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OPERATIONAL, REGULATORY AND TERRITORIAL CONSTRAINTS TO SHALE GAS PRODUCTION IN BRAZIL: A PRODUCTION ENGINEERING PERSPECTIVE (2013–2026)

RESTRIÇÕES OPERACIONAIS, REGULATÓRIAS E TERRITORIAIS À PRODUÇÃO DE GÁS DE XISTO NO BRASIL: UMA PERSPECTIVA DA ENGENHARIA DE PRODUÇÃO (2013–2026)

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ABSTRACT

Shale gas has been identified as a potential contributor to Brazil's energy diversification, however its development has not progressed beyond exploratory initiatives. This study investigates shale gas development and regulatory dynamics in Brazil between 2013 and 2026, with a focus on the Potiguar Basin, in order to identify the systemic constraints across operational, technological, territorial, and regulatory dimensions. Using a Production Engineering framework integrated with territorial and regulatory analysis, the study combines patent data, institutional mapping, environmental assessments, and supply chain diagnostics. The results indicate that the main constraints are not geological, but operational, technological, territorial, and regulatory in nature. In the semi-arid Potiguar Basin, high water requirements for hydraulic fracturing (15,000–45,000 m^3 per well) conflict structurally with local water availability and competing uses. Technological prospecting, however, reveals an emerging innovation trajectory in low-water and waterless fracturing technologies, as well as advanced monitoring systems based on nanotechnology, which may partially mitigate these constraints in the future. Despite these developments, current industrial conditions remain insufficient for large-scale deployment. The study concludes that shale gas stagnation in Brazil is primarily driven by systemic misalignment across supply chains, territorial governance, and technological localization. Without coordinated action across these dimensions, shale gas is likely to remain structurally constrained within the national energy matrix. The findings contribute to the development of multi-criteria governance frameworks for unconventional energy systems.

Keywords: Production Systems Engineering; Unconventional Gas Operations; Potiguar Basin; Technological Prospecting; Supply Chain Resilience; Territorial Risk Assessment.

RESUMO

O gás de xisto tem sido identificado como um potencial contribuinte para a diversificação energética do Brasil, porém seu desenvolvimento não avançou além de iniciativas exploratórias. Este estudo investiga o desenvolvimento do gás de xisto e a dinâmica regulatória no Brasil entre 2013 e 2026, com foco na Bacia Potiguar, a fim de identificar as restrições sistêmicas nas dimensões operacional, tecnológica, territorial e regulatória. Utilizando uma estrutura de Engenharia de Produção integrada com análises territorial e regulatória, o estudo combina dados de patentes, mapeamento institucional, avaliações ambientais e diagnósticos da cadeia de suprimentos. Os resultados indicam que as principais restrições não são geológicas, mas sim operacionais, tecnológicas, territoriais e regulatórias. Na Bacia Potiguar, semiárida, a alta demanda hídrica para fraturamento hidráulico (15.000–45.000 m^3 por poço) entra em conflito estrutural com a disponibilidade hídrica local e com outros usos concorrentes. A prospecção tecnológica, no entanto, revela uma trajetória de inovação emergente em tecnologias de fraturamento com baixo ou nenhum consumo de água, bem como sistemas avançados de monitoramento baseados em nanotecnologia, que podem mitigar parcialmente essas restrições no futuro. Apesar desses desenvolvimentos, as condições industriais atuais permanecem insuficientes para a implantação em larga escala. O estudo conclui que a estagnação do gás de xisto no Brasil é impulsionada principalmente pelo desalinhamento sistêmico nas cadeias de suprimentos, na governança territorial e na localização tecnológica. Sem uma ação coordenada nessas dimensões, é provável que o gás de xisto permaneça estruturalmente limitado dentro da matriz energética nacional. As descobertas contribuem para o desenvolvimento de estruturas de governança multicritério para sistemas de energia não convencional.

Palavras-chave: Engenharia de Sistemas de Produção; Operações de Gás Não Convencional; Bacia Potiguar; Prospecção Tecnológica; Resiliência da Cadeia de Suprimentos; Avaliação de Risco Territorial.

1. INTRODUCTION

The global energy landscape underwent a significant transformation in the early 21st century with the United States' "Shale Revolution," driven by advances in horizontal drilling and multi-stage hydraulic fracturing. This shift has not only repositioned the United States as a major energy producer but has also reshaped global energy markets, stimulating widespread interest in shale gas as a pathway to energy security and industrial competitiveness (International Energy Agency [IEA], 2024).IEA (2025) reinforces the importance of natural gas as a transition fuel, although it highlights the regulatory and environmental challenges for shale gas.

In Brazil, institutional momentum toward shale gas development emerged with the 12th Bidding Round of the National Agency of Petroleum, Natural Gas and Biofuels (ANP) in 2013. The round offered exploratory blocks in basins with significant unconventional potential, including the Parana, Parnaiba, and Potiguar basins. However, the initiative faced immediate resistance due to the absence of basin-wide Environmental Assessment of Sedimentary Area (AAAS in Portuguese acronym), as well as concerns over groundwater contamination, and broader environmental risks. Since then, shale gas development has been shaped by judicial disputes, institutional fragmentation, and increasing territorial constraints, preventing the transition from exploration to production.

Between 2013 and 2026, Brazil's regulatory framework for shale gas remained fragmented and unstable. Although policy initiatives, such Brazil (2022), sought to standardize environmental assessments, fundamental operational, scientific, and territorial challenges persisted. (Sacco et al., 2022) corroborates this view, pointing to the unexplored potential of Brazilian sedimentary basins, but also to the operational barriers that prevent the attraction of investments. The Technical Report GTPEG(2025), issued by the Ministry of Environment and Climate Change (MMA), further underscores the persistence of environmental sensitivities and territorial conflicts, particularly in the Potiguar Basin, which continues to hinder the inclusion of shale-prospective areas in federal energy planning mechanisms.

Despite substantial estimates of technically recoverable shale gas resources, no commercial production has materialized in Brazil. This persistent gap between geological potential and operational reality indicates that constraints on shale gas development extend beyond subsurface characteristics and cannot be explained solely by conventional geological or economic analyses. To date, literature has predominantly addressed shale gas through isolated lenses, focusing on resource potential, fiscal regimes, or environmental risks, while largely neglecting the systemic interactions that shape industrial implementation. This study fills this gap by introducing a Production Engineering framework, conceptualizing shale gas extraction not merely as a resource problem, but as a Continuous Manufacturing System. By doing so, it systematically examines how operational, regulatory, and territorial constraints interact to disrupt the alignment between industrial logic and the institutional environment.

This paper argues that the absence of a shale gas industry in Brazil reflects a systemic misalignment between the continuous manufacturing logic inherent to unconventional resource production and the country's fragmented regulatory framework, limited onshore operational capacity, and complex territorial configuration. Crucially, this misalignment is reinforced by a strong 'Path Dependency' in Brazil's oil and gas sector, which has been structurally optimized for offshore deep-water production (pre-salt) over the last decades. (Kasahara et al., 2026) explores how this path dependency shapes institutions and local content policy in the Brazilian oil and gas sector, creating challenges for diversification. This offshore-centric trajectory has shaped the country's service industry, regulatory routines, and technological expertise, creating institutional and operational lock-ins that hinder the transition to the high-frequency, decentralized drilling cycles required for onshore shale gas. In contrast to conventional oil and gas systems, shale gas production requires tightly synchronized supply chains and infrastructure-intensive logistics, making it particularly sensitive to disruptions arising from these established path-dependent constraints.

From a production engineering perspective, this misalignment can be interpreted as a failure in operations strategy alignment, in which the requirements of the production system have not been supported by the broader institutional and infrastructural environment (Skinner, 1969; Slack & Lewis, 2020). This study explicitly has framed shale gas development as a production system rather than solely a resource extraction problem. In Brazil, these constraints manifest through limited onshore service industry capacity, logistical bottlenecks, fragmented regulatory authority, and socio-environmental conflicts. These dynamics are especially evident in the Potiguar Basin, where overlapping territorial claims and environmental sensitivities intensify operational risks and constrain system scalability.

Accordingly, this study aims to identify and analyse the operational, regulatory, and territorial constraints shaping shale gas development in Brazil between 2013 and 2026. By integrating regulatory analysis, technological prospecting, and production system evaluation, the paper makes three main contributions. This study establishes a production engineering perspective for analysing unconventional energy systems, emphasizing operational feasibility, supply chain dynamics, and cycle-time dependencies. It further develops a systemic framework that captures the interaction between technological, institutional, and territorial dimensions. In addition, it provides empirical evidence from the Brazilian context, offering a structured explanation for the persistent gap between resource potential and industrial realization. Beyond the Brazilian case, the study contributes a transferable analytical framework for assessing the feasibility of continuous industrial extraction systems in institutionally complex and territorially constrained environments, advancing the understanding of how misalignments between industrial logic and governance structures can hinder large-scale energy transitions.

2. THEORETICAL BACKGROUND

2.1. The Shale Gas Production Chain as a Continuous Manufacturing System

Shale gas production differs fundamentally from conventional natural gas extraction in its operational logic, scale, and temporal structure. The operational logic of shale gas has shifted from a project-based approach to a high-frequency regime that has closely resembled a continuous manufacturing system (EIA, 2021; Sterman, 2000). This paradigm relies on repeated drilling and multi-stage hydraulic fracturing to sustain production in low-permeability formations. This operational synchronization has required advanced manufacturing planning and control (MPC) systems to manage high-frequency cycles and resource allocation (Vollmann et al., 2004)

From a production engineering perspective, this configuration requires precisely coordinated operations across all stages of the production chain, including drilling, completion, fracturing, and flowback management. The rapid decline rates observed in shale wells, often exceeding 60% in the first year, create a systemic dependence on continuous drilling activity, commonly referred to as the “drilling treadmill” (Hughes, 2013). Mogck (2024) analyzes this trend in shale well decline rates and operational efficiency, corroborating the need for continuous optimization. Ni & et al. (2023) also analyze this declining trend using transfer learning methods on a vast dataset of wells. The rapid decline rates observed in shale wells, often exceeding 60% in the first year, create a structural dependence on continuous drilling activity, commonly referred to as the “drilling treadmill” (Hughes, 2013).

This operational model imposes significant logistical and technological demands. Large volumes of water, proppants, and chemical inputs must be mobilized within short cycle times, while specialized high-pressure equipment and skilled service providers are essential to ensure process continuity (IEA, 2022). Fu & He, 2024) discuss the frameworks necessary for the large-scale commercial development and utilization of shale gas resources, emphasizing the logistical and technological complexity. Consequently, shale gas systems exhibit a strong degree of operational interdependence, whereby disruptions at any stage propagate across the entire system, increasing cycle times and operational costs. Figure 1 illustrates the continuous manufacturing system, highlighting process interdependencies, logistics flows, and critical operational risk points.

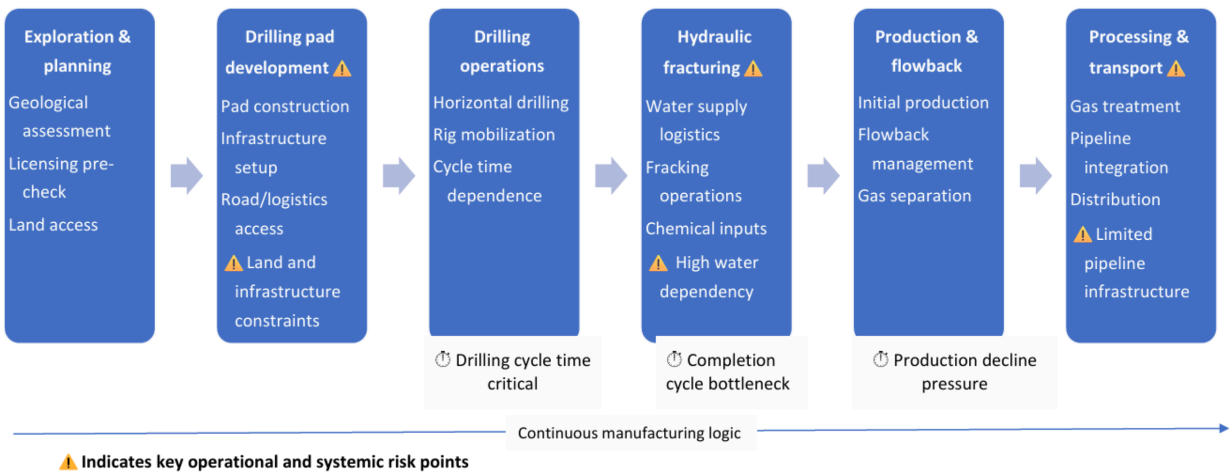

Figure 1. Operational Architecture of the Shale Gas Production Chain

Figure 1 illustrates the operational architecture of shale gas production as a continuous manufacturing system, emphasizing sequential interdependencies between drilling, fracturing, and flowback operations, as well as associated logistics flows and systemic risk points.

To further clarify the operational differences between conventional and unconventional systems, Table 1 summarizes key techno-economic parameters, including capital intensity, water requirements, decline rates, and operational complexity.

Table 1. Techno-Economic Parameters: Comparison Between Conventional and Unconventional Shale Gas Systems.

Parameter	Shale Gas (Unconventional)	Conventional Gas	Source
CAPEX per Well (Drilling & Completion)	US$ 4.9M – US$ 8.3M	US$ 1.5M – US$ 3.0M	U.S. EIA (2021); EPE (2021)
Variable OPEX (Logistics & Maintenance)	US$ 2.50 – US$ 4.20 / MMBtu	US$ 0.50 – US$ 1.50 / MMBtu	IEA (2022)
Water Intensity (m^3 per well)	15,000 – 45,000 m^3	< 1,000 m^3	USGS (2020); Gao et al. (2024)
Annual Production Decline (1st Year)	65% – 85%	5% – 15%	Mogck (2024); SPE (2020)
Proppant Intensity (Tons per well)	1,500 – 3,500 tons	Negligible	U.S. EIA (2021)

Conceptualizing shale gas as a continuous manufacturing system provides a critical analytical lens for understanding its operational vulnerabilities. Unlike conventional extraction, shale systems depend on sustained operational intensity and synchronization, making them inherently sensitive to logistical, regulatory, and institutional disruptions.

2.2. Supply Chain Requirements and Operational Risks

The continuous manufacturing system underpinning shale gas production places significant demands on supply chain performance. Unlike conventional systems, where infrastructure and logistics are relatively stable, shale gas requires highly adaptive and responsive supply networks capable of supporting geographically dispersed and rapidly shifting drilling operations (IEA, 2022). Consequently, shale gas operations have demanded an 'Agile' supply chain strategy to handle high variability, contrasting with the 'Lean' and project-based models typically found in offshore environments (Christopher, 2016).

Three dimensions are particularly critical for operational feasibility: redundancy, responsiveness, and system robustness.

- Redundancy refers to the availability of multiple suppliers and alternative logistical pathways for key inputs such as water, proppants, chemicals, and specialized equipment.
- Responsiveness captures the ability to adapt to rapid changes in drilling schedules and pad locations.
- Robustness reflects the capacity to maintain operations under disruptions, including regulatory shifts, environmental constraints, and resource limitations.

This figure illustrates input flows and identifies bottlenecks affecting system responsiveness and overall resilience.

Analytical Dimensions

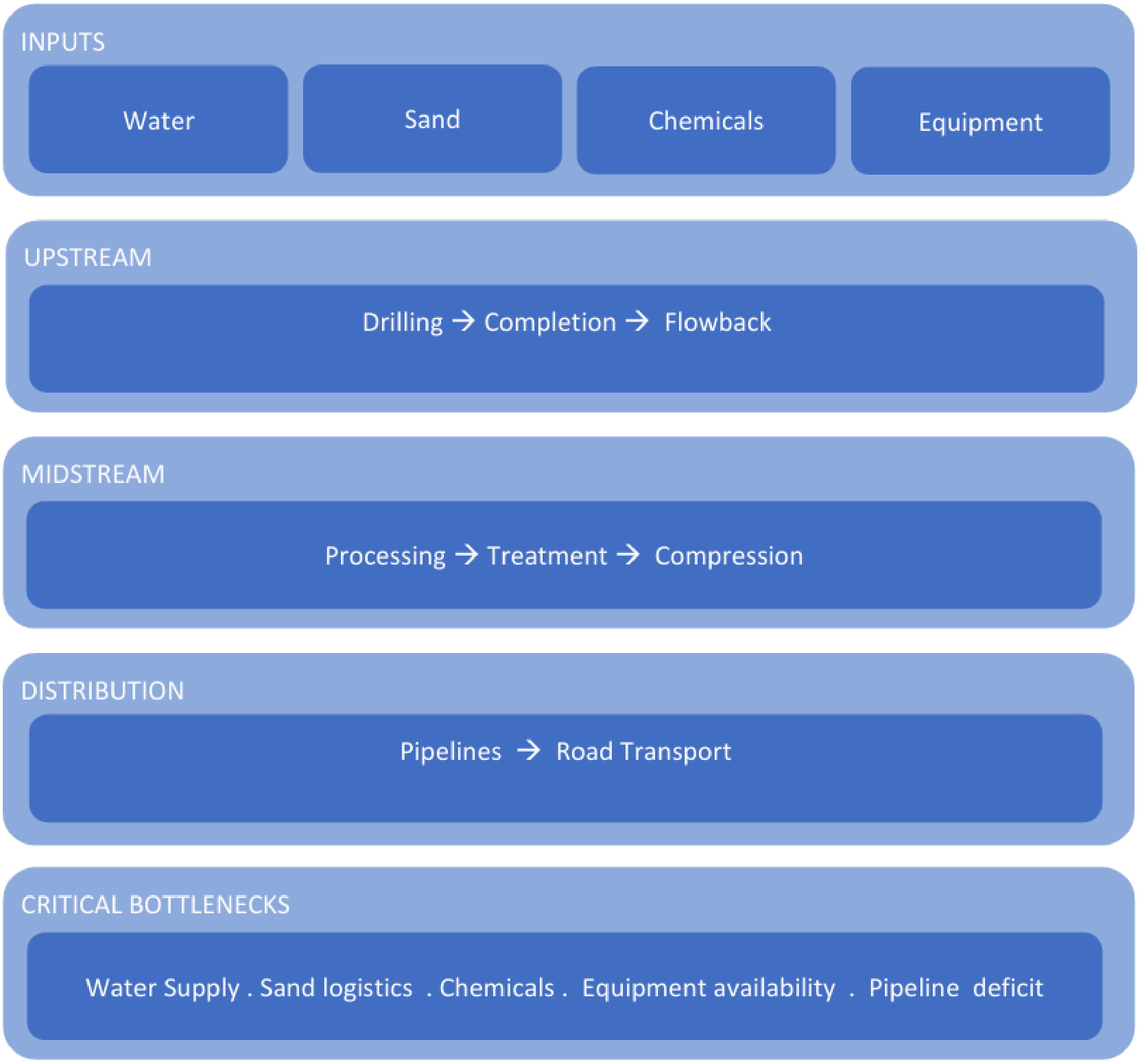

Figure 2. Supply Chain Structure and Critical Dependencies in Shale Gas Operations.

Figure 2 presents the supply chain structure supporting shale gas operations, highlighting critical dependencies and bottlenecks that directly influence system performance.

These dimensions can be operationalized through key performance indicators (KPIs), including supplier diversity, drilling-to-completion lead time, water-sourcing buffer, and logistical load.

Table 2. Supply Chain Resilience KPIs and Gaps in the Potiguar Basin.

Resilience Dimension	Requirement	Performance KPI	Systemic Gap	Source

		(International Benchmark)		
Redundancy	Supplier Diversity	High (>5 regional providers)	**Supplier Fragmentation** (High dependence on imported fleets)	(IBP, 2022; IEA, 2022)
Responsiveness	Lead Time	Short (<30 days for completion)	**Logistical Bottlenecks** (Infrastructure deficits and long cycle times)	(EPE, 2021; Sahai & Moghanloo, 2022)
Robustness	Water Buffer	High (>30% storage capacity)	**Resource Scarcity** (High exposure to water stress and conflict)	(Gao et al., 2024; GTPEG, 2025)
Efficiency	Logistical Intensity	Optimized Truck Trips (<1,500 trips/pad)	**Logistical Overload** (Extreme dependency on road-based transport)	(ANP, 2024a; USGS, 2016)

Table 2 synthesizes these indicators and demonstrates how deficiencies in supply chain performance increase operational risk and reduce system efficiency.

The supply chain literature consistently shows that high-performance industrial systems depend on alignment between operational requirements and logistical capacity (Christopher, 2016). In shale gas systems, achieving such alignment is particularly challenging due to scale, intensity, and spatial dispersion, making supply chain fragility a central constraint on feasibility.

2.3. Territorial Conflicts and Energy Governance

Shale gas production is inherently embedded within territorial and institutional contexts. Unlike offshore or conventional systems, unconventional gas requires extensive surface occupation, including well pads, access roads, water storage facilities, and pipeline infrastructure. This spatial intensity creates direct competition with other land uses, such as agriculture, conservation areas, and traditional communities (IEA, 2022). This spatial intensity has repositioned shale gas within the 'Political Geography of Resources,' where territorial control and social license to operate (SLO) have become as critical as geological availability (Bridge, 2008).

From a governance perspective, shale gas development involves multiple institutional layers operating across different spatial and administrative scales. These overlapping jurisdictions often generate regulatory complexity, inconsistencies, and conflicts (Lenhart et al., 2016). Figure 3 illustrates the supply chain structure and critical dependencies in shale gas operations. The diagram highlights the systemic risk points where logistical bottlenecks in water supply and proppant transport can disrupt the entire production flow, directly affecting the system's responsiveness.

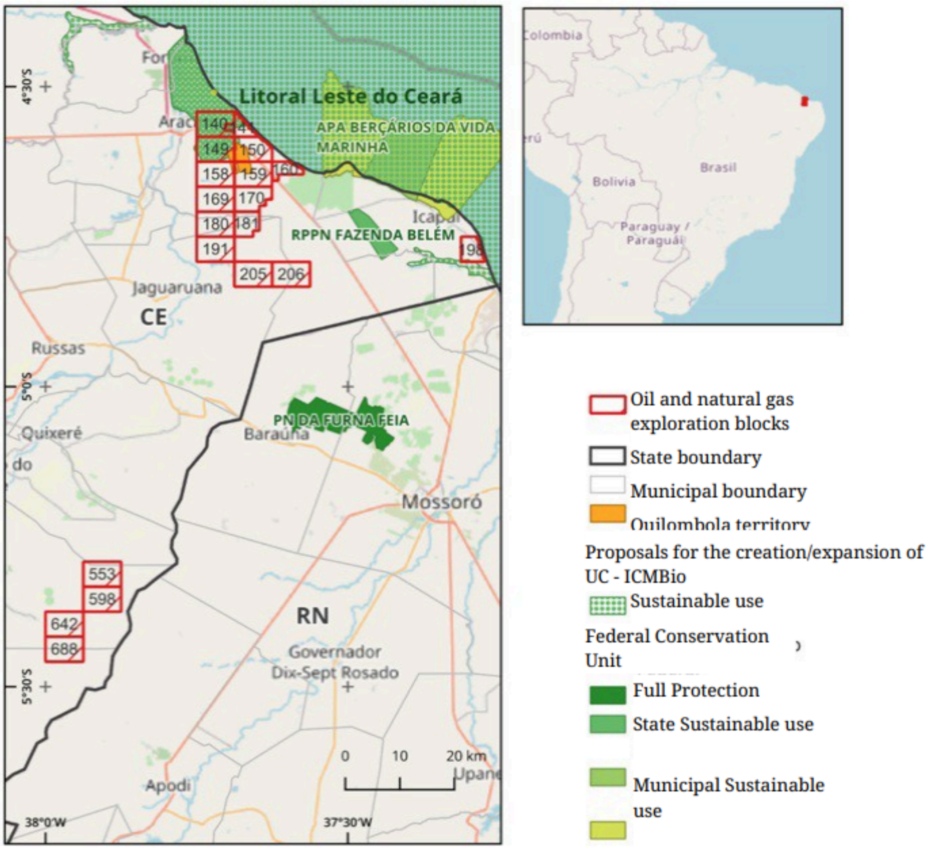

Figure 3. Overlapping Territorial Regimes in the Potiguar Basin: Administrative, Environmental, and Traditional Land Use Systems.

Figure 3 ilustrates how overlapping territorial and institutional constraints increase regulatory complexity and operational risk.

The concept of territoriality in production systems emphasizes that operational feasibility is conditioned by spatial, institutional, and socio-environmental factors. In shale gas systems, territorial constraints limit land access, increase permitting complexity, and heighten the likelihood of social opposition and legal disputes, reinforcing the structural challenges of implementation.

2.4. Operations Strategy and Institutional Constraints

The feasibility of shale gas production depends on the alignment between operational requirements and institutional conditions. From an operations strategy perspective, industrial systems require coherence across process design, capacity planning, technology strategy, regulatory stability, and territorial integration (PORTER, 1985; Slack & Lewis, 2020).

Shale gas production imposes stringent requirements across these dimensions. The continuous manufacturing system demands high drilling throughput, synchronized logistics, and infrastructure-intensive operations, alongside regulatory predictability, technological capability, and territorial coordination.

A systemic institutional misalignment emerges when these requirements are not supported by the broader institutional and infrastructural environment.

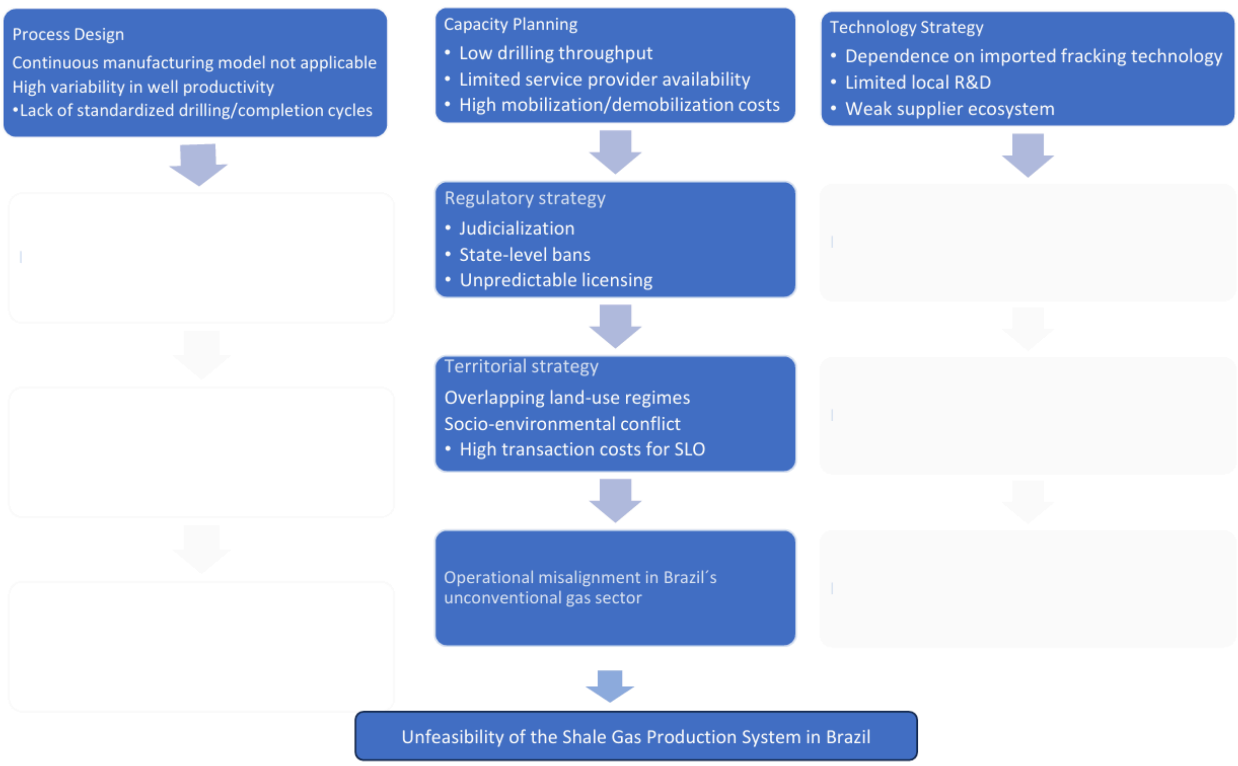

Figure 4. Operations Strategy Misalignment in Shale Gas Systems.

This figure illustrates the gap between operational requirements and institutional conditions.

Figure 4 conceptualizes institutional misalignment as the structural gap between the requirements of shale gas production and the conditions under which it is implemented.

When institutional misalignment persists, the system becomes characterized by high uncertainty, inefficiencies, and elevated operational risk, limiting its capacity to evolve into a stable industrial production model.

2.5. Integrated Conceptual Framework of Systemic constraints

Building on the previous sections, shale gas feasibility can be understood as the outcome of interacting constraints across operational, supply chain, territorial, and institutional dimensions. These constraints do not operate independently; rather, they form a mutually reinforcing system (Sterman, 2000).

Regulatory uncertainty increases investment risk, limiting technological localization and slowing the development of specialized supply chains. Territorial conflicts increase licensing complexity and project delays, while logistical limitations raise costs and reduce operational efficiency.

Operations strategy misalignment in shale gas systems reflects the structural legacy of Brazil's energy sector, where offshore-oriented development has generated a persistent gap between existing institutional arrangements and the requirements of onshore unconventional production systems.

Figure 5 illustrates the multilayered constraint structure affecting shale gas development in Brazil.

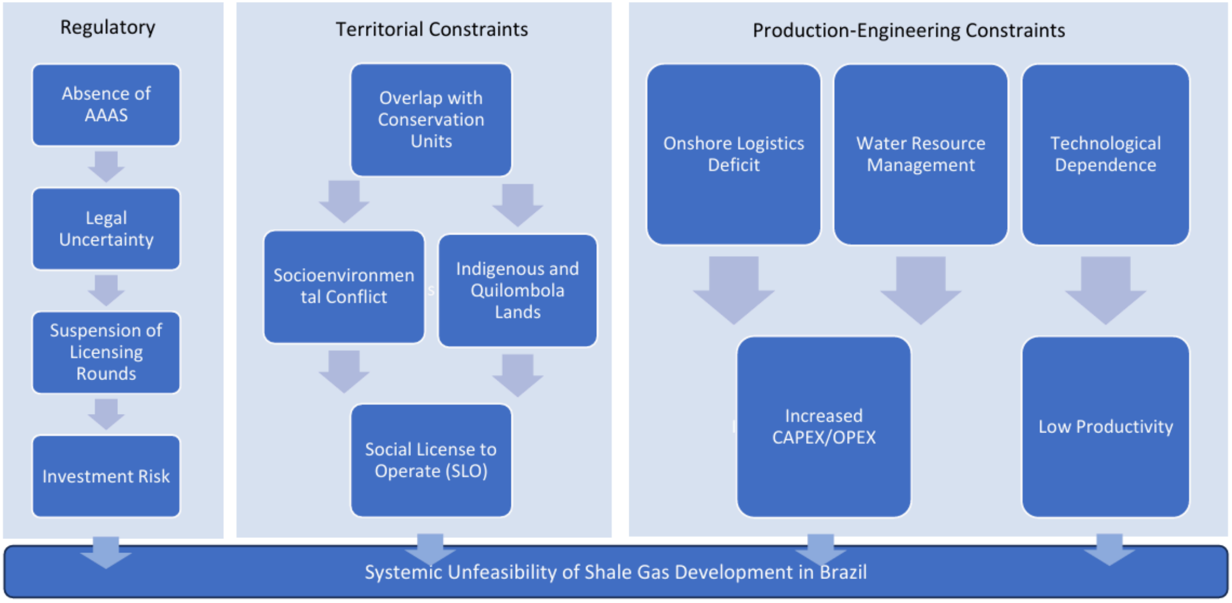

Figure 5. Multilayered Constraint Structure Affecting Shale Gas Development. in Brazil.

The framework integrates operational, supply chain, territorial, and institutional constraints into a unified analytical structure. It shows how these dimensions interact in a non-linear and mutually reinforcing manner, shaping the overall feasibility of shale gas development in the Brazilian context.

This systemic perspective shifts the analysis from isolated barriers to interdependent constraints, providing a more robust explanation of the structural challenges associated with unconventional gas development in institutionally complex environments.

2.6. Theoretical Propositions

Based on the integrated framework, shale gas feasibility is conceptualized as a function of interacting constraints across multiple dimensions. The following propositions formalize these relationships:

Proposition 1

The greater the dependence on continuous drilling cycles, the higher the vulnerability of shale gas systems to operational disruptions.

Proposition 2

Lower levels of supply chain redundancy, responsiveness, and robustness increase operational costs and reduce system efficiency.

Proposition 3

Greater territorial overlap between shale operations and competing land uses increases regulatory complexity and project risk.

Proposition 4

Higher levels of institutional fragmentation increase uncertainty and reduce investment attractiveness.

Proposition 5

Persistent institutional misalignment leads to a high-risk, low-return equilibrium in shale gas systems.

Proposition 6

The interaction of operational, supply chain, territorial, and institutional constraints systematically limit shale gas feasibility, even in resource-rich contexts.

3. METHODOLOGY

This study adopts a multi-method research design to investigate systemic constraints affecting shale gas development in Brazil. The research is grounded in a socio-technical systems perspective, in which regulatory, technological, spatial, and production-related constraints are treated as interdependent and co-evolving dimensions of system feasibility rather than isolated variables.

This integrative approach aligns with recent advances in energy transition research, which emphasizes the need to move beyond single-domain explanations and adopt systemic analytical frameworks.

The unit of analysis was defined as individual regulatory provisions and analytical sections within official documents. Coding was conducted manually using a structured coding protocol based on four predefined analytical dimensions derived from the literature on environmental governance and institutional risk: legal incompatibilities, environmental sensitivity, socio-territorial conflicts, and regulatory uncertainty. A coding guideline was developed and iteratively refined to ensure consistency, with repeated cross-checking of coded segments. These categories guide the coding process, enabling the identification of recurring patterns and the assessment of how overlapping institutional layers contribute to systemic regulatory constraints. This analytical structure is summarized in Figure 1.

3.1. Qualitative Content Analysis (QCA) Of Regulatory Frameworks

A deductive QCA was conducted to systematically assess Brazil's regulatory and environmental framework for unconventional gas development. The analysis focused on key institutional documents, including (ANP, 2024; Brazil, 2022) issued by MMA.

The coding framework was structured around four predefined analytical dimensions derived from the literature on environmental governance and institutional risk: (i) legal incompatibilities, (ii) environmental sensitivity, (iii) socio-territorial conflicts, and (iv) regulatory uncertainty.

Coding was conducted manually and, where applicable, supported by qualitative analysis software MaxQDA, following a standardized protocol to ensure consistency across documents. Ambiguous excerpts were iteratively reviewed to maintain interpretative coherence.

Analytical Dimensions

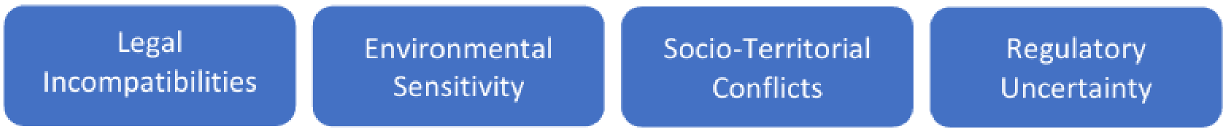

Figure 6. Framework for Deductive Coding of Regulatory and Territorial Constraints.

This figure presents the four analytical dimensions guiding the qualitative content analysis and illustrates how each dimension contributes to the identification of systemic regulatory constraints. As illustrated in Figure 6, the coding framework captures the multidimensional nature of regulatory constraints, enabling the identification of patterns of institutional misalignment affecting shale gas feasibility. Legal incompatibilities define formal restrictions, environmental sensitivity determines precautionary thresholds, socio-territorial conflicts influence social acceptance, and regulatory uncertainty affects predictability and investment conditions.

3.2. Technological Foresight And Innovation Mapping

To assess Technological Readiness Levels (TRL) and innovation gaps in Brazil's unconventional gas sector, a structured technological foresight approach was applied, combining patent landscape analysis and systematic literature review.

Patent Landscape Analysis

Patent searches were conducted in website, Espacenet, of National Institute of Industrial Property (INPI), (2014–2026). Search strings included IPC classes related to hydraulic fracturing (E21B 43/26), "hydraulic fracturing", "shale gas", "unconventional", "proppant" and "well stimulation") as shown in Table 3. Patent ownership (domestic vs. foreign) was mapped to evaluate technological autonomy and dependency structures.

A total of 6136 patents were retrieved, of which 3197 were retained after filtering based on Table relevance and duplication criteria. Patent ownership was analysed to distinguish between domestic and foreign actors, enabling the assessment of technological dependence and localization gaps.

Table 3. Patent Search Strings and IPC Classes Used in the Technological Foresight Analysis

Search Set	Search Strings Used	Filters Applied	IPC Class	Result
Set 1 — Brazil-focused search	E21B43/26 AND ("hydraulic fracturing" OR "shale	Earliest publication date (family): 2014–2026	E21B43/26	1 patent family

	gas" OR "unconventional" OR "proppant" OR "well stimulation")	Applicants' country: BR		
Set 2 — Global search (broad)	E21B43/26 AND ("hydraulic fracturing" OR "shale gas" OR "unconventional" OR "proppant" OR "well stimulation")	Earliest publication date (family): 2014–2026 • Countries (family): No country filter applied	E21B43/26	3,197 patent families
Set 3 — Global search (top-producing countries + BR)	E21B43/26 AND ("hydraulic fracturing" OR "shale gas" OR "unconventional" OR "proppant" OR "well stimulation")	Earliest publication date (family): 2014–2026 • Countries (family): CN, US, WO, CA, AU, EP, AR, MX, RU, BR *(Top 9 patent-producing jurisdictions + Brazil)*	E21B43/26	3,186 patent families

This table details search parameters, IPC codes, and inclusion/exclusion criteria applied in the patent analysis.

The combined analysis of patents and scientific literature enables the identification of technological trajectories and highlights the gap between global innovation trends and domestic capabilities.

Systematic Literature Review

A systematic literature review was conducted using Google Scholar to identify research trends in Production Engineering applied to unconventional reservoirs. The review focused on studies where the title contained specific keywords, employing the following search string: allintitle: ("shale gas governance" OR "water management constraints" OR "unconventional energy resources" OR "regulatory frameworks" OR "territorial integration" OR "production engineering"). Crucially, the search mandatory required the inclusion of the exact phrase "shale gas" within the results. The query was restricted to the period between 2022 and 2026, excluding citations, and yielded 116 results. This rigorous approach ensured the identification of highly relevant and recent literature directly pertaining to the specified research areas.

3.3. Territorial Risk Assessment And Gis-based Layer Integration

Territorial constraints were assessed through spatial analysis of institutional and environmental layers affecting shale gas operations. Official datasets from the MMA, the Chico Mendes Institute for Biodiversity Conservation (ICMBio), the National Indigenous People Foundation (FUNAI), the National Institute for Colonization and Agrarian Reform (INCRA), and the Brazilian Institute of Geography and Statistics (IBGE) were used to map potential conflict zones. Based on the GTPEG technical report nº 244/2025, that spatial analysis was conducted by applying overlay techniques to identify intersections between shale-prospective areas and protected or sensitive territories. These include conservation units, Indigenous lands, Quilombola territories, and priority biodiversity zones, as illustrated in Figure 3 (MMA, 2015).

3.4. Integrative Production Engineering Framework

The final analytical stage integrates the empirical findings through core principles of Production Engineering, combining risk management, supply chain analysis, and operations strategy into a unified analytical framework.

Systemic risks are operationalized according to ISO 31000 principles and structured into four analytical dimensions: regulatory, technological, operational, and territorial. These dimensions are used to systematically organize the assessment of institutional and infrastructural conditions associated with shale gas development in Brazil.

Supply chain constraints are examined through the identification of critical bottlenecks across key functional domains, including water supply, proppant logistics, equipment availability, and waste management. This analytical step emphasizes structural dependencies within upstream and midstream segments of the production system, with particular attention to infrastructural continuity requirements.

From a Production Engineering perspective, the analysis is grounded in the requirements of a continuous production system, which constitutes a defining characteristic of shale gas operations. This production regime is analytically contrasted with the project-based organizational logic of Brazil's offshore oil and gas sector, in which production activities are structured around discrete engineering projects rather than continuous operational flows.

The framework thus provides an integrated analytical structure for mapping the interaction between systemic risks, supply chain constraints, and production system architectures. This allows for a structured examination of how institutional conditions, logistical dependencies, and production regime incompatibilities jointly configure the feasibility space of shale gas development in the Brazilian context.

3.5. Methodological Limitations

This study has several methodological limitations. The use of secondary data inevitably limits empirical depth and may not fully reflect recent regulatory and operational changes, especially in a context where governance and industry practices are evolving. The patent analysis is based only on publicly available databases, which excludes proprietary and non-disclosed innovations. This can lead to an incomplete picture of technological capabilities, particularly in sectors where firms rely heavily on confidentiality and strategic protection of knowledge. Spatial analysis is also constrained by the quality and resolution of available geospatial datasets, which affects how precisely infrastructural and territorial conditions can be represented. Although the qualitative coding followed a structured procedure, interpretation is still involved in the process, meaning that some level of subjectivity cannot be fully avoided. Future research could strengthen these findings by incorporating primary data such as expert interviews, stakeholder engagement, and field validation, as well as more detailed geospatial information and access to proprietary industry datasets where possible.

4. RESULTS

This section presents the empirical findings derived from qualitative content analysis, technological foresight, systematic literature review, and spatial analysis. The results are structured across four analytical dimensions: operational, technological, scientific, and territorial aspects of shale gas development in Brazil.

4.1. Production Chain and Operational and Territorial Constraints in the Potiguar Basin

The Potiguar Basin, located in Brazil's semi-arid region, exhibits significant operational constraints associated with the water–energy nexus. Water demand for hydraulic fracturing directly competes with agricultural and domestic uses, intensifying resource allocation pressures in an already water-stressed context. Global research indicates that these water management constraints are critical bottlenecks for large-scale shale gas expansion, as observed in other water-stressed regions such as the Yangtze River Basin in China (Wu et al., 2025).

Spatial analysis reveals overlaps between shale-prospective areas and environmentally protected territories, including conservation units and Indigenous lands. These overlaps impose substantial socio-environmental constraints on operational feasibility. Additionally, the absence of basin-scale AAAS contributes to regulatory uncertainty. The lack of robust and anticipatory regulatory frameworks has been identified as a primary cause for the failure of shale gas governance in several jurisdictions, where existing legislative frameworks for conventional fossil fuels proved inadequate to address the specific risks of unconventional resources (Aczel et al., 2022).

Brazil's oil and gas sector is structurally oriented toward offshore deep-water production, particularly in the pre-salt province. This specialization results in a misalignment between existing industrial capabilities and the requirements of onshore unconventional resource development.

From a Production Engineering perspective, three primary operational bottlenecks are identified:

Logistical constraints: Brazil has a limited onshore natural gas pipeline network. The main shale-prospective basins, including the Potiguar Basin, are distant from major consumption centers, requiring substantial midstream infrastructure expansion to ensure market integration and flow assurance (Getulio Vargas Foundation (FGV) & Brazilian Competitive Movement (MBC), 2024).

Service industry limitations: Shale gas development depends on a high-frequency, manufacturing-type operational model involving multi-stage fracturing fleets, high-pressure pumping systems, and rapid drilling cycles. These capabilities remain underdeveloped domestically, increasing reliance on imported services and elevating both CAPEX and OPEX.

Water availability constraints: Hydraulic fracturing requires large volumes of water per well. In semi-arid regions such as the Potiguar Basin, and in agricultural regions such as the Paraná Basin, competition for water resources constitutes a critical operational constraint (Emile et al., 2022). Moreover, the enforcement of stringent regulations is essential to protect groundwater resources from contamination during drilling and fracturing stages, a challenge that persists even in developed regulatory environments (Esterhuyse et al., 2022; Pan et al., 2025).

The difficulty of achieving socio-economic and environmental compatibility in rural territories remains a significant barrier to the territorial integration of these energy projects (Duarte et al., 2022).These constraints are integrated into a multilayered analytical structure (Figure 7), which captures the interaction between operational, technological, territorial, and regulatory dimensions.

Figure 7. Multilayered Constraint Structure Affecting Shale Gas Development in Brazil.

This figure synthesizes the interaction between operational, technological, territorial, and regulatory constraints, highlighting their combined effects on lead time, CAPEX, and systemic risk.

Figure 7 illustrates the multilayered interaction between operational, technological, territorial, and regulatory constraints affecting shale gas development in Brazil.

Overall, the results indicate a structural mismatch between Brazil's offshore-oriented production system and the operational requirements of shale gas development, particularly regarding infrastructure intensity, service industry readiness, and resource governance.

4.2. Technological Barriers: Patent and Scientific Trends (2014–2026)

The technological foresight analysis reveals a highly concentrated global distribution of hydraulic fracturing patents across a limited number of jurisdictions. China (CN), the United States (US), and international filings (WO) dominate the dataset, followed by Canada (CA), Australia (AU), and the European Patent Office (EP). Brazil (BR) accounts for a marginal share of total filings. This distribution is detailed in Table 4, which presents the geographic allocation of patent filings alongside the corresponding economic scale of each jurisdiction.

Table 4. Geographic distribution of patent filings in hydraulic fracturing technologies (2014–2026)

Country / Jurisdiction	Patent Count	Nominal GDP[5] (Trillions of USD)
CN (China)	1777	20,65
US (United States)	1524	31,82
WO (WIPO)	1047	N/A (International Organization)
CA (Canada)	670	2,51
AU (Australia)	263	2,12
EP (Europe)	234	22,52
AR (Argentina)	208	0,67

MX (Mexico)	165	1,95
RU (Russia)	162	2,66
BR (Brazil)	86	2,64

Source: Espacenet patent database (retrieved 2014–2026). Data filtered using IPC classification E21B 43/26 and keyword-based screening. IMF World Economic Outlook (2025)

The data show a strong concentration of patenting activity in technologically advanced economies, with China and the United States alone accounting for a substantial share of global filings. This concentration reflects broader structural asymmetries in the global development of shale gas technologies, where innovation capacity is closely associated with industrial maturity, cumulative learning processes, and large-scale field deployment (Pan et al., 2025; Wu et al., 2025b). In these leading jurisdictions, technological development is embedded in established upstream ecosystems, enabling continuous incremental innovation and rapid diffusion of hydraulic fracturing techniques. In contrast, Brazil's participation remains limited in absolute and relative terms.

Within the Brazilian subset (86 filings), only one patent is attributed to a domestic applicant (Petrobras), indicating limited domestic inventive capacity in hydraulic fracturing technologies. This pattern suggests a high level of reliance on external technological sources, particularly in critical domains such as reservoir stimulation, drilling systems, and digital monitoring technologies.

Overall, the dataset exhibits three interrelated structural characteristics: strong geographical concentration of innovation in a small group of technologically advanced economies, limited domestic inventive activity in Brazil, and persistent dependence on external technological providers. These characteristics are consistent with evidence in the literature on shale gas development, which highlights the role of institutional capacity, technological ecosystems, and regulatory maturity in shaping innovation trajectories (Aczel et al., 2022; Wu et al., 2025a).

The observed asymmetry also reflects differences in technological maturity across jurisdictions. High-intensity patenting regions such as China and the United States are associated with advanced stages of technological consolidation and large-scale operational deployment. By contrast, Brazil's limited patent activity indicates an early or fragmented stage of technological development in hydraulic fracturing systems, with reduced integration between research capacity, industrial application, and field validation.

The distribution of patent activity across jurisdictions is further illustrated in Figure 8, highlighting the structural asymmetry between domestic and foreign technological ownership.

Three main empirical patterns emerge from the dataset:

i. concentration of innovation in a limited number of leading economies;

ii. low domestic inventive activity in Brazil within the hydraulic fracturing domain;

iii. reliance on external technological sources, particularly multinational firms and international consortia.

The observed distribution of patent activity also reflects differences in technological maturity levels across countries. Jurisdictions with high patent intensity, such as China and the United States, are associated with more advanced stages of technological development and large-scale field deployment. In contrast, Brazil's limited patent activity suggests a lower level of technological maturity, particularly in terms of field validation and operational scaling. The distribution of patent activity across jurisdictions is further illustrated in Figure 8, which highlights the asymmetry between domestic and foreign technological ownership.

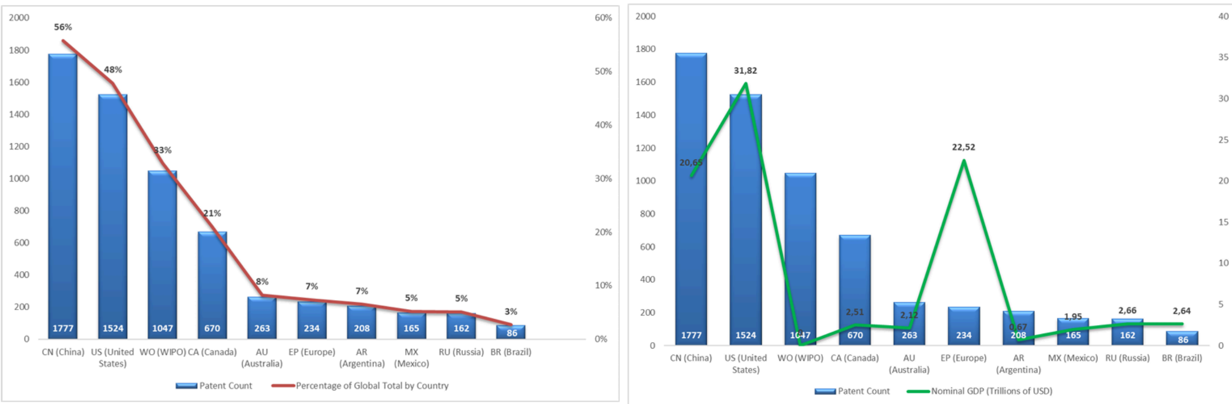

Figure 8. illustrates the distribution of patent activity across jurisdictions and highlights the asymmetry between domestic and foreign technological ownership.

A review of technological trajectories indicates increasing diversification of innovation themes, particularly in water-reduction strategies and advanced monitoring systems. These developments remain concentrated in leading innovation hubs, with limited diffusion to emerging economies.

Brazilian research institutions have contributed to advances in proppant materials and reservoir modelling. However, the absence of large-scale field validation limits their industrial applicability.

These technological patterns are consistent with the systemic constraints identified in Figure 7, particularly those related to limited service industry capacity and restricted technological diffusion. The concentration of innovation in a small number of countries reinforces the technological dimension of these constraints, which are associated with increased dependency and higher operational costs in the Brazilian context.

Overall, the results indicate a persistent asymmetry in technological capabilities between global innovation leaders and Brazil's domestic technological base in shale gas-related technologies.

4.3. Territorial Barriers: Institutional Layers and Sensitivity or Integration: Technology as a Risk Mitigator

Within the Scientific Literature Review (SLR), the thematic clustering process identified territorial constraints and institutional layering as a distinct analytical domain shaping the feasibility of unconventional shale gas development. This cluster emerges at the intersection of technological feasibility, regulatory governance, and spatial risk structuring, highlighting how territorial systems operate as endogenous determinants of innovation adoption rather than exogenous barriers.

In this sense, the integration of technological foresight with territorial risk assessment suggests that shale gas viability in the Potiguar Basin is contingent upon processes of *technological localization*. Although global patent portfolios related to waterless or low-water hydraulic fracturing indicate a mature technological frontier, their transferability is conditional upon adaptation to Brazil's geological, infrastructural, and institutional configurations. The absence of targeted regulatory incentives for low-impact technologies further weakens investment signals, reducing the diffusion potential of these innovations within the national upstream sector.

From a thematic clustering perspective, the “territorial barriers” cluster is structured into three interdependent sub-dimensions: legal-institutional constraints, environmental sensitivity, and socio-territorial conflicts. Together, these dimensions form a layered governance structure that directly influences the spatial feasibility of shale gas development.

Empirical evidence from the GTPEG Technical Report N° 244/2025 reinforces this clustered structure (GTPEG, 2025). At the legal-institutional level, several prospective shale areas overlap with Conservation Units under Integral Protection regimes or are affected by state-level prohibitions on hydraulic fracturing, as observed in Potiguar basin. This regulatory heterogeneity introduces institutional uncertainty, a recurrent theme identified across the SLR corpus.

At the environmental level, more than 60% of the analysed blocks in the Potiguar Basin intersect with Priority Areas for Biodiversity classified as “High” or “Very High Importance” by MMA, indicating strong ecological sensitivity and reinforcing the environmental risk sub-cluster identified in the literature(GTPEG, 2025).

At the socio-territorial level, the presence of Quilombola territories, Indigenous lands, and agrarian reform settlements introduces an additional layer of complexity related to the SLO. In alignment with findings in Production Engineering and energy governance studies, these factors constitute non-technical risks that significantly influence project continuity and operational legitimacy (Arana et al., 2022).

Across these three sub-clusters, territorial constraints converge into an integrated risk system rather than isolated barriers. This convergence is central to the SLR thematic synthesis, as it demonstrates that territoriality functions as a structural condition for technological deployment, shaping both innovation absorption capacity and project viability.

As previously illustrated in Figure 3, the overlap between shale-prospective areas and territorial regimes, administrative, environmental, and traditional land use systems, reveal zones of increased spatial and institutional complexity.

4.4. Regulatory Barriers: The 2026 Perspective

GTPEG (2025) reinforces the application of a precautionary approach to unconventional gas development in Brazil, particularly regarding the inclusion of exploratory blocks in the Permanent Offer system without prior AAAS. The absence of basin-scale environmental planning emerges as a persistent regulatory vulnerability, increasing exposure to environmental, legal, and operational risks.

Although (<i>Interministerial Ordinance no 1/2022: Establishes procedures, criteria and deadlines for joint actions of the Ministry of Mines and Energy and the Ministry of the Environment and Climate Change regarding the planning of oil and natural gas exploration and production blocks.</i>, 2022) aimed to enhance procedural clarity by defining territorial layers and exclusion criteria for oil and gas activities, its practical effectiveness remains limited. Regulatory fragmentation and overlapping institutional mandates continue to generate uncertainty in the authorization process for shale gas development.

This uncertainty was further reinforced by the judicialization of the 12th Bidding Round (2013), which established a relevant legal precedent in Brazil's regulatory framework. Recent interpretations by the Superior Court of Justice (STJ) indicate that unconventional gas activities conducted without basin-wide environmental assessments face elevated litigation risks, including the potential suspension of licensing and exploration processes. This dynamic reflects the increasing role of the judiciary in shaping energy governance under conditions of regulatory incompleteness.

The main regulatory vulnerabilities identified in this study are summarized in Table 5.

Table 5. Regulatory Vulnerabilities Affecting Unconventional Gas Development in Brazil.

Regulatory Dimension	Key Issue / Gap	Evidence / Legal Basis	Risk Implication	Systemic Effect
Environmental Licensing	Absence of basin-scale Strategic Environmental Assessment (SEA) prior to allocation of exploration blocks	(GTPEG, 2013, 2025))	Delays in licensing procedures; increased exposure to environmental litigation	Limited integration between environmental assessment and energy planning systems

Regulatory Planning	Allocation of exploration blocks in Permanent Offer without integrated territorial and socio-environmental assessment	ANP (2014)	Procedural uncertainty in licensing and exploration stages	Fragmentation between upstream energy planning and territorial governance
Institutional Coordination	Overlapping responsibilities across federal environmental governance bodies	(Brazil, 2022)	Administrative duplication and regulatory uncertainty	Institutional fragmentation and reduced coordination efficiency
Judicial Risk	Consolidation of jurisprudence requiring basin-scale environmental assessment for unconventional gas activities	Federal Public Civil Action cluster: ACP nº 0030652-38.2014.4.01.3300 (Bahia); ACP nº 0005610-46.2013.4.01.4003 (Parnaiba basin); ACP nº 0800366-79.2016.4.05.8500 (Alagoas & Sergipe basin); ACP nº 5005509-18.2014.404.7005 (TRF4)	Suspension or invalidation of licensing and exploration projects	Increasing judicialisation of energy governance and regulatory decision-making

Investment Climate	Regulatory uncertainty and limited predictability in unconventional gas governance framework	(ANP, 2024b; ANP., 2015)	Reduced investor confidence and constrained capital allocation	Weak long-term investment signalling and sector underdevelopment

Table 5 synthesizes the key regulatory gaps, legal precedents, and institutional inconsistencies identified in the analysis, highlighting the structural nature of regulatory fragmentation. In particular, it shows how the absence of integrated environmental planning AAAS, combined with overlapping institutional mandates and evolving judicial interpretations, sustains a persistent condition of regulatory uncertainty.

Taken together, the results indicate that regulatory uncertainty constitutes a central structural barrier to investment planning and operational development in the unconventional gas sector.

4.5. Synthesis: Systemic constraints Explaining Shale Gas Stagnation in Brazil

The results indicate that shale gas stagnation in Brazil is primarily associated with systemic misalignments across operational, technological, territorial, and regulatory dimensions, rather than with geological limitations. The analysis reveals the coexistence of two structurally distinct production paradigms: the offshore pre-salt system and the onshore shale gas development model.

Offshore production is characterized by centralized, capital-intensive operations with long development cycles and high technological maturity. In contrast, onshore shale gas development depends on decentralized, high-frequency drilling operations that require continuous execution, rapid learning, and close integration with local supply chains and infrastructure.

These structural differences are illustrated in Figure 9.

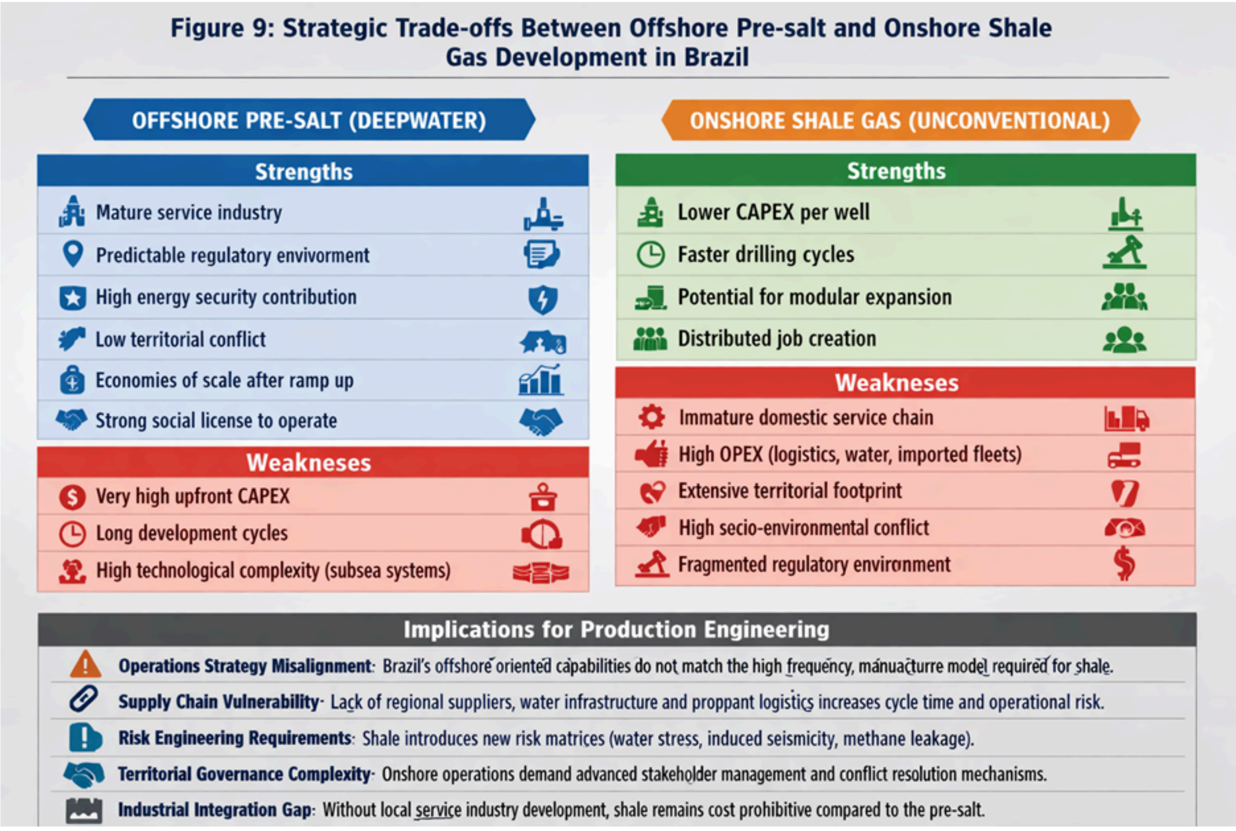

Figure 9. Strategic Tradeoffs Between Offshore (Pre salt) and Onshore Shale Gas Development in Brazil

Figure 9 highlights the contrasting characteristics of each production model and their implications for production engineering. While offshore systems benefit from a mature service industry, relatively stable regulatory conditions, and established operational routines, onshore shale gas development is associated with an underdeveloped domestic service base, higher operational costs driven by import dependence, and extensive territorial interaction that increases socio-environmental constraints.

The main structural differences between these two systems are summarized in Table 6.

Table 6. Strategic Tradeoffs Between Offshore (Pre salt) and Onshore Shale Gas in Brazil (with Verified Sources and Production Engineering Implications)

Feature	Offshore Pre-salt (Deepwater)	Onshore Shale Gas (Unconventional)	Production Engineering Implications
Production Dynamics	Centralized, capital-intensive, long development cycles, high technological maturity.	Decentralized, high-frequency drilling, continuous execution, rapid learning, integration with local supply chains.	Operations Strategy Misalignment: Brazil's offshore-oriented capabilities do not match the high-frequency, continuous manufacturing model required for shale.
Service Industry	Mature and consolidated.	Immature, import-dependent, significant logistical bottlenecks.	Supply Chain Vulnerability: Lack of regional suppliers, water infrastructure, and proppant logistics increases cycle time and operational risk.
CAPEX Structure	Extremely high upfront investment.	Lower CAPEX per well.	CAPEX Inefficiency: The shale model requires aggressive cost-per-well optimization and continuous efficiency gains.

Development Cycles	Long-term project based.	Rapid, modular cycles.	Operations Strategy: Requires a transition from project-based execution to manufacturing-like production.
Territorial Conflict	Low (remote offshore locations).	High (land-use conflicts, water-sensitive regions, biodiversity hotspots, traditional territories).	Territorial Governance Complexity: Onshore operations demand advanced stakeholder management and conflict resolution mechanisms.
Regulatory Environment	Predictable and stable.	Fragmented, overlapping jurisdictions, high levels of judicialization.	Legal Uncertainty: Regulatory ambiguity hinders long-term planning and investment security.
Energy Security	High contribution to national baseload.	Potential for distributed energy contribution.	Matrix Diversification: Potential to enhance energy resilience if systemic constraints are mitigated.
Technological Complexity	High (subsea systems, deepwater expertise).	Low domestic patenting, high import dependency, limited infrastructure adaptation, restricted R&D localization.	Risk Engineering Requirements: Shale introduces new risk matrices (water stress, induced seismicity, methane leakage) requiring specialized mitigation frameworks.

SLO	Strong and established.	High socio-environmental conflict.	Social Acceptance: Necessity for robust community engagement strategies and proactive impact mitigation.
Industrial Integration	Highly consolidated.	Significant industrial integration gap.	Industrial Integration Gap: Without the development of a local service industry, shale remains cost-prohibitive compared to pre-salt.

Source: Adapted by the author based on [Reference 1], [Reference 2], [Reference 3], [Reference 4].

The table consolidates key differences in production dynamics, service industry structure, CAPEX configuration, development cycles, territorial exposure, and regulatory conditions. These contrasts reveal a systemic misalignment between Brazil's offshore-oriented industrial capabilities and the requirements of shale gas development.

From an operational perspective, shale gas development requires a transition from project-based execution to a manufacturing-type production model characterized by repetition, standardization, and learning effects. This transition is constrained by logistical bottlenecks, limited service industry capacity, and cost inefficiencies. Offshore systems, in contrast, operate within a more consolidated industrial framework.

Technological constraints further reinforce this asymmetry. Offshore production is supported by accumulated capabilities and mature innovation systems, whereas shale gas development in Brazil is characterized by low domestic patenting activity, dependence on imported technologies, and limited infrastructure adaptation. The results also indicate restricted localization of R&D activities.

Territorial conditions introduce additional constraints. Offshore production involves limited spatial interaction, while shale gas development occurs in environmentally sensitive and socially contested onshore areas. The analysis highlights the relevance of land-use conflicts, water-stressed regions, biodiversity-sensitive areas, and the presence of traditional territories.

These findings provide the empirical basis for a systemic interpretation of shale gas stagnation, which is further developed in the Discussion section

5. DISCUSSION AND IMPLICATIONS

Shale gas development in the Potiguar Basin remains constrained by systemic failures in operations strategy and territorial governance. The results demonstrate that these constraints are not primarily geological, but stem from misalignments identified across operational, technological, territorial, and regulatory dimensions (Sections 4.1–4.4).

The analysis reveals a persistent gap between the theoretical potential of shale gas in Brazil and the structural conditions required for its development. From a Production Engineering perspective, these barriers reflect a systemic misalignment involving supply chain maturity, institutional coordination, territorial complexity, and operations strategy.

This misalignment is evidenced by logistical bottlenecks, limited domestic service industry capacity, low levels of technological localization, and fragmented regulatory frameworks. Together, these factors constrain scalability, increase operational costs, and limit the continuity of unconventional gas projects.

These findings indicate that policy approaches focused solely on resource availability or technology transfer are insufficient. Effective development depends on the integration of technological prospecting with socio-environmental risk management, including the implementation of AAAS and the alignment of regulatory, territorial, and industrial systems.

5.1. Implications for Production Engineering

From a Production Engineering perspective, shale gas development depends on systemic coordination across operations, logistics, technologies, and institutional frameworks. Unlike offshore production, shale gas follows a continuous manufacturing model characterized by high drilling intensity, rapid decline rates, and the need for uninterrupted operational cycles.

This model requires a high-volume, tightly synchronized supply chain, including water, proppants, chemicals, high-pressure equipment, and waste management systems. In Brazil, the absence of integrated onshore infrastructure and a mature domestic service industry creates a significant efficiency gap.

Empirical results indicate that logistical constraints, particularly related to water availability, transport infrastructure, and service provision, extend cycle times and increase both CAPEX and OPEX. At the same time, limited learning-curve effects reduce cost competitiveness relative to established shale regions such as the Marcellus (USA) and Vaca Muerta (Argentina).

Shale gas development in Brazil is also embedded in a highly complex territorial context. Operations intersect with environmental protection areas, Indigenous lands, Quilombola territories, biodiversity-sensitive regions, and water-stressed zones, as demonstrated in Section 4.3.

These conditions require a shift in Production Engineering approaches—from a focus on technical optimization toward integrated frameworks incorporating risk governance, stakeholder coordination, and territorial systems analysis. In this context, the SLO emerges as a critical determinant of project continuity.

The need to reconcile operational efficiency with socio-territorial constraints places shale gas at a structural disadvantage relative to offshore pre-salt production, where industrial organization, regulatory conditions, and spatial dynamics are more stable. Building on this systemic interpretation, the following section examines the implications for Production Engineering.

5.2. Systemic Risks and International Comparison

Brazil's experience with shale gas (2013–2026) contrasts with international cases where unconventional gas has achieved large-scale development, highlighting how institutional design, supply chain maturity, and operational strategy shape industrial outcomes.

United States

The U.S. shale boom was enabled by a combination of structural conditions, including private mineral rights, a competitive and diversified service industry, extensive drilling infrastructure, and a dense pipeline network. Together, these factors reduced operational costs, accelerated learning curves, and supported the continuous manufacturing model required for shale gas development. The U.S. case illustrates that industrial ecosystem maturity, rather than geological potential alone, is a key determinant of unconventional gas viability.

Argentina

Despite facing environmental and territorial constraints similar to Brazil, Argentina prioritized the development of Vaca Muerta through coordinated state action, infrastructure investment, and targeted fiscal incentives. This strategy enabled partial supply chain development, technological localization, and operational scaling. The Argentine case indicates that policy alignment and coordinated industrial planning can partially offset territorial and environmental constraints.

Brazil

In contrast, Brazil's energy strategy remains strongly focused on offshore pre-salt production, where Petrobras plays a central role as a technologically mature operator. Onshore shale gas development lacks several enabling conditions observed in international cases, including a dominant operator, a dedicated supply chain, a mature service industry, coordinated basin-scale planning AAAS, and regulatory predictability.

As a result, shale gas development in Brazil remains constrained by fragmented governance, judicialization processes, and limited industrial coordination, which collectively hinder the emergence of the continuous manufacturing model required for cost-effective unconventional production.

These systemic differences are consistent with the constraints identified in Figure 7 and the structural trade-offs summarized in Table 6.

Figure 7 provides a diagnostic representation of the systemic constraints, while Table 6 operationalizes these mechanisms through a comparative validation of offshore and onshore production systems, and Section 6 synthesizes these findings into an integrated systemic framework.The results suggest that the stagnation of shale gas in Brazil is primarily associated with systemic misalignments between operational requirements, territorial conditions, and the institutional framework governing onshore energy development.

6. CONCLUSIONS

Shale gas exploration and production in Brazil between 2013 and 2026 reveal a persistent mismatch between geological potential and industrial feasibility. The findings demonstrate that the main constraints are not geological, but operational, technological, territorial, and regulatory in nature. These constraints interact systemically, limiting the advancement of unconventional gas beyond exploratory stages.

6.1. Synthesis of Findings

Operational dimension

Brazil lacks the onshore infrastructure, service ecosystem, and logistics networks required for cost-competitive shale gas development. Consequently, unconventional gas remains significantly more expensive than offshore natural gas, which benefits from mature supply chains, established service providers, and long-term operational learning.

Technological dimension

Although academic research has progressed in areas such as proppants, reservoir modeling, and hydraulic fracturing simulation, Brazil still lacks large-scale field validation and technological adaptation. Low domestic patenting activity in shale-related technologies reinforces dependence on imported equipment and foreign technological systems.

Territorial dimension

The Potiguar Basin exhibits overlaps with biodiversity-sensitive areas, water-stressed regions, and traditional territories. This spatial configuration increases socio-environmental exposure and elevates operational risk, particularly in regions with fragile hydrological conditions and high social presence.

Regulatory dimension

The absence of basin-scale AAAS, combined with recurrent judicialization of unconventional gas activities, generates high regulatory uncertainty for operators and constrains long-term investment and production planning. This instability contrasts sharply with the more consolidated governance framework of offshore pre-salt development.

6.2. Implications and Future Agenda

From a Production Engineering perspective, this study underscores the importance of integrated, multi-layered approaches to energy system design and evaluation. The results suggest that future research and policy development would benefit from focusing on three interdependent domains.

Technological mitigation

Advances in hydraulic fracturing technologies adapted to Brazilian environmental and geological conditions constitute a key pathway for alleviating operational constraints. Priority areas include reductions in water intensity, development of lower-impact chemical formulations, and improvements in flowback and wastewater treatment systems. These innovations are particularly relevant in regions characterized by water stress and high ecological sensitivity, where operational feasibility is tightly coupled with environmental performance.

Integrated supply chain development

The findings highlight the absence of a consolidated onshore supply chain capable of supporting unconventional gas operations. Future development pathways may benefit from the structuring of regionalized logistics systems that integrate energy production with adjacent industrial sectors, including fertilizers, ceramics, and petrochemicals. This requires the development of localized capabilities in proppant production, maintenance services, and multimodal transport infrastructure, reducing dependence on external suppliers and improving operational resilience.

Governance and decision-support systems

The complexity of territorial and regulatory interactions identified in this study highlights the importance of multi-criteria decision-support frameworks that integrate environmental sensitivity, social risk, and territorial constraints at preliminary stages of project evaluation. The integration of AAAS, stakeholder mapping, and risk-based engineering tools can enhance the robustness of investment decisions and reduce exposure to regulatory uncertainty. These results indicate that shale gas development in Brazil depends on the alignment of technological adaptation, supply chain formation, and institutional coordination within a territorially sensitive context. Without such systemic integration, unconventional gas is likely to remain structurally constrained within the national energy matrix.

The viability of shale gas in Brazil depends on the co-evolution of engineering systems, institutional arrangements, and territorial governance structures.

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HIGHLIGHTS

- Territorial, regulatory, and environmental layers are integrated to assess shale gas feasibility in Brazil.
- The 2026 MMA technical ruling exposes systemic operational risks in the Potiguar onshore basin.
- Conflicts with conservation areas, Indigenous and Quilombola territories create production-chain bottlenecks.

- A production engineering lens reveals how regulatory uncertainty disrupts planning, capacity, and risk management.

- Combined technological, territorial, and institutional gaps prevent the establishment of a viable shale gas production system.

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[5] Methodological Note: The values refer to Nominal GDP in current dollars (USD), which reflects the market value of all final goods and services produced, without adjustment for Purchasing Power Parity (PPP).