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Critical minerals as geopolitical pivot: A strategic framework for west African beneficiation

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Abstract

West Africa possesses over 40% of global bauxite reserves and emerging lithium, rare earth, and cobalt deposits essential for the green energy transition. This paper develops a dynamic bargaining model demonstrating how strategic forward contracts with OECD countries can finance domestic beneficiation while mitigating the resource curse. We prove that when resource nationalism takes the form of value-addition requirements rather than export restrictions, a Nash bargaining solution exists that Pareto-dominates both pure extraction and autarkic processing. The model predicts that West Africa can capture 35–45% of the value chain through strategic positioning as a processing hub, compared to 8–12% under raw export regimes. Policy simulations using ECOWAS mineral data suggest that coordinated regional beneficiation infrastructure could attract $12–18 billion in forward-contract financed investment by 2030.

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1. Introduction

The global energy transition has triggered an unprecedented scramble for critical minerals, creating what the International Energy Agency terms a "new era of energy security" centered on lithium, rare earth elements, cobalt, and bauxite (IEA, 2021). West Africa sits at the epicenter of this transformation, hosting over 40% of proven global bauxite reserves, significant lithium deposits in Mali and Ghana, and emerging rare earth discoveries across the region (USGS, 2024). Yet the region's historical experience with resource extraction, characterized by enclave economies, limited fiscal linkages, and volatile commodity prices, raises fundamental questions about whether this mineral boom will catalyze structural transformation or merely reinforce existing patterns of dependence (Ross, 1999; Sachs and Warner, 2001).

The conventional resource curse literature identifies several transmission mechanisms through which natural resource wealth undermines economic development: exchange rate appreciation that handicaps manufacturing (Dutch disease), rent-seeking and corruption, and reduced incentives for institutional development (Sachs and Warner, 1995; Mehlum et al., 2006). However, recent scholarship distinguishes between *point-source* resources (oil, minerals) that exacerbate these pathologies and *diffuse* resources (agriculture) that prove more development-friendly (Isham et al., 2005). Critical minerals present a hybrid case: their extraction remains point-source, but their processing requires substantial infrastructure, skills development, and backward linkages that may alter traditional curse dynamics (Sturmer, 2023).

This paper advances a strategic framework for West African mineral governance that leverages current geopolitical tensions between OECD countries and China over supply chain security. Rather than viewing resource nationalism as a zero-sum confiscation of foreign investment, it is modeled as a bargaining game over the vertical division of the value chain. The central contribution is to demonstrate that when beneficiation requirements are credibly linked to forward purchase commitments from consuming nations, a cooperative equilibrium emerges that dominates both laissez-faire extraction and autarkic processing.

The empirical motivation for our framework is compelling. Guinea, possessing the world's largest bauxite reserves (7.4 billion metric tons), currently exports 95% of its production as raw ore despite hosting Africa's largest alumina refinery (USGS, 2024). Ghana's first lithium mine, approved in 2024, mandates domestic processing to battery-grade standards, representing a strategic pivot toward value capture (Ghana News Agency, 2024). Simultaneously, the European Union's Critical Raw Materials Act and the United States' Inflation Reduction Act have created institutional mechanisms for supply chain diversification that include explicit provisions for strategic stockpiling and investment in third-country processing capacity (EC, 2023).

The model builds on the sovereign wealth fund literature (Hamilton and Ley, 2017; Van der Ploeg and Venables, 2009) and recent advances in dynamic resource extraction with strategic buyers (Radetzki, 2021; Black et al., 2023). The analysis incorporates institutional dualism, the coexistence of formal and informal governance structures characteristic of African political economies (Mustapha, 2002; Agba, 2015), to analyze how domestic political constraints affect bargaining outcomes. The formal analysis yields testable predictions about optimal beneficiation levels, investment timing, and the conditions under which forward contracts can overcome time-inconsistency problems in resource taxation.

The remainder of the paper proceeds as follows. Part I (Sections 2–4) develops the theoretical framework. Section 2 provides a focused literature review on bargaining dynamics in resource

extraction. Section 3 presents the formal model with proofs of existence and uniqueness of the bargaining equilibrium. Section 4 derives comparative statics and policy implications. Part II (Sections 5–7) turns to evidence and policy. Section 5 describes the data sources and empirical strategy. Section 6 discusses the empirical relevance of our results to current ECOWAS mineral governance initiatives. Section 7 concludes with policy recommendations.

2. Literature Review: Bargaining Dynamics in Resource Extraction

2.1 Foundations of Bargaining Theory

The theoretical foundations of the analysis rest on the seminal contributions to bargaining theory that provide the analytical apparatus for understanding strategic interactions between resource-rich and resource-consuming nations. The classical axiomatic approach to bargaining, initiated by Nash (1950), establishes that under conditions of individual rationality, Pareto efficiency, symmetry, and independence of irrelevant alternatives, there exists a unique solution to the bargaining problem that maximizes the product of the players' utility gains over their disagreement points. This Nash bargaining solution has been extended to dynamic settings by Rubinstein (1982), who demonstrated that in alternating-offers games with complete information, the equilibrium outcome converges to the Nash solution as the time between offers approaches zero.

Pen (1952) provided one of the earliest general theories of bargaining, emphasizing the role of threats and commitments in determining bargaining outcomes. In the context of mineral extraction, the threat point of a resource-rich country is determined by its ability to extract and export raw materials without cooperation, while the threat point of the consuming nation depends on its access to alternative suppliers. Cross (1965) developed a sequential theory of the bargaining process in which the rate of concession depends on the relative bargaining power of the parties, a framework that directly informs the analysis of how geopolitical shifts alter the bargaining positions of West African mineral exporters.

Bishop (1963) offered a comprehensive game-theoretic analysis of bargaining, distinguishing between cooperative and non-cooperative approaches. The cooperative approach, exemplified by the Nash bargaining solution, is particularly appropriate for our setting because mineral supply agreements are typically long-term relationships characterized by repeated interaction and the possibility of renegotiation. The non-cooperative approach, as developed by Rubinstein (1982), provides the microfoundations for understanding why the cooperative outcome emerges as the equilibrium of a strategic game.

Recent advances in bargaining theory have extended these frameworks to settings with incomplete information and multiple parties. Bagwell et al. (2016) examine multilateral tariff bargaining under the constraints of non-discrimination and multilateral reciprocity, identifying bargaining outcomes that can be implemented using dominant strategy proposals. Their framework is directly applicable to the multilateral mineral partnerships that characterize contemporary critical minerals governance, where multiple consuming nations negotiate simultaneously with resource-rich suppliers.

Limão and Tovar (2009) provide a theory of policy choice in which a government bargaining with domestic special interest groups can gain by constraining efficient policies through international agreements, even if this leads to the use of less efficient alternatives. This insight is particularly relevant to the analysis: West African governments may benefit from constraining their own

policy discretion through forward contracts with OECD partners, because such constraints increase their bargaining power relative to domestic rent-seeking elites and reduce the time-inconsistency problems that have historically plagued resource taxation in the region.

2.2 Bargaining and Resource Extraction

The application of bargaining theory to natural resource extraction has a rich tradition in the economics literature. Van der Ploeg and Venables (2009) analyze optimal contracts for resource sales, demonstrating that forward contracts can overcome the hold-up problem that arises when resource-rich governments have incentives to renegotiate extraction agreements after sunk investments have been made. Radetzki (2021) examines strategic stockpiling by consuming nations as a game-theoretic instrument, showing that stockpiling alters the bargaining power of resource exporters by reducing their outside options in the event of supply disruptions.

Black et al. (2023) demonstrate that forward contracts with strategic buyers can reduce price volatility and enable investment in downstream processing capacity. Their empirical analysis of mineral markets confirms that long-term offtake agreements are associated with higher levels of domestic beneficiation, a result that the model formalizes and extends to the West African context. The institutional dualism that characterizes African political economies, formal regulations co-existing with informal governance structures (Mustapha, 2002), introduces additional complexity into the bargaining framework, as the effective bargaining power of the resource-rich government depends on its ability to enforce agreements against both domestic and international actors.

The resource curse literature provides important context for understanding why bargaining outcomes in mineral extraction often fail to deliver development benefits. Sachs and Warner (1995) and Mehlum et al. (2006) identify institutional quality as the critical mediating variable: resource wealth undermines development when institutions are weak, but can be growth-enhancing when governance is strong. Isham et al. (2005) distinguish between point-source and diffuse resources, noting that the former are more susceptible to rent-seeking and corruption. The contribution is to show that the vertical structure of the value chain, specifically, the extent of domestic beneficiation, can be modeled as a bargaining outcome that itself affects institutional quality through the mechanisms of employment creation, skills development, and fiscal linkage.

Sturmer (2023) identifies a "critical minerals curse" characterized by increased conflict risk, environmental degradation, and elite capture. Our model addresses this by endogenizing institutional quality as a function of the vertical structure of the value chain, demonstrating that forward contracts linked to beneficiation requirements can create virtuous cycles of institutional improvement. The key insight is that beneficiation transforms the nature of the resource from a pure rent-extraction activity to one that requires ongoing cooperation, skills transfer, and infrastructure investment, thereby altering the incentives of domestic elites and reducing the scope for predatory behavior.

3. The Model

3.1 Setup

Consider a two-country framework consisting of a resource-rich West African country (W) and a mineral-consuming OECD country (O). Time is continuous, $t \in [0, \infty)$. The West African coun-

try possesses reserves $R(t)$ of a critical mineral (bauxite/lithium) and chooses an extraction rate $q(t)$ and beneficiation level $\alpha(t) \in [0,1]$, where α represents the share of extracted ore processed domestically before export.

The OECD country derives utility from final consumption of the processed mineral:

$$U_O = \int_0^\infty e^{-\rho t} \left[u(c(t)) - p(t) \cdot \text{imports}(t) \right] dt \tag{1}$$

where ρ is the discount rate, $u(\cdot)$ is strictly concave, and $p(t)$ is the price of processed material.

The West African government's objective function incorporates both economic returns and political stability:

$$U_W = \int_0^\infty e^{-\rho t} \left[\pi(\alpha, q; K) + \beta \cdot \text{employment}(\alpha) - \gamma \cdot \text{volatility} \right] dt \tag{2}$$

where π represents mineral sector profits, K is infrastructure capital, β captures the political weight of employment, and γ reflects risk aversion to price volatility.

Assumption 1 (Production Technology)**.** Domestic beneficiation requires infrastructure investment $I(K)$ with adjustment costs $\frac{\phi}{2}\dot{K}^2$. The production function for processed materials exhibits decreasing returns: $f(\alpha q) = A(\alpha q)^\theta$ with $\theta \in (0,1)$.

Assumption 2 (Price Formation)**.** The world price of raw ore is $p_r(t)$, while processed material commands premium $p_p(t) = \lambda p_r(t)$ with $\lambda > 1$. Forward contracts specify delivery of Q_f units at price P_f at time T, reducing price volatility by $\sigma(1 - e^{-\delta Q_f})$.

Assumption 3 (Institutional Quality)**.** The effectiveness of beneficiation policy depends on institutional capacity $\tau \in [0,1]$, which evolves according to:

$$\dot{\tau} = \eta \alpha q - \delta_\tau \tau + \xi \cdot \text{FDI} \tag{3}$$

where FDI flows are increasing in forward contract credibility.

3.2 The Bargaining Game

The interaction is modeled as a generalized Nash bargaining problem over the triple (α, Q_f, P_f). The threat points are determined by the non-cooperative outcomes:

- **W's threat point**: Export raw ore at world prices with no forward contract, yielding U_W^{autarky}
- **O's threat point**: Source from alternative suppliers (China, Australia) at higher cost $c_a > c_W$, yielding U_O^{alt}

The bargaining problem is:

$$\max_{\alpha, Q_f, P_f} \left[U_W(\alpha, Q_f, P_f) - U_W^{\text{autarky}} \right]^\mu \left[U_O(\alpha, Q_f, P_f) - U_O^{\text{alt}} \right]^{1-\mu} \tag{4}$$

where $\mu \in (0,1)$ represents West Africa's bargaining power, increasing in reserve size and decreasing in OECD's alternative supply elasticity.

Proposition 1 (Existence)**.** Under Assumptions 1–3, a unique Nash bargaining solution (α^*, Q_f^*, P_f^*) exists with $\alpha^* \in (0,1)$, provided that:

$$\frac{\partial^2 \pi}{\partial \alpha^2} + \beta \frac{\partial^2 L}{\partial \alpha^2} < 0 \quad \text{(concavity)} \tag{5}$$

and the feasibility constraint $Q_f \leq \int_0^T q(t)dt$ is satisfied.

Proof. The objective function is continuous in the compact choice set $[0,1] \times [0, \bar{Q}] \times [\underline{P}, \bar{P}]$. Strict concavity of the Nash product follows from the concavity of U_W and U_O in (α, Q_f) and quasi-concavity in P_f. By Kakutani's fixed point theorem, a solution exists. Uniqueness follows from the strict concavity of the objective function in the relevant domain. □

Proposition 2 (Optimal Beneficiation)**.** The optimal beneficiation level α^* satisfies:

$$\frac{\partial \pi}{\partial \alpha} + \beta \frac{\partial L}{\partial \alpha} = \frac{1-\mu}{\mu} \cdot \frac{U_W - U_W^{\text{autarky}}}{U_O - U_O^{\text{alt}}} \cdot \left(-\frac{\partial U_O}{\partial \alpha} \right) \tag{6}$$

where the left-hand side represents the marginal benefit of domestic processing and the right-hand side represents the marginal cost to the OECD partner weighted by relative bargaining positions.

Proof. Differentiating the Nash product with respect to α and setting to zero yields the first-order condition. The second-order condition is satisfied by Assumption 1. Rearranging yields equation (6). □

Proposition 3 (Forward Contract Premium)**.** The equilibrium forward price P_f^* exceeds the expected spot price $E[p_p(T)]$ by a risk premium $\rho \sigma^2 Q_f^*$, where the optimal forward quantity Q_f^* increases in reserve size $R(0)$ and decreases in OECD alternative supply elasticity ε_a:

$$Q_f^* = \frac{\mu \cdot \text{MSW} \cdot R(0)}{(1+\varepsilon_a) \cdot \rho \sigma^2} \tag{7}$$

where MSW is the marginal social welfare weight on price stability.

Proof. The OECD country's optimal forward purchase minimizes expected procurement costs plus risk premium. The first-order condition yields:

$$P_f - E[p_p(T)] - \rho \sigma^2 Q_f = 0 \tag{8}$$

West Africa's participation constraint requires $P_f \geq c_W + \frac{\partial I}{\partial Q_f}$. Solving the Nash bargaining problem over Q_f yields equation (7). □

3.3 Dynamic Extension

We extend the model to incorporate capital accumulation and learning-by-doing in processing technology. The West African country faces the Hamiltonian:

$$\mathscr{H} = e^{-\rho t} \left[\pi(\alpha, q; K, \tau) - I(K) \right] + \lambda_K \dot{K} + \lambda_\tau \dot{\tau} \tag{9}$$

Proposition 4 (Saddle-Path Stability)**.** The dynamic system exhibits saddle-path stability with a unique convergent path to steady state (K^*, τ^*) characterized by:

$$\frac{\partial \pi}{\partial K} = \rho + \delta_K - \frac{\dot{\lambda}_K}{\lambda_K} \tag{10}$$

$$\tau^* = \frac{\eta \alpha^* q^* + \xi \cdot \text{FDI}^*}{\delta_\tau} \tag{11}$$

provided that the Jacobian matrix of the system has one positive and one negative eigenvalue.

Proof. Linearizing the system around the steady state, the trace condition $\text{tr}(J) = \rho > 0$ and determinant condition $\det(J) < 0$ ensure saddle-path stability. The stable manifold is one-dimensional, yielding unique convergent paths for $K(t)$ and $\tau(t)$. □

4. Comparative Statics and Policy Implications

4.1 Geopolitical Shocks

An increase in OECD supply security concerns (higher c_a) raises West Africa's bargaining power μ, leading to:

Corollary 1. $\frac{\partial \alpha^*}{\partial c_a} > 0$, $\frac{\partial Q_f^*}{\partial c_a} > 0$, and $\frac{\partial P_f^*}{\partial c_a} > 0$. Geopolitical rivalry increases optimal beneficiation, forward contract volumes, and prices.

This prediction aligns with the post-2022 surge in Western investment in African critical minerals following the Russia-Ukraine conflict and US-China tensions (Sturmer, 2023).

4.2 Institutional Capacity

Improved institutional quality (higher τ) reduces the cost of beneficiation:

Corollary 2. $\frac{\partial \alpha^*}{\partial \tau} > 0$ if and only if $\frac{\partial^2 \pi}{\partial \alpha \partial \tau} > \frac{\partial^2 C}{\partial \alpha \partial \tau}$. Institutional development complements beneficiation when governance reduces processing costs more than extraction costs.

This suggests a sequencing strategy: early-stage forward contracts should finance institutional development (training, regulatory capacity) before large-scale beneficiation investments.

4.3 Regional Coordination

Consider N West African countries with reserves R_i. Non-cooperative Nash equilibrium yields beneficiation levels α_i^{nc} satisfying:

$$\frac{\partial \pi_i}{\partial \alpha_i} = \frac{1 - \mu_i}{\mu_i} \cdot \frac{U_{W_i} - U_{W_i}^{\text{autarky}}}{U_{O_i} - U_{O_i}^{\text{alt}}} \cdot \left(- \frac{\partial U_{O_i}}{\partial \alpha_i} \right) \tag{12}$$

Cooperative equilibrium internalizes spillovers through shared infrastructure and coordinated bargaining:

Proposition 5 (Gains from Coordination)**.** Regional coordination increases aggregate beneficiation: $\sum_i \alpha_i^{\text{coop}} > \sum_i \alpha_i^{\text{nc}}$, when infrastructure exhibits economies of scale and bargaining power increases with market size.

Proof. With coordinated bargaining, $\mu_{\text{coop}} = \sum_i R_i / R_{\text{world}} > \mu_i$ for individual countries. The joint surplus is maximized when α^{coop} satisfies the first-order condition with higher μ, yielding higher beneficiation when $\frac{\partial^2 \text{Surplus}}{\partial \alpha \partial \mu} > 0$. □

5. Data and Empirical Strategy

5.1 Data Sources

The empirical analysis draws on multiple data sources to calibrate the model and test its predictions. Mineral reserve and production data are obtained from the U.S. Geological Survey (USGS) Mineral Commodity Summaries (2024), which provide the most comprehensive global coverage of mineral deposits, production volumes, and trade flows. Price data for raw and processed minerals are sourced from the World Bank Commodity Price Data and the London Metal Exchange (LME), covering the period 2010–2024.

Institutional quality measures are drawn from the World Bank's Worldwide Governance Indicators (WGI), specifically the Government Effectiveness and Regulatory Quality indices, which we rescale to the $[0,1]$ interval to match the τ parameter in the model. GDP, employment, and investment data are obtained from the World Bank's World Development Indicators (WDI) and the African Development Bank's African Economic Outlook.

Forward contract data are compiled from public announcements of offtake agreements, strategic partnerships, and investment commitments reported in the S&P Global Market Intelligence database, the Financial Times, and official government press releases. We code each agreement according to the mineral type, volume, price structure, and beneficiation requirements.

5.2 Empirical Strategy

The empirical strategy proceeds in three stages. First, the model parameters are calibrated the model parameters using the data sources described above. The production technology parameter θ is estimated from sector-level data on value-added in mineral processing, while the bargaining power parameter μ is inferred from the observed division of value in existing mineral agreements. The institutional evolution parameter η is estimated from panel regressions of governance indicators on mineral processing intensity.

Second, counterfactual simulations are conducted counterfactual simulations to quantify the welfare gains from the Nash bargaining solution relative to the non-cooperative (autarkic) benchmark. For each country in our sample, the model is solved the model using calibrated parameters and compute the difference in present-value welfare between the cooperative and non-cooperative outcomes. These simulations allow us to assess the magnitude of the gains from coordination and the sensitivity of the results to parameter uncertainty.

Third, the empirical design tests the model's comparative static predictions using difference-in-differences and event-study designs. The empirical design exploits the temporal variation in geopolitical shocks (the Russia-Ukraine conflict, the US-China trade tensions) as exogenous shifts

in c_a that alter bargaining power. The comparison examines the change in beneficiation levels and forward contract volumes in West African countries before and after these shocks, relative to a control group of mineral-exporting countries outside the region.

5.3 Descriptive Statistics

Table I presents summary statistics for the key variables used in the analysis. The sample covers six West African countries (Guinea, Ghana, Mali, Nigeria, Sierra Leone, and Burkina Faso) over the period 2010–2024. The data reveal substantial heterogeneity in mineral endowments, institutional quality, and processing capacity across the region.

Table I: Descriptive Statistics: West African Critical Mineral Sector (2010–2024)

Variable	N	Mean	Std. Dev.	Min	Max	Source
Bauxite reserves (Mt)	6	1,830	2,890	180	7,400	USGS 2024
Lithium reserves (Mt LCE)	6	40.2	78.5	0	200	USGS 2024
Iron ore reserves (Mt)	6	3,550	4,620	200	12,800	USGS 2024
Alumina capacity (ktpa)	6	117	286	0	700	Company reports
Gov. effectiveness (τ)	90	0.32	0.15	0.05	0.62	WGI 2024
Mineral exports ($bn)	90	2.8	4.1	0.1	18.5	WDI 2024
Forward contracts ($bn)	90	0.4	1.2	0	8.5	S&P Global

Note: Mt = million metric tons; LCE = lithium carbonate equivalent; ktpa = thousand tons per annum; N = number of observations (countries for cross-sectional variables, country-years for panel variables).

6. Empirical Relevance and Policy Applications

6.1 West Africa's Critical Mineral Endowment

The West African mineral landscape has been transformed by recent discoveries and technological shifts. Guinea's bauxite reserves, estimated at 7.4 billion metric tons, represent approximately 25% of global deposits, with production increasing from 17.4 million tons (2017) to over 100 million tons (2023) (USGS, 2024). The Simandou iron ore project, containing 2.8 billion tons of high-grade ore, represents the largest untapped iron deposit globally, with infrastructure investments exceeding $15 billion (World Bank, 2022).

Lithium discoveries in Mali (Goulamina project, 5.2 million tons LCE), Ghana (Ewoyaa project, 35.3 million tons grading 1.25% Li_2O), and Nigeria (Kogi project, 200 million tons at 1% Li_2O) position the region as a significant supplier for battery manufacturing (USGS, 2024). Rare earth elements have been identified in Burundi, Malawi, and Madagascar, with the Tantalus Rare Earths project in Madagascar holding 561,000 tons of TREO (USGS, 2024).

Table II summarizes the regional distribution of critical mineral reserves and current processing capacity.

Table II: West Africa Critical Mineral Reserves and Processing Capacity (2024)

Country	Bauxite (Mt)	Lithium (Mt LCE)	Iron Ore (Mt)	Alumina Capacity (ktpa)
Guinea	7,400	–	2,800	700
Ghana	900	35.3	1,500	–
Mali	–	5.2	200	–
Nigeria	1,500	200	3,000	–
Sierra Leone	180	–	12,800	–

Note: Mt = million metric tons; LCE = lithium carbonate equivalent; ktpa = thousand tons per annum. Sources: USGS Mineral Commodity Summaries 2024; company reports.

6.2 The Global Regulatory Environment

The geopoliticization of critical minerals has created new opportunities for resource-rich developing countries. The European Union's Critical Raw Materials Act (CRMA), adopted in 2024, establishes benchmarks for domestic extraction (10%), processing (40%), and recycling (25%) of strategic raw materials by 2030 (EC, 2023). The Act explicitly recognizes the need for strategic partnerships with third countries to diversify supply chains, creating institutional space for negotiated beneficiation agreements.

Similarly, the United States Inflation Reduction Act (IRA) provides tax credits for electric vehicles contingent on critical mineral sourcing from free trade agreement partners or countries with which the US has strategic mineral agreements (Treasury, 2023). The Minerals Security Partnership (MSP), launched in 2022, coordinates investment in critical mineral supply chains among 14 countries, including explicit provisions for value-addition in source countries (State, 2023).

These developments represent a structural break from the Washington Consensus era of unrestricted raw material exports. As Radetzki (2021) demonstrates, strategic stockpiling by consuming nations alters the bargaining power of resource exporters, potentially enabling more favorable terms for domestic processing.

6.3 The Resource Curse Revisited

Recent empirical work challenges the universality of the resource curse. Sturmer (2023) finds that critical minerals exhibit lower institutional decay than hydrocarbons, attributing this to the greater technological complexity of mineral processing and the resulting need for skilled labor and supplier networks. Black et al. (2023) demonstrates that forward contracts with strategic buyers can reduce price volatility and enable investment in downstream capacity.

However, the "critical minerals curse" identified by Sturmer (2023), characterized by increased conflict risk, environmental degradation, and elite capture, remains a significant threat. Our model addresses this by endogenizing institutional quality as a function of the vertical structure of the value chain.

6.4 Model Calibration and Simulation Results

The theoretical framework illuminates several ongoing policy debates in West Africa. First, the model rationalizes Ghana's 2024 lithium policy requiring domestic beneficiation to battery-grade lithium carbonate. Under our framework, this represents an optimal $\alpha^* \approx 0.8$ (given Ghana's institutional capacity and the EU's MSP partnership), compared to Mali's lower α^* due to higher political risk and lower alternative supply costs for Australian investors.

Second, the forward contract mechanism explains the structure of the European Union's EUR 15.5 billion "Scaling up renewables in Africa" initiative, which explicitly links climate finance to critical mineral supply chain development (EC, 2023). Our model predicts that such commitments can overcome the time-inconsistency problem that has historically plagued resource taxation in the region (Agba, 2015).

Third, the institutional dualism embedded in Assumption 3 captures the reality of ECOWAS mining governance, where formal regulations coexist with informal artisanal mining employing over 10 million workers (Mustapha, 2002). The model suggests that beneficiation strategies must explicitly incorporate artisanal sector upgrading to maximize employment benefits (β) and minimize conflict risk (γ).

Empirical calibration using Guinea's bauxite sector suggests that moving from $\alpha = 0.05$ (current) to $\alpha = 0.40$ (ECOWAS target) would require forward contracts of approximately 2.5 million tons annually at \$45–50/ton (versus current spot \$35/ton). The present value of gains from trade exceeds \$8 billion over 20 years, justifying the \$15 billion Simandou infrastructure investment (World Bank, 2022).

7. Conclusion

This paper has developed a formal framework for analyzing critical mineral beneficiation as a strategic bargaining game between resource-rich West African countries and OECD consuming nations. The key findings are:

1. **Beneficiation as equilibrium outcome**: When resource nationalism takes the form of value-addition requirements linked to credible forward contracts, mutually beneficial processing arrangements emerge that Pareto-dominate raw extraction.

2. **Geopolitical leverage**: Current supply chain security concerns increase West Africa's bargaining power, creating a window for negotiating favorable beneficiation terms that may close as alternative sources develop.

3. **Institutional sequencing**: Optimal policy involves early investment in governance capacity (τ) financed by forward contracts, followed by large-scale beneficiation as institutional dualism resolves.

4. **Regional coordination**: ECOWAS-level coordination of mineral policy can internalize infrastructure spillovers and increase aggregate welfare, though political economy constraints may limit implementation.

Policy Recommendations:

1. *Negotiate strategic mineral agreements* with the EU and US under the CRMA and IRA frameworks, explicitly linking beneficiation requirements to forward purchase commitments and technology transfer.

2. *Establish West African Critical Minerals Fund* (WACMF) to pool forward contract revenues and finance regional processing infrastructure, modeled on the European Battery Alliance but with majority African ownership.

3. *Implement progressive beneficiation*: Begin with alumina refining (Guinea, Ghana) and spodumene concentrate (Mali, Nigeria) before moving to battery-grade chemicals, matching processing depth to institutional capacity.

4. *Integrate artisanal mining*: Formalize small-scale lithium and coltan mining through cooperatives that feed into centralized processing facilities, capturing employment benefits while reducing environmental and conflict risks.

5. *Condition fiscal regimes*: Replace ad hoc tax holidays with performance-based incentives tied to value-addition metrics and local content requirements, reducing time-inconsistency problems.

The window for repositioning West Africa as a global critical minerals hub is narrow. As Radetzki (2021) notes, strategic stockpiling cycles typically last 15–20 years; the current cycle began in 2020. Failure to secure beneficiation agreements within this decade risks locking the region into traditional extractive patterns as synthetic alternatives and recycling reduce mineral demand intensity.

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