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Input Security and Industrial Vulnerability: The Impact of U.S.–Iran Tensions on Indonesia’s Nickel Industry

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ABSTRACT

This study examines how geopolitical tensions between the United States and Iran affect Indonesia’s nickel industrialization by disrupting sulfur supply chains linked to the Strait of Hormuz. While existing research focuses primarily on energy markets, the implications for industrial input dependencies remain underexplored. Using a qualitative analytical approach that combines value chain analysis, geopolitical risk assessment, and scenario-based reasoning, the study traces how external shocks propagate through intermediate external shocks propagate through intermediate input constraints into domestic industrial systems. The findings show that High Pressure Acid Leach (HPAL) technology—critical for producing battery-grade nickel—is structurally dependent on sulfur, a largely imported and non-substitutable input sourced from geopolitically sensitive regions. This dependence exposes Indonesia’s nickel industry to chokepoint risks, where supply disruptions increase costs, compress margins, and constrain production. The study advances the concept of input security, demonstrating that industrial upgrading does not eliminate vulnerability but reconfigures it through new external dependencies. It highlights the need for supply diversification, domestic capacity development, and proactive geoeconomic strategies to strengthen industrial resilience.

INTRODUCTION

The global energy transition is fundamentally reshaping the geopolitics of natural resources. While fossil fuels—particularly oil and natural gas—have historically dominated strategic competition, the rapid expansion of electric vehicles (EVs), renewable energy systems, and battery storage technologies has shifted attention toward critical minerals such as nickel, cobalt, and lithium (International Energy Agency [IEA], 2023; World Bank [WB], 2020). This shift marks a new phase in resource geopolitics of resource geopolitics, in which strategic advantage is determined not only by resource endowments but also by a country’s capacity to develop industrial capabilities and participate in technologically complex value chains.

Within this evolving landscape, Indonesia has emerged as a pivotal actor. The country possesses the world’s largest lateritic nickel reserves and has rapidly transitioned from a raw material exporter to a global center for nickel processing (United States Geological Survey [USGS], 2024a; Arif, 2018). This transformation has been driven by assertive industrial policies, particularly the ban on raw nickel ore exports and the promotion of domestic downstream processing. As a result, Indonesia now dominates global nickel supply and hosts major industrial clusters such as Morowali and Weda Bay that are deeply integrated into global value chains.

However, this process of industrial upgrading has also generated new forms of structural dependency. Indonesia’s nickel industry is characterized by two main technological pathways: Rotary Kiln Electric Furnace

(RKEF), which produces nickel pig iron for stainless steel, and High-Pressure Acid Leach (HPAL), which produces battery-grade materials. While RKEF is relatively anchored in domestic inputs, HPAL relies on complex hydrometallurgical processes that are highly dependent on sulfuric acid derived from sulfur (Crundwell *et al.*, 2011; IEA, 2023).

This reliance on sulfur has received limited attention in both policy debates and academic literature, despite representing a critical vulnerability. Unlike nickel ore, which is domestically abundant, sulfur is largely imported and embedded within global supply chains. A significant share of global sulfur supply originates from the Middle East as a by-product of oil and gas processing. For Indonesia, this creates a structural dependence on imports that transit through the Strait of Hormuz one of the world’s most strategically sensitive maritime chokepoints (Yergin, 2011; IEA, 2023).

The fragility of this corridor is highlighted by the persistent geopolitical frictions between the United States and Iran. Episodes of military escalation, sanctions, and threats to maritime security illustrate how geopolitical shocks can disrupt global trade flows. While the implications of such disruptions for oil markets have been extensively studied, their effects on industrial supply chains particularly those underpinning critical mineral processing remain underexplored.

This paper addresses this gap by examining how geopolitical tensions can be transmitted to domestic industrial systems through disruptions in intermediate input supply chains. It introduces the concept of input

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security as a distinct dimension of resource security, emphasizing that industrial resilience depends not only on access to primary resources but also on the stability of critical input flows embedded in global production networks.

Analytically, the study develops a framework linking geopolitical tensions, chokepoint disruptions, input constraints, and industrial outcomes. This framework is applied to Indonesia's HPAL-based nickel processing sector, which serves as a critical case due to its high dependence on imported sulfur and its strategic role in the global EV battery value chain. While HPAL enables Indonesia to move up the value chain, it also introduces new vulnerabilities by tying domestic production to external supply chain dynamics and geopolitical conditions beyond national control.

The study is guided by three research questions: (i) to what extent Indonesia's nickel industry depends on imported sulfur as a critical input; (ii) how disruptions in the Strait of Hormuz may propagate through global sulfur supply chains; and (iii) what economic and strategic implications such disruptions may have for Indonesia's industrialization.

This paper contributes to the literature in three ways. First, it provides an empirical assessment of sulfur dependence within Indonesia's nickel industry. Second, it advances the concept of input security as an extension of resource security in the context of the energy transition. Third, it demonstrates how distant geopolitical shocks can cascade through global supply chains and materialize as localized industrial constraints.

More broadly, the paper argues that in the era of energy transition, industrial vulnerability is increasingly shaped not by the availability of primary resources alone, but by the security and resilience of intermediate input flows that sustain complex production systems.

LITERATURE REVIEW

Geopolitics of Energy and Chokepoints

The geopolitics of energy has traditionally centered on the control of primary resources—particularly oil and natural gas—and the strategic infrastructures that enable their global distribution. Within this framework, maritime chokepoints represent critical nodes where geographic constraints intersect with concentrated trade flows, making them inherently vulnerable to disruption. Among these, the Strait of Hormuz and the Strait of Malacca have long been recognized as key corridors through which a substantial share of global energy trade passes.

The Strait of Hormuz, in particular, occupies a central position in global energy security as a major conduit for internationally traded oil. Its strategic importance has made it a recurring focal point of geopolitical tension, especially in the context of U.S.–Iran relations. Existing literature shows that even limited or anticipated disruptions in such chokepoints can generate disproportionate effects on global markets, reflecting the systemic sensitivity embedded in highly concentrated

transit routes (Yergin, 2011).

More recent scholarship suggests that the analysis of chokepoints should extend beyond hydrocarbons to encompass a broader range of globally traded commodities. As industrial production becomes increasingly fragmented and technologically complex, maritime corridors are not only channels for energy flows but also for intermediate goods, chemicals, and critical industrial inputs. In this broader perspective, chokepoints function as systemic nodes within global production networks, where disruptions can propagate across multiple sectors.

This shift aligns with a broader conceptual transition from energy security to material security. While the former focuses on reliable access to fuels, the latter emphasizes the availability and stability of a wider set of inputs required for modern industrial systems. In such systems, vulnerability arises less from resource scarcity than from the fragility of interconnected supply chains that depend on continuous material flows (IEA, 2023). Consequently, chokepoints such as the Strait of Hormuz must be understood not only as energy transit routes, but also as critical junctures in global industrial supply chains.

Energy Transition and Critical Minerals

The global transition toward low-carbon energy systems has reconfigured the strategic importance of natural resources, placing critical minerals at the core of emerging industrial and geopolitical dynamics. Among these, nickel has gained particular prominence due to its role in enhancing the energy density of lithium-ion batteries, which are essential for electric vehicles (EVs) and energy storage systems (IEA, 2023; WB, 2020; UNCTAD, 2023). In this context, Indonesia has emerged as a key actor by leveraging its extensive lateritic nickel reserves to reposition itself within global value chains. The country has adopted a resource-based industrialization strategy characterized by export restrictions on raw ore and strong incentives for domestic processing. These policies have attracted substantial foreign investment and accelerated the expansion of downstream processing capacity (WB, 2020; OECD, 2019).

However, a growing body of literature cautions that downstreaming does not automatically translate into industrial sovereignty. While such strategies increase domestic value addition, they often introduce new forms of dependency, particularly in technologically complex and input-intensive production processes (UNCTAD, 2023; OECD, 2019). In the case of nickel, the shift toward battery-grade production relies on advanced hydrometallurgical technologies that require stable access to globally sourced inputs (IEA, 2023).

This reflects a broader transformation in the geopolitics of critical minerals. As value creation shifts downstream, participation in high-value segments necessitates integration into complex and geographically dispersed production networks (WB, 2020; IEA, 2023). As a result, control over mineral reserves alone is insufficient

to ensure resilience or strategic autonomy. Instead, vulnerability is increasingly shaped by dependence on technology, capital, and intermediate inputs (UNCTAD, 2023).

This dynamic gives rise to a central paradox of the energy transition: efforts to secure critical mineral supply chains may simultaneously generate new forms of systemic vulnerability. In highly interconnected industrial systems, disruptions in one segment can cascade across the value chain, amplifying risks (OECD, 2019). Accordingly, the analysis of critical minerals must move beyond resource endowments toward a systemic understanding of interdependence, input security, and supply chain resilience. Furthermore, attention must extend to environmental, social, and governance (ESG) considerations (Ahmed, 2025).

Nickel Processing Technologies

Nickel resources are broadly classified into sulfide and laterite deposits. Historically, sulfide ores dominated global production due to their higher grades and simpler processing requirements. However, the depletion of high-grade sulfide deposits has shifted attention toward laterite resources, which now account for the majority of global reserves. This transition is particularly evident in Indonesia, where abundant lateritic deposits underpin the country’s nickel industrialization strategy (Arif, 2018; USGS, 2024a; IEA, 2023).

The processing of laterite ores depends on their geological differentiation into saprolite and limonite layers. Saprolite ores, typically found at greater depths and with higher nickel concentrations, are well-suited to pyrometallurgical processing, particularly through the Rotary Kiln Electric Furnace (RKEF) method. This process produces ferronickel or nickel pig iron (NPI), primarily used in stainless steel production (Dalvi *et al.*, 2004; Mudd, 2010).

In contrast, limonite ores—characterized by lower nickel content and higher iron composition—require hydrometallurgical processing, most notably through High Pressure Acid Leach (HPAL) technology. HPAL produces mixed hydroxide precipitate (MHP), an intermediate product used in battery-grade materials for electric vehicles (Crundwell *et al.*, 2011; IEA, 2023).

Although HPAL enables participation in higher value-added segments, it is significantly more complex and cost-intensive than RKEF. Its cost structure is dominated by sulfuric acid, which accounts for approximately 30–50% of total operating expenses. In addition, the process is highly material-intensive, requiring roughly 11–12 tons of sulfur per ton of MHP produced (Crundwell *et al.*, 2011; Mudd, 2010; USGS, 2024b). As sulfuric acid has no viable large-scale substitute in HPAL operations, sulfur becomes a system-critical and non-substitutable input.

This distinction creates fundamentally different input structures. RKEF relies largely on domestically available inputs ore and energy whereas HPAL depends on imported sulfur integrated into global supply chains. As a result, HPAL links industrial performance directly to the stability of external input markets, particularly the global sulfur trade.

These technological differences translate into contrasting risk profiles. RKEF-based systems are relatively insulated from global supply disruptions, while HPAL-based systems are structurally exposed to external shocks, especially those affecting input availability and prices. The expansion of HPAL therefore reflects not only technological upgrading but also a shift toward greater integration and vulnerability within global production networks.

The fundamental differences between RKEF and HPAL are summarized in Table 1.

Table 1 highlights Indonesia’s nickel refining system.

Table 1: Simplified Comparison between RKEF and HPAL Technologies

Aspect	RKEF	HPAL
Ore Type	Saprolite	Limonite
Processing Method	Pyrometallurgical (smelting)	Hydrometallurgical (acid leaching)
Main Output	Ferronickel / Nickel Pig Iron (NPI)	Mixed Hydroxide Precipitate (MHP)
End-Use	Stainless steel	EV batteries
Key Input	Energy (coal, electricity)	Sulfuric acid (from sulfur)
Sulfur Requirement	Not required	~11–12 tons sulfur per ton MHP
Cost Structure (Dominant)	Energy-intensive	Chemical-intensive (sulfur ≈30–50% OPEX)
Input Source (Indonesia Case)	Entirely domestic (for coal)	Mostly imported (sulfur)
Exposure to Global Risk (Indonesia Case)	Relatively low	Relatively high

Sources: Dalvi *et al.* (2004); Mudd (2010); Crundwell *et al.* (2011); International Energy Agency (2023); United States Geological Survey (2024).

RKEF represents an energy-intensive and largely domestically anchored production model, with key inputs sourced within national boundaries (IEA, 2023). In contrast, HPAL is a chemically intensive and globally

dependent system, where production is contingent on access to internationally traded inputs such as sulfur (USGS, 2024b).

This divergence has important implications for industrial

resilience. RKEF operations are relatively robust to global supply disruptions due to their reliance on local inputs. By contrast, HPAL operations face higher exposure to external risks, including price volatility and supply uncertainty in global sulfur markets (IEA, 2023; USGS, 2024b).

The transition toward HPAL therefore represents more than a technological shift—it marks a structural transformation in Indonesia's industrial model. Dependency moves from domestic resource availability to the stability of global input markets. While this transition enables integration into higher value-added segments such as EV battery supply chains, it simultaneously embeds new vulnerabilities within the production system. This underscores the importance of incorporating supply chain risk into industrial strategy, particularly in an increasingly volatile geopolitical environment.

Supply Chain Vulnerability

Supply chain vulnerability has emerged as a central concern in the study of critical materials and industrial resilience in the context of the energy transition. While earlier analyses focused primarily on access to primary resources, recent literature emphasizes that vulnerability is increasingly embedded in complex value chains involving intermediate inputs, logistics networks, and external markets (IEA, 2023; WB, 2020).

From this perspective, resilience is not determined solely by resource availability, but by the robustness of interconnected production systems. Vulnerability arises when critical inputs are exposed to external disruptions, including geopolitical tensions, trade restrictions, and logistical constraints. These risks are particularly pronounced in sectors characterized by high input specificity, limited substitutability, and geographically concentrated supply (UNCTAD, 2023; IEA, 2023).

The contrast between RKEF and HPAL technologies illustrates these dynamics. RKEF systems, which rely primarily on domestically sourced inputs, are relatively insulated from global supply disruptions. In contrast, HPAL systems depend heavily on sulfur—a globally traded input with limited substitutability—thereby embedding structural vulnerability into the production process (Crundwell *et al.*, 2011; Mudd, 2010).

This vulnerability is further reinforced by the characteristics of the global sulfur market. Sulfur production is geographically concentrated and largely derived as a by-product of oil and gas refining, making its supply dependent on hydrocarbon sector dynamics rather than direct industrial demand (USGS, 2024b; IEA, 2023). In addition, the sulfur trade is highly reliant on maritime transport, particularly through strategic chokepoints such as the Strait of Hormuz, where geopolitical tensions can disrupt flows.

These factors position sulfur as a strategic intermediate input whose importance is determined not by scarcity, but by its critical role in specialized industrial processes. This aligns with broader arguments that the strategic

significance of materials in modern economies is increasingly defined by their function within complex production systems (UNCTAD, 2023). From several cases, it can be inferred that regional instability may significantly affect the security of raw material supplies required for industry; therefore, such risks must be anticipated and mitigated through appropriate supply security measures (Udim *et al.*, 2025).

The implications for industrial strategy are significant. In countries lacking domestic sulfur resources, dependence on imported inputs becomes structurally embedded, increasing exposure to external shocks. In this context, industrial upgrading—while enabling higher value addition—may simultaneously increase systemic vulnerability by deepening integration into global supply chains.

Synthesis

The literature points to a fundamental transformation in the geopolitics of the energy transition. While control over natural resources remains important, it is no longer sufficient to ensure industrial resilience or strategic advantage. Instead, resilience increasingly depends on secure access to critical inputs, the stability of supply chains, and the capacity to manage geopolitical risks (IEA, 2023; WB, 2020).

Indonesia exemplifies this transformation. The country has successfully leveraged its nickel resource endowment to become a global leader in production and processing. However, its growing reliance on imported sulfur introduces a new and underexplored dimension of vulnerability. This study builds on the existing literature by examining how disruptions at global chokepoints—particularly the Strait of Hormuz—can affect the availability of critical inputs and, in turn, the performance of domestic industrial systems.

MATERIALS AND METHODS

Analytical Framework

This study develops an analytical framework to examine how geopolitical tensions translate into industrial outcomes through disruptions in critical input supply chains. Specifically, it investigates how tensions between the United States and Iran may affect Indonesia's nickel industrialization by constraining sulfur supply flows through the Strait of Hormuz.

The framework departs from resource-centric approaches by emphasizing that industrial resilience depends not only on access to primary resources but also on the stability of intermediate inputs embedded in global production networks (IEA, 2023; WB, 2020). It conceptualizes a four-stage transmission mechanism: (i) geopolitical tension, (ii) chokepoint disruption, (iii) input constraint, and (iv) industrial impact.

This causal chain provides a structured basis for tracing how external shocks propagate across spatial and sectoral boundaries. In particular, it highlights the role of maritime chokepoints as critical transmission nodes through

which geopolitical risks are converted into supply chain disruptions and, ultimately, production constraints. The framework is applied to the HPAL segment of Indonesia's nickel industry, where dependence on imported sulfur is most pronounced.

Research Design

The study adopts a qualitative-analytical case study design, focusing on Indonesia's nickel industry as a critical case of resource-based industrialization under conditions of global supply chain dependency. This approach is appropriate for examining complex, multi-scalar relationships between geopolitics, trade networks, and industrial systems (Yin, 2018).

Two complementary methods are employed: process tracing and scenario analysis.

First, process tracing is used to identify and validate the causal pathways linking geopolitical tensions to industrial outcomes. This method enables a step-by-step reconstruction of how disruptions in the Strait of Hormuz affect sulfur supply chains and, in turn, HPAL production (George & Bennett, 2005). The analysis focuses on three transmission channels: (i) physical disruption of trade flows, (ii) cost escalation through logistics and insurance, and (iii) market expectations reflected in price volatility.

Second, scenario analysis is applied to assess the sensitivity of HPAL operations to varying degrees of supply disruption. Three stylized scenarios are developed: (i) a baseline scenario characterized by stable supply and prices, (ii) a moderate disruption scenario involving increased costs and partial delays, and (iii) a severe disruption scenario involving significant supply constraints and potential shortages. These scenarios are not predictive but are designed to illustrate threshold effects and system responses under different levels of stress (IEA, 2023).

Data Sources

The analysis draws on multiple secondary data sources to ensure triangulation and robustness. Industrial data—including nickel production, smelter capacity (RKEF and HPAL), and ore characteristics—are obtained from national institutions such as the Ministry of Energy and Mineral Resources (MEMR) and Badan Pusat Statistik, as well as international sources such as the United States Geological Survey (USGS).

Trade and input data include sulfur import volumes, sulfur and sulfuric acid prices, and cost structures of HPAL operations. These are compiled from international trade databases, industry reports (e.g., Argus Media, Shanghai Metals Market), and corporate disclosures where available. These data provide the basis for assessing input dependency and cost sensitivity.

Geopolitical and logistics data are derived from reports by the International Energy Agency (IEA), the U.S. Energy Information Administration, and relevant policy and industry analyses. These sources provide information on maritime trade flows, chokepoint utilization, and

geopolitical risk dynamics, particularly in relation to the Strait of Hormuz.

Analytical Approach and Variable Definition

The study integrates value chain analysis, geopolitical risk analysis, and scenario-based modeling to examine the relationship between input dependency and industrial vulnerability.

Value chain analysis is used to map the flow of production from ore extraction (sapolite and limonite) to processing (RKEF and HPAL) and final outputs (NPI and MHP). Particular attention is given to identifying critical nodes where dependency on external inputs is concentrated, especially the role of sulfur in HPAL processing.

Geopolitical risk analysis evaluates how external shocks affect supply chain stability. It focuses on chokepoint vulnerability, particularly the Strait of Hormuz, and examines three channels of impact: physical disruption, cost escalation, and market expectations (Yergin, 2011; IEA, 2023).

Scenario analysis operationalizes the relationship between sulfur price changes and industrial performance. The analysis defines three categories of variables:

- Input variables: sulfur import volume, sulfur price, and degree of import dependence
- Industrial variables: HPAL capacity, sulfur consumption intensity, and cost structure
- Output variables: MHP production, operating margins, and downstream supply availability

To formalize cost sensitivity, the study adopts a simplified cost function for HPAL operations:

$$CHPAL = \alpha + \beta P_s + \gamma P_e + \delta P_o \quad (\text{Equation 1})$$

where P_s represents sulfur prices, P_e energy costs, and P_o other operating costs. The parameter β captures the degree of cost sensitivity to sulfur price changes, reflecting the dominant role of sulfuric acid in HPAL cost structures. This formulation provides a basis for evaluating how input price shocks translate into industrial cost pressures under different scenarios.

Scenario assumptions are based on industry estimates, including: (i) sulfuric acid accounts for approximately 30–50% of total operating costs, (ii) short-term cost pass-through from sulfur price changes is approximately linear, (iii) no large-scale substitution exists for sulfuric acid, and (iv) ore and energy costs are held constant to isolate the effect of sulfur price variation.

Limitations

This study has several limitations. First, the scenario analysis relies on stylized assumptions rather than real-time firm-level data, which may limit predictive precision. Second, the absence of disaggregated operational data constrains the ability to capture firm-level heterogeneity and adaptive strategies. Third, geopolitical developments are inherently uncertain and may evolve in ways not fully captured by the scenarios.

Despite these limitations, the combination of process tracing, value chain analysis, and scenario-based modelling

provides a coherent and policy-relevant framework for understanding how geopolitical shocks propagate through supply chains and affect industrial systems.

RESULTS AND DISCUSSION

Import Dependence and Geopolitical Vulnerability in Indonesia's Sulfur Supply Chain

Indonesia's sulfur supply structure exhibits a high degree of import dependence, particularly in support of HPAL operations. In 2025, Indonesia imported approximately 5.35 million tonnes (Mt) of sulfur, with around 75% sourced from Middle Eastern producers, including Saudi Arabia, Qatar, the United Arab Emirates, Kuwait, and

Oman (Argus Media, 2026). This concentration indicates a strong reliance on supply routes that pass through the Strait of Hormuz, one of the world's most geopolitically sensitive maritime chokepoints.

Figure 1 illustrates sulfur price dynamics over both short-term (one-year) and longer-term (five-year) periods. A sharp price surge is observed in early 2026, with prices reaching approximately 5,500 CNY per ton in March at an unprecedented level.

This spike coincides with heightened geopolitical tensions between the United States and Iran, suggesting a strong linkage between geopolitical instability and sulfur market volatility. The figure highlights not only the magnitude

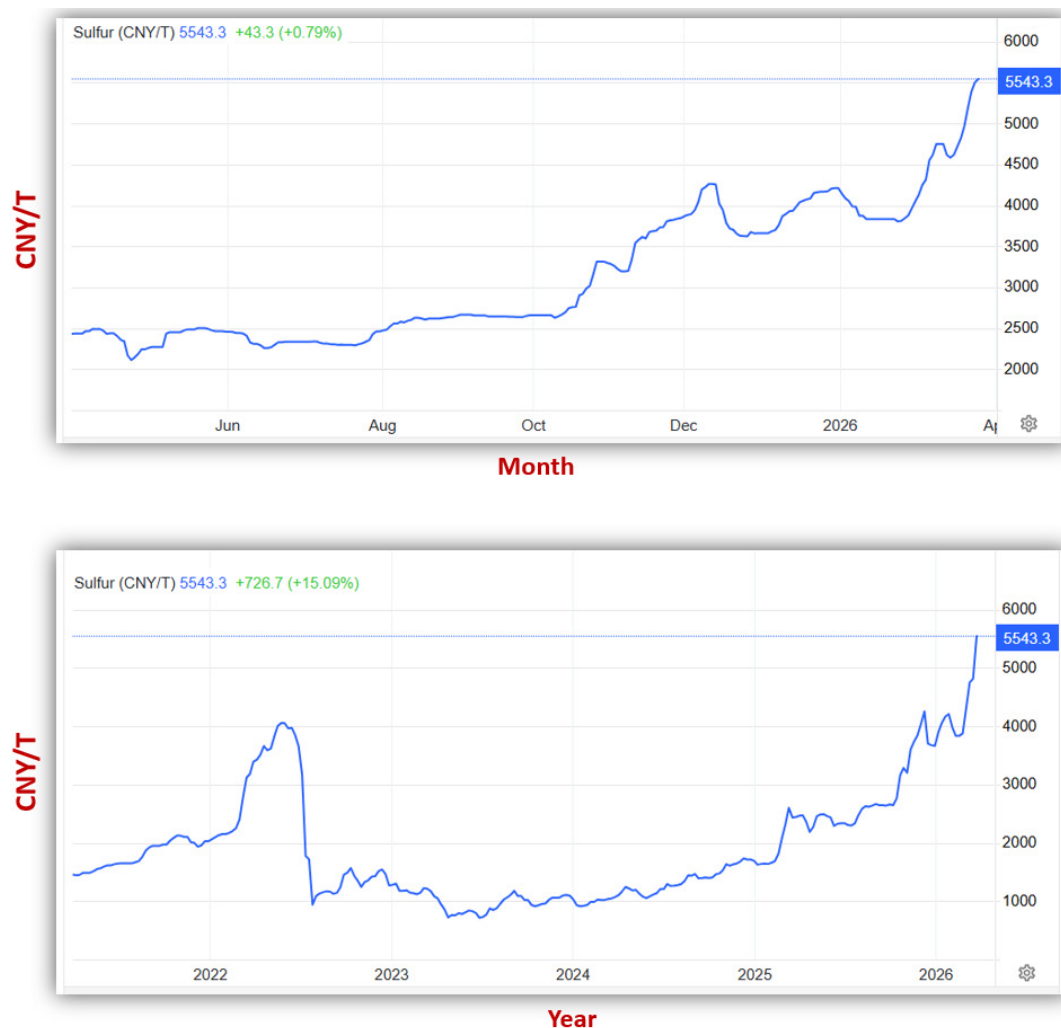


Figure 1: Sulfur price development (CNY/T), in the last 1 year (top) and 5 years (bottom)

Source: Trading Economics

of recent price increases but also the broader pattern of volatility, reinforcing the sensitivity of sulfur supply chains to external shocks.

Taken together, concentrated sourcing and price volatility reveal a structurally embedded vulnerability. In this context, chokepoints such as the Strait of Hormuz function as critical transmission channels through which geopolitical risks propagate into industrial systems. This extends the conventional understanding of chokepoints beyond energy security to include their role in shaping the

stability of intermediate input flows.

Under baseline conditions, sulfur supply chains operate with relative stability, allowing HPAL facilities to maintain predictable cost structures. However, this stability masks latent fragility. Even moderate disruptions—such as increases in freight costs, insurance premiums, or delivery delays can significantly raise sulfur prices. Given that sulfuric acid accounts for approximately 30–50% of HPAL operating costs, such increases can rapidly compress margins (Mudd, 2010).

Under more severe scenarios, the impact shifts from cost escalation to physical constraint. Supply disruptions can reduce sulfur availability, leading to partial or complete shutdowns of HPAL operations. This indicates a threshold dynamic, whereby incremental price and logistics shocks eventually translate into production losses. The analysis thus demonstrates how distant geopolitical tensions can materialize as localized industrial disruptions.

Indonesia’s Nickel Industrialization: Resource Strength, Input Vulnerability

Indonesia holds approximately 55% of global nickel

reserves and accounted for more than 60% of global nickel production in 2024 (USGS, 2024). This dominant position is illustrated in Figure 2, which compares Indonesia’s share of global reserves and production.

The figure underscores Indonesia’s dual advantage in both resource endowment and production scale. This foundation has enabled a dual-track industrialization strategy: RKEF-based processing for stainless steel and HPAL-based processing for battery-grade materials.

Despite this strength, Indonesia’s nickel industrialization exhibits a structural paradox. While upstream resource

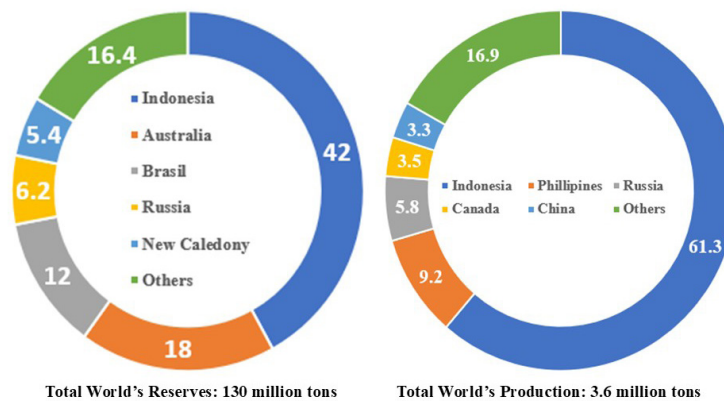


Figure 2: Global nickel reserves (left) and production (right), 2024

Source: USGS; Statista

control is strong, downstream production remains vulnerable due to dependence on imported inputs—most notably sulfur. This vulnerability extends beyond technology and capital dependence to include exposure to global supply chain disruptions and limited control over critical intermediate materials.

The expansion of HPAL capacity—central to Indonesia’s ambition to integrate into global electric vehicle (EV) battery supply chains—has intensified this dependence. Unlike RKEF, which relies primarily on domestic inputs, HPAL is structurally linked to global sulfur markets. As a result, industrial upgrading has not reduced dependency but rather transformed it, shifting the locus of vulnerability from resource access to input security.

This finding challenges the assumption that downstreaming inherently enhances industrial sovereignty. Instead, it suggests that deeper integration into global value chains may increase exposure to external risks, particularly in input-intensive sectors. Indonesia’s experience thus reflects a broader pattern in the energy transition, where technological advancement is accompanied by increasingly complex and geopolitically embedded dependencies.

RKEF versus HPAL: Sulfur as a Strategic Bottleneck

Indonesia’s nickel smelting industry is dominated by RKEF technology, while HPAL represents a smaller but rapidly expanding segment. Despite its smaller share,

HPAL plays a disproportionate role in value creation due to its production of mixed hydroxide precipitate (MHP), a key intermediate for EV batteries.

A central finding of this study is that sulfur constitutes a strategic bottleneck in HPAL-based production. Its consumption intensity—approximately 11–12 tons per ton of MHP—creates a rigid input structure that cannot easily adjust to supply disruptions (Mudd, 2010; USGS, 2024). Moreover, sulfur has no viable large-scale substitute in HPAL operations, reinforcing its role as a system-critical input.

This dependency is compounded by the structure of the global sulfur market. Supply is geographically concentrated and largely derived as a by-product of oil and gas refining, making it sensitive to both hydrocarbon market dynamics and geopolitical developments. In addition, sulfur trade depends heavily on maritime transport through chokepoints such as the Strait of Hormuz, further amplifying exposure to external risks.

From a cost perspective, sulfur functions as a system-defining input. As indicated in Equation (1), HPAL operating costs are highly sensitive to sulfur price movements, reflecting the substantial contribution of sulfuric acid to total operating expenditures. This implies that even moderate increases in sulfur prices can translate rapidly into overall cost escalation, affecting both profitability and operational stability.

Scenario Analysis: Cost Sensitivity and Systemic

Risk

The scenario analysis builds on the cost structure defined in Equation (1) to assess how sulfur price shocks affect HPAL operations. Given the dominant role of sulfur in the cost function, changes in sulfur prices have a disproportionate impact on total operating costs. The results are summarized in Table 2.

The results demonstrate a high degree of cost sensitivity. Even moderate increases in sulfur prices significantly

raise total operating costs, compressing margins and affecting investment decisions. This reflects the strong dependence of HPAL cost structures on sulfur inputs, as captured in Equation (1). As price increases intensify, the relationship becomes nonlinear, with cost escalation rapidly approaching levels that threaten operational viability.

At higher levels of disruption, the system transitions

Table 2: Scenario Analysis of Sulfur Price Shocks and HPAL Cost Impacts

Scenario	Sulfur Price Increase	Share of Sulfur in Cost	Change in Estimated Total OPEX (Estimated)	Implication for HPAL Operation
Baseline	0%	40%	0%	Normal operation, stable margins
Low Shock	+25%	→ 50%	+10%	Margin compression is still viable
Moderate Shock	+50%	→ 60%	+20%	Significant margin pressure, delayed expansion
High Shock	+100%	→ 80%	+40%	Operations under stress, risk of partial shutdown
Extreme Shock	+150%	→ ~100%	+60%	Economically unviable, shutdown likely
Supply Disruption	Quantity constraint	Not applicable	Non-linear (production loss)	Physical shortage → output collapse

from cost pressure to operational constraint. When sulfur prices double, total operating costs may increase by up to 40%, pushing many HPAL operations toward economic infeasibility. In extreme cases, where price shocks are accompanied by physical supply disruptions, the impact shifts decisively toward production loss.

Given the absence of substitutes and the continuous nature of HPAL operations, disruptions in sulfur supply can lead to partial or complete shutdowns. This results in reduced output of MHP and cascading effects across downstream supply chains.

Overall, the scenario analysis reinforces the central argument of this study: sulfur is not merely a cost component but a system-critical input that determines both cost structure and operational continuity. Consequently, Indonesia’s reliance on imported sulfur represents a structural vulnerability with direct implications for the sustainability of its nickel industrialization strategy.

CONCLUSION

This study examines how geopolitical tensions especially between the United States and Iran can affect Indonesia’s nickel industrialization by disrupting sulfur supply chains linked to the Strait of Hormuz. It highlights a critical but often overlooked issue: the vulnerability of industrial systems to disruptions in intermediate inputs.

Indonesia’s rapid rise as a global leader in nickel has been

driven by abundant resources and strong downstream policies, particularly through the development of RKEF and HPAL processing. While this strategy has strengthened its position in stainless steel and EV battery value chains, it has also introduced new dependencies. In particular, HPAL technology relies heavily on sulfur, a non-substitutable imported input.

This dependence exposes Indonesia’s industrial performance to global supply chain risks. Disruptions in sulfur supply can increase production costs, reduce output, and weaken industrial upgrading. The study introduces “input security” as an extension of resource security, arguing that control over raw materials alone is insufficient; resilience depends on stable access to all critical inputs.

More broadly, the findings reveal a paradox of the energy transition: while industrial upgrading enhances value capture, it also increases exposure to external vulnerabilities, showing that resource strength can coexist with input dependence.

Policy Recommendations

The findings of this study suggest that Indonesia’s nickel industrialization strategy must evolve beyond a narrow focus on resource endowments and downstream expansion toward a broader emphasis on supply chain resilience and input security.

First, diversification of sulfur supply sources is essential. Indonesia's current reliance on suppliers linked to the Strait of Hormuz creates significant geopolitical exposure. Expanding procurement to alternative suppliers—such as those in North America or East Asia—through long-term contracts and flexible sourcing arrangements can reduce concentration risk and enhance supply stability. Second, strengthening domestic sulfur production capacity should be prioritized. As sulfur is largely a by-product of oil and gas refining, upgrading domestic refining infrastructure—such as through enhanced desulfurization processes—can increase local sulfur recovery. Expanding production from natural gas processing and petrochemical industries can further reduce dependence on imports while creating synergies across energy and mineral sectors. Third, greater industrial integration is needed. Closer coordination between sulfur production, sulfuric acid manufacturing, and HPAL operations—potentially through co-location strategies—can reduce logistical costs and improve supply reliability. Such integration would enhance efficiency while mitigating exposure to global transport disruptions. Fourth, technological innovation should be encouraged to reduce input intensity. Improvements in acid recycling, process efficiency, and alternative leaching techniques can lower sulfur consumption over time. While these measures may not eliminate dependence on sulfur, they can reduce vulnerability by moderating demand growth and improving cost resilience. Finally, input security should be embedded within Indonesia's broader geo-economic strategy. Securing access to critical industrial inputs requires proactive international engagement, including bilateral agreements with key suppliers and participation in multilateral supply chain initiatives. In an increasingly competitive global landscape, managing input dependencies is as important as controlling resource endowments. In conclusion, the long-term viability of Indonesia's nickel industrialization hinges on a strategic transition from a purely resource-oriented mindset to a more holistic framework that incorporates input security, supply chain resilience, and the management of geopolitical risks. Failure to reduce dependence on imported sulfur could ultimately jeopardize the very industrial progress made possible by the country's abundant resource endowment.

REFERENCES

- Ahmed, W. (2025). Big data and ESG (environmental, social, governance) reporting in finance. *American Journal of Economics and Business Innovation*, 4(3). <https://orcid.org/0009-0004-5322-2333>
- Arif, I. (2018). *Nikel Indonesia*. Gramedia.
- Argus Media. (2026). *Sulfur market analysis and price report*. <https://www.argusmedia.com/en/solutions/products/argus-sulphur>
- Asian Development Bank. (2023). *Indonesia's critical minerals development and value chain integration*. Asian.
- Asosiasi Pertambangan Nikel Indonesia. (2026, March). APNI. <https://www.apni.or.id/>
- Badan Pusat Statistik. (2026, March). *Ekspor dan impor*. <https://www.bps.go.id/id/exim>
- Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, W. G. (2011). *Extractive metallurgy of nickel, cobalt and platinum group metals*. Elsevier.
- Dalvi, A. D., Bacon, W. G., & Osborne, R. C. (2004). *The past and the future of nickel laterites*. Prospectors & Developers Association of Canada.
- Fastmarkets. (2025). *Battery raw materials outlook 2025*. Fastmarkets.
- George, A. L., & Bennett, A. (2005). *Case studies and theory development in the social sciences*. MIT Press.
- Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy*, 12(1), 78–104.
- Humphreys, D. (2013). *The remaking of the mining industry*. Palgrave Macmillan.
- International Energy Agency. (2021). *The role of critical minerals in clean energy transitions*. IEA.
- International Energy Agency. (2023). *Critical minerals market review 2023*. IEA.
- Ministry of Energy and Mineral Resources. (2021). *Grand strategy for mineral and coal: Direction for upstream and downstream development*. MEMR.
- Ministry of Energy and Mineral Resources. (2025). *Indonesia mineral and coal statistics 2025*. MEMR.
- Mudd, G. M. (2010). Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, 38(1–2), 9–26. <https://doi.org/10.1016/j.oregeorev.2010.05.003>
- Nugroho, H., & Al-Wafy, M. (2026). Evolusi industri nikel global dan Indonesia: Tinjauan historis dan pelajaran kebijakan. *Bappenas Working Papers*, 9(2), 236–255. <https://doi.org/10.47266/bwp.v9i2.560>
- Organisation for Economic Co-operation and Development. (2019). *Global material resources outlook to 2060*. OECD.
- Overland, I. (2019). The geopolitics of renewable energy: Debunking four emerging myths. *Energy Research & Social Science*, 49, 36–40.
- Shanghai Metals Market. (2026, March). *Metal prices and market data*. <https://www.metal.com/>
- Trading Economics. (2026, March). Sulfur. <https://tradingeconomics.com/commodity/sulfur>
- Udim, I. O., Daniel, N. E., & Abioye, G. T. (2025). Regional instability and transnational security threats in West and Central Africa: Implications for international peacebuilding. *American Journal of Development Studies*, 3(2). <https://doi.org/10.54536/ajds.v3i2.5609>
- United Nations Conference on Trade and Development. (2023). *Commodities at a glance: Special issue on critical minerals*. UNCTAD.
- United States Geological Survey. (2024a). *Mineral commodity summaries 2024: Nickel*. USGS.
- United States Geological Survey. (2024b). *Mineral commodity summaries 2024: Sulfur*. USGS.
- World Bank. (2020). *Minerals for climate action: The mineral*

- intensity of the clean energy transition.* World Bank.
- Yergin, D. (2011). *The quest: Energy, security, and the remaking of the modern world.* Penguin Press.
- Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). Sage Publications.