

**A  
PRODUCTION-ENGINEERING  
VIEW OF SHALE GAS  
GOVERNANCE: CAUSAL  
FEEDBACKS AND  
SUSTAINABILITY  
TRADE-OFFS IN THE  
PARANÁ BASIN**

**UMA VISÃO DA GOVERNANÇA DO GÁS DE XISTO SOB A PERSPECTIVA DA  
ENGENHARIA DE PRODUÇÃO: RETROALIMENTAÇÕES CAUSAIS E  
COMPENSAÇÕES DE SUSTENTABILIDADE NA BACIA DO PARANÁ**

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## **ABSTRACT**

Shale gas development in environmentally sensitive and institutionally fragmented regions operates as a feedback-dominant socio-technical system in which production, environmental, and governance dynamics co-evolve through asymmetric and temporally differentiated causal structures. This study adopts a production engineering perspective combined with a qualitative SD approach to examine the Paraná Basin, focusing on the underlying feedback architecture that shapes system behavior rather than predictive simulation. The analysis identifies a reinforcing production mechanism driven by drilling-dependent expansion and well productivity decline, generating a structurally constrained growth regime characterized by continuous reinvestment requirements. This reinforcing dynamic is progressively counterbalanced by a hierarchy of balancing feedbacks: technical productivity decline, cumulative environmental pressure, and endogenous regulatory responses. Results show that system behavior is fundamentally shaped by temporal asymmetries across feedback loops. Reinforcing production dynamics operate rapidly, while environmental accumulation and governance responses are delayed, producing a structural window in which expansion precedes constraint activation. Environmental variables act as cumulative system stocks linking production activity to regulatory pressure, while governance emerges endogenously through adaptive but delayed responses to environmental and socio-political signals. The interaction between subsystems generates a tightly coupled cross-domain structure in which production expansion, environmental degradation, and regulatory adaptation continuously reshape system trajectories. This coupling produces non-linear, path-dependent behavior in which sustainability outcomes emerge from feedback dominance rather than exogenous policy design. By formalizing these interactions

through a causal loop framework, the study provides a structural interpretation of shale gas governance as an emergent property of interacting with feedback systems. The findings highlight that sustainability trade-offs are not incidental but structurally embedded in the system architecture, with implications for anticipatory governance and energy transition planning in emerging shale gas regions.

**Keywords:** Qualitative System Dynamics; Production-Engineering Perspective; Shale Gas Governance; Sustainability Trade-offs; Energy Transition.

## RESUMO

O desenvolvimento de gás de xisto em regiões ambientalmente sensíveis e institucionalmente fragmentadas opera como um sistema sociotécnico dominado por retroalimentação, no qual as dinâmicas de produção, ambientais e de governança coevoluem por meio de estruturas causais assimétricas e temporalmente diferenciadas. Este estudo adota uma perspectiva de engenharia de produção combinada com uma abordagem qualitativa de dinâmica de sistemas para examinar a Bacia do Paraná, com foco na arquitetura de retroalimentação subjacente que molda o comportamento do sistema, em vez de simulação preditiva. A análise identifica um mecanismo de produção reforçador impulsionado pela expansão dependente da perfuração e pelo declínio da produtividade dos poços, gerando um regime de crescimento estruturalmente restrito, caracterizado por requisitos contínuos de reinvestimento. Essa dinâmica reforçadora é progressivamente contrabalançada por uma hierarquia de retroalimentações balanceadoras: declínio da produtividade técnica, pressão ambiental cumulativa e respostas regulatórias endógenas. Os resultados mostram que o comportamento do sistema é

fundamentalmente moldado por assimetrias temporais nos ciclos de retroalimentação. As dinâmicas de produção reforçadoras operam rapidamente, enquanto a acumulação ambiental e as respostas de governança são retardadas, produzindo uma janela estrutural na qual a expansão precede a ativação das restrições. As variáveis ambientais atuam como estoques cumulativos do sistema, conectando a atividade de produção à pressão regulatória, enquanto a governança emerge endogenamente por meio de respostas adaptativas, porém tardias, a sinais ambientais e sociopolíticos. A interação entre os subsistemas gera uma estrutura interdomínio fortemente acoplada, na qual a expansão da produção, a degradação ambiental e a adaptação regulatória remodelam continuamente as trajetórias do sistema. Esse acoplamento produz um comportamento não linear e dependente da trajetória, no qual os resultados de sustentabilidade emergem da dominância do feedback, em vez do planejamento de políticas exógenas. Ao formalizar essas interações por meio de uma estrutura de circuito causal, o estudo fornece uma interpretação estrutural da governança do gás de xisto como uma propriedade emergente da interação com sistemas de feedback. As descobertas destacam que as compensações de sustentabilidade não são incidentais, mas estruturalmente incorporadas na arquitetura do sistema, com implicações para a governança antecipatória e o planejamento da transição energética em regiões emergentes de gás de xisto.

**Palavras-chave:** Dinâmica de Sistemas Qualitativa; Perspectiva de Engenharia de Produção; Governança do Gás de Xisto; Compensações de Sustentabilidade; Transição Energética.

## 1. INTRODUCTION

The accelerating global demand for reliable, affordable, and low-carbon energy systems has intensified scholarly and policy interest in unconventional hydrocarbon resources, particularly shale gas. Positioned at the intersection of energy security imperatives and climate mitigation commitments, shale gas has been widely framed as a transitional fuel capable of facilitating fuel switching from coal to lower-carbon alternatives. Major energy institutions such as the (Baynes et al., 2023; (International Energy Agency [IEA], 2024) and leading corporate actors including (Shell PLC, 2024) have consistently incorporated natural gas into transitional energy scenarios, reinforcing its role as a flexible component in decarbonization pathways.

However, the sustainability of shale gas expansion remains highly contested within both academic and policy domains. Empirical evidence highlights that the environmental performance of shale gas is strongly conditioned by methane leakage, water consumption, induced seismicity, and cumulative land-use pressures, which collectively challenge its characterization as a low-carbon transition fuel (Zhang et al., 2025). Methane emissions have been identified as a critical uncertainty factor undermining lifecycle climate benefits, especially when regulatory monitoring systems are fragmented or weakly enforced (EPA, 2024).

Beyond environmental externalities, shale gas development is deeply embedded in complex socio-technical and institutional systems. Unlike conventional hydrocarbon extraction, shale gas production requires spatially intensive infrastructure, including well pads, access roads, water storage systems, and pipeline networks, generating direct competition with agriculture, biodiversity conservation, and local land-use regimes. This territorial

embeddedness has been increasingly conceptualized within broader debates on resource governance and social license to operate, where legitimacy is not only regulatory but also socially negotiated (M. R. Aczel et al., 2018; Malin et al., 2023).

From a governance perspective, shale gas expansion exposes significant institutional tensions. Regulatory regimes often struggle to adapt to the rapid technological evolution and distributed nature of unconventional extraction systems. Adaptive governance approaches have therefore been proposed to manage uncertainty in water and wastewater systems, as well as broader environmental risks associated with hydraulic fracturing. Simultaneously, anticipatory regulatory frameworks have been suggested as necessary instruments to address emerging environmental risks and technological uncertainties before large-scale deployment occurs (M. Aczel et al., 2022)

At the geopolitical level, shale gas has become increasingly entangled with energy security strategies and decarbonization pathways. The European Union, for instance, faces structural tensions between climate neutrality objectives and external energy dependencies, particularly under conditions of geopolitical volatility (Proedrou, 2023). These dynamics reinforce the role of gas as a strategic commodity while simultaneously complicating long-term decarbonization trajectories.

Recent advances in energy systems research further emphasize the importance of systemic interactions, policy uncertainty spillovers, and multi-factor governance complexity in shaping energy transitions (Martinez et al., 2018; Wu, 2025). Bibliometric and knowledge-mapping studies also reveal an increasing

fragmentation of research agendas in energy security and transition studies, reflecting the multidimensional nature of contemporary energy challenges (Huang & Zheng, 2023; Liu, 2024).

Despite this expanding body of literature, there remains a critical gap in integrated analytical frameworks that simultaneously account for regulatory, technological, environmental, and geopolitical constraints shaping shale gas development. Existing studies tend to be fragmented, often focusing either on environmental impacts, economic viability, or governance structures in isolation. This fragmentation limits the capacity to fully understand the systemic nature of shale gas deployment and its role within broader energy transition pathways.

Accordingly, this study contributes to the literature by synthesizing these dimensions into a structured systemic framework that captures the multi-layered constraints influencing shale gas development.

## **2. THEORETICAL BACKGROUND**

### **2.1. Unconventional Gas Development And Global Energy Transitions**

The role of unconventional gas within global energy transitions has been extensively debated in the energy systems literature, particularly in relation to its function as a transitional fuel in decarbonization pathways. Shale gas has been widely positioned as a strategic energy resource capable of enhancing supply security, improving system flexibility, and enabling fuel switching away from more carbon-intensive sources such as coal. This narrative is strongly reflected in global energy outlooks produced by major institutions

such as IEA, EIA, BP, Shell, ADNOC, and TotalEnergies, all of which incorporate natural gas as a stabilizing element in medium-term transition scenarios.

The rapid expansion of shale gas production, particularly in the United States, demonstrated the disruptive potential of technological innovation in horizontal drilling and hydraulic fracturing, fundamentally reshaping domestic energy systems and global gas markets. More recent evidence from SD modelling further reinforces the idea that shale gas trajectories are highly sensitive to technological learning curves, regulatory constraints, and market volatility (Chen & Zhang, 2025).

However, despite its short- to medium-term role in improving energy security, the contribution of shale gas to long-term decarbonization pathways remains highly contested. Lifecycle assessments indicate that while natural gas combustion emits lower levels of carbon dioxide compared to coal, these advantages may be significantly reduced or even negated when fugitive methane emissions are incorporated into system boundaries (Alvarez et al., 2018; Liu et al., 2025). Methane leakage therefore emerges as a critical uncertainty factor in evaluating the climate mitigation potential of unconventional gas systems, particularly under conditions of incomplete monitoring and weak regulatory enforcement (EPA, 2024).

Within this context, shale gas is increasingly conceptualized not as a stable “bridge fuel,” but as a contested transitional technology embedded within broader geopolitical and institutional dynamics. The European experience, for example, highlights how energy security concerns intersect with decarbonization targets under

Ferreira & Lima (2024) conditions of geopolitical pressure, reinforcing the political complexity of gas dependency. Similarly, uncertainty spillovers in climate policy further complicate long-term investment decisions in fossil-based infrastructure, particularly in transition-sensitive economies (Martinez et al., 2018).

## **2.2. Environmental And Socio-technical Risks Of Hydraulic Fracturing**

The environmental implications of hydraulic fracturing have been widely documented and remain central to debates on the sustainability of unconventional gas development. Empirical studies consistently associate shale gas extraction with multiple environmental stressors, including intensive water consumption, large volumes of contaminated wastewater, risks of groundwater contamination, induced seismicity, and localized air pollution (Jackson, 2020; Vengosh et al., 2013). These impacts are not isolated but cumulative, often unfolding across spatially distributed infrastructures and long temporal horizons, which complicates traditional environmental assessment frameworks.

Methane emissions constitute one of the most critical environmental externalities associated with shale gas systems. Recent empirical evidence indicates that methane leakage across the oil and gas supply chain may be systematically underestimated, thereby reducing the net climate benefit of natural gas relative to coal under certain conditions (Álvarez-Ramos et al., 2020; Liu et al., 2025). This has direct implications for global mitigation strategies, particularly in scenarios aligned with stringent carbon budgets and net-zero pathways.

Beyond biophysical impacts, shale gas development is deeply embedded within complex socio-technical systems characterized by institutional fragmentation, governance uncertainty, and contested legitimacy. Hydraulic fracturing operations generate significant land-use conflicts, often competing with agriculture, biodiversity conservation, and local community livelihoods. These dynamics have been conceptualized within broader frameworks of environmental inequality and distributive justice, highlighting the uneven exposure of social groups to environmental risks (Malin et al., 2023).

From a governance perspective, the literature increasingly emphasizes the need for adaptive and anticipatory regulatory frameworks capable of addressing uncertainty, technological complexity, and long-term environmental risks. Adaptive management approaches have been proposed for water and wastewater governance in shale gas regions, particularly in contexts where regulatory systems struggle to keep pace with rapid industrial expansion (Ahaneku et al., 2025). In parallel, anticipatory regulation has been identified as a critical governance innovation for managing emerging environmental risks before large-scale technological lock-in occurs (Aczel et al., 2022).

These governance challenges are further amplified by the legal and institutional structures underpinning extractive industries, which often reinforce asymmetric power relations between corporations, states, and local communities (Sovacool et al., 2020; Young, 2023). As a result, shale gas development cannot be understood solely as a technological or economic phenomenon, but rather as a deeply political process embedded within contested regulatory regimes and multi-level governance systems.

### **2.3. Governance, Regulatory Stringency, And Institutional Uncertainty**

The governance of unconventional gas resources is inherently multi-scalar and institutionally complex, involving interactions among state agencies, subnational governments, regulatory authorities, industry actors, and civil society. Within the context of unconventional energy systems, such as shale gas, governance structures are further complicated by the spatially distributed nature of extraction activities, which increases regulatory entry points and amplifies institutional coordination challenges. As a result, regulatory arrangements tend to vary significantly across jurisdictions, reflecting differences in administrative capacity, environmental priorities, and levels of public acceptance of hydraulic fracturing (Stephenson & Shaw, 2013).

From a qualitative SD perspective, regulatory frameworks should not be interpreted as static institutional structures but rather as evolving components within a broader system of interacting feedback processes. Regulatory stringency emerges as a dynamic governance attribute shaped by reinforcing and balancing feedback loops between environmental risk perceptions, policy responses, technological performance, and societal pressure. In this sense, regulatory evolution is better understood as an endogenous system behavior rather than an exogenously imposed constraint.

Recent literature on anticipatory and adaptive governance highlights that regulatory responses to unconventional gas development are frequently driven by early signals of environmental risk, particularly in relation to water contamination, land-use conflicts, and methane emissions. These signals can trigger

balancing feedback loops, leading to increased regulatory restrictions, or reinforcing loops, where economic or energy security pressures promote deregulation or regulatory relaxation (Aczel et al., 2022). This dynamic interaction reinforces the non-linear and path-dependent nature of governance systems governing shale gas development.

Within this systemic perspective, methane emissions uncertainty plays a central role in shaping governance feedback structures. Incomplete monitoring systems or underestimation of fugitive emissions can delay regulatory responses, weakening balancing feedback mechanisms intended to mitigate environmental impacts. Conversely, improved scientific evidence on methane leakage strengthens policy responsiveness and can accelerate regulatory tightening within the system (EPA, 2015; Liu et al., 2025).

Furthermore, institutional uncertainty is not only a technical issue but also a structural feature of extractive governance regimes. Legal and political asymmetries embedded in extractive systems influence the strength and direction of feedback loops between regulatory institutions and industry actors. As highlighted in the literature on extractive power, these asymmetries may generate reinforcing dynamics of regulatory capture or delayed enforcement, particularly in contexts with weaker institutional capacity (Shaffer et al., 2013).

At the geopolitical level, shale gas governance is also influenced by competing systemic pressures arising from energy security concerns and decarbonization commitments. These pressures generate conflicting feedback structures within policy systems, where short-term energy security imperatives may reinforce fossil fuel dependence, while long-term climate objectives activate balancing

mechanisms aimed at system transition (Ford, 2020; Proedrou, 2023).

In emerging economies such as Brazil, these dynamics are further intensified by fragmented regulatory authority, legal disputes over land-use governance, and precautionary environmental principles. These conditions contribute to a highly uncertain institutional environment in which feedback processes are often delayed, weakened, or unevenly distributed across governance levels. Such fragmentation increases the complexity of system behaviour and reinforces uncertainty within regulatory decision-making processes.

Accordingly, regulatory stringency in unconventional gas systems is conceptualized in this study as an emergent property of interacting feedback loops within a complex socio-technical system. This perspective is consistent with a qualitative SD approach, where causal loop structures are used to capture the interdependencies between governance, environmental risk, technological development, and societal responses, without requiring numerical simulation or quantitative calibration.

#### **2.4. SD In Energy Systems Modeling (qualitative Causal-loop Perspective)**

SD has emerged as a robust methodological approach for analysing complex socio-technical systems characterized by feedback loops, time delays, accumulations, and non-linear interactions. Originally developed by Forrester, the approach has been extensively applied across industrial, organizational, and policy domains to investigate long-term system behaviour and the unintended consequences of decision-making under uncertainty (Sterman, 2000).

Within energy systems research, SD provides a particularly suitable framework for capturing the co-evolution of technological, economic, environmental, and institutional dimensions within a unified analytical structure. Unlike linear or equilibrium-based approaches, SD emphasizes endogenous system behaviour generated through interacting feedback processes, making it highly appropriate for the analysis of energy transitions, where policy interventions often produce delayed, indirect, and non-intuitive outcomes.

A central strength of SD lies in its ability to represent complex systems through causal feedback structures that explain how system behaviour emerges over time. These structures allow the identification of reinforcing loops, which amplify system dynamics, and balancing loops, which counteract change and promote stabilization. In energy systems, such feedback interactions are particularly relevant for understanding investment cycles, resource depletion patterns, regulatory responses, and technological diffusion processes.

In the context of shale gas systems, this methodological perspective is especially relevant due to the presence of strong structural feedback mechanisms governing production dynamics, infrastructure expansion, and environmental constraints. For instance, production decline rates at the well level generate systemic pressures for continuous reinvestment and drilling activity, reinforcing short-term output while increasing long-term operational intensity (Hughes, 2013). At the same time, environmental constraints, regulatory responses, and social resistance introduce balancing feedback mechanisms that may dampen or reshape system trajectories over time.

Importantly, this study adopts a qualitative SD approach, in which system structure is represented through causal relationships rather than numerical simulation or calibration. This approach is particularly appropriate in contexts where data uncertainty, institutional complexity, and heterogeneous system boundaries limit the feasibility of quantitative modelling. The objective is therefore structural understanding rather than prediction.

The formal representation of these causal feedback structures is developed in Section 3 (Methodology), where a Causal Loop Diagram (CLD) is constructed to map the interactions between governance structures, environmental pressures, technological dynamics, and socio-economic constraints shaping shale gas development. This diagram serves as the primary analytical instrument for visualizing system structure and identifying dominant reinforcing and balancing feedback mechanisms.

Accordingly, SD in this study is not used as a simulation tool, but as a conceptual and structural modelling approach that enables the synthesis of fragmented literature into an integrated systemic representation of shale gas governance and sustainability dynamics.

## **2.5. Sustainability Assessment Frameworks And Cumulative Impacts**

Sustainability assessment frameworks for shale gas development have traditionally been structured around three core pillars: economic viability, environmental integrity, and social acceptance. While this tripartite structure provides a foundational basis for evaluation, much of the existing literature continues to rely on static indicators and fragmented analytical approaches that are

insufficient to capture the systemic complexity of unconventional gas systems. Conventional assessment methods often fail to represent feedback processes, interdependencies, and cumulative effects that unfold over extended temporal horizons.

Recent advances in energy systems research have increasingly emphasized the importance of integrated assessment approaches capable of capturing cross-sectoral interactions. Among these, the water–energy–environment nexus has emerged as a prominent analytical framework, highlighting the intrinsic interdependencies between resource extraction, energy production, and environmental externalities. Within shale gas systems, these interdependencies are particularly pronounced, as water consumption, wastewater generation, methane emissions, and land-use transformations are tightly coupled within the production process. Importantly, the cumulative nature of these impacts implies that their full environmental significance may only become apparent over long time scales, often exceeding the temporal scope of conventional assessment tools.

Empirical and conceptual studies in unconventional gas systems further indicate that environmental impacts are not merely additive but often non-linear, driven by reinforcing feedbacks between production intensity, infrastructure expansion, and environmental stress accumulation. Methane emissions, for example, interact with regulatory responses and technological mitigation strategies, generating evolving system conditions that cannot be adequately captured through static life-cycle assessment alone (Baynes et al., 2023; Liu et al., 2025). Similarly, institutional and governance responses to environmental stressors introduce additional layers of complexity, reinforcing the need for dynamic analytical perspectives.

In this context, dynamic modelling approaches, particularly SD, offer a more robust analytical foundation for sustainability assessment. By explicitly incorporating feedback loops, delays, and path-dependent processes, SD enables the representation of cumulative environmental impacts and evolving system behaviour under policy and technological change. This is especially relevant for shale gas systems, where production dynamics, regulatory adaptation, and environmental constraints co-evolve in ways that generate non-linear and sometimes counterintuitive outcomes.

From a qualitative system perspective, sustainability assessment should therefore be understood not as a fixed evaluation exercise, but as a structural analysis of interacting feedback processes shaping system performance over time. This perspective aligns with recent advances in anticipatory governance and adaptive management, which emphasize the need to account for uncertainty, evolving knowledge, and delayed system responses in environmental decision-making (Aczel et al., 2022).

Accordingly, SD provides an appropriate conceptual foundation for integrating sustainability dimensions within a unified causal representation. Rather than producing numerical optimization outputs, its primary contribution lies in structuring the interdependencies between energy production, environmental pressures, and regulatory constraints. This enables a more holistic understanding of trade-offs and systemic tensions inherent in shale gas development under conditions of uncertainty.

### **3. MODEL CONSTRUCTION AND CAUSAL LOOP DIAGRAM (CLD) DEVELOPMENT**

### **3.1. Literature Search Procedure And Filtering Criteria**

A structured literature search was conducted using the Google Scholar database to support the identification of key variables and causal relationships underlying the construction of the causal loop diagram (CLD). The search strategy was intentionally designed to capture interdisciplinary contributions at the intersection of shale gas development, environmental processes, and governance dynamics, rather than to produce an exhaustive or systematic review.

The search query required the exact phrase “shale gas” and included at least one of the following terms: “Paraná Basin,” “governance,” “regulatory framework,” “regulatory uncertainty,” “system dynamics,” “causal loop diagram,” “energy governance,” “produced water,” and “water–energy nexus.” All terms were searched across the full text of the documents to maximize coverage of relevant studies.

An initial search including the terms “energy” and “policy” returned approximately 6,820 results, reflecting a broad and heterogeneous literature base. To improve thematic specificity, these terms were subsequently removed, reducing the dataset to 263 publications more directly aligned with the research scope.

A further filtering step excluded studies containing the term “Africa” and “Asia” to limit geographic and institutional heterogeneity and maintain analytical focus on contexts with regulatory and socio-technical conditions more comparable to the Brazilian case. Following this step, duplicate records and non-English publications (including articles in Russian) were removed, resulting in a final dataset of 136 documents.

The screening process involved title and abstract review, followed by selective full-text assessment. Studies were retained based on their relevance to at least one of the core analytical dimensions of the model: (i) production dynamics, (ii) environmental accumulation processes, and (iii) governance and regulatory responses. Particular emphasis was placed on contributions that provided insights into feedback mechanisms, system interdependencies, and sustainability trade-offs.

This approach does not follow a formal systematic review or bibliometric protocol. Instead, it is consistent with qualitative System Dynamics applications, where literature-informed model building is used to construct theoretically grounded representations of complex systems under conditions of uncertainty and limited data availability.

### **3.2. System Boundary And Model Structure**

This study adopts a qualitative System Dynamics (SD) approach to analyse structural interactions governing shale gas development under regulatory uncertainty, environmental pressure, and institutional complexity. SD is suited to representing socio-technical systems with feedback loops, time delays, and non-linear interdependencies, where behaviour emerges endogenously from reinforcing and balancing mechanisms rather than linear cause-effect relationships (Sterman, 2000).

Rather than simulation, the analysis focuses on structural representation to identify the causal architecture of shale gas development without producing numerical forecasts.

The system boundary integrates production processes, environmental externalities, and governance mechanisms within a unified socio-technical framework, reflecting the co-evolving nature of energy systems.

Three interdependent subsystems are defined: production, environmental, and governance. Production includes drilling activity, active wells, output levels, and productivity decline. Environmental processes comprise water use, wastewater generation, methane emissions, and cumulative pressure. Governance includes regulatory stringency, licensing constraints, and legal uncertainty. Interactions among these subsystems are structured through reinforcing and balancing feedbacks that shape system behaviour over time.

Variables included in the CLD were selected through a literature-informed process, based on their relevance and ability to capture key feedback processes, rather than quantitative estimation (Hu et al., 2020; Mistré et al., 2018).

Production variables reflect the endogenous growth logic of shale gas systems, in which sustained output depends on continuous drilling and reinvestment (Hughes, 2013). Environmental variables represent cumulative and non-linear impact processes associated with hydraulic fracturing, particularly water use, wastewater generation, and methane emissions (IEA, 2024; Liu et al., 2025), which activate balancing responses.

Governance variables capture institutional feedbacks regulating system expansion. Regulatory stringency, licensing constraints, and legal uncertainty are interpreted as adaptive responses to

environmental and social pressures (Aczel et al., 2022; Proedrou, 2023), and are treated as endogenous components.

Together, these elements form an integrated representation in which production, environmental, and governance dimensions are coupled through feedback loops. This structure underpins the CLD and supports the subsequent analysis.

### **3.3. CLD Loop Structure And Feedback Mechanisms**

The causal structure of the system is represented through a CLD, which formalizes the interdependencies among production, environmental, and governance subsystems. The CLD does not aim to provide numerical representation or predictive outputs, but rather to map the structural feedback architecture that governs shale gas development under conditions of regulatory uncertainty and environmental constraint.

Within this structure, system behaviour is driven by the interaction of reinforcing and balancing feedback loops that operate across different temporal and institutional scales.

A reinforcing feedback loop (R1 – production expansion) links drilling activity, production levels, and reinvestment dynamics. Increased drilling activity leads to higher production, which generates economic returns that incentivize further drilling investment. This reinforcing structure captures the expansion logic of shale gas systems driven by continuous capital reinvestment and operational scaling.

A balancing feedback loop (B1 – productivity decline constraint) reflects the progressive decline in well productivity over time. As

individual well output decreases, maintaining production levels requires additional drilling activity, introducing a structural constraint that increases operational intensity and reduces system efficiency.

A balancing feedback loop (B2 – environmental constraint) links cumulative environmental pressures—such as water consumption, wastewater generation, and methane emissions—to regulatory response mechanisms. As environmental impacts accumulate, regulatory pressure increases, leading to constraints on drilling activity and production expansion.

A balancing feedback loop (B3 – governance response) captures the institutional dimension of system regulation. Regulatory stringency evolves in response to environmental risk accumulation and socio-political pressures, affecting licensing conditions and operational flexibility within the system.

Together, these feedback loops define the dominant causal architecture of the system, where reinforcing production dynamics are continuously counteracted by environmental and institutional balancing mechanisms. The interaction among these loops generates non-linear system behaviour characterized by structural tension between expansionary and constraining forces.

The resulting CLD provides the conceptual foundation for the system analysis presented in the subsequent sections, where alternative regulatory conditions and system behaviours are discussed in structural terms.

### **3.4. CLD Representation And Analytical Scope**

The CLD synthesizes the structural relationships described in the previous sections into an integrated representation of the shale gas system. It provides a qualitative mapping of the interactions among production dynamics, environmental pressures, and governance responses, highlighting how reinforcing and balancing feedback loops jointly shape system behaviour over time.

The CLD is constructed as a structural representation rather than a computational or predictive model. Accordingly, it does not generate numerical outputs or simulate temporal trajectories. Instead, it is used to identify dominant feedback structures, interdependencies among system variables, and potential points of systemic tension arising from the interaction between expansionary and constraining mechanisms.

Within this representation, production-related variables are linked through reinforcing mechanisms that support system expansion, while environmental and governance variables operate primarily through balancing feedback structures that constrain growth. The diagram therefore captures the dual nature of shale gas development as a system driven simultaneously by economic expansion dynamics and environmental-regulatory limitations.

The CLD also enables the identification of cross-domain interactions, particularly the coupling between environmental accumulation processes and regulatory responses. These interactions introduce non-linearities and delays into the system structure, affecting the timing and intensity of balancing feedback activation.

Overall, the CLD serves as the central analytical device of the study, providing a coherent framework for understanding the structural

organization of the system. It forms the basis for the interpretation of system behaviour presented in the subsequent sections, which explore how different configurations of feedback dominance influence overall SD under varying governance conditions.

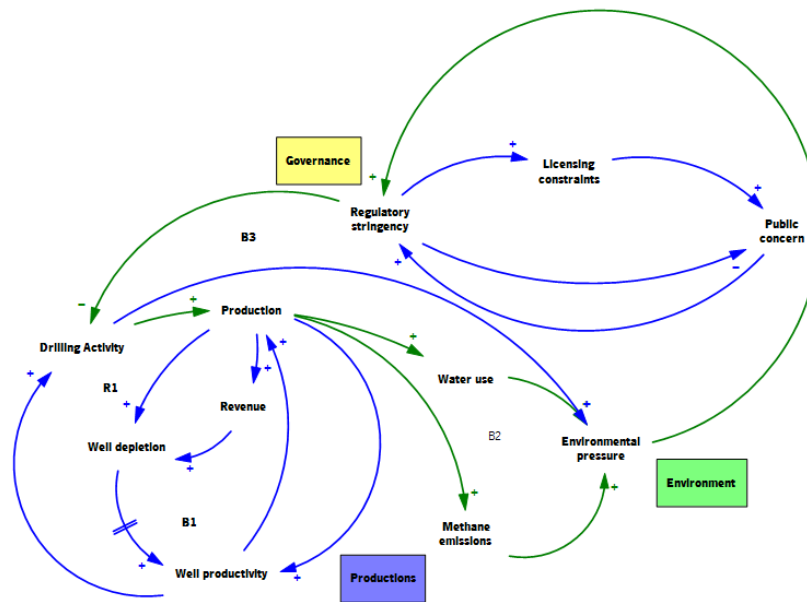
## **4. RESULTS**

### **4.1. System-wide Feedback Architecture**

The shale gas system is structurally organized around a set of interdependent feedback mechanisms linking production dynamics, environmental accumulation processes, and governance responses. Rather than operating as isolated domains, these dimensions co-evolve through reinforcing and balancing interactions that collectively define system behaviour.

At the core of this structure lies a reinforcing production mechanism driven by drilling activity, which simultaneously increases output and reinforces reinvestment dynamics. This expansionary logic is progressively counteracted by multiple balancing forces, including productivity decline, environmental accumulation, and regulatory responses. The resulting configuration is not linear but structurally constrained, with system behaviour emerging from the relative dominance and interaction of these feedback loops.

This feedback architecture aligns with established SD interpretations of socio-technical energy systems, where system behaviour is understood as an emergent property of interacting feedback structures rather than isolated causal chains (Sterman, 2000; Ford et al., 2025).



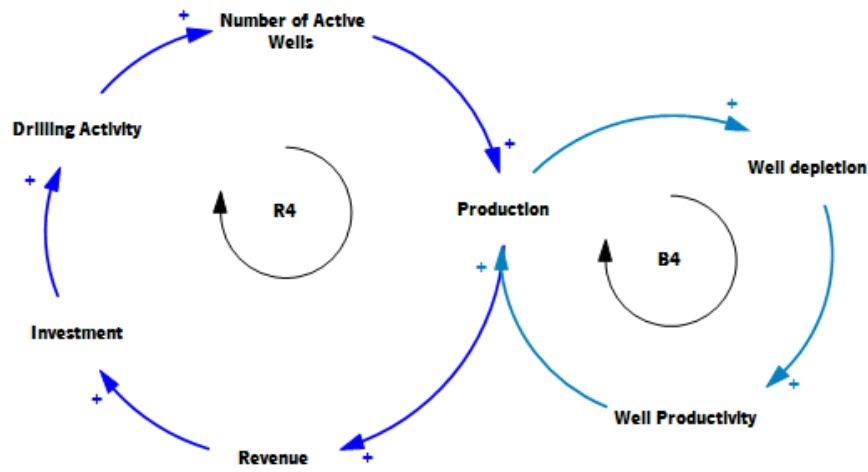
**Figure 1.** Feedback-dominant structure of shale gas development in the Paraná Basin

**Source:** Adapted by Author (2026)

## 4.2. Production Dynamics And Structural Dependence On Drilling

Production behaviour is embedded in a structural dependency on continuous drilling activity. As individual well productivity declines over time, maintaining aggregate output requires sustained reinvestment in new drilling operations. This generates a reinforcing operational logic commonly identified as the “drilling treadmill,” in which declining marginal productivity induces escalating activity intensity (Hughes, 2013).

Rather than representing a simple growth process, production dynamics reflect a structurally fragile expansion regime characterized by high sensitivity to investment continuity and operational scaling. In this configuration, short-term output gains are inherently linked to long-term efficiency decline, producing a persistent tension between expansion and sustainability of production capacity.



**Figure 2.** Production Is Structurally Dependent on Continuous Drilling (“Drilling Treadmill”)

**Source:** Adapted by Author (2026)

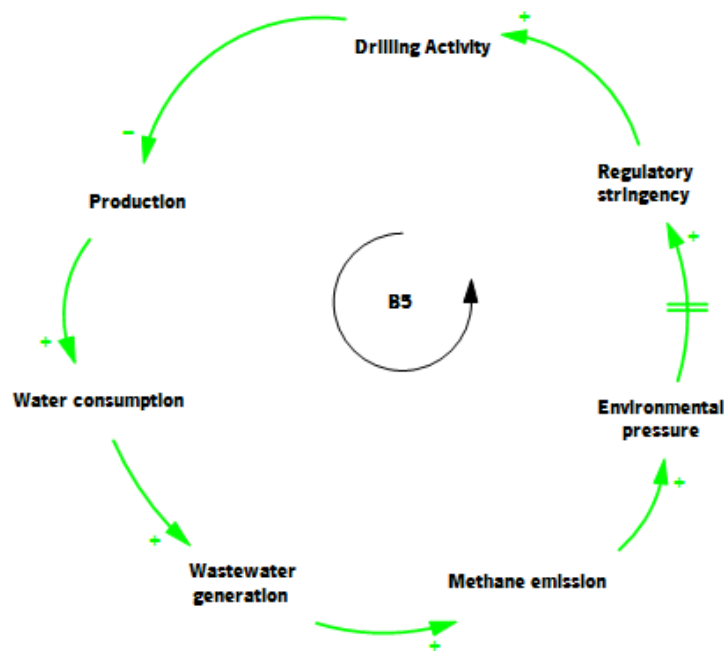
### 4.3. Environmental Accumulation And Systemic Pressure Formation

Environmental dynamics emerge as cumulative system-level processes that intensify over time in response to production activity. Water consumption, wastewater generation, and methane emissions are not isolated externalities but interconnected accumulation processes that progressively increase system-wide environmental pressure.

This accumulation does not remain confined to the environmental domain; instead, it propagates through the system by activating governance responses and altering institutional conditions. In this sense, environmental variables function as key mediators of balancing feedback loops, shaping both regulatory intensity and the constraints imposed on production dynamics.

This cumulative behaviour is consistent with broader empirical evidence highlighting the non-linear and persistent nature of environmental impacts associated with unconventional gas

development, particularly in relation to methane leakage and lifecycle emissions uncertainty (IEA, 2024; Liu et al., 2025).



**Figure 3.** Environmental Impacts Accumulate and Propagate into Governance Feedback.

**Source:** Adapted by Author (2026)

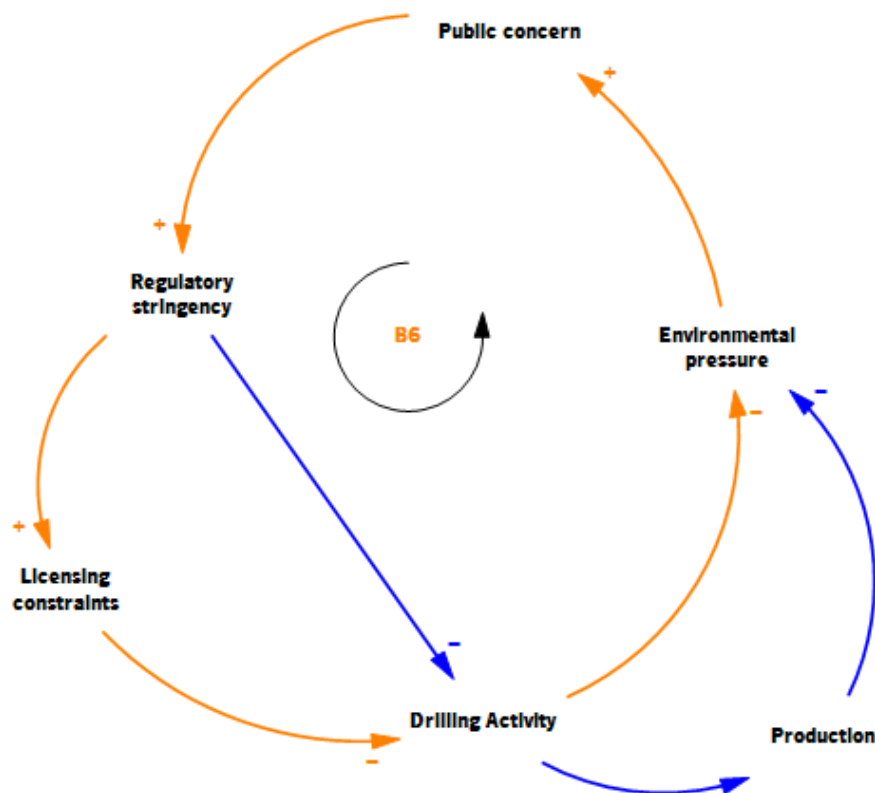
#### **4.4. Governance Dynamics And Endogenous Regulatory Feedback**

Governance structures operate as endogenous components of the system rather than external constraints. Regulatory stringency evolves in response to accumulated environmental pressure and socio-political concerns, thereby forming a balancing feedback mechanism that directly influences production behaviour.

As environmental risks intensify, regulatory responses tend to strengthen, introducing licensing constraints and operational limitations that moderate system expansion. However, these responses are not instantaneous; instead, they are characterized by institutional delays and adaptive adjustments, which create

temporal mismatches between environmental accumulation and policy intervention.

This dynamic is consistent with anticipatory governance frameworks, where regulatory systems respond to emerging risks through iterative and often delayed adjustments rather than immediate stabilization (Aczel et al., 2022). In contexts characterized by institutional complexity and legal uncertainty, such as emerging energy economies, these delays become structurally significant in shaping system trajectories.



**Figure 4.** Regulation Emerges as a Delayed Balancing Feedback Mechanism

**Source:** Adapted by Author (2026)

#### 4.5. Integrated System Behavior And Cross-domain Coupling

The integration of production, environmental, and governance subsystems reveals a tightly coupled socio-technical system governed by competing feedback structures. Reinforcing

production dynamics drive expansion through investment and operational scaling, while balancing environmental and regulatory mechanisms progressively constrain system growth.

Importantly, these feedback mechanisms do not operate independently but are structurally interlinked. Environmental accumulation acts as a trigger for regulatory strengthening, while governance responses feed back into production dynamics by shaping investment conditions and operational feasibility. This cross-domain coupling introduces non-linearity and path dependency into system behaviour.

Across all structural configurations, system evolution is therefore characterized by the continuous rebalancing of reinforcing and balancing forces. The resulting behaviour reflects a dynamic tension between expansionary economic drivers and constraining environmental-institutional feedbacks, consistent with complex adaptive systems in energy transitions (Proedrou, 2023; Malin et al., 2023).

#### **4.6. Structural Scenario Configurations (qualitative System Regimes)**

Alternative system configurations can be interpreted as different dominance regimes of the same underlying feedback structure. In a baseline configuration, reinforcing and balancing loops coexist in a dynamic equilibrium, with production expansion gradually counterbalanced by environmental and regulatory pressures.

In a precautionary configuration, balancing mechanisms gain structural dominance earlier in the system evolution, primarily through stronger regulatory responsiveness to environmental

accumulation. This shifts the system toward constrained expansion and reduced environmental pressure accumulation.

Conversely, in a development-oriented configuration, reinforcing production dynamics dominate for a longer period, allowing accelerated expansion but simultaneously amplifying environmental pressures and increasing structural tension within the system.

Rather than representing distinct outcomes, these configurations reflect variations in feedback dominance and timing, highlighting the sensitivity of system behaviour to the relative strength and responsiveness of regulatory and environmental feedback loops.

#### **4.7. Synthesis: Feedback-dominant System Structure**

Overall, the shale gas system is best characterized as a feedback-dominant socio-technical system in which reinforcing production dynamics are continuously moderated by environmental accumulation and governance responses. System behaviour emerges from the interaction of these feedback structures rather than from linear causal relationships.

This structural configuration produces inherently path-dependent dynamics, where early reinforcing processes shape later system constraints through cumulative environmental and institutional feedback. As a result, system behaviour is neither stable nor fully predictable but continuously reshaped by evolving feedback interactions across domains.

### **5. DISCUSSION AND IMPLICATIONS**

This study demonstrates that shale gas development in the Paraná Basin is structurally governed by a feedback-dominant socio-technical architecture in which production, environmental, and governance subsystems co-evolve through asymmetric and temporally differentiated feedback mechanisms. Rather than being shaped by discrete policy interventions or linear causal relations, system behaviour emerges endogenously from the interaction, dominance shifts, and time delays embedded within reinforcing and balancing feedback loops.

At the core of this structure lies a reinforcing production regime (R1) characterized by a drilling-dependent expansion logic. Consistent with the production engineering constraints of unconventional reservoirs, output is structurally contingent on continuous drilling activity due to rapid well productivity decline (Hughes, 2013). This generates a treadmill-like dynamic in which production growth is not self-sustaining but must be continuously reproduced through escalating operational intensity and reinvestment. As a result, system expansion is inherently fragile, as it depends on uninterrupted reinforcement of capital and drilling cycles.

This reinforcing regime is progressively counterbalanced by a hierarchy of balancing mechanisms with distinct temporal and structural properties. The first constraint (B1) arises from inherent well productivity decline, which introduces a technical ceiling on output efficiency. The second (B2) emerges from cumulative environmental accumulation, where water consumption, wastewater generation, and methane emissions generate escalating system pressure that intensifies over time. The third (B3) operates through governance response, where regulatory stringency adjusts

to environmental and socio-political signals, constraining drilling activity and investment conditions.

Crucially, these balancing feedbacks are not simultaneously activated. Instead, they exhibit systematic temporal asymmetry. Reinforcing production dynamics operate rapidly and continuously, while environmental and governance responses are delayed, partial, and institutionally mediated. This mismatch in feedback timing produces a structural advantage for reinforcing processes in early system stages, enabling accelerated expansion prior to the full activation of balancing constraints.

Environmental dynamics occupy a central mediating role in this structure. Rather than functioning as isolated externalities, environmental variables operate as cumulative system stocks that translate production activity into progressively intensifying system-wide pressure. This accumulation mechanism links operational dynamics to governance responses, reinforcing the non-linear nature of system evolution (Hong et al., 2025; EPA, 2024). Consequently, environmental degradation is not a side effect but a structural intermediary in feedback transmission.

Governance, in turn, emerges as an endogenous balancing mechanism embedded within the system rather than an external regulatory correction layer. Regulatory stringency evolves in response to accumulated environmental pressure and institutional signals, forming a feedback loop that directly conditions production trajectories. However, consistent with anticipatory governance literature, this mechanism is structurally delayed and informationally constrained, resulting in lagged policy responses that allow

reinforcing dynamics to temporarily dominate system evolution (Aczel et al., 2022).

The interaction between subsystems generates a tightly coupled cross-domain structure in which production, environment, and governance continuously reshape one another. Production drives environmental accumulation, environmental pressure activates governance tightening, and governance feeds back into production through investment constraints and operational restrictions. This triadic coupling produces non-linear system behaviour and reinforces path dependency, aligning with broader interpretations of energy transitions as complex adaptive systems (Ford et al., 2025; Proedrou, 2023).

From a structural sustainability perspective, the system exhibits an inherent trade-off between expansion velocity and long-term stability. This trade-off is not contingent on policy design alone but is embedded in the feedback architecture of the system itself. Reinforcing-dominant regimes enable rapid production scaling but amplify environmental and institutional stress. Conversely, strengthening or accelerating balancing feedbacks reduces environmental accumulation but structurally constrains production expansion. Sustainability outcomes therefore emerge from feedback configuration rather than isolated interventions.

A key implication of this structure is that regulatory stringency should be interpreted as a dynamic leverage point within a feedback system rather than as an external policy parameter. Its effectiveness depends on both its timing and its sensitivity to environmental accumulation. Where regulatory responses are delayed or weakened, reinforcing production dynamics dominate system

behaviour, increasing the likelihood of high-impact environmental trajectories and operational inefficiencies.

Finally, the study demonstrates the analytical value of qualitative SD for integrating fragmented dimensions of shale gas systems into a unified structural representation. By focusing on feedback architecture rather than isolated causal variables, the approach enables a coherent interpretation of socio-technical complexity in contexts characterized by uncertainty, institutional fragmentation, and limited data availability. This is particularly relevant for emerging shale gas regions such as the Paraná Basin, where system behaviour is shaped by strong interactions between technological constraints, environmental accumulation, and governance delays.

Overall, shale gas governance is shown to be an emergent property of interacting feedback structures. System behaviour is determined not by isolated drivers but by the asymmetric interaction, temporal ordering, and dominance shifts of reinforcing and balancing loops, producing inherently path-dependent, non-linear, and structurally constrained system evolution.

## **6. CONCLUSIONS**

This study developed a structural interpretation of shale gas development in the Paraná Basin through a qualitative SD framework combined with a production engineering perspective. The main contribution is the identification of shale gas as a feedback-dominant socio-technical system in which production, environmental, and governance dynamics co-evolve through asymmetric and temporally differentiated feedback structures, rather than through linear or exogenous cause–effect relationships.

The results demonstrate that system behaviour is governed by a reinforcing drilling-dependent production regime constrained by intrinsic well productivity decline, cumulative environmental accumulation, and endogenous regulatory responses. This configuration generates a structurally fragile expansion logic, in which sustained output is only maintained through continuous reinvestment and escalating operational intensity. Environmental and institutional constraints do not operate as external boundaries but as internal balancing feedback mechanisms that progressively reshape system evolution.

A central finding is the presence of systematic temporal asymmetry across feedback structures. Reinforcing production dynamics operate rapidly through investment–drilling cycles, while environmental accumulation and governance responses unfold with inherent delays. This structural mismatch enables early dominance of reinforcing mechanisms, creating path-dependent trajectories in which environmental and institutional constraints are activated only after significant system expansion has already occurred.

From a governance perspective, the study shows that regulatory effectiveness is structurally dependent on feedback timing rather than solely on policy intensity. Regulatory systems function as endogenous components of the socio-technical system, where delayed responsiveness weakens balancing capacity and allows reinforcing dynamics to dominate system behaviour. This highlights the critical importance of anticipatory, feedback-sensitive governance capable of responding to early-stage environmental signals before structural lock-in occurs.

Methodologically, the study contributes to energy systems literature by demonstrating the value of qualitative SD for integrating fragmented production, environmental, and institutional dimensions into a unified causal framework. The combination of a production engineering lens with feedback-based system structuring enables a more coherent representation of shale gas systems under uncertainty, particularly in contexts where data limitations constrain quantitative modelling approaches.

Several limitations should be acknowledged. The model is intentionally qualitative and does not include numerical calibration, stock–flow simulation, or predictive validation. Its primary function is therefore structural interpretation rather than forecasting. In addition, causal relationships are derived from literature-based synthesis, which introduces interpretive rather than empirical specification of system structure.

Future research should extend this framework through quantitative SD modelling calibrated with regional production, emissions, and regulatory datasets, enabling scenario testing and policy simulation. Comparative applications across different shale basins would further strengthen the generalizability of the proposed feedback structure. Integration with high-resolution methane emissions inventories and regulatory enforcement data would also improve empirical grounding of the identified balancing mechanisms.

Ultimately, the study suggests that in feedback-dominant energy systems, governance does not determine outcomes; it only negotiates the constraints imposed by the system's own structure.

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## HIGHLIGHTS

- Examines shale gas development through a production-engineering lens, emphasizing system behaviour and operational interdependencies.
- Identifies key variables and causal relationships linking production dynamics, environmental pressures, and regulatory governance.
- Maps reinforcing and balancing feedback loops that shape sustainability trade-offs in the Paraná Basin.
- Shows how regulatory stringency and institutional fragmentation act as central drivers of system performance.
- Provides a qualitative system dynamics (SD) framework to support decision-making before large-scale shale gas policies

are implemented.

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