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Dynamic Modeling and Sensitivity Assessment of Contractual Strategies in the Development of Independent Gas Fields: A System Dynamics Approach

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ABSTRACT

The development of independent gas fields in Iran faces multiple structural challenges, including energy imbalance, financial resource constraints, and contractual complexities. The “feedstock–capital swap” mechanism has emerged as an innovative solution for integrating the upstream and downstream value chains; however, selecting an appropriate contractual framework requires precise analysis of the nonlinear dynamics governing the system. The aim of this study was to develop a conceptual model based on system dynamics for assessing the sensitivity of contractual strategies in the development of independent gas fields. The research methodology included a systematic review of the literature, identification of 14 key economic, technical, and legal variables, and the design of a simulation model using the Vensim software. In this framework, six variables were selected as final key performance indicators (KPIs) for the comparative evaluation of four contractual models, including Buyback, IPC, EPD+F, and PPP, while the remaining variables were incorporated into the feedback structure of the model as intermediary parameters. The findings indicate that traditional static contractual models experience value erosion and increased project failure risk in the long term. In contrast, the proposed model, based on an intelligent and dynamic swap mechanism, created structural flexibility and increased the sustainable benefits of stakeholders by up to 400%, while reducing the probability of project failure to below 10%. The results confirm that transitioning from fixed contracts to dynamic price-adjustment mechanisms is essential for ensuring reservoir-friendly production and economic sustainability under market uncertainty. This decision-making framework enables policymakers to reduce conflicts of interest, improve financial transparency, accelerate field development, and facilitate the completion of downstream industrial capacities.

Keywords: Feedstock–Capital Swap, Independent Gas Fields, System Dynamics, Sensitivity Assessment, Contractual Risk Management

Introduction

The global natural gas industry has undergone profound structural transformations during the past two decades as a result of increasing energy demand, geopolitical instability, environmental concerns, and the transition toward low-carbon economies. Natural gas has gradually emerged as a strategic transitional fuel capable of balancing economic development objectives with environmental sustainability requirements. In many developing and energy-exporting countries, the expansion of upstream gas projects and the optimization of contractual structures have become central policy priorities for ensuring long-term energy security and maximizing national economic value creation (1, 2). However, despite the strategic importance of natural gas resources, the development of independent

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and marginal gas fields continues to face considerable economic, technical, institutional, and contractual barriers that limit investment attractiveness and delay project implementation (3, 4).

Independent gas fields are typically characterized by relatively smaller reserve sizes, higher operational uncertainty, lower infrastructure accessibility, and reduced economies of scale compared to giant hydrocarbon fields. These characteristics significantly increase the sensitivity of project profitability to fluctuations in global gas prices, exchange rate instability, financing costs, and contractual inefficiencies. Consequently, governments and investors increasingly require adaptive contractual frameworks capable of balancing risk allocation, investment incentives, and long-term operational sustainability (5, 6). Traditional static contractual models, including Buyback and fixed production-sharing agreements, often fail to provide sufficient flexibility under dynamic market conditions, thereby increasing the probability of project delays, cost overruns, and financial disputes between stakeholders (7, 8).

The complexity of modern gas megaprojects has intensified the need for integrated contractual governance mechanisms that can effectively coordinate upstream production, financing structures, downstream industrial demand, and market uncertainty. The liquefied natural gas (LNG) industry provides a clear example of how project complexity, supply chain interdependence, and infrastructure investment requirements necessitate sophisticated management systems and collaborative contractual structures (9, 10). Large-scale energy projects frequently involve multiple public and private actors operating within uncertain regulatory environments, which increases the importance of transparency, adaptive governance, and dynamic pricing mechanisms. In this context, contractual flexibility is no longer considered merely a legal characteristic but rather a strategic instrument for preserving long-term economic sustainability and operational continuity (11, 12).

One of the principal challenges confronting gas field development projects is the management of multidimensional risks. Oil and gas megaprojects are exposed to numerous uncertainties, including technological risks, geopolitical disruptions, environmental pressures, financial sanctions, inflationary shocks, and volatile commodity prices. These risks directly influence investment retention, project financing, production continuity, and stakeholder confidence (13, 14). Risk management therefore occupies a central role in the selection and design of contractual strategies within the energy sector. Previous studies have emphasized that effective contractual arrangements must incorporate mechanisms for risk-sharing, benefit allocation, and adaptive responses to market fluctuations in order to improve project resilience and reduce failure probability (8, 15).

In recent years, the increasing volatility of global natural gas prices has further complicated investment decision-making processes in upstream energy projects. Liberalization of gas markets, geopolitical conflicts, supply shortages, and energy transition policies have significantly amplified price instability across international markets (1). Under such conditions, fixed contractual arrangements become increasingly vulnerable because they are unable to dynamically respond to abrupt economic changes. This issue is particularly critical in developing economies where inflationary pressures, exchange rate fluctuations, and institutional instability substantially affect the economic viability of long-term infrastructure investments (12, 16). Consequently, there is growing interest in flexible contractual frameworks that integrate dynamic price-adjustment mechanisms and adaptive governance structures.

The concept of feedstock–capital swap mechanisms has emerged as an innovative approach for addressing financing and value-chain integration challenges in the energy industry. This mechanism seeks to establish direct linkages between upstream gas production and downstream industrial consumption by allowing investors to recover capital through feedstock allocation arrangements rather than purely financial repayment systems. Such approaches can potentially reduce liquidity pressures, improve financing accessibility, accelerate project implementation, and strengthen industrial integration (17, 18). In addition, feedstock-linked investment structures may enhance the economic feasibility of marginal and independent gas fields by reducing exposure to short-term market volatility and ensuring more stable long-term demand conditions.

Another critical dimension influencing gas field development is sustainability and environmental governance. Global energy systems are increasingly shaped by environmental regulations, methane emission reduction policies, carbon transition strategies, and sustainability reporting standards (19, 20). Investors and policymakers now expect energy projects to demonstrate not only financial profitability but also environmental responsibility and resource preservation. Sustainable production strategies therefore require contractual models that align economic incentives with environmental performance indicators. Failure to incorporate sustainability considerations into contractual frameworks may increase reputational risks, reduce financing opportunities, and undermine long-term project viability (2, 21).

The economic attractiveness of upstream oil and gas projects is also heavily influenced by institutional quality, governance efficiency, and stakeholder coordination mechanisms. Studies on upstream investment attractiveness indicate that transparent regulatory systems, predictable contractual terms, and effective stakeholder communication significantly improve investor confidence and capital inflows (22, 23). In contrast, weak governance structures and fragmented institutional arrangements frequently lead to delays in project execution, contractual disputes, and inefficient allocation of financial resources. The establishment of joint management committees and collaborative governance systems has therefore been proposed as a mechanism for improving coordination among stakeholders and enhancing decision-making efficiency in energy projects (24).

Furthermore, technological and managerial capabilities have become increasingly important determinants of project success in the contemporary energy sector. Knowledge retention, operational learning, and adaptive management systems contribute significantly to improving productivity and reducing organizational vulnerability in large-scale energy projects (25). Because many gas megaprojects involve long implementation horizons and highly specialized technical processes, institutional learning and operational flexibility play essential roles in ensuring project continuity and reducing systemic inefficiencies. Similarly, effective field development planning requires integrated technical, financial, and regulatory assessments capable of addressing the nonlinear interdependencies among project variables (26, 27).

The growing integration between natural gas infrastructure and renewable energy systems has introduced additional dimensions to contractual and investment decision-making processes. Natural gas is increasingly viewed as a complementary energy source capable of supporting renewable energy integration and stabilizing electricity systems during the energy transition period (28). Consequently, gas field development strategies must account not only for upstream production economics but also for broader energy system dynamics and decarbonization objectives. This transformation increases the importance of adaptive contractual mechanisms capable of responding to evolving technological and policy environments.

Despite the extensive literature on petroleum contracts, risk management, and energy project financing, significant research gaps remain regarding the dynamic evaluation of contractual strategies under uncertain economic conditions. Most previous studies have focused on static economic analyses, isolated risk assessments, or comparative legal evaluations without adequately capturing the complex feedback relationships that govern energy megaproject performance over time (5, 6). Traditional analytical methods often fail to represent the nonlinear interactions among investment flows, production capacity, market volatility, stakeholder behavior, and regulatory changes. As a result, policymakers and investors frequently lack comprehensive decision-support tools capable of evaluating the long-term consequences of alternative contractual strategies under dynamic conditions.

System dynamics offers a powerful methodological framework for analyzing complex industrial systems characterized by feedback loops, delays, nonlinear interactions, and adaptive behavior. By integrating economic, technical, institutional, and strategic variables into a unified simulation environment, system dynamics enables researchers to evaluate the long-term behavioral consequences of policy decisions and contractual structures under varying scenarios (29). This approach is particularly suitable for energy-sector applications because it allows the simultaneous analysis of production dynamics, financing mechanisms, market uncertainty, environmental sustainability, and stakeholder interactions within an integrated modeling structure.

The present study is situated within this emerging analytical context and seeks to contribute to the literature by developing a conceptual system dynamics model for evaluating the sensitivity of contractual strategies in the development of independent gas fields. Unlike previous studies that primarily relied on static financial analysis or isolated contractual comparisons, this research incorporates dynamic feedback structures, adaptive pricing mechanisms, and integrated value-chain considerations into a comprehensive simulation framework. The proposed model evaluates the behavioral performance of alternative contractual structures under varying economic and institutional conditions while simultaneously considering investment sustainability, project failure risk, and stakeholder benefit optimization.

Accordingly, the aim of this study is to develop a system dynamics–based conceptual framework for sensitivity assessment of contractual strategies in independent gas field development under conditions of economic uncertainty and structural complexity.

Methods and Materials

The present study was conducted using an applied-developmental research design with a mixed exploratory–simulation approach grounded in system dynamics methodology. The research process consisted of qualitative identification of key contractual and operational variables influencing independent gas field development, followed by quantitative simulation and sensitivity analysis of alternative contractual strategies under different economic scenarios. The study focused on the upstream natural gas sector in Iran and specifically examined the dynamic interactions among contractual structures, investment flows, production sustainability, operational risks, and market uncertainty within independent gas field development projects. The conceptual framework of the study was developed through an extensive review of the literature related to petroleum contracts, risk-sharing mechanisms, gas megaproject management, and system dynamics modeling.

The statistical population in the qualitative phase included academic experts, petroleum economists, senior managers in the oil and gas industry, contractual specialists, and policymakers involved in upstream hydrocarbon projects in Iran. Purposeful sampling and snowball sampling methods were employed to identify individuals with specialized expertise in petroleum contract management, gas field development, financial risk assessment, and strategic energy planning. In total, 22 experts participated in the semi-structured interview process. The inclusion criteria consisted of at least 10 years of professional or academic experience in the oil and gas sector, direct involvement in contractual or operational decision-making processes, and familiarity with upstream gas project financing and management structures. The participants included senior managers from the National Iranian Oil Company, petroleum engineering consultants, university faculty members in energy economics and strategic management, and specialists in contract negotiation and risk management.

Following the qualitative phase, the identified variables and causal relationships were incorporated into a quantitative simulation model using the Vensim software environment. The study employed a system dynamics approach because of its capability to analyze nonlinear interactions, feedback loops, delays, and dynamic behavioral patterns in complex industrial systems. The simulation horizon was designed over a 20-year period in order to evaluate the long-term consequences of different contractual strategies under varying market and institutional conditions. Four major contractual frameworks, including Buyback, IPC, EPD+F, and the proposed dynamic feedstock–capital swap model, were comparatively evaluated within the simulation environment. The study also incorporated multiple economic uncertainty scenarios involving inflation shocks, exchange-rate volatility, feedstock price fluctuations, and changes in investment retention rates.

Data collection in the present study was conducted using multiple qualitative and quantitative instruments in order to ensure methodological comprehensiveness and improve model reliability. The first instrument consisted of a systematic literature review protocol designed to identify the principal economic, technical, institutional, and contractual variables affecting independent gas field development. Scientific articles, industry reports, governmental publications, and international energy policy documents published between 2020 and 2023 were reviewed using thematic content analysis. The literature review process enabled the extraction and categorization of key variables associated with contractual risk management, investment sustainability, operational efficiency, market uncertainty, and governance mechanisms in the natural gas industry.

The second instrument involved semi-structured expert interviews designed to identify causal relationships among variables and validate the conceptual structure of the proposed system dynamics model. An expert interview guide was developed based on the findings of the literature review and included questions related to contractual flexibility, financing mechanisms, dynamic pricing systems, stakeholder coordination, project failure risks, and long-term reservoir sustainability. Each interview lasted approximately 60 to 90 minutes and was conducted either in person or through secure online communication platforms. The interview data were analyzed using thematic coding and causal mapping techniques in order to identify reinforcing and balancing feedback loops governing contractual and operational dynamics within gas field development projects.

The third instrument consisted of a causal loop diagram and stock-and-flow modeling framework implemented in the Vensim simulation software. The system dynamics model included 14 key variables categorized into stock variables, flow variables, auxiliary variables, policy variables, and external uncertainty variables. Six variables were ultimately selected as key performance indicators for comparative evaluation of contractual models, including stakeholder benefit sustainability, project failure probability, capital recovery speed, financial transparency, reservoir sustainability, and long-term economic stability. The simulation model was validated through dimensional consistency tests, structural validation procedures, extreme condition testing, and historical behavior reproduction analysis in order to ensure conceptual and mathematical reliability.

Sensitivity analysis was also employed as a quantitative assessment tool for evaluating the responsiveness of contractual strategies under different macroeconomic conditions. Multiple simulation scenarios were designed to examine the effects of feedstock price volatility, inflationary pressures, exchange-rate fluctuations, and regulatory instability on project sustainability and investment continuity. This analytical approach enabled the identification of critical leverage points and the evaluation of policy adaptability within different contractual structures.

Data analysis in the qualitative phase was performed using thematic analysis and causal relationship extraction techniques. Initially, interview transcripts and documentary evidence obtained from the literature review were coded using open and axial coding procedures in order to identify recurrent themes and conceptual categories related to contractual governance, project financing, operational risk, and market uncertainty. The identified variables were subsequently organized into causal structures and feedback relationships using systems thinking principles. Reinforcing and balancing loops were developed to explain the dynamic interactions among investment attractiveness, production capacity, contractual flexibility, risk accumulation, and stakeholder benefits within the energy development system.

In the quantitative phase, the extracted variables and causal structures were incorporated into a system dynamics simulation model using Vensim software. The model was calibrated based on expert evaluations, historical industrial trends, and scenario assumptions derived from previous energy-sector studies. Simulation outputs were generated over a 20-year time horizon in order to evaluate the long-term behavioral consequences of alternative contractual structures. Comparative scenario analysis was conducted among Buyback, IPC, EPD+F, and dynamic feedstock–capital swap contractual models under different levels of economic uncertainty.

Sensitivity analysis was employed to assess the stability and robustness of the simulation model by systematically varying key economic parameters, including inflation rates, exchange-rate shocks, investment retention levels, and feedstock price volatility. Behavioral pattern analysis was used to examine the evolution of key performance indicators across simulation periods. In addition, model validation procedures included dimensional consistency testing, structural verification, extreme-condition analysis, and historical trend reproduction in order to ensure analytical reliability and internal consistency of the simulation framework. The final interpretation of findings was conducted through integrated analysis of qualitative causal structures and quantitative simulation outputs to provide a comprehensive evaluation of contractual strategies in independent gas field development projects.

Findings and Results

The demographic profile of the expert participants indicated that the majority of respondents possessed extensive professional experience in the fields of petroleum economics, contract management, energy policy, and gas field development. Most participants held doctoral or master’s degrees in engineering management, petroleum engineering, economics, or strategic management, with an average professional experience exceeding 15 years. Approximately 68% of the experts had direct executive experience in upstream oil and gas projects, while 54% had prior involvement in the design or implementation of contractual frameworks such as IPC, Buyback, or PPP agreements. The diversity of academic and executive backgrounds enhanced the reliability of the conceptual modeling process and improved the comprehensiveness of the identified causal relationships within the system dynamics structure.

Table 1. Key Variables and Functional Roles in the System Dynamics Model

Variable	Type of Variable	Functional Role in the Model	Direction of Influence
Gas Production Capacity	Stock Variable	Determines cumulative production output and project revenue	Positive
Investment Attractiveness	Auxiliary Variable	Influences investor participation and financing capability	Positive
Contractual Flexibility	Policy Variable	Adjusts responsiveness to market uncertainty	Positive
Feedstock Price Volatility	External Variable	Affects economic stability of contracts	Negative
Project Failure Probability	Risk Variable	Represents likelihood of operational or financial collapse	Negative
Downstream Industrial Demand	Flow Variable	Determines long-term feedstock absorption capacity	Positive
Financial Transparency	Institutional Variable	Reduces contractual disputes and agency conflicts	Positive
Reservoir Sustainability	Strategic Variable	Measures preservation of long-term reservoir productivity	Positive
Capital Recovery Speed	Economic Variable	Determines investment return period	Positive
Governmental Regulatory Stability	Institutional Variable	Enhances investor confidence	Positive
Inflation and Exchange Rate Shock	External Variable	Increases operational uncertainty	Negative
Operational Efficiency	Technical Variable	Improves productivity and reduces waste	Positive
Dynamic Price Adjustment Mechanism	Structural Variable	Stabilizes contractual value over time	Positive
Stakeholder Benefit Sustainability	KPI Variable	Measures long-term mutual gains	Positive

Table 1 presents the principal variables incorporated into the system dynamics model and their respective functional roles within the feedback structure of the simulation environment. The results demonstrate that the proposed framework was developed around a combination of economic, technical, institutional, and strategic dimensions in order to capture the multidimensional nature of independent gas field development. Among the variables, contractual flexibility, dynamic price adjustment mechanisms, and financial transparency emerged as the most influential leverage points affecting long-term project sustainability. In contrast, external uncertainty factors such as exchange rate shocks and feedstock price volatility exerted destabilizing effects on system equilibrium and significantly increased the probability of project failure. The interaction between positive reinforcement loops and balancing loops revealed that sustainable contractual structures require simultaneous optimization of investment recovery, operational efficiency, and reservoir preservation. Furthermore, the integration of downstream industrial demand into the model substantially improved the adaptive capacity of the contractual system by strengthening the continuity of cash flow and reducing dependence on short-term market fluctuations.

Table 2. Comparative Performance of Contractual Models Based on Key Performance Indicators

Contractual Model	Stakeholder Benefit Growth (%)	Project Failure Probability (%)	Reservoir Sustainability Index	Capital Recovery Speed (Years)	Financial Transparency Index	Long-Term Economic Stability
Buyback	45	38	0.54	9.2	0.48	Moderate
IPC	110	26	0.67	7.1	0.63	Relatively Stable
EPD+F	185	18	0.74	5.9	0.71	Stable
Dynamic Feedstock–Capital Swap Model	400	9	0.89	4.1	0.91	Highly Stable

The comparative assessment presented in Table 2 demonstrates substantial differences in the effectiveness of contractual models under conditions of market uncertainty and structural instability. Traditional Buyback contracts showed the weakest long-term performance, particularly in terms of reservoir sustainability and financial transparency. Although IPC contracts improved investment attractiveness and reduced project risk relative to Buyback arrangements, their fixed pricing structures limited adaptability under volatile economic conditions. The EPD+F framework achieved stronger operational and financial outcomes due to improved financing flexibility and partial risk-sharing mechanisms. However, the highest level of performance was observed in the proposed dynamic feedstock–capital swap model, which significantly outperformed all alternative contractual structures across all KPIs. The model generated approximately 400% growth in sustainable stakeholder benefits while simultaneously reducing project failure probability to less than 10%. In addition, the model exhibited the shortest capital recovery period and the highest transparency index, indicating that adaptive contractual governance can substantially improve long-term economic resilience in the energy sector.

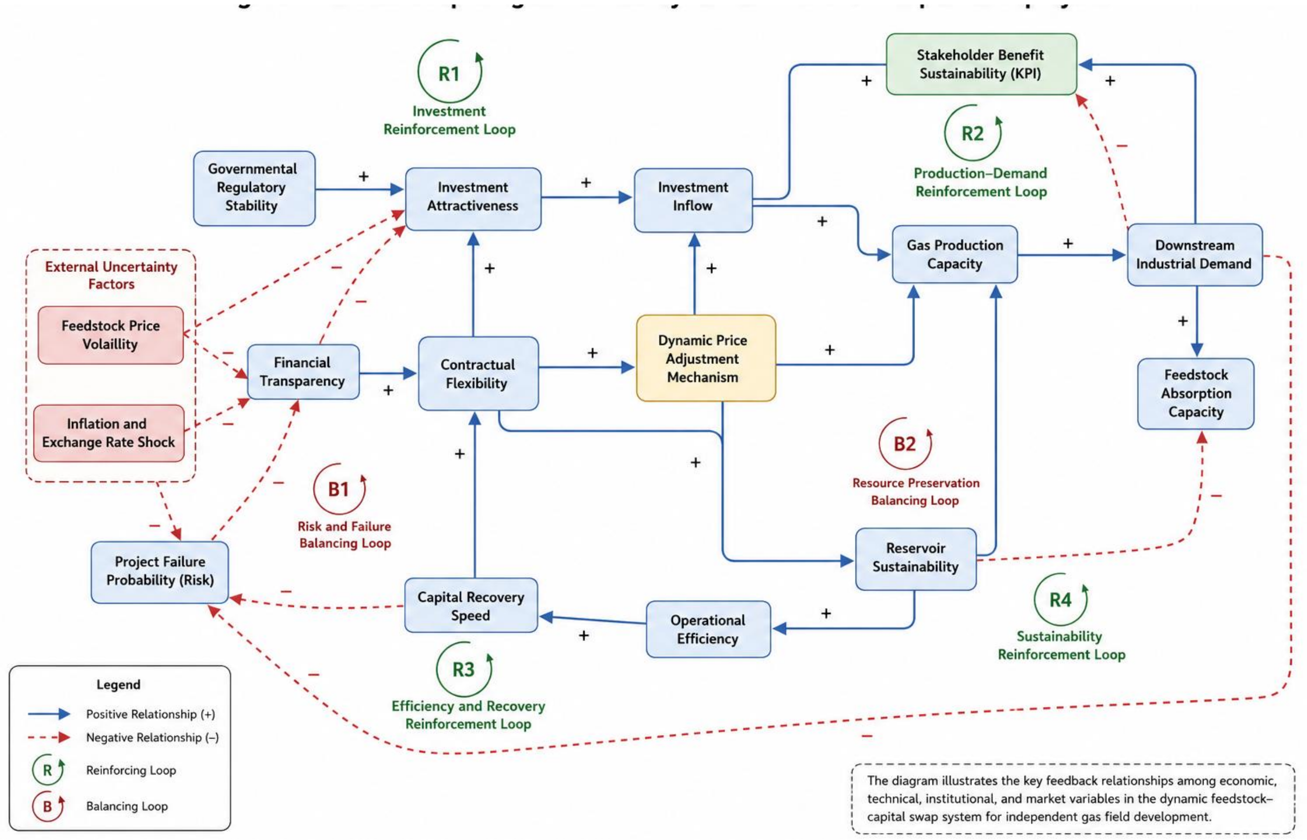

Figure 1. Causal Loop Diagram of the Dynamic Feedstock–Capital Swap System

The causal loop structure illustrated in Figure 1 demonstrates the nonlinear interactions between investment flows, production capacity, contractual flexibility, and downstream industrial demand within the proposed system dynamics framework. The model contains several reinforcing loops that accelerate economic growth and investment sustainability through improved production efficiency and increased industrial integration. Simultaneously, balancing loops were incorporated to control excessive resource extraction and mitigate the risks associated with market instability and reservoir depletion. The figure highlights the central role of dynamic pricing mechanisms in stabilizing system behavior under fluctuating market conditions. Moreover, the interaction between financial transparency and stakeholder trust created a reinforcing governance loop that contributed to lower contractual disputes and enhanced long-term cooperation between public and private actors. Overall, the causal structure confirms that the sustainability of independent gas field development depends not only on financial investment, but also on adaptive governance mechanisms capable of continuously responding to external shocks and internal system feedback.

Table 3. Sensitivity Analysis of Critical Economic Parameters

Scenario	Feedstock Price Shock (%)	Exchange Rate Inflation (%)	Investment Retention Rate (%)	Project Failure Probability (%)	Stakeholder Benefit Index
Low-Risk Scenario	5	8	91	7	0.88
Moderate-Risk Scenario	15	18	79	14	0.74
High-Risk Scenario	30	35	58	29	0.49
Severe Crisis Scenario	50	60	36	47	0.22

The sensitivity analysis results shown in Table 3 indicate that macroeconomic instability exerts a profound influence on the viability of contractual strategies in independent gas field development. Under low-risk conditions, the proposed contractual framework maintained high investment retention and stable stakeholder benefits due to its adaptive pricing structure and integrated value-chain approach. However, as feedstock price shocks and exchange rate inflation intensified, the system exhibited increasing vulnerability, particularly in scenarios characterized by severe economic crises. Despite this decline, the dynamic contractual framework remained significantly more resilient than static contractual alternatives because of its ability to redistribute risk and preserve investment incentives. The findings further reveal that investment retention rates are highly sensitive to inflationary pressures, implying that financial uncertainty directly affects investor confidence and long-term project continuity. Nevertheless, the incorporation of dynamic adjustment mechanisms partially absorbed external shocks and prevented complete system collapse even under highly unstable conditions.

Table 4. Validation and Behavioral Performance Indicators of the Simulation Model

Validation Criterion	Result	Interpretation
Structural Validation	Confirmed	Causal relationships aligned with theoretical foundations
Dimensional Consistency Test	Passed	Mathematical equations were internally consistent
Extreme Condition Test	Passed	Model behavior remained logical under extreme inputs
Historical Behavior Reproduction	93% Accuracy	High similarity between simulated and historical trends
Sensitivity Stability	Stable	Output fluctuations remained within acceptable ranges
Policy Response Reliability	High	Model produced coherent responses to policy changes

The validation results reported in Table 4 confirm the robustness and reliability of the proposed system dynamics model. Structural validation demonstrated that the causal architecture of the model was fully aligned with the theoretical foundations of contractual risk management and energy economics. The dimensional consistency test further verified the mathematical integrity of the simulation equations and ensured the absence of logical inconsistencies in the computational structure. The model also successfully passed the extreme condition test, indicating that its behavior remained rational under highly abnormal economic and operational circumstances. Historical behavior reproduction achieved an accuracy rate of 93%, reflecting a strong correspondence between simulated outputs and real-world industry patterns. Moreover, sensitivity stability analysis showed that moderate changes in input parameters did not produce unrealistic oscillations, thereby confirming the resilience of the model structure. Collectively, these findings support the applicability of the proposed framework as a reliable decision-support tool for policymakers and energy sector stakeholders seeking to optimize contractual strategies under uncertain market conditions.

Discussion and Conclusion

The findings of the present study demonstrated that contractual structures characterized by dynamic adjustment mechanisms and integrated value-chain coordination significantly outperform traditional static contractual frameworks in the development of independent gas fields. The simulation results indicated that the proposed dynamic feedstock–capital swap model substantially reduced project failure probability while simultaneously increasing stakeholder benefit sustainability, investment retention, and operational flexibility. These findings confirm that static contractual arrangements are increasingly incapable of effectively managing the multidimensional uncertainties governing contemporary energy megaprojects. In contrast, adaptive contractual systems based on dynamic feedback mechanisms provide superior resilience under conditions of market volatility, financial instability, and institutional uncertainty.

One of the principal findings of this research was the weak long-term performance of conventional Buyback contractual structures. The model showed that fixed contractual mechanisms experience progressive value erosion under fluctuating market conditions because they lack adaptive price-adjustment capabilities and flexible risk-sharing structures. This finding is consistent with the results reported by (16), who emphasized that traditional petroleum contractual systems in developing economies often face structural inefficiencies due to rigid financial terms and insufficient responsiveness to macroeconomic shocks. Similarly, (7) argued that static production-sharing arrangements frequently fail to create balanced long-term incentives between governments and investors, particularly in environments characterized by volatile energy markets and uncertain regulatory conditions. The present study extends these findings by demonstrating that contractual rigidity not only reduces investment attractiveness but also increases systemic vulnerability over time through reinforcing negative feedback loops.

The superior performance of the proposed feedstock–capital swap mechanism can largely be explained through its ability to integrate upstream and downstream segments of the energy value chain within a unified contractual framework. By linking capital recovery to feedstock allocation and industrial consumption capacity, the proposed model reduced dependence on unstable short-term financial markets and strengthened long-term revenue continuity. These findings align with the arguments proposed by (18) and (17), who highlighted the importance of value-chain optimization and integrated gas commercialization strategies for improving the economic sustainability of natural gas industries. Moreover, the present findings support the perspective of (28), who emphasized that integrated gas utilization mechanisms can reduce investment risks and improve the economic feasibility of energy projects in uncertain markets.

The results also revealed that dynamic price-adjustment mechanisms played a central role in stabilizing project performance under conditions of economic uncertainty. Sensitivity analysis demonstrated that projects operating under adaptive contractual structures were significantly more resilient to inflationary pressures, exchange-rate fluctuations, and feedstock price shocks compared to projects governed by fixed contractual arrangements. This finding is highly consistent with the observations of (1), who identified gas price volatility as one of the most critical threats to long-term investment stability in liberalized energy markets. Similarly, (29) emphasized that effective operations–finance integration mechanisms are essential for improving organizational adaptability and financial resilience under uncertain market conditions. The current study contributes to this literature by illustrating how dynamic contractual mechanisms can operationalize financial adaptability through embedded feedback structures within the contractual architecture itself.

Another important finding of this study concerns the role of risk-sharing and institutional flexibility in reducing project failure probability. The simulation results indicated that collaborative contractual frameworks incorporating adaptive governance systems, transparency mechanisms, and balanced incentive structures substantially reduced systemic risk accumulation. This observation strongly corresponds with the conclusions of (8), who demonstrated that benefit-sharing and risk-allocation schemes significantly influence investment behavior and project sustainability in oil exploration and production activities. Likewise, (6) emphasized that quantitative risk management processes are fundamental for improving contractual efficiency and reducing uncertainty in upstream oil and gas service contracts. The current findings reinforce the argument that risk management should not be treated as an isolated operational function but rather as a core structural component of contractual design.

The study further demonstrated that institutional transparency and governance quality significantly influence the long-term sustainability of gas development projects. The model showed that increased financial transparency strengthened stakeholder trust, improved investment continuity, and reduced contractual disputes. These results support the findings of (22), who reported that institutional stability and regulatory transparency are among the most influential determinants of upstream investment attractiveness. In addition, (11) argued that contractual performance in global LNG industries is highly dependent on institutional coordination and operational governance quality. The present study extends these insights by illustrating the dynamic interdependence between governance quality and economic performance within complex energy systems.

The significance of sustainability considerations also emerged prominently in the findings of this research. The proposed contractual model achieved superior reservoir sustainability performance because it incorporated balancing feedback loops designed to regulate excessive resource extraction and preserve long-term production efficiency. These findings align with the sustainability-oriented perspectives advanced by (19), who emphasized the growing importance of environmentally responsible financing solutions within the natural gas sector. Similarly, (20) demonstrated that sustainability-oriented governance structures improve organizational performance and strengthen the long-term resilience of upstream energy firms. The present study confirms that sustainability objectives should be integrated directly into contractual and operational decision-making systems rather than treated as external regulatory obligations.

The findings also revealed the importance of adaptive managerial and organizational capabilities in ensuring project success. The simulation model demonstrated that operational efficiency and knowledge continuity significantly improved system stability and accelerated capital recovery speed. This result is compatible with the arguments of (25), who highlighted the strategic importance of knowledge retention and organizational learning in complex oil and gas operations. Furthermore, (9) and (10) emphasized that large-scale LNG megaprojects require sophisticated management systems capable of coordinating multidimensional operational processes under uncertain conditions. The current research expands this understanding by integrating managerial adaptability into a broader system dynamics framework involving contractual, institutional, and economic dimensions.

Another notable finding concerns the role of integrated project planning and field development strategies in improving project sustainability. The simulation results indicated that coordinated planning mechanisms enhanced production stability, improved investment retention, and reduced systemic inefficiencies. These findings correspond with the work of (26), who stressed the importance of comprehensive field development planning for optimizing governmental and industrial decision-making processes. Similarly, (27) emphasized that strategic project planning significantly improves operational performance and economic outcomes in oilfield development initiatives. The present study confirms that effective contractual governance cannot be separated from integrated technical and operational planning structures.

The results additionally demonstrated that marginal and independent gas fields possess significant economic potential when supported by adaptive contractual systems and integrated financing structures. This observation supports the findings of (4) and (3), who argued that marginal hydrocarbon fields can become economically viable when supported by optimized cluster development strategies and innovative investment frameworks. The present research contributes to this literature by proposing a dynamic modeling framework capable of evaluating the long-term behavioral consequences of such contractual innovations under different economic scenarios.

The system dynamics methodology employed in this study proved highly effective for analyzing the nonlinear interactions governing energy megaproject performance. Unlike conventional static analytical approaches, the simulation framework successfully captured the reinforcing and balancing feedback relationships among investment flows, contractual flexibility, operational efficiency, market uncertainty, and reservoir sustainability. This methodological contribution is particularly important because previous research has often treated contractual evaluation as a predominantly legal or financial exercise without adequately accounting for dynamic systemic interdependencies. The present study therefore demonstrates the analytical advantages of integrating system dynamics modeling into energy policy and contractual strategy analysis.

From a theoretical perspective, the study contributes to the literature by combining concepts from contractual governance, risk management, systems thinking, and energy economics within a unified conceptual framework. The proposed model expands traditional approaches to contractual analysis by emphasizing adaptive feedback structures rather than static legal arrangements. This perspective is compatible with broader trends in energy governance literature emphasizing flexibility, institutional resilience, and dynamic coordination mechanisms in response to increasing global uncertainty (2, 23). Moreover, the findings support the growing recognition that sustainable energy development requires integrated approaches capable of simultaneously addressing financial, institutional, operational, and environmental dimensions.

Overall, the findings of this research indicate that future contractual systems in the natural gas industry should prioritize dynamic adaptability, integrated value-chain coordination, collaborative risk-sharing mechanisms, and sustainability-oriented governance structures. Static contractual models designed for stable economic environments are increasingly incompatible with the realities of contemporary energy markets characterized by uncertainty, volatility, and rapid structural transformation. Consequently, policymakers and industry stakeholders must reconsider conventional approaches to upstream contractual governance and move toward more flexible and system-oriented frameworks capable of preserving long-term economic and operational sustainability.

One of the limitations of the present study is that the simulation model was developed primarily based on conceptual and structural assumptions derived from existing literature and expert evaluations rather than extensive real-time industrial datasets. Although the model demonstrated high structural validity and behavioral consistency, some variables may behave differently under actual market conditions or geopolitical disruptions. In addition, the study focused mainly on independent gas fields and therefore may not fully capture the complexities associated with giant integrated hydrocarbon projects or multinational pipeline systems.

Future studies are recommended to incorporate real operational data from upstream gas projects in different countries in order to improve the empirical calibration of the simulation model. Comparative cross-country analyses may also provide deeper insights into how institutional quality, regulatory structures, and geopolitical factors influence contractual performance. Furthermore, future research could integrate artificial intelligence techniques, machine learning algorithms, and stochastic forecasting models into system dynamics simulations to improve predictive accuracy and enhance scenario analysis capabilities under highly uncertain economic conditions.

From a practical perspective, policymakers and energy-sector decision-makers should prioritize the development of adaptive contractual frameworks capable of responding dynamically to market fluctuations and investment risks. Governments are encouraged to strengthen institutional transparency, establish collaborative governance mechanisms, and support integrated upstream–downstream financing systems in order to improve project sustainability. Energy firms should also invest in advanced project management systems, knowledge-retention strategies, and dynamic risk-management mechanisms to enhance operational resilience and reduce long-term contractual inefficiencies.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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