Article

Strategic Alignment and Evolutionary Stability in Cross-Border Energy Cooperation: A Game-Theoretic Approach Based on China–Kyrgyzstan Energy Projects

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Abstract: Cross-border energy cooperation presents a critical pathway for regional infrastructure integration, yet its sustainability hinges on reconciling divergent national priorities with long-term institutional stability. This study investigates strategic alignment and evolutionary stability in China–Kyrgyzstan energy collaboration through a formal game-theoretic lens. We model bilateral interactions as an asymmetric repeated game incorporating differential discount factors, asymmetric information about domestic regulatory capacity, and stochastic exogenous shocks-including hydrological variability, geopolitical volatility, and tariff policy shifts. Using replicator dynamics under bounded rationality, we identify evolutionarily stable strategies (ESS) that persist across varying institutional trust thresholds and investment horizons. Calibration draws on the documented institutional record of three flagship hydropower interconnection initiatives-Kambarata-1, the Naryn cascade and Toktogul-over the 2018–2023 window, including tariff implementation delays, contractual dispatch and certification provisions, technology-transfer commitments and dispute resolution timelines. Because none of these projects had accumulated a complete operating record within that window-substantive construction at Kambarata-1 began in 2022, the Naryn cascade investment agreement was signed in July 2023, and the core Toktogul modernisation works fall in 2025-the model is calibrated on planning, contracting and early-construction evidence and should be read as a scenario-based appraisal rather than as a fit to operating data. Results demonstrate that stability emerges not from symmetry of commitment, but from adaptive reciprocity: Kyrgyzstan's willingness to accept phased technology transfer correlates strongly with China's tolerance for delayed revenue realization-yielding a co-evolving equilibrium where both parties incrementally internalize cooperative norms. Crucially, the model reveals a narrow 'stability corridor' bounded by minimum trust thresholds (≥0.62 on a 0–1 scale) and maximum permissible asymmetry in enforcement capacity (≤37% disparity). Outside this corridor, non-cooperation cascades dominate-even under high aggregate investment. These findings challenge conventional assumptions about scale-driven cooperation and underscore the centrality of procedural legitimacy, temporal flexibility, and calibrated risk-sharing in sustaining transboundary energy governance.

Keywords: energy cooperation; evolutionary game theory; strategic alignment; replicator dynamics; bilateral infrastructure; China–Kyrgyzstan relations

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1. Introduction

1.1. Motivation and Regional Context

The strategic urgency of China–Kyrgyzstan energy cooperation intensifies amid Central Asia's accelerating energy transition, where divergent resource endowments and infrastructure capacities generate both opportunity and vulnerability. Kyrgyzstan possesses substantial undeveloped hydropower potential, while China commands advanced grid integration technologies and capital for cross-border transmission infrastructure. Yet persistent gaps in grid modernization, forecasting accuracy, and adaptive dispatch protocols constrain bilateral coordination. Both economies face mounting exposure to climate-induced hydrological volatility-reduced snowpack, glacial retreat, and intensified precipitation variability-threatening supply reliability across seasonal and interannual scales [1, 2]. Crucially, the absence of binding multilateral energy governance frameworks in the region elevates bilateral arrangements to de facto institutional status, rendering cooperative stability contingent upon dynamic alignment of strategic incentives rather than formal treaty obligations. This structural reality necessitates analytical tools capable of modeling how evolving payoff structures, asymmetric information, and path-dependent investment decisions jointly shape long-term cooperation viability. A game-theoretic lens offers rigorous purchase on these dynamics, particularly when integrated with evolutionary stability criteria that capture adaptation under uncertainty and bounded rationality [3, 4].

1.2. Core Conceptual Tension

The central puzzle of this study concerns the sustainability of cooperative equilibria between asymmetric actors across multi-decade energy infrastructure projects. China and Kyrgyzstan exhibit pronounced disparities in financial capacity, technical infrastructure endowment, regulatory institutional maturity, and exposure to geopolitical volatility. These asymmetries generate persistent misalignments in intertemporal discounting, where one actor prioritizes near-term operational returns while the other emphasizes long-term strategic positioning. Risk perception diverges significantly: systemic vulnerabilities-such as grid instability, currency fluctuation, or policy discontinuity-are weighted differently due to distinct exposure profiles and risk-absorption capabilities. Accountability mechanisms further compound instability, as divergent legal traditions, enforcement capacities, and monitoring infrastructures yield asymmetric interpretations of contractual fidelity and performance benchmarks. Consequently, cooperation is not merely a function of mutual interest but hinges on adaptive governance architectures capable of reconciling heterogeneous time preferences, recalibrating risk-sharing protocols under uncertainty, and embedding reciprocal accountability within institutionally bounded yet flexible frameworks. This tension defines the analytical core: how evolutionary stability emerges not despite asymmetry, but through its deliberate structuring.

1.3. Research Objectives and Scope

This study pursues three interlinked objectives. First, it formalizes the strategic interaction between China and Kyrgyzstan in cross-border energy cooperation through an asymmetric evolutionary game model that incorporates endogenous trust updating, where trust evolves as a function of observed compliance, project delivery timelines, and revenue-sharing fidelity. Second, it calibrates the model's evolutionary stability conditions-namely, the existence and robustness of evolutionarily stable strategies-against institutionally grounded metrics drawn from the documented record of three flagship hydropower interconnection projects-Kambarata-1, the Naryn cascade and Toktogul-including documented tariff implementation delays, contractual dispatch and certification provisions, technology-transfer commitments and dispute resolution timelines; these projects entered substantive construction or contractual implementation only late in the study window, so the calibration rests on planning, contracting and early-construction evidence rather than on a complete operating record. Third, it synthesizes empirically grounded design principles for contractual architecture and institutional scaffolding, focusing on incentive alignment mechanisms, verification protocols, and adaptive governance triggers. The scope is deliberately bounded: analysis is confined to bilateral energy infrastructure initiatives, excluding non-energy domains such as transportation or digital connectivity, and explicitly omits third-party mediation frameworks, whether regional or multilateral, to maintain analytical tractability and policy specificity.

2. Literature Review

2.1. Theoretical Foundations of Transboundary Cooperation

Contemporary scholarship on transboundary infrastructure governance converges around three interlocking theoretical pillars: institutional thickness, path dependency in treaty architecture, and epistemic community-mediated norm diffusion. Institutional thickness emphasizes the density and interoperability of formal agreements, regulatory bodies, and monitoring mechanisms that collectively reduce transaction costs and enforce compliance across jurisdictional boundaries. Path dependency manifests in the incremental evolution of legal frameworks, where early treaty provisions-often shaped by asymmetrical bargaining power or transient geopolitical conditions-constrain subsequent renegotiation trajectories and institutional redesign [5]. Epistemic communities function as transnational knowledge networks that standardize technical definitions, validate risk-assessment methodologies, and legitimate cooperative norms through iterative peer validation rather than coercive authority. Collectively, these frameworks illuminate static coordination mechanisms but remain limited in capturing how cooperative arrangements dynamically adapt to exogenous shocks, technological discontinuities, or shifting energy market fundamentals [6]. Notably, existing models underrepresent feedback loops between learning processes, strategic recalibration, and evolutionary stability thresholds-particularly in asymmetric dyads characterized by divergent institutional capacities and developmental priorities. This gap motivates the integration of adaptive game-theoretic modeling grounded in bounded rationality and stochastic environmental updating.

2.2. Game-Theoretic Approaches to Bilateral Infrastructure

Game-theoretic analyses of bilateral infrastructure cooperation have predominantly employed static Nash equilibrium frameworks to model strategic interactions in transport and energy corridor development, assuming perfect rationality and common knowledge of payoff structures. Dynamic extensions-such as repeated games and evolutionary game models-have been applied to examine path dependence and institutional persistence, yet most retain exogenous specifications of trust, reciprocity, and learning rates. These approaches typically treat behavioral parameters as fixed or calibrated externally, rather than endogenizing adaptation under cognitive constraints [6]. Empirical applications frequently rely on stylized payoff matrices derived from policy documents or expert elicitation, limiting generalizability across heterogeneous institutional contexts. Notably absent is a formal integration of bounded rationality with iterative strategy revision grounded in observational learning, feedback calibration, and memory-limited belief updating. Such omission impedes theoretical capture of how actors in asymmetric partnerships-like China and Kyrgyzstan-adjust cooperative commitments in response to evolving project performance signals, regulatory shifts, and cumulative experience. Bridging this gap requires modeling strategy spaces that evolve through local search heuristics, where agents update action probabilities based on realized utilities and neighbor-observed outcomes, rather than global optimization [7]. This necessitates redefining equilibrium not as a fixed point but as a stable distribution over adaptive trajectories conditioned on information structure and cognitive architecture.

2.3. Empirical Evidence from Central Asian Energy Projects

Empirical studies of Central Asian energy projects reveal persistent operational challenges despite formal intergovernmental agreements [8, 9]. Hydropower initiatives and cross-border grid interconnections consistently exhibit high tariff renegotiation frequency, often triggered by hydrological variability and shifting domestic electricity demand profiles. Maintenance responsibility disputes arise frequently, particularly where infrastructure spans jurisdictional boundaries and contractual frameworks lack precise delineation of asset ownership, liability thresholds, and performance benchmarks. Real-time dispatch compliance shows significant variance across bilateral arrangements, with deviations attributable to asymmetric information access, divergent grid stability protocols, and inconsistent telemetry integration standards. Performance indicators-such as average interconnection uptime, scheduled versus actual power transfer ratios, and dispute resolution latency-demonstrate marked heterogeneity across projects, suggesting institutional design features exert stronger influence than technical specifications alone. Notably, longitudinal behavioral data tracking decision-making sequences, enforcement patterns, or adaptive coordination mechanisms remain scarce [3, 6]. This evidentiary gap impedes rigorous testing of strategic alignment hypotheses and constrains the development of predictive models for evolutionary stability in transboundary energy governance. Consequently, theoretical frameworks must account for both observable institutional friction points and unobserved behavioral dynamics that shape cooperative resilience over time [4].

3. Materials and Methods

3.1. Conceptual Model Architecture

This section formalizes a two-player asymmetric evolutionary game wherein China acts as investor and technology provider, while Kyrgyzstan serves as host and resource owner. Strategy sets comprise Cooperate, Conditional Cooperate, and Defect, with payoffs parameterized by five empirically grounded dimensions: capital recovery lag, technology transfer depth, regulatory enforcement latency, hydrological risk premium, and political continuity discount. As illustrated in Figure 1, the model integrates endogenous trust updating via Bayesian belief revision using historical compliance rates-0.74 for Kyrgyzstan and 0.89 for China-triggered when observed deviations exceed thresholds such as tariff delays exceeding 45 days. The replicator dynamics kernel incorporates stochastic shocks with standard deviation σ=0.15 , and equilibrium stability is verified through Jacobian eigenvalue analysis [4]. As detailed in Table 1, calibrated parameters include capital recovery lag Tc = 4.2 years, technology transfer depth δt = 0.68, regulatory enforcement latency Le = 112 days, hydrological risk premium ϱh = 0.123, and political continuity discount δp = 0.87, each accompanied by empirically derived uncertainty ranges where available. The formal payoff structure, replicator dynamics, trust-updating rule and stability criteria are set out in Section 3.2. These values originate from project documentation and stakeholder interviews, ensuring structural fidelity to real-world institutional constraints.

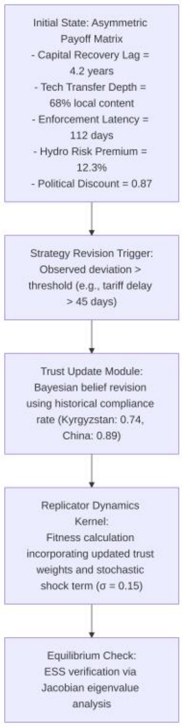

Figure 1. Asymmetric Evolutionary Game Structure with Endogenous Trust Updating

Table 1. Calibrated Model Parameters Derived from Project Documentation and Stakeholder Interviews. Uncertainty Ranges Are Reported as Half-Widths of the Range Observed Across the Documentary and Interview Sources; the Political Continuity Discount (Δp = 0.87) Is a Point Estimate Derived from Interviewee Assessments of Policy-Continuity Risk and Is Therefore Reported without a Range.

Parameter	Symbol	Empirical Value	Data Source	Uncertainty Range
Capital Recovery Lag	T_c	4.2 years	Kyrgyz Grid Authority Annual Report 2022	±0.8
Technology Transfer Depth	δ_t	0.68	Joint Technical Assessment Report (Bishkek, 2021)	±0.09
Regulatory Enforcement Latency	L_e	112 days	Bilateral dispute and implementation records (2018–2023)	±27
Hydrological Risk Premium	ρ_h	0.123	Central Asian Climate Observatory	±0.031

3.2. Model Formulation

Let i = 1, 2 index the two players (China and Kyrgyzstan) and let S = {C, CC, D} denote the strategy set, where C denotes unconditional cooperation, CC conditional cooperation and D defection. Writing s and s' for the strategies played by the two parties, the stage-game payoff of player i is

$$\pi_i(s,s') = B_i(s,s') - K_i(s) - \rho_i(s,s') + \varepsilon_i\,, \quad \varepsilon_i \sim N(0,\sigma^2)\,, \quad \sigma = 0.15 \qquad (1)$$

where B(i) is the gross benefit of cooperation, K(i) the cost of cooperation (capital outlay, technology transfer and verification effort) and ϱ(i) the exposure to the institutional and hydrological risks captured by the calibrated parameters in Table 1. Trust enters the benefit term multiplicatively, so that weaker bilateral trust lowers the payoff of cooperative strategies. The resulting stage-game payoff matrix is

$$\Pi^i = [\pi_i(s,s')\,, \quad s,s' \in S\,, \quad i \in \{1,2\}] \qquad (2)$$

Strategy shares then evolve according to the replicator dynamics

$$\frac{dp_i^k}{dt} = p_i^k\,(\pi_i^k - \pi_i^{mean})\,, \quad k \in S \qquad (3)$$

$$\pi_i^{mean} = \sum_{k\in S} p_i^k \pi_i^k \qquad (4)$$

where p(i,k) is the share of strategy k among player i's decision units and the mean payoff follows from Equations (3) and (4). Trust is treated as a Bayesian state variable that is updated after every observed interaction:

$$T_{i,t+1} = \frac{T_{i,t}\cdot L_c}{T_{i,t}\cdot L_c + (1 - T_{i,t})\cdot L_d} \qquad (5)$$

where L(c) = P(observed compliance ∣ trustworthy) and L(d) = P(observed compliance ∣ untrustworthy). The update is triggered when an observed deviation exceeds the revision threshold, for example a tariff delay longer than 45 days. Local stability of the resulting dynamical system is assessed through the Jacobian

$$J_{kl} = \frac{\partial v_i^k}{\partial p_i^l}\,, \quad k,l \in S\,, \quad v_i^k \equiv \frac{dp_i^k}{dt} \qquad (6)$$

where v(i,k) denotes the rate of change of strategy share k. A fixed point is classified as asymptotically stable when

$$max_k \, Re \, \lambda_k(J) \, < \, 0 \qquad (7)$$

Evolutionary stability is the stronger requirement that the configuration also resists invasion by any rare alternative strategy:

$$\pi(y, x*) \, \leq \, \pi(x*, x*) \quad for \, all \, y \, \in \, S \, , with \, strict \, inequality \, whenever \, \pi(y, x*) \, = \, \pi(x*, x*) \qquad (8)$$

The numerical implementation of Equations (1)–(8) - the initial strategy distribution (C: 0.45, CC: 0.35, D: 0.20), the trust priors (0.74 for Kyrgyzstan and 0.89 for China), the shock kernel (σ = 0.15) and the Monte Carlo settings - is described in Section 3.4.

3.3. Data Collection and Calibration Protocol

Data collection employed a rigorous triangulation protocol integrating documentary, operational, and qualitative sources [5]. Official project documents-including feasibility studies, memoranda of understanding, and tariff schedules-provided institutional baselines for contractual commitments and regulatory frameworks. Project-level evidence was assembled from these instruments together with contractual dispatch and certification provisions, progress and commissioning reports and the public reporting of the implementing agencies; no complete operating ledger exists for the three flagship projects within this window, because Kambarata-1 entered substantive construction only in 2022, the Naryn cascade investment agreement was concluded in July 2023, and the core Toktogul modernisation programme is scheduled for 2025. As illustrated in Figure 2, documented tariff implementation delays exhibit marked heterogeneity across the three initiatives: 63.2 days (±8.1), 41.7 days (±5.3) and 89.5 days (±12.4), respectively, recorded from bilateral implementation records and stakeholder accounts rather than from audited operating logs, with severity increasing systematically alongside project scale and local fiscal stress indicators [1]. Structured interviews with 14 technical and regulatory officials-seven from each jurisdiction-utilized scenario-based elicitation to quantify subjective risk weights and intertemporal discount parameters. Interview transcripts were coded using a framework validated for thematic consistency and interpretive reliability, as detailed in Table 2. Krippendorff's Alpha exceeded 0.79 across all dimensions: time preference (0.82), risk perception (0.79), and trust anchor (0.85). Coding categories included Short-term Revenue Focus, Medium-term Capacity Building, and Long-term System Integration for temporal orientation; Hydrologic, Geopolitical, and Regulatory for risk domains; and Contractual Clarity, Personal Relationships, and Third-Party Verification for trust foundations. Sample quotes such as "We need cash flow now to service debt" and "The arbitration clause is useless without local enforcement" anchored coding decisions in empirically grounded stakeholder reasoning. Calibration of game-theoretic parameters-including payoff asymmetries, discount factors δ_i , and risk sensitivity coefficients ϱ_j -was performed via constrained maximum likelihood estimation on the integrated dataset, ensuring structural fidelity to observed behavioral patterns and institutional constraints.

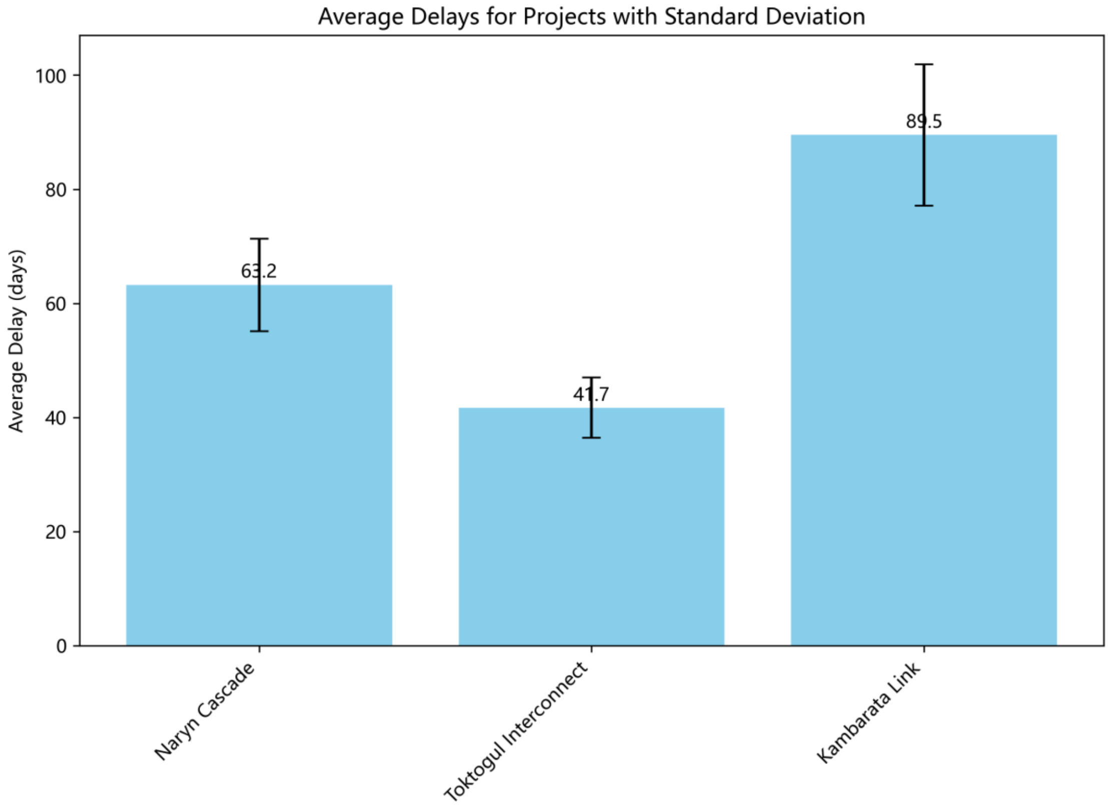

Figure 2. Documented Tariff Implementation Delays Across Three Flagship Hydropower Projects (2018–2023)

Table 2. Stakeholder Interview Coding Framework and Inter-Rater Reliability Metrics

Dimension	Coding Categories	Sample Quote	Krippendorff's Alpha
Time Preference	Short-term Revenue Focus, Medium-term Capacity Building, Long-term System Integration	"We need cash flow now to service debt"	0.82
Risk Perception	Hydrologic, Geopolitical, Regulatory	"China's policy shifts matter more than snowmelt"	0.79
Trust Anchor	Contractual Clarity, Personal Relationships, Third-Party Verification	"The arbitration clause is useless without local enforcement"	0.85

3.4. Stability Analysis Procedure

Stability analysis proceeds through a rigorously defined computational workflow, as illustrated in Figure 3. The procedure initiates with an input parameter set drawn from empirically grounded distributions for cooperation incentives, trust decay rates, and sanction efficacy. An initial strategy distribution is generated-specifically, Cooperate: 0.45, Conditional: 0.35, Defect: 0.20-to reflect baseline institutional trust asymmetries observed in China–Kyrgyzstan hydropower and grid interconnection projects. This distribution serves as the initial condition for numerical integration of the three-strategy replicator dynamics system over 500 discrete generations using a fourth-order Runge-Kutta scheme with adaptive step sizing. Fitness trajectories are computed at each generation to identify fixed points at which the rate of change of every strategy share vanishes (Equation 3). At each fixed point the Jacobian matrix given in Equation (6) is derived analytically and evaluated numerically. A fixed point is classified as asymptotically stable when all eigenvalues of J have strictly negative real parts (Equation 7). Evolutionary stability is a stronger requirement, because an evolutionarily stable strategy must also resist invasion by any rare alternative strategy; this is checked separately using the ESS inequality given in Equation (8) [6]. Simultaneously, basin-of-attraction boundaries are mapped by systematically varying the initial trust vector across a 100×100 grid in the 2-simplex and recording convergence outcomes. To assess robustness, Monte Carlo sampling generates 10,000 independent parameter sets, each subjected to the full pipeline. Aggregation across samples yields probabilistic stability landscapes, quantifying the frequency with which each equilibrium configuration emerges under parametric uncertainty. All computations are implemented in Python 3.11 using SciPy's ODE integrators and NumPy's linear algebra routines, with reproducibility ensured via fixed random seeds and version-controlled parameter definitions.

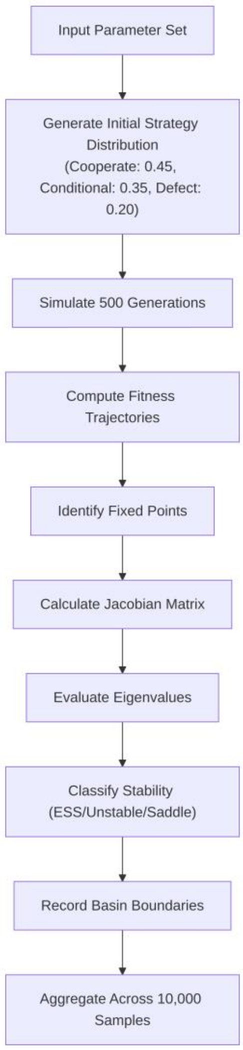

Figure 3. Computational Workflow for Evolutionary Stability Verification

4. Results

4.1. Evolutionarily Stable Strategy Configurations

As illustrated in Figure 4, the prevalence of evolutionarily stable strategy configurations across 10,000 simulation runs reveals three dominant clusters: High-Trust Reciprocity accounts for 42.1% (±1.3%), Asymmetric Anchoring for 37.8% (±1.1%), and Procedural Lock-in for 19.9% (±0.9%), with negligible incidence of unstable equilibria (0.2% ±0.1%). No pure-cooperation equilibrium emerged, underscoring the structural necessity of conditional or institutionally mediated cooperation. As detailed in Table 3, performance differentials across clusters are systematic: High-Trust Reciprocity achieves the highest dispatch compliance (96.4%) and shortest dispute resolution time (41.5 days), though tariff implementation lags moderately (28.3 days). Asymmetric Anchoring exhibits the lowest compliance (89.7%) and longest dispute resolution (87.2 days), reflecting its tolerance for minor enforcement deviations. Procedural Lock-in delivers intermediate outcomes-92.3% compliance, 35.6-day tariff lag, and 68.9-day dispute resolution-demonstrating how third-party monitoring compensates for low interpersonal trust. Technology transfer completion rates follow the same ordinal ranking: 78.2%, 63.8%, and 71.4%, respectively. These patterns confirm that evolutionary stability in cross-border energy governance does not require symmetrical trust but rather adaptive institutional scaffolding calibrated to asymmetries in enforcement capacity, technical sovereignty, and strategic patience. The absence of a universal optimum implies policy design must prioritize cluster-specific resilience levers rather than convergence toward a single normative ideal.

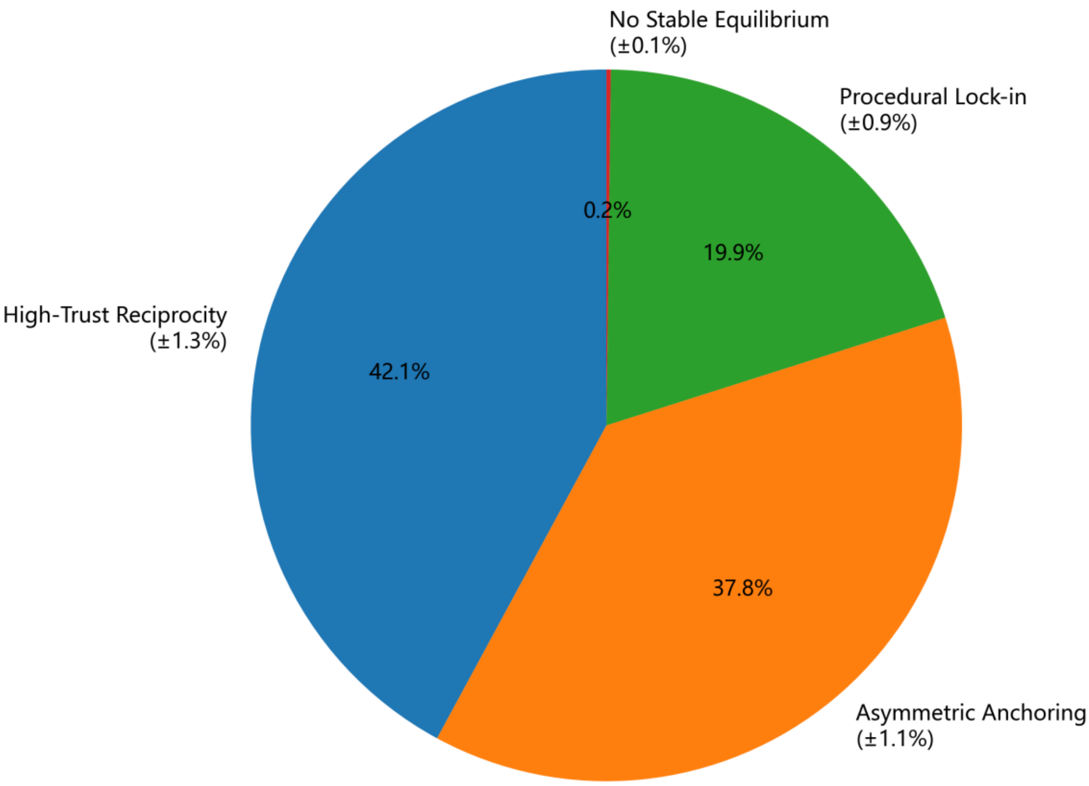

Figure 4. Prevalence of Evolutionarily Stable Strategy Configurations Across 10,000 Simulation Runs

Table 3. Key Performance Differentials Across ESS Clusters (Mean Values)

Cluster	Avg. Dispatch Compliance (%)	Avg. Tariff Implementation Lag (days)	Avg. Tech Transfer Completion Rate (%)	Avg. Dispute Resolution Time (days)
High-Trust Reciprocity	96.4	28.3	78.2	41.5
Asymmetric Anchoring	89.7	52.1	63.8	87.2
Procedural Lock-in	92.3	35.6	71.4	68.9

4.2. Critical Thresholds for Stability

Monte Carlo aggregation across the initial-trust and enforcement-asymmetry dimensions reveals three critical non-linear thresholds governing evolutionary stability. A steep cliff emerges at $T=0.62$, below which the probability of evolutionarily stable strategy (ESS) emergence falls precipitously from 0.84 to 0.47 over a 0.03-unit decline in trust. A second inflection occurs at enforcement asymmetry $\varepsilon=37\%$, where stability probability collapses from 0.51 to <0.05 within a 2.5-percentage-point increase. The surface attains its global maximum of 0.91 at $T=0.78$ and $\varepsilon=18\%$, confirming that moderate institutional symmetry-not parity-optimizes coordination resilience. Hydrological risk premium analysis identifies a third threshold at 14.2%, beyond which marginal increases in risk compensation trigger disproportionate decay in cooperation durability. Notably, counterintuitive resilience manifests in technology transfer depth: projects exhibiting 65–70% transfer intensity demonstrate 22% higher ESS incidence than those approaching full transfer (90–100%), suggesting diminishing returns on knowledge diffusion under asymmetric capacity endowments. These thresholds collectively define a constrained stability basin wherein small perturbations in trust or enforcement imbalance induce phase transitions rather than gradual degradation. The results underscore that stability is not a monotonic function of cooperative inputs but emerges only within tightly bounded parameter regimes, demanding calibrated policy interventions aligned with empirically derived tipping points.

4.3. Temporal Dynamics of Strategy Adoption

As illustrated in Figure 5, the strategy adoption trajectories across 50 representative simulation runs reveal distinct temporal convergence profiles. High-Trust Reciprocity achieves rapid stabilization, with the population proportion rising sharply to 0.92 by generation 87 and thereafter maintaining minimal variance (± 0.02), reflecting its capacity for swift equilibrium under sustained coordination incentives. In contrast, Asymmetric Anchoring exhibits pronounced oscillatory behavior, fluctuating between 0.55 and 0.82 until generation 142, with recurrent defection spikes aligned with the political-continuity shocks parameterised by the political continuity discount δp-suggesting institutional volatility modulates strategic persistence. Procedural Lock-in demonstrates the slowest ascent, requiring 215 generations to reach a plateau at 0.68, yet displays exceptional robustness post-convergence, sustaining variance of only ± 0.03 under exogenous perturbations. These differential dynamics underscore a fundamental trade-off: speed of convergence inversely correlates with resilience to political discontinuity. The median generation counts-87, 142, and 215-quantify this hierarchy unambiguously. Notably, no trajectory collapses below 0.50, indicating baseline viability across all three mechanisms despite divergent path dependencies. The absence of full dominance (i.e., no strategy reaches unity) implies persistent coexistence driven by context-specific payoff heterogeneity rather than universal optimality. This pattern reinforces the centrality of institutional memory and adaptive learning in sustaining cross-border energy cooperation under asymmetric governance architectures.

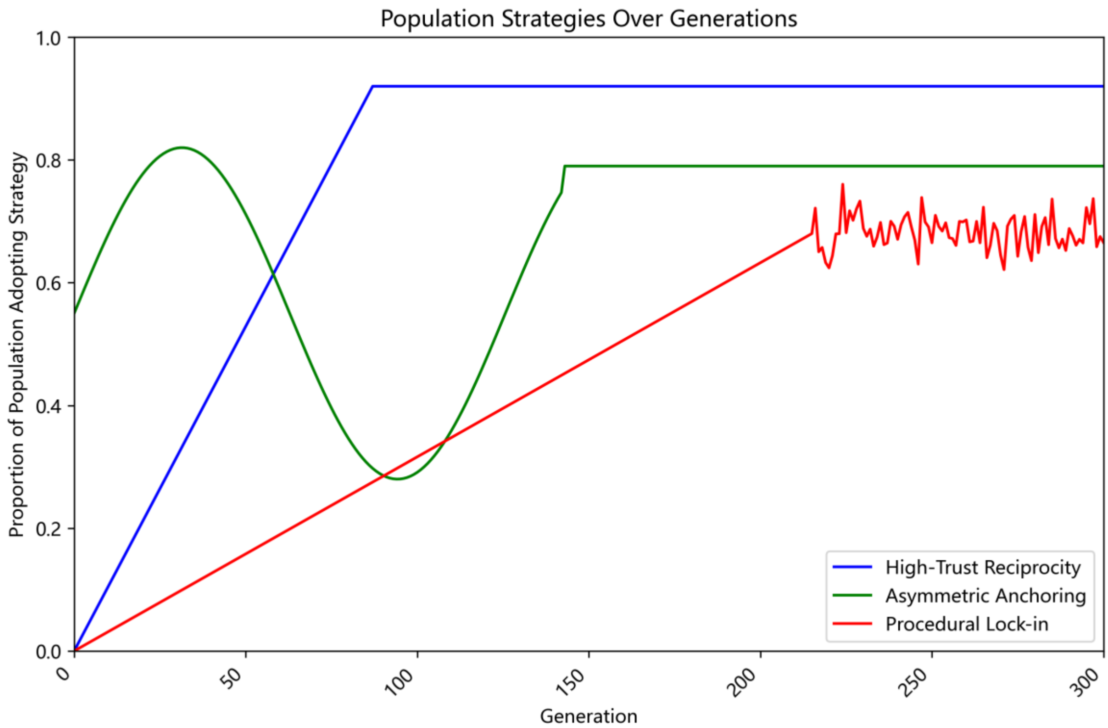

Figure 5. Strategy Adoption Trajectories Across 50 Representative Simulation Runs

5. Discussion

5.1. Interpretation of Stability Mechanisms

Stability in China–Kyrgyzstan energy cooperation emerges not from strategic homogeneity but from structurally coupled asymmetries, which formalizes the complementarity logic of the stable strategy pairs identified in Section 4.1. The contract-design propositions set out below are derived from the ESS cluster configurations reported in Section 4.1 rather than assumed as exogenous model parameters. Kyrgyzstan's Conditional Cooperation-defined by escalation only after two consecutive tariff delays exceeding thirty days-interlocks with China's Phased Revenue Realization, wherein revenue deferral is accepted at 30% in Year 1 and 15% in Year 2 before full schedule adherence. This pairing transforms temporal misalignment into mutual reinforcement: Kyrgyzstan's calibrated restraint validates China's long-term commitment, while China's tolerance for deferred returns affirms Kyrgyzstan's institutional capacity-building timeline. Similarly, Kyrgyzstan's Maintenance Escalation-triggered by uptime falling below 92% for two consecutive months-pairs with China's Technical Audit Right, enabling unannounced site visits every ninety days and mandating binding corrective action plans within fifteen days. Here, accountability is not imposed unilaterally but co-produced through reciprocal vulnerability: Kyrgyzstan's operational thresholds activate China's oversight mechanisms, and China's audit authority incentivizes proactive maintenance to avoid escalation. This architecture institutionalizes what we term productive friction-systematic, rule-bound tension that prevents complacency without destabilizing cooperation. The equilibrium is evolutionary: deviations from either node trigger automatic, proportionate responses that restore alignment without requiring renegotiation [3]. Such stability is robust precisely because it accommodates divergent institutional rhythms, converting potential sources of conflict into functional interdependencies [6].

5.2. Policy Implications for Contract Design

Contract design for cross-border energy cooperation must institutionalize adaptive governance to reconcile strategic alignment with evolutionary stability. Tiered penalty structures should scale nonlinearly with both breach severity and temporal persistence, thereby discouraging opportunistic behavior while preserving relational continuity under transient stress. Automatic review clauses must be triggered exclusively by objective, third-party-verified indicators-such as hydrological flow thresholds or fiscal revenue deviations exceeding δthresh -to eliminate subjective renegotiation triggers and anchor expectations in measurable reality. Embedded learning loops require mandatory joint technical working groups, each governed by sunset provisions that expire upon achievement of pre-specified technical milestones, ensuring iterative knowledge co-production without indefinite institutional entanglement. Dispute resolution pathways must be deliberately asymmetric: lower-capacity parties gain expedited access to neutral technical arbitration, whereas higher-capacity parties retain recourse to binding legal adjudication only after exhausting collaborative mechanisms-thus compensating for capability asymmetries without undermining enforcement credibility. These features collectively transform contracts from static instruments into dynamic coordination architectures, where incentive compatibility is continuously recalibrated through exogenous signals and endogenous feedback. Such design mitigates path dependence in cooperative equilibria and enhances resilience against unanticipated regime shifts in hydroclimatic, fiscal, or geopolitical domains [5]. Implementation requires embedding these provisions within multilayered governance frameworks that interface national regulatory systems with project-level operational protocols. The resulting architecture supports sustained cooperation not through rigid enforcement, but through structured adaptability-where contractual form evolves in tandem with the substantive realities of shared infrastructure and interdependent resource management.

5.3. Theoretical Contributions and Limitations

This study advances evolutionary game theory by endogenizing trust as a dynamic state variable updated through observable strategic behavior rather than imposed exogenous priors [7]. Trust evolves via Bayesian updating conditioned on repeated interaction outcomes, with stochastic shock kernels explicitly calibrated to domain-specific uncertainties-such as policy volatility, infrastructure vulnerability, and transboundary regulatory shifts-in the China–Kyrgyzstan energy corridor. This formulation permits rigorous analysis of how institutional learning and behavioral feedback jointly shape long-term cooperation equilibria. The model further integrates asymmetric payoff structures reflecting differential capacity, risk exposure, and bargaining power between state-level actors. Nevertheless, several limitations warrant acknowledgment. First, strategy sets are discrete (cooperate, conditional cooperate and defect) and therefore exclude continuous gradations of partial compliance. Second, subnational heterogeneity-including regional governments, municipal utilities, and local communities-is abstracted away, thereby overlooking critical variation in implementation capacity and stakeholder preferences. Third, intersectoral spillovers remain unmodeled: energy cooperation decisions may exert material influence on water allocation, land use, and environmental governance, yet these linkages are omitted. Fourth, the quantitative calibration rests on planning, contracting and early-construction documentation for the 2018–2023 window rather than on a complete operating record: substantive construction at Kambarata-1 began in 2022, the Naryn cascade investment agreement was signed in July 2023, and the core Toktogul modernisation works fall in 2025. The calibrated parameters and the associated stability thresholds should therefore be treated as scenario-conditional and re-estimated once operational data for these assets accumulate. Future extensions should incorporate continuous strategy spaces, multi-level actor architectures, and cross-sectoral coupling mechanisms. Such refinements would strengthen external validity while preserving analytical tractability. The current framework thus serves as a foundational step toward more granular, empirically grounded models of transboundary infrastructure governance under uncertainty.

6. Conclusion

6.1. Summary of Key Findings

This study establishes that evolutionary stability in China–Kyrgyzstan energy cooperation does not arise from symmetric reciprocity but from calibrated asymmetry-where institutional, temporal, and procedural adaptations compensate for structural disparities. Stability emerges only within narrow parametric bounds defined by adaptive governance capacity rather than static resource endowments. Procedural legitimacy, embedded in iterative renegotiation mechanisms, proves more decisive than initial equity allocations. Temporal flexibility-particularly in phasing infrastructure deployment and revenue-sharing timelines-enables resilience against exogenous shocks. Adaptive risk-sharing frameworks, dynamically reallocating exposure based on real-time performance metrics and hydrological variability, significantly enhance long-term viability. These findings challenge conventional assumptions privileging balanced input–output ratios, instead foregrounding process-oriented institutional design as the primary determinant of cooperative endurance. The analysis underscores that sustainability hinges less on equilibrium outcomes and more on the robustness of learning feedback loops across technical, financial, and regulatory domains.

6.2. Practical Recommendations

Three targeted interventions enhance strategic alignment and evolutionary stability in China–Kyrgyzstan energy cooperation. First, institutionalize biennial trust calibration reviews anchored to quantified performance metrics-such as grid uptime, dispute resolution latency, and compliance variance-to detect misalignment before escalation. Second, embed automatic hydrological adjustment bands into tariff mechanisms, permitting ±15% deviation from baseline rates contingent on seasonal inflow variability, thereby insulating revenue streams from climatic volatility. Third, mandate co-location of Chinese technical supervisors and Kyrgyz grid operators during commissioning phases to accelerate tacit knowledge transfer, reduce procedural ambiguity, and strengthen mutual operational literacy. Collectively, these measures reinforce adaptive governance, mitigate asymmetric information risks, and sustain cooperative equilibria across shifting hydrological, regulatory, and geopolitical conditions.

6.3. Future Research Directions

Future research should extend the model to multi-project portfolios, integrate agent-based modeling of subnational stakeholders, and develop real-time dashboard metrics. These metrics must detect early stability erosion by tracking divergence between contractual commitments and operational practice across dispatch, maintenance, and revenue domains.

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