DOI: 10.1478/AAPP.104S1A9

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 104, No. S1, A9 (2026)

NAVIGATING UNCERTAINTIES: ASSESSING THE ROLE OF NATURAL GAS IN UZBEKISTAN'S ENERGY SECURITY THROUGH SYSTEM DYNAMICS MODELING

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ABSTRACT. Natural gas is vital for transitioning to a low-carbon energy future; however, its role in ensuring Uzbekistan's energy security remains uncertain. This study aims to assess the future contribution of natural gas to Uzbekistan's energy security by developing a system dynamics model for the domestic natural gas sector. This study develops a system dynamics model to analyze the extended interactions among sales revenue, exploration investment, and demand. Methodologically, the study simulates the supply and demand structures under three distinct scenarios: price regulation, demand shifts, and improvements in technical efficiency. The results reveal significant sensitivity to these factors, suggesting that Uzbekistan's energy security framework, which is heavily reliant on natural gas, is at risk. Drawing on these insights, the study provides recommendations for policy adjustments and strategic planning to mitigate potential vulnerabilities and support the country's energy transition.

1. Introduction

Fundamentally, the natural gas industry significantly influences Uzbekistan's energy system by enhancing power production and overall energy security. Predominantly utilized in thermal power plants for steam-driven turbine generation, natural gas constitutes a substantial portion of the country's energy consumption (International Energy Agency, 2020 (IEA) 2020). The primary energy source has been validated by the fuel's relative cost-effectiveness and local availability. Moreover, its comparatively lower carbon footprint than coal characterizes natural gas as a transitional fuel that promotes both energy security and environmental objectives (Bui *et al.*, 2023 Bui *et al.* 2023).

Despite its strategic importance, Uzbekistan's natural gas industry faces significant challenges. Notably, major declines in key production areas managed by Uzbekneftegaz, such as the Amu Darya Basin and Ustyurt Plateau, have resulted in a 21% decrease in oil output and only a 4% increase in natural gas output from 2008 to 2022 (IEA, 2024). These output constraints have strained the national energy system, increased reliance on

expensive imports, and heightened vulnerability to supply disruptions (Khan *et al.*, 2023 Khan, Khurshid, and Cifuentes-Faura 2023; Meyer *et al.*, 2021 Meyer, Magda, and Bozsik 2021). Structural inefficiencies, including outdated infrastructure—approximately 40% of thermal power plants are antiquated (Kenisarin & Kenisarina, 2007 Kenisarin and Kenisarina 2007)—and declining natural gas discovery rates in the face of rising domestic demand, are significant contributors to this issue.

These challenges are exacerbated by policy constraints. Policies such as tax incentives and price controls present trade-offs in resource management, necessitating that policymakers reconcile short-term consumption with long-term sustainability (Energy Charter Secretariat, 2022 Secretariat n.d.). Furthermore, systemic inefficiencies, geopolitical concerns, and the complex interactions among stakeholders impede exploratory activities and investments, thereby disrupting the natural gas value chain (Gao *et al.*, 2024 Gao, Zhao, and Li 2024). Traditional analytical methods often fail to capture the dynamic and interconnected nature of these issues. Linear models frequently overlook feedback loops, time lags, and policy-induced non-linearities related to business operations. Consequently, there is an urgent need for systems-based analytical tools capable of replicating long-term behavior and guiding effective policy responses (Sterman & Richardson, 1985 Sterman and Richardson 1985).

Despite the growing body of research employing system dynamics to analyze energy systems (Barlas, 1996 Barlas 1996; Daneshzand *et al.*, 2018 Sterman and Richardson 2018; Mu *et al.*, 2018 Mu, Li, and Hu 2018; Laimon *et al.*, 2020 Laimon *et al.* 2020), limited attention has been devoted to resource-dependent transition economies such as Uzbekistan, where state dominance, restricted competition, and technological inefficiencies give rise to distinct feedback mechanisms. Existing studies often focus on either supply or demand facets in isolation, overlooking the interconnected effects of price, reinvestment, and resource depletion.

To address this gap, this paper aims to develop a comprehensive system dynamics model of Uzbekistan's natural gas sector. The model incorporates essential factors such as prices, investments, exploration costs, proven reserves, demand trends, and technical losses. Through feedback-rich interactions among the system's components, the model serves as a policy laboratory for testing various scenarios and interventions. The application of system dynamics in a strategically significant yet underexplored area of national resource management distinguishes this study. Unlike previous research that focuses on discrete components of the gas sector, this study comprehensively integrates economic, technical, and policy factors to simulate the lifecycle of natural gas resource development.

The anticipated outcomes are expected to contribute significantly to academic literature and practical policy formulation. By generating forward-looking insights and scenario analyzes, the model will facilitate the development of informed, adaptive strategies for natural gas management in Uzbekistan, thereby supporting overarching goals related to environmental sustainability, economic resilience, and energy security.

2. Materials and methods

The intricate framework of Uzbekistan's natural gas production system requires the adoption of management policy options only after thorough modeling and simulation of

many alternatives. Forrester's system dynamics technique provides a robust framework for developing computer models that provide systematic assessments of the structure, interconnections, and behaviors of complex socio-economic, technical, and environmental systems, therefore surpassing human cognitive constraints. This methodology relies on feedback principles and adeptly addresses multi-loop, non-linear, and time-lagged complex systems. Traditional econometric techniques sometimes inadequately address the intricacies of these non-linear dynamic connections (Stephens *et al.*, 2013 **Stephens**). System dynamics is especially adept at tackling issues associated with continuous processes, because input profoundly impacts system behavior and triggers dynamic alterations.

2.1. Dynamic hypothesis. This study's conceptual model is characterized by a causal loop diagram, a stock-flow diagram, or a combination thereof. The fundamental objective of this model is to identify the essential feedback loops that govern the system's behavior. This task is enabled when the model generates structural behaviors that are similar to those of the system, including the influence of endogenous structure (Sterman, 2000, Sterman n.d.).

A causal loop diagram was used for qualitative analysis in this study, while a stock flow diagram was used for quantitative analysis, to represent the natural gas production system. Natural gas production systems' dynamic behaviors in relation to observed natural gas stocks are explained by the structures and linkages. The stock-and-flow diagram and the causal loop diagram both show how stocks deplete.

The national supply of fossil fuels appears to be approaching a tipping point, as it is becoming increasingly difficult to obtain the energy required to meet energy consumption using domestic sources (Oracle, 2023, Oracle 2023). The model presented here is intended to include the factors and interactions that regulate the discovery and supply of natural gas in Uzbekistan. It is a useful tool for determining the type of supply and assessing the feasibility of alternative solutions to the problem. Annual statistics books and key informant interviews were used to obtain parameter values. Many aspects of the natural gas sector should be addressed, such as seasonality of demand changes or pipeline distribution issues. The model excludes the effect of imports and exports on system behavior. Furthermore, the model makes no explicit reference to technological advancements in exploration or production.

2.2. Causal loop diagram. The goal of this study is to look at how strategies affect long-term trends and behavior patterns in industry supply. The model posits a monopolistic market structure within Uzbekistan's natural gas sector, primarily highlighting the dominance of state-owned enterprises, particularly Uzbekneftegaz JSC, in the domains of exploration, production, and distribution. This premise aligns with the nation's prevailing institutional framework, wherein private sector participation and third-party access are significantly restricted (IEA, 2020 (IEA) 2020; Energy Charter Secretariat, 2022 Secretariat n.d.).

To assess the sensitivity of this assumption, an alternative quasi-competitive scenario was simulated. This extended framework allows for partial liberalization, incorporating multiple producers who compete under regulated pricing mechanisms. The findings suggest that while competition may enhance short-term production and investment incentives, it also increases system volatility in the absence of stringent price regulation.

Consequently, the monopolistic baseline accurately reflects Uzbekistan's current market structure, whereas the alternative scenario elucidates potential transitional dynamics that

may arise during a gradual liberalization of the industry. These supplementary simulations contribute to the robustness of the model and its policy implications.

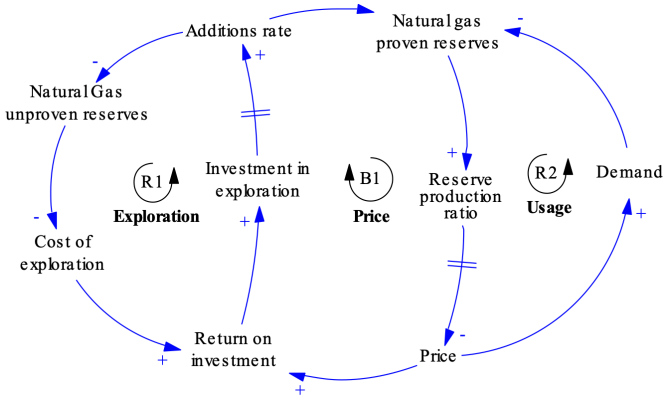

FIGURE 1. Causal loop diagram of the natural gas production system in Uzbekistan

Natural gas unproven reserves, cost of exploration, return on investment, natural gas proven reserves, price, and demand are the key factors influencing natural gas production (Figure 1). Uzbekistan's natural gas production is divided into two reinforcing loops (exploration and utilization) and one balancing loop (price). This study utilizes three interconnected yet distinct terms: "Price" refers to the current selling price of natural gas within the market system at any specific point in time. "Contract price" denotes the agreed-upon price established between producers and consumers within regulated or long-term supply agreements, typically determined through administrative or cost-plus methodologies. "Market-based pricing" signifies a pricing system dictated by the dynamics of supply and demand, which includes production costs, investment recovery, and prevailing market conditions, independent of direct governmental intervention. These distinctions are essential for evaluating policy scenarios that transition from regulated to market-oriented frameworks in Uzbekistan's natural gas sector.

The cost of discovery rises as unproven reserves are depleted (Figure 1). When the amount of gas discovered per meter of drilling decreases, further exploration may take place in more difficult areas. A difficult environment slows the rate of discovery, slowing the depletion of undiscovered deposits (Daneshzand *et al.*, 2018 Sterman and Richardson 2018; Laimon *et al.*, 2020, Laimon *et al.* 2020; Ur Rehman *et al.*, 2017, Ur Rehman *et al.* 2017). Increasing exploration expenses generally reduce the return on investment, as corporations are necessitated to pursue deeper or less accessible areas once easily extractable resources have been depleted (Daneshzand *et al.*, 2018 Sterman and Richardson 2018). Reduced exploration spending slows the rate of Proven Reserve additions.

As proven gas reserves increase, the RPR rises, resulting in a decline in prices due to an oversupply. This reduction in prices stimulates consumption, leading to an increase in utilization rates of proven gas reserves. Conversely, heightened utilization results in increased sales revenue, which incentivizes investment in exploration (Chyong Chi *et al.*,

2009 Sterman and Richardson 2009; Mu *et al.*, 2018 Mu, Li, and Hu 2018). When the RPR surpasses a certain threshold, the necessity for new discoveries diminishes.

The proposed comprehensive system dynamics model integrates the fundamental components of Uzbekistan's natural gas framework into a cohesive feedback structure. It consists of four interrelated subsystems. Resource subsystem-this encompasses natural gas reserves, exploration activities, depletion rates, and reserve-to-production (RPR) dynamics. Production subsystem- this records extraction rates, technological efficiency, and infrastructural investments. Demand subsystem-this illustrates domestic consumption patterns across industrial, residential, and energy-generation sectors. Economic and policy subsystem-this connects gas pricing, revenue generation, reinvestment rates, and governmental regulatory measures, including taxation and subsidies.

The subsystems are interlinked through feedback loops that elucidate the co-evolution of economic incentives and the availability of physical resources. The model aims to simulate long-term system performance across various policy and market scenarios by adjusting parameters such as gas pricing, demand growth, and technological advancements. This integrative framework enables the assessment of both immediate market responses and long-term sustainability outcomes.

2.3. Stock-and-flow model. Dynamic systems consist of interconnected feedback loops that replicate the dynamic behavior of the system. Within each loop, stock and flow components represent two categories of variable elements that underpin a system dynamics model. Stock serves as a state variable, indicating the status or condition of the system at any specified time, t. Conversely, flow illustrates the rate at which the stock varies over time. A flow diagram visualizes the interactions between stocks and flows, which collectively generate feedback loops that influence the overall system. The stock-flow diagram of Uzbekistan's natural gas production systems is presented in Figure 2. The relationships depicted in the flow diagram are articulated through algebraic equations, which establish a quantitative foundation for simulating dynamic behavior (Bala *et al.*, 2017 Bala 1991; Qudrat-Ullah, 2013 Qudrat-Ullah 2013; Sterman, 2002 Sterman and Richardson 2002). The primary feedback loops of the model are illustrated in Figure 2 through the stock and flow diagram of natural gas exploration. The model incorporates three critical variables: unproven reserves, proven reserves, and pricing.

The system dynamics model was implemented using Vensim DSS (Version 9.3) to simulate the dynamic interactions among key variables. The model operates on an annual time frame over the simulation period from 2000 to 2050. Calibration was performed utilizing historical data from 2000 to 2022, sourced from the International Energy Agency (IEA, 2020 (IEA) 2020), the Energy Charter Secretariat (2022) Secretariat n.d., and statistical bulletins from Uzbekneftegaz.

The simulation process encompasses three principal phases. Initialization-base-year figures for reserves, output, and consumption are established based on official statistics. Parameterization-key model coefficients (e.g., depletion rate, reinvestment ratio, and demand elasticity) are derived through regression analysis and expert validation. Iteration and convergence-the stock-and-flow framework is modeled using Euler integration with an annual time step.

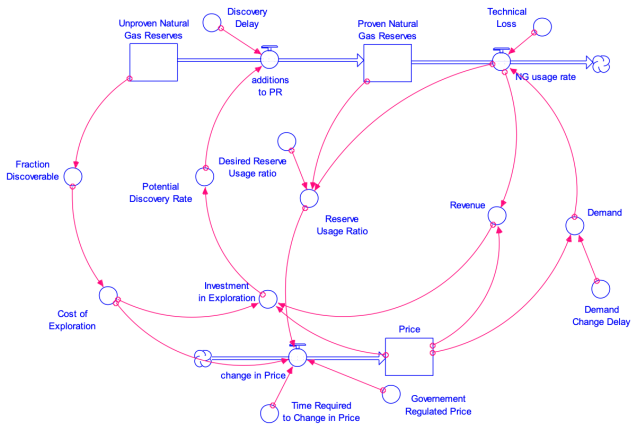

FIGURE 2. Stock-and-flow diagram of Uzbekistan's natural gas exploration system

2.4. Natural gas discovery sub-model. The value of unproven reserves has long been a source of contention (Chong *et al.*, 2015, Chong *et al.* 2015). Because of the close relationship between gas and oil discoveries. The potential for oil and gas production in Uzbekistan is estimated to encompass 63.1% of the country's land area, as per the Institute of Geology, Oil, and Gas Exploration (OECD/IEA, 2015 OECD/IEA n.d.). The discovery rate is expressed as a function of the remaining reserves and their anticipated production capacity. The constant $1e+013$ within the model serves as a scaling parameter to align the units of measurement between reserves (in billion cubic meters, bcm) and production flows (in billion cubic meters per year, bcm/year).

$$\text{Natural gas unproven reserve}(t) = \int_{t_0}^{t} [-\text{additions to PR}]\, dt + 1 \times 10^{13} \tag{1}$$

$$\text{additions to PR} = \text{SMOOTH}\big(\text{Investment in Exploration}/\text{Cost of Exploration}, \text{Discovery Delay}\big) \tag{2}$$

This figure, on the other hand, can be simply adjusted from simulation to simulation to investigate the dynamic consequences of other hypothetical unverified reserve bases. One advantage of a simulation model is the ease with which one can assess the implications of changes in fundamental assumptions, such as reserve estimation differences.

$$\begin{gathered}\text{Relative unproven natural gas reserve} = \\ \text{Natural Gas Unproven Reserve/Initial Natural Gas Unproven Reserve}\end{gathered} \tag{3}$$

The value of relative unproven natural gas reserve decreases as more unproven reserves are discovered and utilized:

$$\begin{gathered}\text{Effect of Fraction of Unproven Reserves Remaining} = \\ f(\text{Natural Gas Unproven Reserves/Initial Natural Gas Unproven Reserves}); \\ f' \leq 0;\ f(0) = 10,\ f(1) = 1.\end{gathered} \tag{4}$$

In this application, function refers to a non-linear decreasing function that represents the diminishing rewards associated with exploration activities as the proportion of remaining untested reserves decreases. When unconfirmed reserves are abundant, the function approaches 1, indicating a significant possibility for discovery. Conversely, when reserves diminish, functionality approaches zero, signifying heightened costs and diminished finding rates.

$$\begin{gathered}\text{Relative Cost of Exploration = Cost of Exploration/Initial Cost of Exploration with Margin} \\ \text{Exploration Cost Effect on New Contract Price} = f(\text{Relative Cost of Exploration}); \\ f' \geq 0;\ f'(0) = 0.\end{gathered} \tag{5}$$

The cost of exploration and reserves have a negative relationship: as reserves are depleted, the cost of exploration rises. As resources are identified, companies must explore in less accessible areas (such as the highlands). Exploration costs thus increase (Yunna *et al.*, 2015 Yunna *et al.* 2015).

$$\text{Return on Investment} = f(\text{New Contract Price/Cost of Exploration}) \tag{6}$$

$$\begin{gathered}\text{Additions to PR} = \\ \text{SMOOTH (Investment in Exploration / Cost of Exploration, Discovery Delay)}\end{gathered} \tag{7}$$

The results of an investment in exploration are typically not known for four to five years due to the time required to locate a potential drilling site, set up and drill the wells, and determine the amount of the discovery (Xiao *et al.*, 2017 Xiao *et al.* 2017; Zhang *et al.*, 2016Zhang *et al.* 2016).

$$\text{Additions Delay} = 4.5. \tag{8}$$

The model considers the addition rate—the total amount added yearly to proven natural gas reserves—to be a delayed function of exploration investment divided by exploration cost.

2.5. Demand sub-model.

$$\text{Sales Revenue} = \text{Usage rate} \times \text{Price}. \tag{9}$$

Sales revenue reflects the total revenue obtained from the sale of natural gas. It is determined by the usage rate and the price. The industry's capacity to spend in gas exploration is believed to correlate with its existing revenue. An anticipated rise in sales revenue is projected to positively influence the additions to proven reserve rates (Kiani & Ali Pourfakhraei, 2010 Kiani and Ali Pourfakhraei 2010).

$$\text{Proven Natural Gas Reserves}(t) = \int_{t_0}^{t} [\text{Additions to PR} - \text{Usage Rate}]\, dt + 1.85 \times 10^{12} \tag{10}$$

The relationship between the average wellhead price of natural gas and its impact on demand is multifaceted and pivotal within the energy market. Elevated wellhead prices often prompt shifts in consumer behavior, with end-users seeking alternatives or implementing conservation measures to mitigate increased costs. Concurrently, industries and consumers may pivot towards substitute energy sources in response to heightened natural gas prices, influenced by factors such as availability and relative pricing.

$$\text{Usage rate} = \text{Normal Demand} \times \text{Price Effect on Demand} \tag{11}$$

$$\begin{gathered}\text{Price Effect on Demand} = f(\text{Relative Average Wellhead Price});\\ f' \leq 0;\ f(0) = 5,\ f(1) = 1.\end{gathered} \tag{12}$$

Moreover, fluctuations in natural gas prices can influence broader economic activity, potentially affecting production levels and overall demand. Seasonal variations further complicate this relationship, with demand typically peaking during colder months for heating purposes. However, long-term responses may include increased investment in exploration and infrastructure development, potentially moderating the impact of price increases on demand.

3. Results and discussions

3.1. Model validation. The model captures the fundamental aspects of gas extraction and exploration in Uzbekistan. It is crucial to determine if the model effectively integrates dynamic reliability and is applicable to the specified variables, as well as to assess the degree of its conformity with empirical data (Qudrat-Ullah, 2013). As examples, proven natural gas reserves, utilization rate, and reserve production ratio are used. Figure 3 depicts the historical and simulated time series for the RPR and usage rate (based on n=22 data points).

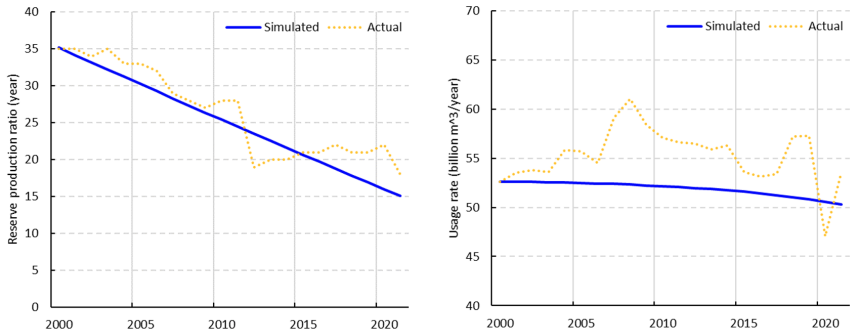

FIGURE 3. Behavior reproduction of usage rate and RPR

The simulation results aligned with historical data, demonstrating the model's consistency. The behavior reproduction test yielded the Root Mean Square Percentage Error (RMSPE) as shown in Table 1, which quantified the total error. Additionally, Theil's inequality statistics provided a decomposition of the total error into its components: bias (Um), unequal variation (Us), and unequal covariation (Uc) (Jones *et al.*, 2002 Jones, Seville,

and Meadows n.d.; Sterman, 2000, Sterman n.d.). The RMSPEs varied from 0.04 to 0.23 percent. The Uc component constituted the majority of the total errors, whereas Um and Us were relatively minor. The differences between actual and simulated values are outlined point-by-point (Schwaninger & Grösser, 2008, Schwaninger and Grösser 2008), suggesting that the majority of these errors are likely unsystematic (Barlas, 1996 Barlas 1996).

Table 1: Summary statistics of behavior reproduction

Variable	RMSPE (%)	Theil Inequality Statistics		
		Um (%)	Us (%)	Uc (%)
RPR	0.12	0.29	0.00	0.71
Usage rate	0.04	0.22	0.36	0.42

TABLE 1. Summary statistics of behavior reproduction

Following this, a multivariate sensitivity test was conducted using a Monte Carlo simulation (Figure 4) (Bala, 1991 Bala 1991). This analysis was essential due to the lack of evidence for certain parameters (see Table 2). Subsequently, observations, factual evidence, and expert opinions were solicited. The model demonstrates sensitivity to variations in parameters such as normal demand, the desired RPR, and the price adjustment delay, which affect RPR, as illustrated in Figure 3. The range of confirmed RPR has widened significantly over time, with a 50% chance of totaling 12 years to 27 years. Tests aided in the validation of model assumptions by demonstrating credible model behavior and structure.

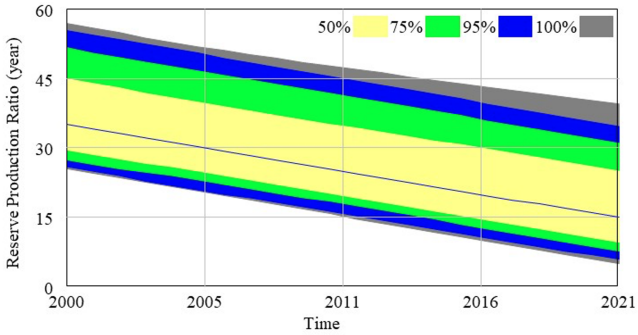

FIGURE 4. Sensitivity test on proven natural gas reserves

Component	Base value	Units	Range of uncertainty
Normal demand	53	bcm	Random uniform (33, 73)
Desired reserve- production ratio	20	years	Random uniform (15, 25)
Price adjustment delay	1	years	Random uniform (0.5, 2)

TABLE 2. Uncertain parameters in the natural gas exploration model

3.2. Scenario Analysis. Three potential policy interventions (scenarios) were investigated for their effects on usage rate, reserve production ratio, proven natural gas reserves and additions to proven natural gas reserves: scenario 1 (S1) investigates the effects of market-based pricing; scenario 2 (S2) considers change in demand; and scenario 3 (S3) investigates technical losses caused by a lack of maintenance reinvestment (Table 3). For the next 25 years, beginning in 2025, projections based on these policy scenarios are presented.

Scenario	Definition	Unit
BAU	Business as usual	–
S1	Market-based pricing	\$ / m^3
S2	Increase in demand	m^3
S3	Technical loss	%

TABLE 3. Summary of scenarios

3.3. Pricing Scenario. Scenario 1 demonstrates quantifiable enhancements in resource sustainability and consumption efficiency attributable to the transition to market-based pricing in 2025. By 2050, the Reserve-to-Production Ratio (RPR) stabilizes at 15 years (Figure 5), exceeding the 12 years projected under the Business-As-Usual (BAU) scenario. This stabilization indicates a gradual depletion of resources while simultaneously enhancing long-term durability.

A reduction in annual gas consumption from 52.47 billion cubic meters (bcm) in 2024 to 49.54 bcm in 2050 suggests that price signals effectively promote more judicious consumer behavior (Figure 6). These changes underscore the dual advantages of market reforms: they facilitate demand moderation through pricing elasticity and stimulate exploration investments. This scenario highlights the capacity of market-driven policies to bolster energy security and extend the lifespan of reserves, thereby enabling Uzbekistan's comprehensive transition to a sustainable energy framework.

As of January 1, 2021, the mechanism for determining end-use tariffs or tariffs for natural gas transmission and distribution in Uzbekistan had not been officially established. The Ministry of Finance and the Ministry of Energy use the cost-plus method to determine all natural gas rates. With the technical assistance of international financial institutions, foreign governmental financial organizations, and international consulting firms, a methodology for calculating tariffs for oil products, natural gas, and liquefied gas is being developed.

The new methodology is expected to account for the full recovery of operating, maintenance, and investment costs associated with natural gas production, processing, transportation, and sale. Under that regime, natural gas pricing will transition from a "production cost" model to a "market net return" framework. Upstream producers are likely to reduce investment in exploration and production activities. The domestic cost-plus regulated price for natural gas is lower than that of competing sources (Kenisarin, 2004). Implementing a market-driven pricing system will enhance the performance of downstream industries.

A market-based price, more specifically a supply and demand-regulated price, was tested in the pricing scenario. It is anticipated that gas prices will rise faster than in the baseline scenario. The price represents the average per cubic meter price for all gas sold during a

given time period. This value influences sales income and gas demand.

$$\text{New contract price} = \text{INTEG}\ (\text{change in NCP}, 30) \tag{13}$$

$$\begin{gathered}\text{Change in NCP} = \\ \text{Exploration Cost Effect on New Contract Price} \times \text{New Contract Price} \\ \text{Effect of Relative Inventory Ratio on NCP/Price Adjustment Delay}\end{gathered} \tag{14}$$

When the reserve-to-production ratio is around 20 years and the return on investment is moderate, producers typically limit their discovery investment to 25%. Historically, this has been the normal cost of exploration as a percentage of average income. When reserves exceed expectations, producers will reduce exploration to save further discoveries. Producers expect to increase their exploration investment if the RPR falls below the required ratio (Forrester, 1961, p. 15 Forrester 1961; Sterman & Richardson, 1985 Sterman and Richardson 1985).

$$\begin{gathered}\text{Effect of Relative Inventory Ratio on NCP} = f\Big(\text{Reserve production ratio}/ \\ \text{Desired reserve production ratio}\Big), \\ f' \geq 0.\end{gathered} \tag{15}$$

The RPR contrasts proven natural gas reserves with utilization rates. Producers raise prices to stabilize the RPR when it falls below the desired level. Higher prices dampen consumption, resulting in lower utilization. This shifts the RPR in favor of growth. The relative inventory ratio describes how producer prices are adjusted in response to changing supply and demand conditions (Bodger & May, 1992, Bodger and May 1992).

Figure 5: Simulation results for Reserve production ratio under the price change scenario The pricing reform scenario (S1) demonstrates that market-driven pricing mechanisms can enhance the sustainability of natural gas reserves by decreasing consumption and fostering reinvestment. However, pricing regulations alone may not sufficiently address the system's vulnerabilities, particularly if demand continues to escalate. The subsequent scenario (S2) examines the effects of increased consumption on reserve longevity and exploration dynamics, thereby highlighting the importance of demand fluctuations.

3.4. Demand Change Scenario. Scenario 2 anticipates a 25% escalation in demand commencing in 2025, leading to a rapid decline of the RPR to 8 years by 2050—significantly lower than the projections in the BAU scenario (Figure 7). Although the increase in consumption is not matched by a proportional rise in proven reserves, there is a marked increase in reserve additions (from 28 bcm/year in 2026 to 44 bcm/year by 2050) (Figure 8). The disparity between consumption and reserve replacement underscores a fundamental mismatch that accentuates the unsustainability of unchecked demand growth. This scenario illustrates the systematic vulnerabilities introduced by demand-side shocks, despite augmented supply-side investments. It necessitates the implementation of additional demand management strategies, such as energy conservation initiatives, strategic reserve planning, and diversification of renewable sources. The findings indicate that unrestrained demand may surpass even robust exploration efforts, ultimately jeopardizing national energy security.

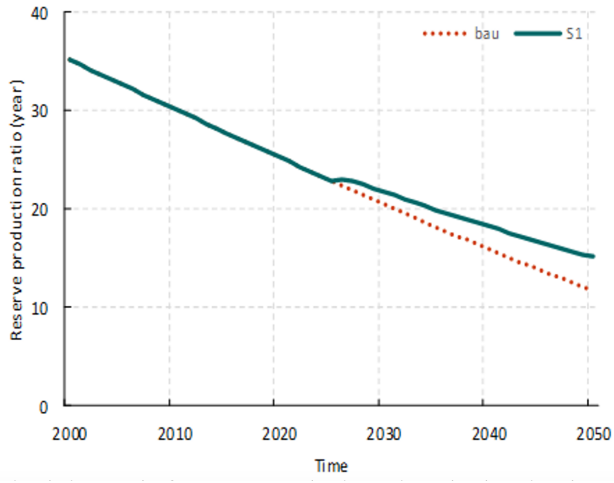

FIGURE 5. Simulation results for Reserve production ratio under the price change scenario

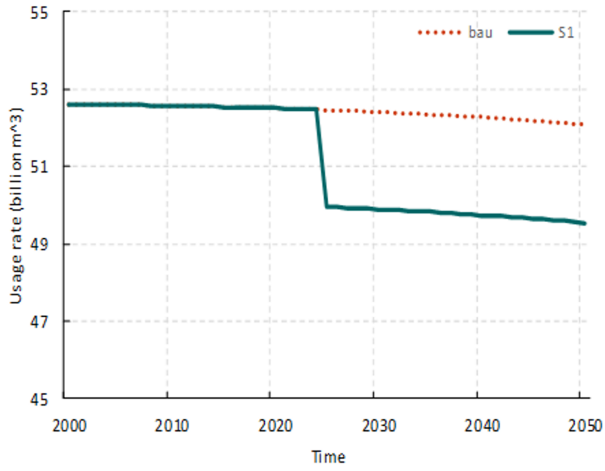

FIGURE 6. Simulation results for Usage rate under the price change scenario

$$\begin{gathered}\text{Price Effect on Demand} = f(\text{Relative price});\\ f' \le 0;\ f(0) = 5;\ f(1) = 1.\end{gathered} \tag{16}$$

Price setting is used by producers to respond to changing supply and demand situations in the price effect on demand. For extrapolating long-term behavior, this model takes into account the cyclical nature of economies. It allows for the simulation of both producer and consumer behavioral dynamics in the face of changing supply and pricing conditions:

consumption levels affect resource (un)availability, which in turn determines producer pricing strategy.

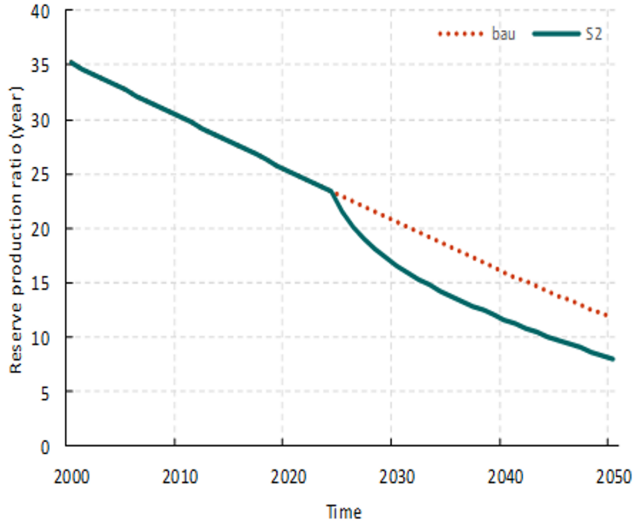

FIGURE 7. Simulation results for RPR under the demand change scenario

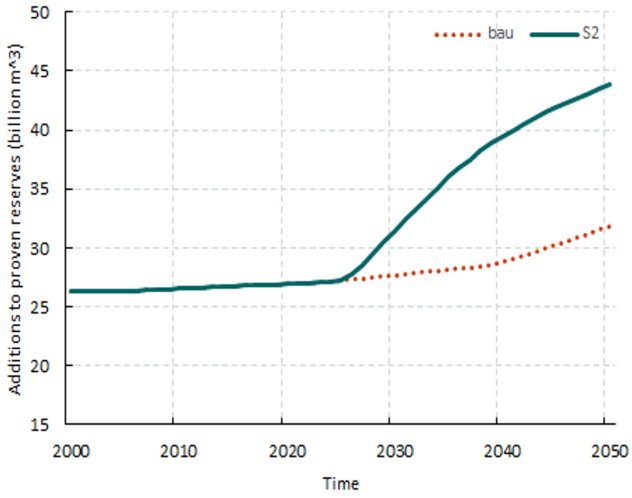

FIGURE 8. Simulation results for Additions to proven reserves under the demand change scenario

The second scenario assumed that interventions would increase (S2) by 25% from the baseline, while all other variables remained constant. This kind of change is common (Yukseltan *et al.*, 2021 Yukseltan *et al.* 2021).

3.5. Lack of Investment and Technical Deficiencies. Scenario 3 (S3) improves technical efficiency, and the simulation results are shown in Figure 10. Uzbekistan's lack of infrastructure maintenance and investment has resulted in inefficiency, limiting natural gas conversion to electricity in the past 30 years. Underutilization has resulted in high fixed maintenance costs per unit, risk of hazards, and economic losses (Ghazi & Hosseinzadeh Lotfi, 2019, Ghazi and Hosseinzadeh Lotfi 2019). Furthermore, insufficient capital reinvestment has resulted in technical losses equal to 15% of total Uzbek gas export volumes. This is a threat to the country's energy and economic security.

The outcomes of the demand escalation scenario (S2) highlight the system's vulnerability to uncontrollable consumption increases, even in the presence of stable pricing and investment conditions. Demand-side shocks expose inherent structural vulnerabilities, while operational inefficiencies may further exacerbate these effects. Consequently, Scenario 3 (S3) investigates the impact of technological constraints and deficiencies in reinvestment on the long-term efficacy of the system.

Scenario 3 reveals technological inefficiencies characterized by increased losses and diminished maintenance investment, resulting in lower reserve additions (Figure 9) and accelerated depletion of reserves. By 2050, proven reserve levels decline to 0.5 trillion cubic meters (m^3), compared to 0.6 trillion m^3 under business-as-usual conditions; annual reserve additions exhibit a shortfall of 5–6 bcm/year post-2024 (Figure 10). This scenario emphasizes the cumulative impact of infrastructure neglect, whereby avoidable losses manifest as a form of "hidden consumption". Despite consistent or modest increases in exploratory activity, the absence of maintenance and technological advancements precipitates a significantly more rapid depletion trend. These findings underscore the imperative of investing in the enhancement of gas infrastructure, including Supervisory Control and Data Acquisition (SCADA) systems, upgraded compression stations, and maintenance protocols, as a prerequisite for the sustainability of long-term reserves.

Reinvestments are critical for maintaining and upgrading the gas transmission system. There is still a financial need for maintenance and repair, such as compressors. For a national system of natural gas, significant capital investment is required for transmission modernization, automation, and system management. Capital expenditure is also necessary to improve existing operation through centralized monitoring and evaluation of supply and demand.

In accordance with Presidential Decree No. 4388, the restructuring of the joint-stock company "Uztransgaz" resulted in the establishment of the joint-stock companies "Hududgaztaminot" and "Uztransgaz." "Uztransgaz" is responsible for the procurement and distribution of natural gas from production and processing facilities, in addition to acting as the sole operator in the international natural gas trade. Furthermore, "Uztransgaz" provides natural gas to industrial enterprises that are strategically significant, such as thermal power facilities and the chemical industry. In contrast, the domestic gas distribution network is overseen by the joint-stock corporation "Hududgaztaminot" for commission-based sales.

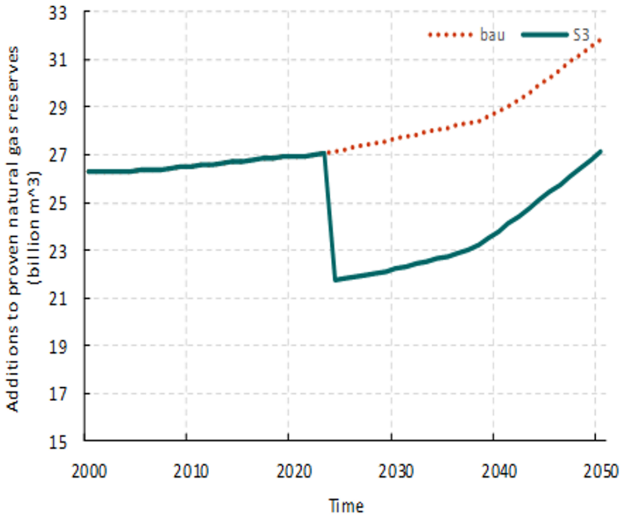

FIGURE 9. Simulation results for Additions to proven reserves under the technical loss scenario

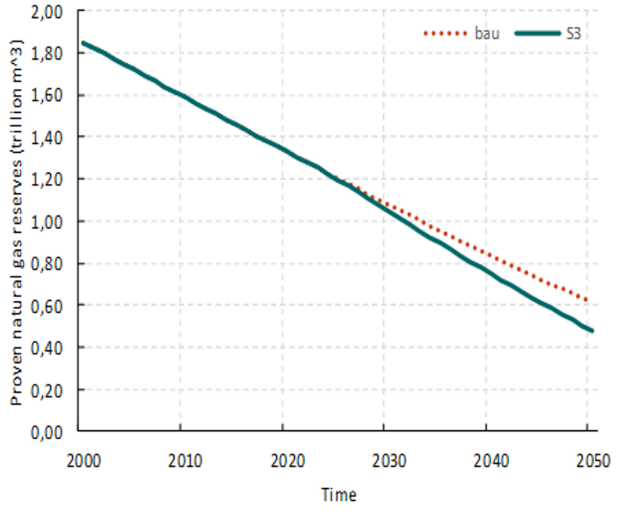

FIGURE 10. Simulation results for Additions to proven natural gas reserves under the technical loss scenario

Natural gas logistics market structure has consolidated in tandem with the industry's increasing technical efficiency. JSC "Hududgaztaminot" incurred 22% of natural gas loss in the region annually (Bozorov, 2021, Bozorov 2021), whereas "Uztransgaz" incurred 78% of natural gas loss. "Hududgaztaminot" in particular increased their market share to 51%.

The three scenarios collectively illustrate that Uzbekistan's natural gas security is contingent upon a delicate balance of pricing policy, demand management, and infrastructure efficiency. The comparative analysis of scenarios S1 through S3 underscores the imperative for a comprehensive policy strategy that simultaneously addresses the economic, technical, and environmental dimensions of the gas sector.

A comprehensive analysis of the three scenarios reveals the following key insights:

(1) While safeguarding supply security, pricing reforms (S1) serve as an effective mechanism for regulating demand and prolonging reserve longevity.
(2) Even with heightened exploration yields, unchecked demand growth (S2) can impose substantial stress on the system, necessitating a balanced approach that considers both supply and demand dynamics.
(3) Operational efficiency and reinvestment (S3) are as critical as exploration; neglecting technical losses will render reserve sustainability unattainable. The findings indicate that Uzbekistan's natural gas sector requires an integrated policy framework encompassing market reforms, demand-side efficiency, and infrastructure enhancement. Each scenario provides unique insights that collectively reinforce the central thesis of this paper: sustainable energy policy must regulate demand, enhance efficiency, and ensure reinvestment in resources and infrastructure.

The proposed system dynamics model provides a comprehensive framework for analyzing Uzbekistan's natural gas sector; however, several limitations warrant acknowledgment.

Firstly, the model initially excludes the direct effects of imports and exports on domestic supply dynamics. The cross-border gas trade, particularly with neighboring countries such as Kazakhstan and Turkmenistan, can significantly influence both pricing and reserve stability. The incorporation of trade flows in subsequent iterations of the model would augment the authenticity of simulated energy security scenarios.

Secondly, the model assumes a constant level of technological efficiency in exploration and production activities. Technological advancements, including advanced drilling techniques, reservoir monitoring, and carbon sequestration, can substantially affect production costs and the longevity of reserves. Future research may benefit from integrating dynamic characteristics to evaluate the impact of technology adoption and infrastructure improvements on the reserve-production ratio.

Additionally, the study predominantly focuses on domestic policy and market processes while overlooking potential external shocks such as geopolitical tensions, investment inflows, or fluctuations in global energy prices. The inclusion of exogenous factors in extended models could enhance the reliability of long-term forecasts.

Despite these limitations, the model remains a valuable analytical tool for examining the endogenous relationships among pricing, demand, and resource management within Uzbekistan's natural gas sector. Future enhancements will aim to integrate cross-border trade and technological advancements to improve the predictive and policy relevance of the model.

4. Conclusion and policy implications

This research employed a system dynamics methodology to assess Uzbekistan's natural gas industry and its significance for national energy security. The findings indicate that pricing mechanisms, demand expansion, and infrastructure efficiency are critical determinants influencing long-term reserve sustainability and overall system stability. Scenario analyses suggest several practical policy recommendations:

(1) Implement a gradual transition to market-driven gas pricing from 2025 to 2030. Transitioning from cost-plus to market-based pricing will enhance investment incentives, promote exploration, and improve fiscal transparency. Regulatory measures should be instituted to mitigate price volatility for vulnerable consumers.
(2) Enhance energy efficiency through demand-side management by 2030. The implementation of incentive programs for industrial modernization, smart metering, and energy-efficient technologies can help reduce excessive gas consumption and align demand with sustainable supply levels.
(3) Allocate resources for infrastructure modernization and digital surveillance systems from 2025 to 2035. Upgrading pipelines, storage, and compression facilities—supplemented by digital SCADA and real-time diagnostics—will decrease technical losses and extend asset longevity.
(4) Broaden the national energy portfolio by 2040. Increasing investments in renewable and low-carbon energy sources, such as solar, wind, and nuclear power, will reduce dependence on natural gas, alleviate supply challenges, and meet Uzbekistan's decarbonization commitments.
(5) Establish long-term regional cooperation frameworks for natural gas commerce. Collaborative infrastructure and trade strategies with Central Asian partners will enhance supply resilience and optimize transboundary energy flows.

This study not only possesses significant policy implications but also contributes to the existing literature by offering a comprehensive and context-specific system dynamics model tailored for a resource-dependent transition economy such as Uzbekistan. This methodology integrates technical, economic, and regulatory characteristics through a cohesive feedback mechanism, diverging from traditional energy models that typically isolate supply and demand factors. Moreover, it incorporates dynamic reinvestment mechanisms that elucidate the relationship between gas revenues, exploration activities, and depletion rates—an aspect that has been infrequently addressed in prior research. Additionally, the research broadens the application of system dynamics in energy policy by modeling regulatory transitions from monopolistic control to partial liberalization and assessing the impacts of various pricing strategies and efficiency improvements. These enhancements facilitate a more nuanced understanding of the interaction between policy reforms and technological advancements in shaping long-term energy security outcomes. These recommendations collectively form a cohesive policy framework that integrates economic efficiency, energy security, and sustainability. Future research should expand the existing model to incorporate international trade dynamics, technological advancements, and renewable energy integration to create a comprehensive foundation for long-term energy planning.

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Paper contributed to the #ApplMath2025 International Workshop
held in Messina, Italy (9-11 June 2025) under the patronage of the *Accademia Peloritana dei Pericolanti.*

Manuscript received 25 June 2025; published online 18 November 2026

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