electricity production and feedstock logistics (Aramco, 2022; Aramco, 2024a).

Optimization that disregards these factors can result in a project lock-in with high costs or negative public value implications. Hence, metrics of water management and emissions control should be monitored alongside the production KPIs.

For instance, methane monitoring and mitigation help secure the commercial value of the resource and optimize its carbon footprint. Likewise, water reuse and recycling enhance project flexibility and minimize external dependency risks. Another lesson from the reviewed papers concerns multi-objective economic optimization.

Papers that deal with multi-objective optimization of unconventional production tend to focus on cost, emissions, uncertainties, and block ranking in addition to maximizing production (Liu et al., 2025; Wang et al., 2023).

For Saudi Arabia, this is important since the goal is not about developing one single successful well but using limited capital resources to develop an entire portfolio of wells. Process optimization in such a setting should consider a portfolio perspective, which means evaluating each process design not just in terms of local productivity but also scalability and its impacts on costs and service demands.

3.6 Infrastructure synchronization and portfolio delivery

Finally, an important under-recognized theme in the literature is infrastructure synchronization, which plays a critical role in optimizing unconventional gas developments. A technically sound well becomes economically unattractive when it is held back by slower infrastructure deployment such as processing, gathering lines, water management, and service crew scheduling. Reports from Saudi Arabia's official sources on expanding gas production show that its unconventional gas upstream development was accompanied by significant investment in midstream development, directional drilling services, tie-ins, and system expansion (Aramco, 2024a; Aramco, 2025).

In light of this, process optimization should consider subsurface and completion optimization within the context of surface systems, facility optimization, and system start up. For a Saudi project, this means that a successful optimization goal is not simply a technically optimal well but a better well to be deployed in a timely manner without delays.

This discussion of infrastructure highlights the need for a different approach to pad sequencing. Where drilling proceeds at a pace that is quicker than the stimulation fleet can cope with, or where stimulation advances more rapidly than gas processing or water treatment facilities, then the project loses potential efficiencies.

The literature on overall field optimization and flexible gas allocation shows the advantage of considering integrated well, surface, and demand scheduling in order to extract benefits from process optimization that would otherwise be overlooked (Yusuf et al., 2024; Zhou et al., 2025). This implies that Saudi unconventional gas development should include stage gate development from appraisal to pad development to completion and facilities management.

Figure 1. Integrated optimization architecture for unconventional gas production in Saudi Arabia.

3.7 Pilot design, comparability, and learning efficiency

Finally, this review demonstrates that the pilot design should be considered an optimization tool in its own right rather than a rudimentary proof-of-concept procedure. When designing pilots for unconventional plays at early stages, there is a tendency to overload the process with too many objectives. It is more rational to assign a distinct decision-making task to each pilot, such as the discrimination between landing benches, spacing patterns, completion fluids, and proppant mixes.

Considering that the scale of unconventional development in Saudi Arabia is highly strategic, learning efficiency can deliver exceptionally high economic gains, while any premature commitment to a suboptimal standard would cause a disproportionate loss. Recent papers addressing the issues of data-based optimization, interpretable machine learning, and multi-criteria investment allocation suggest that learning efficiency should be optimized explicitly (Rahmanifard and Gates, 2024; Chen et al., 2025; Liu et al., 2025). The methodological recommendations described above have several implications for operators and researchers working on Saudi unconventional development projects.

First, pilot data should be collected with future comparison purposes in mind, including the uniformity of metadata, treatment protocols, diagnostics formats, and surveillance schedules. Second, benchmarks should be compared based on productivity indices other than initial production rate.

In particular, the literature on productivity assessment consistently highlights that relying on a single metric would result in an incorrect identification of the optimal designs and underlying reasons for underperformance (Huang et al., 2024; Dheyauldeen et al., 2021). As far as a Saudi unconventional-gas program is concerned, the conclusion is straightforward: pilot management must be formalized within the framework of the process optimization methodology.

3.8 Risk-aware optimization and robustness under uncertainty

Risk management is yet another area implicit to the emerging themes of recent optimization studies.

Uncertainty about geology, completion outcomes, inflation, supply chain vulnerabilities, water management risks, and emissions pose a threat to planning processes. The risks faced are such that they not only complicate the process of planning but also make it impossible to optimize in terms of deterministic expectations. Optimality in such a case will depend greatly on volatile service rates, uncertain fracture performance, and infrastructure delays.

This is why recent works on oilfield optimization increasingly integrate forecasting, optimization, and scenario analysis (Wang et al., 2023; Zhang et al., 2025). In Saudi Arabia, where unconventional gas development is a part of a larger strategy of energy resource exploitation, robust optimization makes more sense than narrow peak-case optimization. An acceptable design is one that shows reasonable performance in terms of reservoir characteristics, operational excellence, and commercial viability.

Four specific safeguards are suggested in light of conventional risk management practices. Firstly, uncertainty ranges for underground conditions should provide input to design envelopes rather than to a fixed design program. Secondly, parent-child interference should be estimated at pad level before standardization through general guidelines.

Thirdly, production performance during early-time operation should be interpreted with the effects of cleanup taken into account. Finally, economic ranking of unconventional resources should take into account sensitivity to water logistics and infrastructure load during field expansion.

All these considerations can be found in various studies related to unconventional drilling, although in a variety of basin types and unconventional techniques. The point is that high-quality optimization depends on early confrontation of uncertainties.

IV. PROPOSED FRAMEWORK FOR SAUDI UNCONVENTIONAL GAS DEVELOPMENTS

Based on the synthesis of the literature reviewed, a stage-gate operating approach to unconventional gas optimization appears to offer many advantages for Saudi Arabia. At the first gate, the approval process should include the ranking of rock quality and stress, fluid system properties, and uncertainty in all aspects so as to establish unique landing corridors rather than simply defining an average development window.

At the second gate, the design of the pilots needs to consider spacing, completion intensity, and fluid systems in combinations that rigorously test existing hypotheses. The execution quality can be measured through completion diagnostics and operational control in the third gate. At the fourth gate, ramp-up planning should emphasize proper flowback strategy, pressure management, and early-time surveillance.

Mature data streams will play a key role in establishing forecasts, optimizing production, and ranking interventions at the fifth gate. In the final gate, closed loop learning should involve a codification of design standards and remaining uncertainties.

There are several important principles within this operating framework for the Saudi context. First, there is a need to prioritize learning before standardization in field-scale up.

While operational consistency is rewarded at the outset of development, premature standardization can create sub-optimal completion designs throughout an acreage position. Secondly, there should be no separation between economics and any of the gates. Cost-normalized productivity, water intensity, and infrastructure requirements must be considered alongside reservoir and completion considerations.

Lastly, digitalization efforts should serve engineering decision making processes, not operate in parallel. As seen in the recent examples of the forecasting and optimization literature, it is data pipelines that have generated value when applied to well ranking, spacing, and completion optimization (Rahmanifard and Gates, 2024; Chen et al., 2025).

The implementation steps for the next phase of optimizing Saudi unconventional gas can be clearly articulated. First is the creation of a unified basin-wide data model incorporating petrophysical analysis, geomechanical calibrations, completion records, and production surveillance into one governed environment.

Second is the institutionalization of pilot review committees that will make consistent decisions regarding whether to accept or reject any design changes based on technical and economic criteria. Third is the definition of a core set of decision-making KPIs for every pad: normalized productivity, capital intensity per productive foot, cleanup times, water intensity, methane control, and facility readiness. Fourth, these KPIs are used not only to compare wells but also to rank recipes, drilling teams, and development sequences. Fifth is the rapid translation of lessons learned into contract and facilities planning for future pads.

By combining these priorities, Saudi Arabia can turn optimization into an ongoing management practice rather than a series of disconnected technical sessions. This is the implication of current literature most directly relevant to Saudi Arabia's transition to commercial unconventional gas development. It is also the kind of optimization process that creates a durable record of learning despite any changes to service cycle, project portfolios, or emerging technologies Cycles.

In future efforts to optimize Saudi Arabia's unconventional gas, there should be an emphasis on combining mechanical and data-driven modeling approaches rather than favoring either exclusively. While mechanics-based models are still crucial for fracture mechanics, pressure depletion calculations, and design physics, data-centric methods become increasingly valuable as field experience grows and as well counts increase.

Some of the best-reviewed articles published recently were hybrid in nature: while maintaining physical reservoir understanding, they use machine learning and other forms of surrogate modeling to accelerate forecasting, ranking, and sensitivity analysis (Xue et al., 2021; Rahmanifard and Gates, 2024; Chen et al., 2025).

With the development of the Saudi unconventional program, a similar hybrid approach can form the foundation of a digital twin-type development logic where each development phase informs the next via consistent data standards, rapid analytics, and engineering review.

From the standpoint of research and policymaking, some clear recommendations emerge. Specifically, there are areas in need of more Saudi-focused work on carbonate mudrock fracture complexity, water-reuse economics under local conditions, methane monitoring architecture in unconventional plants, and pad sequencing effects on midstream optimization.

Comparative studies may also be useful in testing the feasibility of applying selected North American optimization practices to the Arab case. All such research will not only advance development economics but also add knowledge to the public domain on developing unconventional hydrocarbon reserves in arid climates and on strategically integrated energy systems.

Table 2. Stage-gate process framework proposed for Saudi unconventional gas developments.

Stage gate	Key decision question	Data required	Optimization output	Recommended control metric
Appraisal	Which benches and stress regimes justify pilot investment?	core, logs, DFIT, petrophysics, geomechanics	ranked landing corridors and uncertainty map	quality-weighted inventory
Pilot design	Which spacing and completion combinations discriminate among hypotheses?	pilot matrix, service data, budget limits	testable design envelope	learning value per dollar

Execution	Was fracture treatment quality delivered as planned?	live treatment data, diagnostics, QA/QC logs	treatment-quality score and redesign triggers	execution conformance
Ramp-up	How should cleanup and drawdown be controlled?	flowback, pressure, water, early production	optimized startup strategy	cleanup duration and early normalized productivity
Steady-state operations	Which wells and pads merit redesign or intervention?	forecast models, RTA, cost and emissions data	ranked intervention and next-pad options	cost-normalized forecast uplift

Figure 2. Stage-gate roadmap linking appraisal, pilot learning, execution assurance, ramp-up, and continuous improvement.

V. DISCUSSION

A generalization one can make about the literature reviewed is that Saudi unconventional gas could be seen as a test for process-oriented development beyond North America. While many principles of optimization were first applied in shale formations in the United States and Canada, the Saudi example stands out from its peers due to geological conditions, supply chain characteristics, development pace, and strategic considerations. Instead of transplanting the approach used in another basin, what should be transferred here is an approach to designing a rigorous decision process that can adapt quickly, maintain options, and optimize technical efforts vis-à-vis capital.

CONCLUSION

Process optimization for unconventional gas production in Saudi Arabia must be seen as a holistic approach to operating systems involving reservoir knowledge, fracture completion design, execution quality, production analytics, and sustainable management. It has been shown repeatedly in recent literature that improvements in production can best be achieved when these components work together through closed-loop learning.

What seems to work best for the case of Saudi Arabia is the combination of probabilistic geological modelling, anisotropic completion design, execution control, forecasting, and cost screening across multiple wells within the context of portfolio analysis. As such, unconventional gas production in Saudi Arabia is more than just a matter of resource development; it is also a matter of process development.

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