INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

Technological Resilience in Nickel Downstreaming: Energy Policy, Critical Material Security, and Indonesia's Transition to Battery Materials

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DOI: https://doi.org/10.51244/IJRSI.2026.1308000033

Received: 14 August 2026; Accepted: 19 August 2026; Published: 29 August 2026

ABSTRACT

Indonesia has emerged as a global centre of nickel downstreaming, transforming its role from a raw nickel ore exporter into a major producer of processed nickel products. However, the next stage of downstream industrialisation—particularly the development of a domestic electric-vehicle (EV) battery materials industry—raises new challenges concerning energy security, critical-input dependence, environmental sustainability, and geopolitical vulnerability. This study examines the strategic implications of alternative nickel-processing technologies through a qualitative Strategic Policy Assessment (SPA), comparing Rotary Kiln Electric Furnace (RKEF), High-Pressure Acid Leaching (HPAL), and the emerging Oxygen-Enriched Side-Blown Furnace (OESBF). The analysis evaluates these technologies across six dimensions of technological resilience: resource utilisation, energy and input requirements, critical-material and supply-chain security, environmental sustainability, industrial upgrading potential, and policy compatibility. The findings indicate that RKEF remains important for Indonesia's stainless-steel-oriented nickel industry but is highly energy-intensive and dependent on high-grade saprolite resources. HPAL provides a pathway to battery materials from limonite ores but introduces significant dependence on sulfuric acid and imported sulfur, creating new geopolitical and supply-chain vulnerabilities. OESBF, although still at an emerging stage, offers potential for technological diversification, reduced sulfur dependence, and greater flexibility in producing battery-related nickel intermediates. The study argues that Indonesia's future downstreaming strategy should move beyond capacity expansion and value addition toward a diversified technological portfolio that strengthens industrial competitiveness, energy security, environmental performance, and supply-chain resilience.

Keywords: Nickel downstreaming; technological resilience; energy security; critical minerals; OESBF; Indonesia

INTRODUCTION

The global energy transition has significantly reshaped the strategic importance of nickel. Once valued primarily as an alloying metal for stainless steel production, nickel has increasingly become a critical mineral supporting the expansion of electric vehicles (EVs) and battery energy storage systems. Accelerating transport electrification and increasingly ambitious net-zero commitments have stimulated demand for battery-grade nickel, placing resource-rich countries such as Indonesia at the centre of the emerging clean energy economy (IEA, 2025a; World Bank, 2020).

Indonesia possesses the world's largest lateritic nickel reserves and has become the world's dominant nickel producer. Building on this resource advantage, the Government of Indonesia has pursued an ambitious downstream industrialisation strategy through restrictions on unprocessed nickel ore exports, incentives for domestic processing, and the development of integrated industrial parks. These policies have fundamentally transformed Indonesia's position in the global nickel value chain. Rather than exporting raw ore, Indonesia now produces a range of intermediate nickel products, including nickel pig iron (NPI), ferronickel, nickel matte, and mixed hydroxide precipitate (MHP), substantially increasing domestic value added and export earnings (United States Geological Survey [USGS], 2024; Nugroho et al., 2026b).

Indonesia's emergence as a global nickel-processing hub has been closely associated with its abundant and relatively low-cost coal resources. Coal-based electricity has enabled large-scale, energy-intensive smelting operations and supported the rapid development of integrated nickel industrial parks. However, this energy advantage also creates a fundamental policy paradox. While inexpensive coal-fired electricity strengthens the competitiveness of Indonesia's nickel industry, its high carbon intensity raises serious concerns about the environmental sustainability of downstreaming and its compatibility with the broader global energy transition (Nugroho et al., 2026b; Ramadhani & Paksi, 2025).

Despite substantial progress, Indonesia's downstream nickel industry remains concentrated in products primarily serving the stainless-steel sector rather than the battery industry. This reflects a broader limitation of Indonesia's upgrading trajectory. Although the country has moved decisively from raw-material exports towards large-scale processing, much of its industrial activity remains concentrated in upstream and midstream stages, with continuing dependence on foreign technology and limited domestic innovation capabilities (Nugroho et al., 2026b). Most existing smelters employ Rotary Kiln Electric Furnace (RKEF) technology to process saprolite ore into NPI and ferronickel, which are predominantly used in stainless-steel production. RKEF has therefore played a central role in Indonesia's industrial expansion, but its contribution to the domestic EV battery supply chain remains relatively limited.

By contrast, battery-material production increasingly relies on High-Pressure Acid Leaching (HPAL), a hydrometallurgical process capable of processing lower-grade limonite ore to produce MHP, which can subsequently be refined into battery-grade nickel chemicals (Nugroho et al., 2026b; IEA, 2025). The expansion of HPAL provides an important pathway for Indonesia to utilise its substantial limonite resources and strengthen its position in the global battery supply chain. However, it also introduces new technological, environmental, and strategic vulnerabilities.

Unlike RKEF, which is highly electricity-intensive, HPAL depends heavily on sulfuric acid and consequently requires large and continuous supplies of elemental sulfur. Indonesia has limited domestic sulfur production and therefore relies substantially on imports, a significant proportion of which originates in the Middle East. This dependence creates a potential supply-chain vulnerability because disruptions to maritime trade routes, particularly around the Strait of Hormuz, could affect the availability and cost of critical inputs for Indonesia's battery-material industry (Nugroho et al., 2026a; Crundwell et al., 2011). Thus, the transition from RKEF to HPAL does not simply represent technological upgrading; it also changes the structure of Indonesia's strategic dependencies.

HPAL also raises significant environmental concerns. The process generates substantial quantities of acidic residues and tailings requiring careful and long-term management. Potential impacts on marine ecosystems, water quality, land, and surrounding communities have become increasingly important as Indonesia seeks to reconcile rapid industrialisation with sustainable development and decarbonisation objectives (Mudd, 2010; Zhang et al., 2025). The environmental footprint of nickel processing is therefore becoming an increasingly important determinant of the long-term competitiveness and social legitimacy of Indonesia's downstreaming strategy.

These challenges are particularly significant because Indonesia's industrial and energy policies increasingly emphasise the development of a domestic EV and battery ecosystem as part of broader objectives of decarbonisation, economic transformation, and industrial upgrading. Achieving these objectives requires expanded production of battery-grade nickel and associated materials. Yet greater reliance on HPAL simultaneously creates new dependencies on imported critical inputs and generates environmental risks. Indonesia therefore faces a strategic choice: downstreaming cannot be evaluated solely on the basis of production capacity or export value but must also consider energy security, critical-input resilience, environmental performance, and technological capability (IEA, 2026; Nugroho et al., 2026b).

One potentially important alternative is Oxygen-Enriched Side-Blown Furnace (OESBF) technology. Originally developed to improve metallurgical efficiency and reduce processing costs, OESBF has attracted growing attention for potential application in nickel processing. Compared with conventional HPAL, it offers the possibility of producing nickel intermediates for battery applications while reducing reliance on sulfur-intensive hydrometallurgical processing and potentially mitigating some associated environmental impacts. Although OESBF remains an emerging technology whose commercial application to nickel requires further assessment, it may provide an alternative pathway for Indonesia's next phase of downstream industrialisation (Liu et al., 2020; Zhang et al., 2025).

While considerable research has examined Indonesia's nickel export restrictions, downstream industrialisation, foreign investment, and EV ambitions, comparatively limited attention has been given to processing-technology choices from the perspectives of energy policy, critical-input security, geopolitical exposure, and strategic industrial resilience. Existing studies tend to assess technologies primarily in terms of technical performance, production efficiency, or economic feasibility, while their broader implications for energy systems, supply-chain security, environmental sustainability, and national industrial strategy remain underexplored (Gereffi et al., 2005; Nugroho et al., 2026b).

This paper addresses this gap by examining how alternative nickel-processing technologies shape Indonesia's downstream industrial strategy, energy policy, and supply-chain resilience. It comparatively assesses RKEF, HPAL, and the emerging OESBF technology in terms of their implications for battery-material production, critical-mineral security, environmental sustainability, and industrial development. By integrating technological assessment with energy-policy and strategic-resilience perspectives, the paper develops a framework for guiding Indonesia's transition from predominantly stainless-steel-oriented downstreaming towards a more diversified, resilient, and sustainable battery-materials industry.

LITERATURE REVIEW

Indonesia's Nickel Downstreaming: Achievements and Remaining Challenges

Indonesia's downstream industrialisation policy represents one of the world's most ambitious attempts to capture greater value from mineral resources. Through a combination of export restrictions on unprocessed nickel ore, fiscal incentives, coal abundance, and the development of integrated industrial parks, the country has successfully transformed itself from a major exporter of raw nickel ore into one of the world's leading producers of processed nickel products. Since the implementation of the nickel ore export ban, investment in smelting facilities has expanded rapidly, particularly in the Indonesia Morowali Industrial Park (IMIP) and Indonesia Weda Bay Industrial Park (IWIP), supported largely by foreign direct investment. (Nugroho et al., 2026b; Widyastuti et al., 2026)

Most of this expansion, however, has been concentrated in the production of nickel pig iron (NPI) and ferronickel for stainless steel manufacturing. Consequently, although Indonesia has successfully moved downstream, much of its industrial development remains positioned in the intermediate segment of the global value chain. (Nugroho et al., 2026b). Battery-grade nickel products, such as mixed hydroxide precipitate (MHP) and nickel sulphate, still account for a relatively small share of total production. This mismatch has become increasingly significant as Indonesia seeks to establish a globally competitive EV battery industry.

Recent studies have therefore argued that the next phase of downstream industrialisation should prioritise upgrading from stainless steel-oriented production towards battery materials. Such a transition requires not only additional investment but also careful consideration of alternative processing technologies that are capable of supporting long-term industrial competitiveness. (Nugroho et al., 2026b; Andreoni & Chang, 2019)

Indonesia's downstreaming experience also illustrates the distinction between value addition and structural upgrading**.** The rapid expansion of smelting and refining capacity has clearly increased domestic processing and export value, but this does not necessarily imply technological autonomy or movement into the highest-value segments of the nickel value chain. Nugroho et al. (2026b) argue that Indonesia's upgrading remains incomplete and uneven, characterised by strong concentration in upstream and midstream activities, continued reliance on foreign technologies, and limited domestic innovation capabilities. This suggests that the next phase of downstream industrialisation should be assessed not simply by the expansion of processing capacity but by the extent to which it generates technological learning, domestic capabilities, and greater control over higher-value activities. (Nugroho et al., 2026b; Humphrey & Schmitz, 2002)

Nickel Processing Technologies: From Pyrometallurgy to Hydrometallurgy

Nickel laterite ores are commonly processed through two principal technological pathways, each corresponding to different ore characteristics and industrial objectives. (Fan et al., 2024; Zhang et al., 2025)

High-grade saprolite ores are generally processed using pyrometallurgical technologies, particularly the Rotary Kiln Electric Furnace (RKEF) process. RKEF has become the dominant technology in Indonesia because it efficiently converts saprolite into nickel pig iron (NPI), the principal feedstock for stainless steel production. The technology is mature, commercially proven, and capable of operating at large industrial scales. However, RKEF requires substantial electricity consumption and offers limited flexibility for producing battery-grade nickel chemicals. (Fan et al., 2024; Zhang et al., 2025)

Lower-grade limonite ores, by contrast, are typically processed using High Pressure Acid Leaching (HPAL), a hydrometallurgical technology that produces mixed hydroxide precipitate (MHP), an important precursor for lithium-ion battery cathodes. HPAL enables Indonesia to utilise limonite resources that were previously considered uneconomic, thereby significantly increasing overall resource utilisation. (McDonald & Whittington, 2008; Zhang et al., 2025)

Despite these advantages, HPAL presents several technical and operational challenges. The process requires large quantities of sulfuric acid, operates under extremely high temperature and pressure, involves high capital investment, and produces considerable volumes of chemical residues requiring long-term environmental management. Operational complexity and relatively high failure rates have also affected commercial performance in several countries. (McDonald & Whittington, 2008; Zhang et al., 2025)

Consequently, technology selection is no longer simply an engineering decision but has become an increasingly important component of industrial strategy. (Andreoni & Chang, 2019)

Energy Policy and the Emerging Battery Economy

Energy policy has evolved beyond the traditional objective of ensuring adequate fuel supply toward facilitating broader industrial transformation under the global energy transition. As countries pursue decarbonisation, critical minerals have become increasingly integrated into national energy-security frameworks because they underpin renewable power generation, battery storage, and electric mobility. In this context, energy policy and mineral policy are becoming increasingly interconnected. (IEA, 2023; World Bank, 2020)

Indonesia has adopted ambitious targets for electric-vehicle (EV) deployment and domestic battery manufacturing. Consequently, nickel downstreaming has become closely linked to national energy and industrial policy rather than remaining solely a matter of mineral-resource management. The strategic objective is not simply to process nickel domestically, but to capture a larger share of the value created along the emerging EV and battery value chains. (Nugroho et al., 2026b; IEA, 2025)

Indonesia's ambition to become a major player in the global EV supply chain faces increasing uncertainty from rapid changes in battery technology. The growing adoption of lithium iron phosphate (LFP) batteries, which do not require nickel, challenges the long-term demand for nickel-based chemistries. This creates technological risks for Indonesia's capital-intensive downstream investments. Nevertheless, substantial economic incentives remain for moving beyond mining and intermediate processing towards higher-value battery materials. The success of Indonesia's downstreaming strategy will therefore depend on its ability to adapt to technological change, diversify its processing capabilities, and strengthen domestic value creation. Failure to do so could limit the long-term economic benefits of nickel industrialisation (Nugroho et al., 2026b).

The technological pathways adopted for nickel downstreaming also have important implications for energy policy. Processing technologies differ substantially in their energy and input requirements. Rotary kiln-electric furnace (RKEF) technology depends primarily on a continuous and reliable supply of electricity, whereas high-pressure acid leaching (HPAL) relies heavily on chemical inputs, particularly sulfuric acid derived from elemental sulfur. Consequently, downstream technologies cannot be evaluated solely in terms of processing efficiency, production costs, or output value. Their assessment must also consider energy security, input availability, industrial resilience, and the stability of the associated supply chains. The growing integration of mineral processing with the energy system therefore requires an analytical perspective capable of capturing these interdependencies. (Zhang et al., 2025; Fan et al., 2024)

Critical Material Security and Supply-Chain Resilience

Recent geopolitical developments have further highlighted the importance of securing not only critical minerals but also the critical industrial inputs required to process them. Although much of the international literature and policy debate focuses on lithium, cobalt, nickel, and rare-earth elements, comparatively limited attention has been devoted to sulfur, despite its indispensable role in hydrometallurgical nickel processing. (IEA, 2025; Nugroho et al., 2026a)

Indonesia currently relies heavily on imported elemental sulfur to support HPAL operations. A substantial share of global sulfur supply originates as a by-product of oil and gas production in the Middle East. This creates an indirect exposure of Indonesia's emerging battery-material industry to geopolitical disruptions affecting maritime trade routes, particularly the Strait of Hormuz. The vulnerability is therefore not confined to the availability of nickel ore itself; it extends to the availability and affordability of essential inputs required to transform nickel into higher-value products. (Nugroho et al., 2026a; USGS, 2024b)

This dependence introduces a broader dimension of resource security. This dependence introduces a broader dimension of resource security**.** As argued by Nugroho et al. (2026a), industrial upgrading can reconfigure rather than eliminate vulnerability: moving from raw nickel exports to higher-value battery-material production may create new dependencies on imported processing inputs. In the case of HPAL, sulfur constitutes a critical intermediate input whose availability and price are exposed to geopolitical and maritime risks. Disruptions in sulfur supply associated with regional geopolitical conflicts demonstrate that supply-chain resilience depends not only on access to mineral resources but also on the secure availability of critical processing inputs. In other words, a country may possess abundant reserves of a critical mineral while remaining vulnerable to external disruptions in the industrial inputs required to process that mineral. Downstream industrial policy should therefore incorporate systematic assessments of imported chemical and energy inputs alongside assessments of domestic mineral availability. (Nugroho et al., 2026a)

Indonesia's downstream nickel industry also faces significant supply-chain pressures from both domestic resource constraints and external geopolitical developments. Domestically, the rapid expansion of RKEF smelting capacity has raised concerns about the accelerated depletion of high-grade saprolite ore, the principal feedstock for this processing route. These concerns have prompted the government to strengthen resource controls and impose production quotas to prevent potential shortages of suitable feedstock. The issue is particularly important because the expansion of processing capacity can generate a structural mismatch between installed smelter capacity and the long-term availability of appropriate domestic ore. (APNI, 2026; Nugroho et al., 2026b)

Externally, the concentration of investment, technology, and industrial ownership among Chinese companies in strategic industrial parks such as the IMIP and IWIP creates an additional layer of geopolitical vulnerability. This ownership and technological structure expose Indonesian nickel products to the evolving trade and industrial policies of major consuming economies. One important example is the United States' Inflation Reduction Act (IRA), which restricts access to certain EV incentives for supply chains involving materials associated with Foreign Entities of Concern (FEOC). Such restrictions illustrate how geopolitical competition can influence the commercial viability of Indonesian nickel products even when the underlying mineral resources and processing capacity are domestically available. (Nugroho et al., 2026b)

These developments suggest that technological resilience in the nickel industry should be understood more broadly than the country's ability to extract and process nickel ore. It also depends on the industry's capacity to adapt to changing battery chemistries, secure critical imported inputs, manage domestic resource constraints, diversify technology and ownership structures, and navigate increasingly restrictive international trade regimes. Energy policy, mineral policy, and industrial policy therefore need to be considered as interconnected components of Indonesia's strategy for building a resilient battery economy. (Nugroho et al., 2026a, 2026b; IEA, 2025)

Environmental Sustainability of Nickel Processing

Environmental sustainability has become an increasingly important criterion in evaluating downstream technologies. Although both pyrometallurgical and hydrometallurgical processes generate environmental impacts, the nature of these impacts differs considerably. (Mudd, 2010; Zhang et al., 2025)

RKEF is associated primarily with high energy consumption and greenhouse gas emissions, particularly when electricity is generated from coal-fired power plants. HPAL, on the other hand, raises concerns regarding acid consumption, wastewater treatment, tailings disposal, and potential contamination of terrestrial and marine ecosystems. (IEA, 2023; Zhang et al., 2025)

These environmental considerations have become particularly important because downstream industrialisation increasingly serves not only economic objectives but also supports the production of clean energy technologies. Consequently, the environmental footprint of battery material production itself has become subject to growing international scrutiny. (World Bank, 2020; IEA, 2025)

Future processing technologies are therefore expected to achieve improvements in both production efficiency and environmental performance.

Towards Technological Resilience: An Emerging Analytical Perspective

Although existing literature has extensively examined export restrictions, industrial policy, global value chains, and EV battery development, relatively few studies have integrated technology choice with energy security, environmental sustainability, and geopolitical resilience within a single analytical framework. (Gereffi et al., 2005; Nugroho et al., 2026b)

This paper proposes the concept of technological resilience to bridge this gap. The concept of technological resilience developed in this study builds on two related dimensions identified in recent analyses of Indonesia's nickel industrialisation. First, industrial upgrading can generate new forms of external dependence when higher-value processing remains reliant on imported technologies and critical inputs (Nugroho et al., 2026b). Second, the security of industrial development depends not only on access to mineral resources but also on the reliability of critical processing inputs exposed to geopolitical and logistical disruptions (Nugroho et al., 2026a). **Technological resilience therefore combines the capability dimension of industrial upgrading with the vulnerability dimension of input security.** Under this framework, processing technologies should not be evaluated solely according to metallurgical efficiency or production cost. Instead, they should also be assessed against broader strategic criteria, including: (Nugroho et al., 2026a, 2026b)

- resource utilisation efficiency;
- energy requirements;
- dependence on imported critical inputs;
- environmental performance;
- supply-chain resilience;
- compatibility with national energy transition objectives; and

- long-term industrial competitiveness.

Viewed through this perspective, the emergence of Oxygen-Enriched Side-Blown Furnace (OESBF) technology represents more than a technological innovation. It may constitute an alternative strategic pathway for Indonesia's next phase of nickel downstreaming by strengthening both industrial resilience and national energy security. (Liu et al., 2020; Zhang et al., 2025)

The foregoing review demonstrates that existing studies have largely examined Indonesia's nickel downstreaming from economic, technological, or industrial policy perspectives in isolation. Less attention has been paid to how technology choice shapes energy security, supply-chain resilience, and environmental sustainability simultaneously. To address this gap, this study adopts a qualitative Strategic Policy Assessment (SPA) that integrates these dimensions into a unified analytical framework for evaluating alternative nickel processing technologies. (Nugroho et al., 2026a, 2026b)

Table 1. SPA Matrix for Evaluating Alternative Nickel Processing Technologies

Evaluation Criteria	Pyrometallurgy (RKEF)	Hydrometallurgy (HPAL)	Alternative Pathway (OESBF)
Primary Target Market	Stainless Steel (NPI/Ferronickel)	EV Batteries (MHP/Sulphate)	Flexible (Matte to Battery Materials)
Raw Material Limitations	Vulnerable (High-grade saprolite depletion)	Abundant (Utilizes low-grade limonite)	High Flexibility (Capable of processing various grades)
Import Dependency	Low	High (Heavily dependent on sulfur/acid supply)	Moderate to Low
Environmental/Carbon Risk	Very High (Reliance on coal-fired power plants)	High (Tailings waste & acid management issues)	Lower (Geothermal/oxygen energy efficiency)
Geopolitical Resilience	Low (Single-capital dominance)	Low (Risk of Western market exclusion/IRA)	Higher (If partner diversification is done early) [Sources: Fan et al., 2024; Liu et al., 2020; Nugroho et al., 2026a, 2026b; Zhang et al., 2025.]

METHODOLOGY

Research Design

This study employs a qualitative Strategic Policy Assessment (SPA) to examine alternative nickel-processing technologies within the broader context of Indonesia's downstream industrialisation, energy transition, and emerging battery economy. The study does not seek to perform an engineering feasibility assessment, detailed life-cycle assessment, or techno-economic optimisation. Rather, it evaluates how alternative processing pathways may affect Indonesia's strategic objectives in terms of resource security, energy security, industrial upgrading, supply-chain resilience, environmental sustainability, and the development of a domestic electric-vehicle (EV) battery ecosystem. (George & Bennett, 2005; Yin, 2018)

A qualitative policy-oriented approach is appropriate because technology choice in the nickel industry is not determined solely by technical efficiency or production costs. Processing technologies also embody different requirements for ore quality, energy, chemical inputs, infrastructure, capital, environmental management, and

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

technological capabilities. These characteristics interact with broader policy objectives and external conditions, including geopolitical risks, critical-material dependencies, environmental regulation, and changes in global battery technologies. (Andreoni & Chang, 2019; Gereffi et al., 2005)

The SPA therefore assesses nickel-processing technologies not simply as alternative production technologies but as strategic industrial pathways. The central question is whether a given technology can contribute to Indonesia's long-term industrial development while remaining sufficiently resilient to resource, energy, environmental, technological, and geopolitical disruptions.

Analytical Framework: Technological Resilience

The study introduces the concept of Technological Resilience as its principal analytical lens. Technological resilience refers to the capacity of a processing technology and the industrial system surrounding it to sustain competitiveness and strategic relevance under changing market, technological, resource, environmental, and geopolitical conditions. (Nugroho et al., 2026a; Nugroho et al., 2026b)

This concept extends conventional assessments of processing technologies beyond production efficiency and cost competitiveness. A technology may be economically attractive under current market conditions but become strategically vulnerable if it depends heavily on scarce domestic resources, imported critical inputs, unstable energy supplies, or technologies that are losing relevance because of changes in global demand. (Nugroho et al., 2026a; IEA, 2025)

Within this framework, RKEF, HPAL, and OESBF are assessed across six interrelated dimensions:

1. Resource utilisation and availability, including the type and grade of lateritic nickel ore that can be processed, resource intensity, and the long-term availability of suitable domestic feedstock.

2. Energy and input requirements, including electricity and fuel requirements, energy intensity, process reliability, and dependence on externally sourced energy-related or chemical inputs.

3. Critical-material and supply-chain security, particularly dependence on imported sulfur and other critical inputs, exposure to international price volatility, and vulnerability to geopolitical or logistical disruptions.

4. Environmental sustainability, including greenhouse-gas emissions, waste generation, tailings characteristics, water requirements, chemical use, and potential impacts on terrestrial and marine ecosystems.

5. Industrial competitiveness and upgrading potential, including the value and market relevance of products, technological capabilities required, opportunities for domestic value creation, and compatibility with Indonesia's emerging battery-materials ecosystem.

6. Policy and strategic compatibility, including consistency with Indonesia's downstream industrialisation strategy, energy-transition objectives, critical-mineral policy, environmental goals, and broader long-term development priorities.

These dimensions are analytically interconnected rather than independent. For example, a technology that provides access to higher-value battery materials may simultaneously increase dependence on imported chemical inputs or impose greater environmental-management requirements. Similarly, a technology that is less dependent on imported inputs may face constraints in terms of feedstock availability or product-market relevance.

The framework therefore does not assign numerical scores or generate a single technological ranking. Instead, it provides a **structured qualitative comparison** that identifies the relative strengths, vulnerabilities, and strategic trade-offs associated with each processing pathway.

Comparative Technologies

The analysis compares three processing technologies that represent different technological pathways within Indonesia's evolving nickel downstream industry: Rotary Kiln Electric Furnace (RKEF), High Pressure Acid Leaching (HPAL), and Oxygen-Enriched Side-Blown Furnace (OESBF). (Fan et al., 2024; Zhang et al., 2025; Liu et al., 2020)

Rotary Kiln Electric Furnace (RKEF)

RKEF is currently the dominant pyrometallurgical processing route in Indonesia's nickel industry. It is primarily used to process saprolite ore and produce nickel pig iron (NPI) and ferronickel, which are predominantly used as feedstock for stainless-steel production. Its importance to the analysis derives from its established industrial scale, extensive supporting infrastructure, and strong integration with Indonesia's rapidly expanding stainless-steel industry. (Fan et al., 2024; Zhang et al., 2025). As of the current assessment, approximately 55 RKEF units are operating in Indonesia. (APNI, 2026)

At the same time, RKEF raises important strategic questions concerning its high electricity and energy requirements, dependence on high-grade saprolite resources, greenhouse-gas emissions, and the long-term availability of suitable ore. It therefore provides an important benchmark against which alternative nickel-processing pathways can be assessed, particularly in terms of energy security, resource sustainability, environmental performance, and industrial resilience. (Zhang et al., 2025; IEA, 2023)

High-Pressure Acid Leaching (HPAL)

HPAL is a hydrometallurgical technology used primarily to process limonite ore and produce mixed hydroxide precipitate (MHP), an important intermediate in the production of nickel and cobalt products for battery materials. HPAL has become strategically important because it provides a pathway for integrating Indonesia's abundant lateritic nickel resources into the rapidly expanding battery-material value chain. (McDonald & Whittington, 2008; Zhang et al., 2025)

However, HPAL also involves substantial chemical and process requirements, particularly the intensive use of sulfuric acid. This creates potential exposure to imported sulfur and, consequently, to geopolitical, price, and supply-chain risks. Its environmental performance, high capital requirements, process complexity, and dependence on chemical inputs therefore constitute important dimensions of the resilience assessment. Currently, 11 HPAL units are reported to be operating in Indonesia. (Nugroho et al., 2026a; McDonald & Whittington, 2008, APNI 2026)

Oxygen-Enriched Side-Blown Furnace (OESBF)

OESBF represents an emerging pyrometallurgical pathway that has attracted increasing attention as a potential alternative for producing nickel intermediates while reducing dependence on conventional sulfur-intensive hydrometallurgical processing. Unlike RKEF and HPAL, however, OESBF has not yet achieved the same level of commercial deployment in Indonesia. At present, only four OESBF units are operating, all located in Morowali. (Liu et al., 2020; Zhang et al., 2025)

The technology is therefore treated in this study as an emerging strategic option rather than as an established commercial benchmark. Its inclusion enables the analysis to examine whether technological diversification could reduce some of the vulnerabilities associated with Indonesia's current nickel-processing structure. Given its more limited commercial track record and large-scale deployment experience, the assessment focuses on its strategic potential, technological characteristics, and possible contribution to industrial resilience rather than assuming that OESBF is already a proven substitute for the established RKEF and HPAL pathways. (Liu et al., 2020; Zhang et al., 2025)

Data Sources

The study relies exclusively on secondary data drawn from multiple sources to support evidence triangulation and strengthen analytical reliability. The principal sources include: (George & Bennett, 2005; Yin, 2018)

- peer-reviewed academic literature on nickel metallurgy, mineral processing, energy systems, industrial policy, and critical-mineral supply chains;
- publications and statistical databases from international organisations, including the International Energy Agency (IEA), World Bank, OECD, U.S. Geological Survey (USGS), and United Nations Conference on Trade and Development (UNCTAD); (IEA, 2023; World Bank, 2020; OECD, 2019; USGS, 2024)
- official policies, regulations, statistical publications, and strategic documents issued by the Government of Indonesia, particularly the Ministry of Energy and Mineral Resources (MEMR), Ministry of Industry, and Ministry of National Development Planning/Bappenas;
- company reports, technical publications, and industry studies relating to nickel mining, smelting, battery materials, and processing technologies; and
- recent market and policy analyses addressing critical-mineral security, geopolitical risks, battery-technology developments, energy requirements, and the environmental performance of nickel-processing technologies.

Where possible, information from different sources is cross-checked to identify inconsistencies and avoid reliance on a single data provider. Particular attention is given to information concerning energy consumption, ore requirements, chemical inputs, product characteristics, environmental impacts, and technology maturity because these factors directly affect the assessment of technological resilience. (George & Bennett, 2005; Yin, 2018)

Analytical Procedure

The analysis proceeds through four sequential stages.

First, characterisation of Indonesia's downstream nickel industry. The study establishes the current structure of Indonesia's nickel value chain, including major ore types, dominant processing routes, principal products, energy requirements, and linkages with stainless-steel and battery-material industries. This stage provides the industrial and policy baseline for the subsequent comparison.

Second, technological assessment. The technical and industrial characteristics of RKEF, HPAL, and OESBF are examined with particular attention to feedstock requirements, energy use, chemical inputs, output products, technological maturity, infrastructure requirements, and environmental implications.

Third, strategic resilience assessment**.** Each technology is assessed against the six dimensions of the Technological Resilience Framework: resource utilisation and availability; energy and input requirements; critical-material and supply-chain security; environmental sustainability; industrial competitiveness and upgrading potential; and policy and strategic compatibility. The assessment identifies both advantages and vulnerabilities rather than producing a single numerical score.

Fourth, policy synthesis**.** The findings are integrated to identify the strategic implications of alternative processing pathways for Indonesia's downstream industrialisation and energy policy. Particular attention is given to technology diversification, resource management, energy-system requirements, critical-input security, environmental governance, and the ability of Indonesian industry to move toward higher-value battery materials.

This sequential procedure enables the analysis to move from technology characteristics to strategic vulnerabilities and ultimately to policy implications, thereby linking mineral-processing decisions with Indonesia's broader industrial and energy-transition objectives.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

Research Contribution

The principal contribution of this study is to reposition nickel-processing technology as a strategic policy issue rather than merely a technical or economic choice. Existing assessments of nickel-processing technologies tend to emphasise metallurgical performance, production costs, investment requirements, or environmental impacts. While these dimensions are important, they do not fully capture the vulnerabilities that emerge when processing technologies become embedded in national industrial and energy systems. (Gereffi et al., 2005; Andreoni & Chang, 2019)

By integrating technology choice with energy security, critical-material security, supply-chain resilience, environmental sustainability, and industrial upgrading, this study develops a broader policy framework for evaluating nickel-processing pathways under conditions of accelerating technological change and geopolitical uncertainty. (Nugroho et al., 2026a, 2026b; IEA, 2025)

The concept of Technological Resilience provides a basis for assessing whether Indonesia's current and emerging processing technologies can remain strategically relevant over the longer term. This is particularly important as the global battery industry evolves rapidly, alternative battery chemistries such as lithium iron phosphate (LFP) gain market share, and competition over critical minerals increasingly intersects with trade, industrial, and geopolitical policy. (Nugroho et al., 2026a, 2026b)

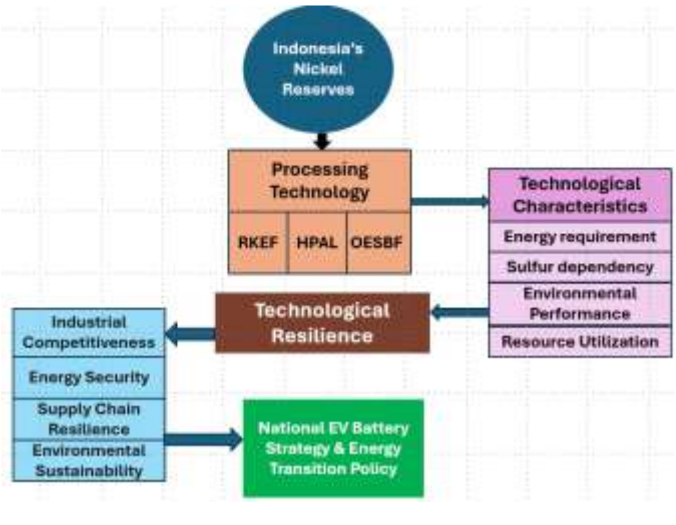
The study consequently shifts the central policy question from "Which technology is the most efficient?" to "Which combination of technologies provides Indonesia with the greatest capacity to capture value while maintaining resource, energy, environmental, technological, and geopolitical resilience?" This perspective is particularly relevant for a resource-rich country seeking to transform mineral abundance into durable industrial capabilities.

CONCEPTUAL FRAMEWORK

Figure 1 presents the conceptual framework used in the study. It links Indonesia's nickel resource base and downstream industrial structure to alternative processing technologies and, subsequently, to the six dimensions of Technological Resilience. The framework illustrates how technology choice affects not only the type and value of nickel products but also energy demand, critical-input dependence, environmental pressures, industrial upgrading, and exposure to geopolitical and supply-chain risks. (Nugroho et al., 2026a, 2026b; IEA, 2025)

The framework ultimately connects these technological characteristics to broader policy outcomes, including industrial competitiveness, energy security, supply-chain resilience, environmental sustainability, and the development of Indonesia's battery-material industry.

Figure 1. Conceptual Framework for the Strategic Policy Assessment of Nickel-Processing Technologies



Source: Developed by the Author.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

RESULTS AND DISCUSSION

Indonesia's Nickel Downstreaming: Successes and Structural Limitations

Indonesia's downstream nickel policy has fundamentally transformed the country's position in the global mineral value chain. Before the implementation of the nickel ore export ban, Indonesia primarily exported unprocessed laterite ore, allowing much of the value-added processing to occur abroad. Over the past decade, however, substantial investment in domestic smelting capacity has enabled Indonesia to become the world's largest producer of nickel pig iron (NPI) and one of the leading producers of ferronickel and nickel matte. This transformation has generated significant increases in export earnings, industrial employment, and foreign direct investment, demonstrating the effectiveness of downstream industrialisation as an instrument of resource-based development. (Nugroho et al., 2026b; USGS, 2024)

Nevertheless, the current industrial structure reveals an important limitation. Most downstream production remains concentrated in intermediate products serving the global stainless-steel industry rather than the rapidly growing electric vehicle (EV) battery market. The dominance of RKEF technology has largely shaped this production profile because it is specifically designed to convert saprolite ore into NPI. As a result, Indonesia has successfully moved downstream but has not yet fully upgraded into the higher-value battery materials segment that is expected to drive future global nickel demand. (Nugroho et al., 2026b; IEA, 2025)

This structural imbalance suggests that the next stage of downstream industrialisation should focus not merely on increasing smelting capacity but on diversifying processing technologies capable of producing battery-grade materials while maintaining industrial competitiveness. (Nugroho et al., 2026b)

Technology Choice and Indonesia's Energy Policy

One of the central findings of this study is that the choice of processing technology has become an integral component of national energy policy. Traditionally, energy policy focused on ensuring adequate supplies of electricity and fuels for industrial development. Under the global energy transition, however, energy policy increasingly encompasses the security of critical minerals and industrial inputs required to support low-carbon technologies. (IEA, 2023; IEA, 2025) The three technologies considered in this study illustrate distinct energy characteristics. RKEF is highly electricity-intensive because it relies on electric furnaces operating at extremely high temperatures. Consequently, its competitiveness depends heavily on reliable and affordable electricity supply, which in Indonesia is still largely generated from coal-fired power plants. (Zhang et al., 2025; IEA, 2023)

HPAL presents a different profile. Although it requires considerably less electrical energy than RKEF, it depends on continuous supplies of sulfuric acid produced from elemental sulfur. In effect, HPAL substitutes one strategic dependency—electricity—with another equally important dependency on imported chemical inputs. This distinction is highly relevant from a policy perspective because disruptions affecting sulfur supply may jeopardise battery material production even when electricity remains available. (Nugroho et al., 2026a; McDonald & Whittington, 2008)

OESBF potentially represents an intermediate pathway. By reducing reliance on sulfur-intensive hydrometallurgical processing while maintaining the capability to produce battery-grade intermediates, OESBF could diversify Indonesia's technological portfolio and reduce exposure to external supply risks. From an energy policy perspective, technology diversification therefore becomes an important element of national energy security. (Liu et al., 2020; Zhang et al., 2025)

Sulfur Dependency: A New Dimension of Energy Security

An important finding of this study, consistent with the emerging concept of input security, is that Indonesia's transition towards battery-material production introduces a previously underappreciated form of strategic vulnerability (Nugroho et al., 2026a). Unlike conventional assessments of energy security, which primarily emphasise oil, gas, or electricity supply, battery-material production depends on secure access to industrial processing inputs. HPAL requires large quantities of sulfuric acid, making elemental sulfur an indispensable component of the production process. Because Indonesia currently imports almost all of its sulfur requirements, the country's battery industry has become indirectly dependent on international sulfur markets and the geopolitical stability of major exporting regions.

Recent geopolitical tensions involving the Middle East and maritime transport through the Strait of Hormuz have highlighted this vulnerability. Disruptions to sulfur exports, rising freight costs, or supply uncertainties can significantly increase operating costs for HPAL facilities and undermine the competitiveness of Indonesia's battery industry. This experience demonstrates that resource-rich countries are not necessarily insulated from external supply shocks if critical processing inputs remain import-dependent. (Nugroho et al., 2026a)

The findings therefore suggest that **critical material security** should become an integral component of Indonesia's energy policy. While considerable attention has been devoted to securing nickel resources, comparable attention should also be directed towards securing the industrial inputs required to process those resources into battery materials. (Nugroho et al., 2026a; IEA, 2025)

Environmental Sustainability and the Green Industrialisation Paradox

The expansion of battery material production also raises important environmental questions. Indonesia's downstream policy is intended to support the global transition towards cleaner energy systems; however, some of the technologies used to produce battery materials generate significant environmental externalities. (World Bank, 2020; IEA, 2025)

HPAL has attracted increasing attention because of its large consumption of sulfuric acid and the generation of acidic residues and tailings requiring long-term management. Concerns have been raised regarding wastewater disposal, marine ecosystems, groundwater quality, and land rehabilitation, particularly in regions where multiple HPAL facilities operate simultaneously. (Mudd, 2010; Zhang et al., 2025)

Conversely, RKEF's principal environmental challenge lies in its high electricity demand. Since much of Indonesia's industrial electricity is still supplied by captive coal-fired power plants, the carbon intensity of NPI production remains relatively high. Consequently, Indonesia faces a "green industrialisation paradox": minerals required for clean energy technologies are themselves produced through carbon-intensive industrial processes. (IEA, 2023; Zhang et al., 2025)

This paradox indicates that evaluating downstream technologies solely in terms of economic value added is insufficient. Environmental performance must become an equally important criterion for future technology selection. (Zhang et al., 2025; World Bank, 2020)

OESBF as a Strategic Option for Indonesia's Next Phase of Downstream Industrialisation

Against this backdrop, OESBF offers an alternative technological pathway that merits serious policy consideration. Rather than viewing OESBF simply as another metallurgical innovation, it should be understood as a strategic technology capable of addressing several structural weaknesses associated with existing processing systems. (Liu et al., 2020; Zhang et al., 2025)

Compared with HPAL, OESBF has the potential to reduce dependence on imported sulfur while producing nickel intermediates suitable for further processing into battery materials. Compared with RKEF, it offers opportunities to diversify Indonesia's downstream production beyond stainless steel-oriented products. Equally important, the technology may contribute to improved environmental performance through more efficient resource utilisation and reduced generation of chemical residues. (Liu et al., 2020; Nugroho et al., 2026a)

Nevertheless, OESBF should not be regarded as a universal replacement for existing technologies. RKEF will likely remain the most appropriate technology for processing saprolite ores destined for stainless steel production, while HPAL will continue to play an important role in processing limonite resources. Instead, OESBF should be considered part of a broader technology diversification strategy that enhances resilience, expands production flexibility, and reduces strategic vulnerabilities. (Fan et al., 2024; Zhang et al., 2025)

Accordingly, Indonesia's future competitiveness may depend less on replacing one technology with another than on developing a balanced technological portfolio capable of responding to changing market conditions, environmental requirements, and geopolitical risks. (Gereffi et al., 2005; Andreoni & Chang, 2019)

Towards a Technological Resilience Framework

The findings of this study suggest that the future success of Indonesia's nickel downstreaming strategy should be evaluated through a broader framework than conventional measures of value addition or export performance. A resilient downstream industry remains competitive under conditions of geopolitical uncertainty, fluctuating commodity prices, tightening environmental standards, and rapidly evolving battery technologies. (Nugroho et al., 2026a, 2026b; IEA, 2025)

This study therefore proposes Technological Resilience as an integrated framework for evaluating future processing technologies. Under this approach, technologies should be assessed according to five strategic dimensions (Nugroho et al., 2026a, 2026b)

Table 2. Strategic Dimension of Technological Resilience

Dimension	Strategic Question
Industrial competitiveness	Does the technology produce products demanded by future markets?
Energy security	Does it minimise dependence on vulnerable energy or industrial inputs?
Supply-chain resilience	Can it withstand geopolitical and logistical disruptions?
Environmental sustainability	Does it reduce emissions, waste, and ecological impacts?
Policy alignment	Does it support Indonesia's industrial, energy, and climate objectives? [Source: Author's synthesis based on Nugroho et al., 2026a, 2026b.]

Viewed through this framework, technological choice becomes a strategic policy decision rather than a purely engineering or commercial one. Indonesia's next phase of downstream industrialisation should therefore prioritise technologies that strengthen long-term resilience alongside economic efficiency. (Andreoni & Chang, 2019; Nugroho et al., 2026b)

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

Indonesia's nickel downstreaming policy has fundamentally transformed the country's position in the global mineral value chain. By restricting exports of unprocessed nickel ore and promoting domestic processing, Indonesia has successfully shifted from a supplier of raw materials to a major producer of intermediate nickel products, particularly nickel pig iron (NPI), ferronickel, and nickel matte. This transformation has generated substantial economic benefits through increased value addition, industrial investment, export earnings, and employment. (Nugroho et al., 2026b; USGS, 2024)

However, the findings of this study demonstrate that the next phase of downstream industrialisation presents a different challenge. While existing processing capacity has been highly successful in supporting stainless steel production, Indonesia's ambition to become a global hub for electric vehicle (EV) battery manufacturing requires a technological transition towards greater production of battery-grade nickel materials. This transition cannot be achieved simply by expanding existing processing capacity. Instead, it requires careful selection of processing technologies that support long-term industrial competitiveness while reducing strategic vulnerabilities. (IEA, 2026; Nugroho et al., 2026b)

The analysis further demonstrates that technology choice should no longer be viewed solely as a metallurgical or engineering decision. Different processing technologies create fundamentally different patterns of energy use, dependence on critical industrial inputs, environmental impacts, and exposure to geopolitical risks. In particular, HPAL technology's heavy reliance on imported sulfur introduces a new dimension of supply-chain vulnerability that has received relatively little attention in discussions of Indonesia's battery industry. Recent geopolitical tensions affecting sulfur markets illustrate that resource abundance alone does not guarantee industrial resilience when critical processing inputs remain externally dependent. (Zhang et al., 2025; Nugroho et al., 2026a)

Against this background, OESBF emerges as a promising strategic option for Indonesia's future downstream development. Rather than replacing existing technologies, OESBF has the potential to complement the current processing portfolio by reducing sulfur dependency, improving environmental performance, and expanding the production of battery-grade nickel intermediates. Technology diversification, therefore, should become a central element of Indonesia's downstream strategy. (Liu et al., 2020; Nugroho et al., 2026a)

More broadly, this study argues that the future success of Indonesia's nickel downstreaming should be evaluated not only by the extent of value addition achieved but also by the resilience of the technologies supporting industrial development. Economic upgrading alone is insufficient if industrial production remains vulnerable to geopolitical disruption, environmental constraints, or critical input shortages. (Nugroho et al., 2026b; IEA, 2025)

Accordingly, this paper proposes Technological Resilience as an integrated framework for evaluating future mineral processing technologies. By incorporating industrial competitiveness, energy security, critical material security, environmental sustainability, and policy alignment into a single analytical perspective, the framework offers a broader basis for assessing downstream industrialisation under conditions of accelerating global energy transition. (Nugroho et al., 2026a, 2026b)

Policy Implications

The findings of this study have several important implications for Indonesia's industrial and energy policies.

First, downstream industrial policy should move beyond measuring success solely by the number of smelters or export values. Future policy should prioritise technologies that produce higher-value battery materials while strengthening industrial resilience and reducing strategic vulnerabilities. (Nugroho et al., 2026b; Andreoni & Chang, 2019)

Second, Indonesia's energy policy should explicitly recognise critical industrial inputs as an integral component of energy security. The dependence of HPAL facilities on imported sulfur demonstrates that industrial resilience increasingly depends not only on electricity supply but also on secure access to essential processing materials. National resource security strategies should therefore incorporate critical industrial chemicals alongside conventional energy resources. (Nugroho et al., 2026a)

Third, the Government should encourage technological diversification within the nickel processing industry. While RKEF will remain appropriate for stainless steel production and HPAL will continue to play an important role in processing limonite ores, emerging technologies such as OESBF deserve greater attention through pilot projects, research collaboration, technology transfer, and investment incentives. A diversified technological portfolio would reduce dependence on any single processing route and enhance the adaptability of Indonesia's downstream industry. (Liu et al., 2020; Zhang et al., 2025)

Fourth, environmental performance should become a primary criterion in future downstream investment decisions. The expansion of Indonesia's battery industry should support, rather than undermine, the country's broader sustainability objectives. Environmental standards should therefore evolve alongside technological innovation, encouraging cleaner processing methods and improved waste management. (Mudd, 2010; Zhang et al., 2025)

Finally, industrial policy, energy policy, and critical mineral policy should be formulated within a unified strategic framework. Indonesia's ambition to become a leading global producer of EV batteries requires integrated policymaking that simultaneously addresses resource utilisation, technology development, supply-chain resilience, environmental governance, and international competitiveness. (Nugroho et al., 2026a, 2026b; IEA, 2025)

Limitations and Future Research

This study has several limitations that also provide opportunities for future research.

First, the analysis is based on qualitative policy assessment rather than detailed engineering or techno-economic modelling. Future studies could complement the present findings through quantitative comparisons of capital costs, operating costs, life-cycle emissions, and resource efficiency across different processing technologies. (George & Bennett, 2005; Yin, 2018)

Second, the evaluation of OESBF reflects its current stage of technological development. As commercial deployment expands, additional empirical evidence will be required to assess its operational performance under Indonesian geological and industrial conditions. (Liu et al., 2020; Zhang et al., 2025)

Third, future research should examine how alternative processing technologies influence Indonesia's broader critical mineral strategy, including cobalt, manganese, copper, and rare earth elements, thereby extending the concept of technological resilience to the wider clean energy supply chain. (IEA, 2025; World Bank, 2020)

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