



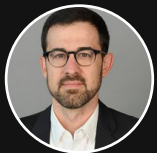
INSPIRE REPORT

# The Lux Raw Materials Criticality Framework

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# Foreword

Inspire Reports are an exclusive deliverable of Lux Research and Advisory Services. The genesis of why we created these Inspire Reports was to inspire, illuminate, and ignite your thinking.

At Lux, our research focuses on our clients' top priorities and key initiatives, helping them navigate today's central dilemma: balancing profitability with corporate sustainability goals.

These reports provide insights, frameworks, and recommendations that clarify your company's innovation paths and support confident decision-making.

## Clarity

These reports address executive, C-suite, and board-level discussions related to sustainability and carbon neutrality. We place technology in the context of these incredibly daunting business issues you are trying to solve.

## Performance

Lux has the most powerful network of innovators in the world across energy, manufacturing, and consumer packaged goods. These reports bring forward this cross-industry knowledge, enabling you to tap into our experience and learnings from working in that ecosystem and supporting best-in-class leaders, to drive higher performance of your own teams.

## Trust

Executives trust Lux's research because it follows a rigorous methodology and peer-review process, ensuring confidence in critical business decisions. These are not just reports or "content" — they are vetted, tested, and peer-reviewed research and analyses.

I hope you find our Lux Inspire Reports inspiring and helpful to support the conversations, thinking, and decisions you make every day to grow your company and solve for sustainability, carbon neutrality, and the long-term resilience of your business.



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Change the world.

**Marisa Kopec**  
*President*

# Executive Summary

## Leveraging innovation to turn raw materials risks into resilience and competitive advantage

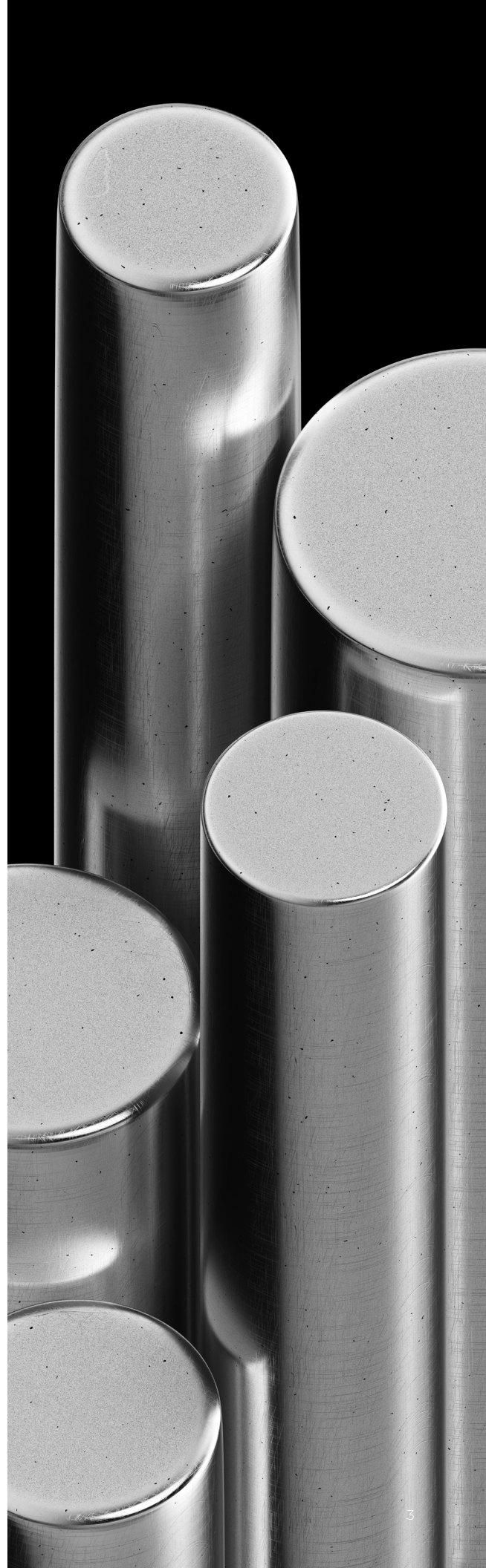
The global race for raw materials is shifting from routine supply chain management to a defining factor in economic growth. Once seen as stable commodities, minerals and metals are now strategic levers of national security and geopolitical negotiations. Governments worldwide are formalizing critical minerals and materials lists, underscoring the intensifying competition to secure access. This moment mirrors past industrial transformations — just as coal, steel, and oil enabled past eras of growth, the future of numerous industries from energy to electronics will hinge on how organizations can secure, substitute, and innovate their raw materials.

Risks extend beyond high-profile critical minerals as a widening gap between supply and demand threatens both the rollout of emerging technologies and the stability of existing industries. Traditional supply-side approaches such as mining expansion or stockpiling are likely to be insufficient in an era of accelerated growth. Organizations must complement them with innovation-driven resilience strategies that reduce exposure, unlock efficiency, and create entirely new pathways for growth.

This report introduces the Lux Raw Materials Criticality Framework, a methodology for assessing raw materials through two dimensions — supply risk and criticality — and for guiding innovation strategies to strengthen resilience. From this analysis, four strategic pathways emerge that provide organizations with a toolkit to future-proof operations and capitalize on new opportunities amid geopolitical volatility.

## THIS REPORT ADDRESSES SEVERAL PIVOTAL QUESTIONS, INCLUDING:

- 1 Which raw materials pose the greatest risks to technology deployment?
- 2 How can organizations adapt innovation strategies to anticipate and mitigate shortages?
- 3 Where can unmet raw materials demand be turned into lasting competitive advantages?



# Critical Minerals & Materials

Raw materials shortages are a limiting factor to global economic growth.

Raw materials are the foundation of the global economy: from concrete and steel holding up the world's infrastructure to ubiquitous plastics in everyday products and essential metals for electronic devices. In recent years, a new subset of raw materials, due to the emergence of energy transition technologies, has become a strategic priority for national security worldwide. Major economies such as the U.S., EU, Japan, Canada, and Australia have formalized their strategies with lists of critical minerals and materials\*, updating them regularly to reflect the dynamic nature of both supply and demand. The EU is the primary trailblazer in this domain, with the EU Commission establishing its first list of 14 critical raw materials in 2011, updating it every three years, with its fifth list published in 2023, consisting of 34 critical raw materials (Figure 1). The U.S. Geological Survey followed in 2018, with a list of 35 critical minerals and materials, which increased to 50 in 2022. Japan, Canada, and Australia all released updated lists within the last two years, consisting of 31, 34, and 30 critical minerals and strategic materials, respectively. There are numerous commonalities between the lists, especially for rare earth elements and platinum group metals, highlighting the global race for raw materials security and the policy recommendations and mechanisms to ensure reliable supplies, such as those from the [International Energy Agency](#) (IEA).

These lists of critical minerals and materials provide insights into supply risks and geopolitical vulnerabilities, serving as valuable policy tools in guiding resource security strategies, such as expanding domestic mining, investing in refining capacity, stockpiling materials, and forming international trade agreements. However, organizations are not simply facing the matter of securing raw materials but must also address the fundamental issue of the growing gap between raw materials supply and demand from advances in and deployment of new technologies. Organizations must pair supply-side risk management with innovation-driven resilience strategies to proactively address potential shortages, not just of high-profile critical minerals, but also of essential raw materials vital to manufacturing and construction. In applications where the supply looks highly unlikely to meet projected demand, companies should revisit their fundamental assumptions about the rollout of new technologies. This emerging need resulted in the development of the Lux Raw Materials Criticality Framework, a methodology specifically designed for R&D and innovation executives to actively shape the future of raw materials usage through technology-driven innovations.

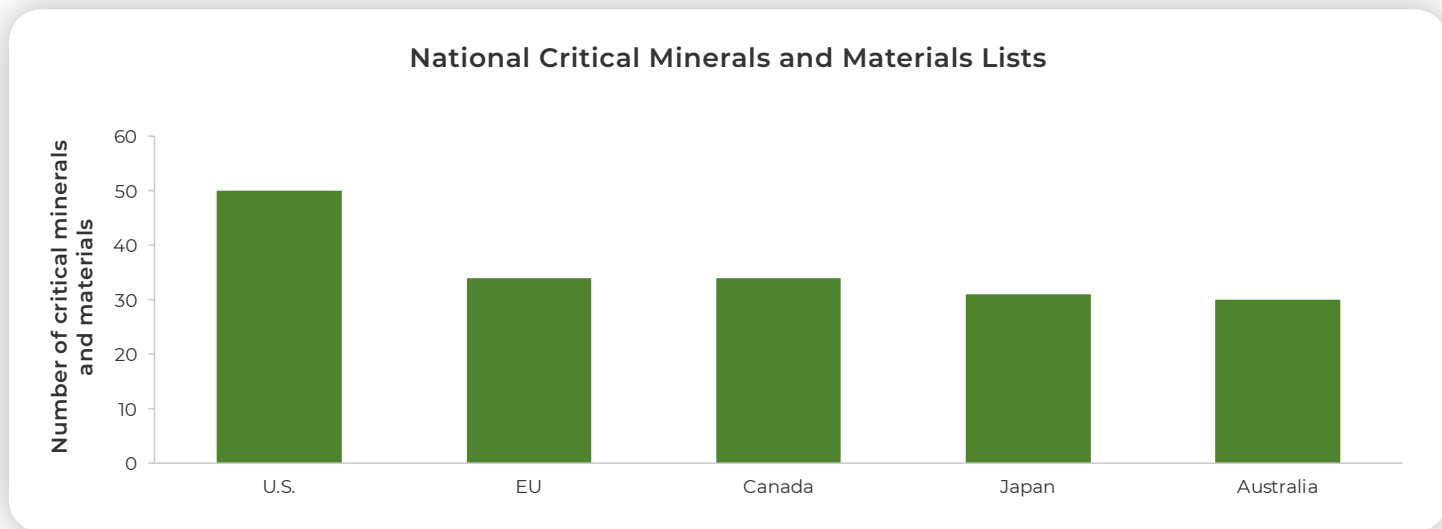


Figure 1. The number of critical minerals identified by each country on the most recent list published by the corresponding government agency. Sources: U.S. Geological Survey, EU Commission, Australian Department of Industry, Science and Resources, Critical Minerals Institute, and Canadian Critical Minerals Center of Excellence.

\*The term “critical minerals and materials” is used broadly, as countries vary in their terminology — referring to them as critical raw materials, critical materials, critical minerals, or strategic materials — based on national definitions.



# The Lux Raw Materials Criticality Framework

Lux Research developed the Raw Materials Criticality Framework to help organizations identify innovation opportunities and strategies arising from increased demand and supply risks (Figure 2) of raw materials essential to incumbent and emerging technologies. The framework defines two key metrics — **criticality** and **supply risk** — to assess both the demand for raw materials and the stability of their sources.

## Criticality

Criticality is the measure of a given raw material's requirements in meeting the projected deployment capacity of a technology in an outlook scenario. For the projections in this report, Lux applied its framework on energy technologies and the IEA's 2023 Update of its Net Zero Energy Scenario (NZE Scenario). The criticality value is expressed as a proportion of the total stock of the raw material required to reach the NZE Scenario to the annual global supply. It is calculated based on a technology's raw material requirement per unit (i.e., in megawatt-hours, megawatts, number of devices, etc.), current global raw material supply (in metric tons produced), and projected deployment of the outlook scenario (i.e., in megawatt-hours, megawatts, number of devices, etc.). For a technology's raw materials requirements, Lux calculated the average requirements of raw materials for a fully installed and operational system with the consideration that technological variations result in differences in both the type and amounts of raw materials. Lux collected global raw materials supply data for each relevant raw material from government and industry databases that are specific to production capacity and do not include global reserves.

## Supply risk

Supply risk is the measure of the resilience of the raw material's supply chain based on its geographical spread and stability of its producers. This value is expressed in a range of 0–5 and is an adaptation of a methodology developed by the European Commission in 2017 to determine the critical raw materials for the EU. It is calculated based on the Herfindahl-Hirschman Index (HHI) and a risk index derived from the World Bank's World Governance Index (WGI) of each individual country producing the raw material. For each country, the HHI is calculated based on the square of the country's share (%) of global capacity for the raw material. The risk index for each country is calculated based on the percentile rank of the WGI's six indicators — voice and accountability, political stability and absence of violence and terrorism, government effectiveness, regulatory quality, rule of law, control of corruption — and normalized to a score ranging from 0–10 with a higher score denoting more risk. The supply risk value is calculated based on the sum of the products of the two values for all countries producing the raw material.

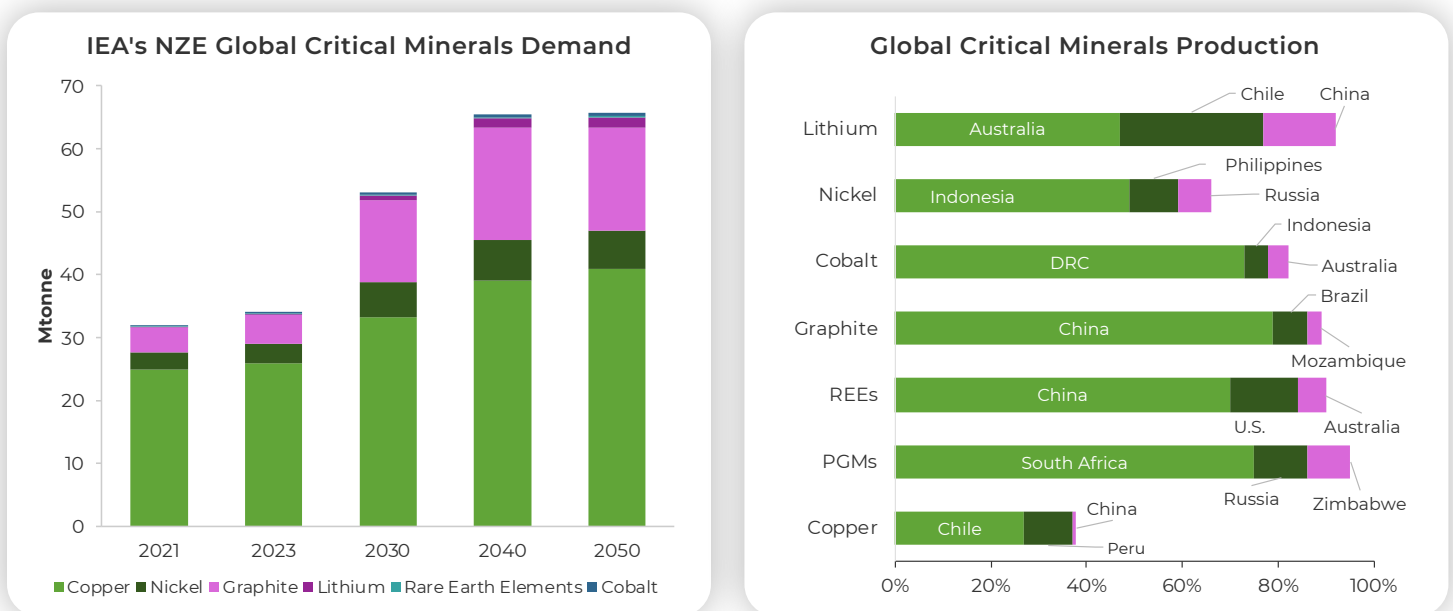


Figure 2. Left. Global demand projections for select critical minerals in all uses, including clean and non-clean energy technology applications; Right. Share of the top three countries' production capacity for select critical minerals. Source: IEA, Global Critical Minerals Outlook 2024.



# Four Innovation Strategies for Raw Materials Resiliency

This framework identifies four risk assessment outlooks (supply volatility, growth limitations, long-term stability, impending shortages) based on the raw material's position in terms of supply risk and criticality (Figure 3).

From these outlooks, Lux devised four innovation strategies: materials optimization, novel sources, recycling and circularity, and alternative materials. While each quadrant presents a priority innovation strategy, they are not limited to a specific quadrant. Organizations can leverage the Raw Materials Criticality Framework to assess their raw materials risks and leverage the innovation toolkit to build out a robust portfolio of solutions aligned to their strategic needs to mitigate future disruptions to their deployment scenarios.

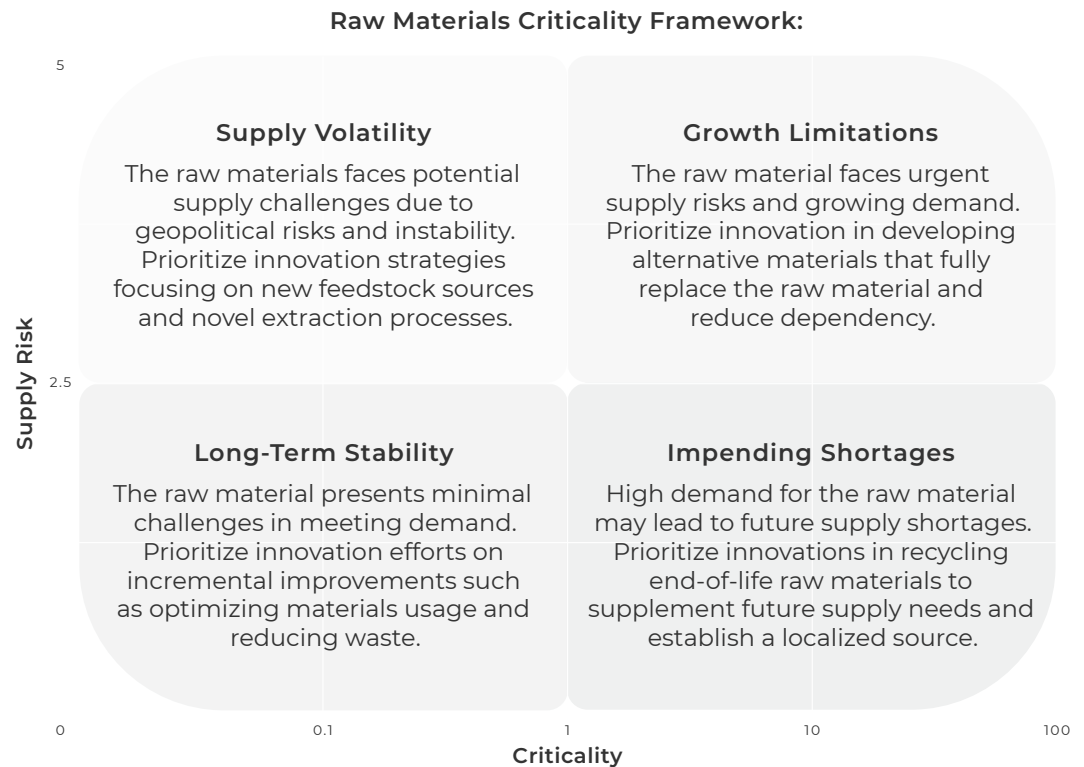


Figure 3. The Lux Raw Materials Criticality Framework assesses the supply risk and criticality of raw materials in future scenarios. Supply risk is a unitless value expressed from 0 to 5, where values below and above 2.5 represent low supply risk and high supply risk, respectively. Low supply risk indicates the supply of the raw material is diversified and sourced from low-risk countries; high supply risk indicates the supply of the raw material is highly monopolized and sourced from high-risk countries. Criticality is a value expressed as a ratio between future demand and current production supply. A ratio of 1 serves as the threshold between low criticality and high criticality. Low criticality indicates the demand for the raw material in the scenario does not exceed current global production supply; high criticality indicates the demand for the raw material in the scenario exceeds the current global production supply.

## Materials Optimization

Optimizing materials usage is key to any manufacturing process. This approach can be deployed for materials across the Raw Materials Criticality Framework, although it is likely to deliver greater results for materials with high criticality.

## Novel Sources

Finding and developing new feedstock sources and extraction processes for minerals and metals, including from byproducts can mitigate overall shortages. While the added volume will not be enormous, it is a best fit for materials with high supply risk, for which disruptions tend to be temporary.

## Recycling & Circularity

Designing systems for circularity and recycling end-of-life components helps recover critical minerals in a potentially indefinite manner. This approach provides a path to bridging impending supply gaps with established localized sources.

## Alternative Materials

Identify alternative materials that fully replace and/or reduce dependency on a supply-constrained material is most relevant for materials with high criticality, where recycling is not a long-term strategy, or alternatives deliver better efficiency than incumbents.



# Materials Optimization

Incremental innovations optimizing materials usage and reducing waste.

## Opportunities

Materials optimization is a proactive strategy for organizations looking to improve operational efficiency in near-term costs and resource utilization. Cost advantages can be achieved through lower production costs, higher-efficiency yields, and reduced waste generation, especially for high-volume manufacturing where materials costs are a significant portion of operational expenditure. This will be important in maintaining near-term competitiveness and differentiation in the market while also proactively addressing stricter compliance requirements around waste reduction and energy efficiency.

## Challenges

While ongoing efforts in manufacturing process efficiency improvements can be achieved through smart manufacturing solutions, novel manufacturing processes to achieve substantial materials optimization may face integration and product challenges. Reduction in materials use, especially reactive materials core to the functionality of the technology, may impact performance; thus, finding a balance of tradeoffs between materials and product performance should not be overlooked. For more established manufacturing processes, integration of novel approaches may lead to complexities in optimized processes if they are not plug-and-play solutions.

## Example Innovations

### 3D PRINTING

Use of 3D printing for specific components can minimize materials usage and waste, particularly for high-value raw materials

### THIN-FILM DEPOSITION

Approaches such as atomic layer deposition and chemical vapor deposition can transfer the minimal materials requirements to achieve the necessary properties of the component

### AI-DRIVEN PROCESS CONTROL

A combination of AI and industrial robotics can optimize material feed rates, reduce defects, and optimize materials usage

Sakuu's Kavian platform is a dry-process, 3D printing technology for the manufacturing of battery electrodes. The company claims the lack of solvents and water use in the Kavian process reduces energy consumption by 30% and an undisclosed amount of materials usage through the deposition of electrode materials. The company entered a development agreement in 2024 with South Korean battery manufacturer SK On to scale the technology for large-scale battery manufacturing.

Von Ardenne's use of physical vapor deposition in place of electroplating creates thin, homogeneous, and impurity-free layers of metallic coatings on electrolyzer components like catalyst-coated membranes, porous transport layers, and bipolar plates. Its process improves the electrical, chemical, thermal, or mechanical properties of a component while also lowering production costs by an order of magnitude.

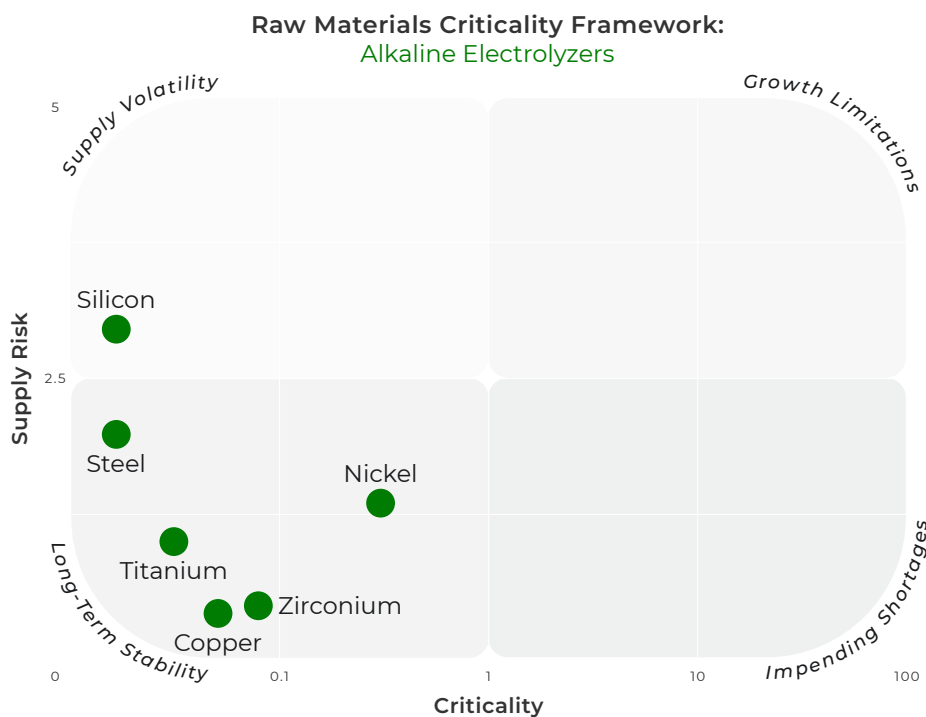


Figure 4. The Lux Raw Materials Criticality Framework assessing the supply risk and criticality of raw materials for alkaline electrolyzers. In this analysis, Lux assumes a share of 1,750 GW of alkaline electrolyzers in the IEA's NZE of 3,300 GW of total electrolyzer capacity deployed in 2050.



# Novel Sources

New feedstock sources and novel extraction processes.

## Opportunities

Organizations must explore novel sources for access to raw materials, especially critical minerals sourced from a few dominant regions, to maintain a stable supply. The development of independent supplies enables organizations to scale technologies by limiting potential raw materials bottlenecks that may impact long-term growth. In addition, organizations gain a competitive edge by insulating themselves from geopolitical disruptions and price volatility through the development and control of domestic resources, independent of traditional supply chain dynamics.

## Challenges

Despite the prospects of onshoring raw materials production, new feedstock sources may have limitations in the quantity and quality in a given region. Even if novel sources are available, technical challenges and high costs remain barriers to cost competitiveness with traditional sources, in addition to the need to create an inherently new supply chain including infrastructure, logistics, and cross-industry collaboration for integration. This remains a balancing act of near-term cost savings against the long-term advantages on the prospects of raw materials instability, challenging for organizations to justify in the short term.

## Example Innovations

### DIRECT LITHIUM EXTRACTION

Recovery of lithium from nontraditional, low-grade sources such as geothermal brines and oil field brines

### INDUSTRIAL BYPRODUCTS

Metals recovery from industry waste streams such as steel slag, coal fly ash, and electronic waste

### DEEP SEA MINING

Mining of copper, nickel, cobalt, manganese, and rare earths that are present hundreds of meters below the surface of the ocean

### MARINE RESOURCES

Biological extraction from seawater through the collection and concentration of target critical minerals in algae

American Resources' subsidiary, REElement Technologies, uses a common chromatographic separation process, typically used for purification in the pharmaceutical industry, for the separation and purification of rare earths using ion-exchange resins. The avoidance of high-capex solvent extraction and energy-intensive pyrometallurgy enables the modular separation and purification systems to be deployed directly at landfills and coal-ash ponds to target coal fly ash feedstock.

Latrobe Magnesium a 1,000-tonne/y power plant in Australia to produce magnesium from fly ash waste. Its hybrid hydrometallurgical and thermal reduction process lowers CO<sub>2</sub> emissions by 70% (8.2 kg CO<sub>2</sub>eq/kg MgO) compared to the incumbent Pidgeon process (28 kg CO<sub>2</sub>eq/kg MgO), primarily used in China.

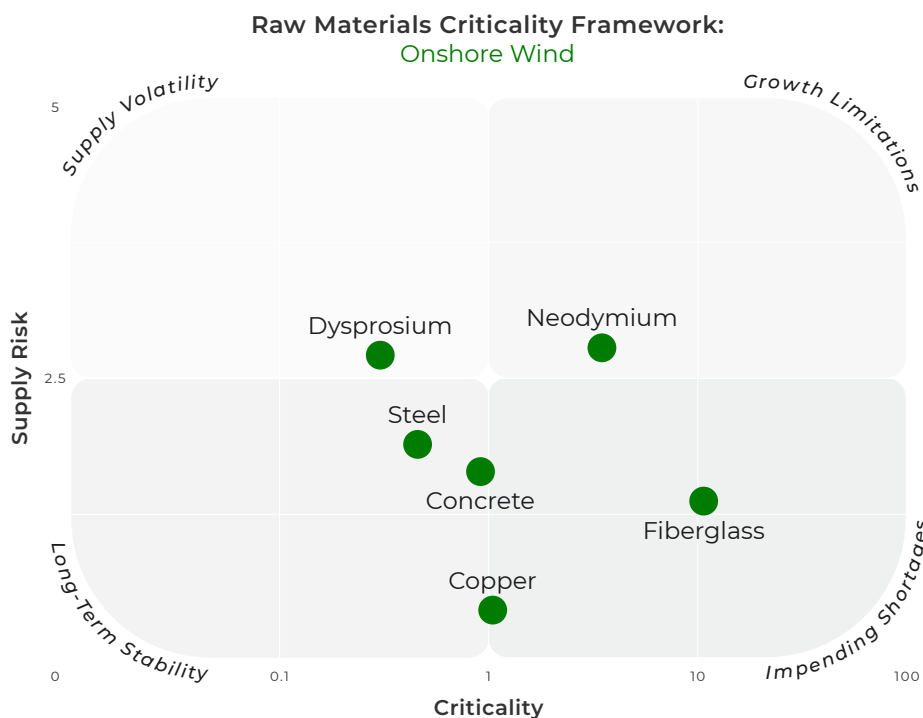


Figure 5. The Lux Raw Materials Criticality Framework assessing the supply risk and criticality of raw materials for gear-driven onshore wind. In this analysis, Lux assumes gear-driven onshore wind accounts for all the 7,616 GW of total installed wind capacity in the IEA's NZE in 2050. Lux recognizes that onshore wind currently accounts for approximately 93% of the global wind market, while offshore wind and next-generation turbines are expected to gain market share between now and 2050.



# Recycling & Circularity

Recovering end-of-life raw materials for reintroduction back into the supply chain.

## Opportunities

While recycling will unlikely fully replace demand for primary raw materials, it provides a supplement for traditionally mined materials, often at a lower overall carbon and energy footprint. In addition, a recycling strategy is crucial for regions or countries with limited natural access to critical minerals, enabling them to retain and maximize the resources that cross their borders. Given the current low recycling rates of critical minerals outside of the automotive sector, organizations can lean on recycling as a lever for materials supply stability. Circularity benefits are also instrumental, enabling organizations to build regulatory resilience as policies surrounding waste and end-of-life responsibility will inevitably arise.

## Challenges

Collection and reverse logistics are complex, especially as many technologies are still in early commercialization with fragmented efforts in developing infrastructure and materials reintegration processes. Beyond the reintroduction of raw materials into the supply chain, quality and contamination issues are key challenges, as several materials have key functional roles in the performance and efficiency of the technology. Technology developers will remain skeptical and unwilling to sacrifice performance standards for recycled materials that demand a premium, at least at smaller production volumes, limiting widespread adoption without regulatory mandates.

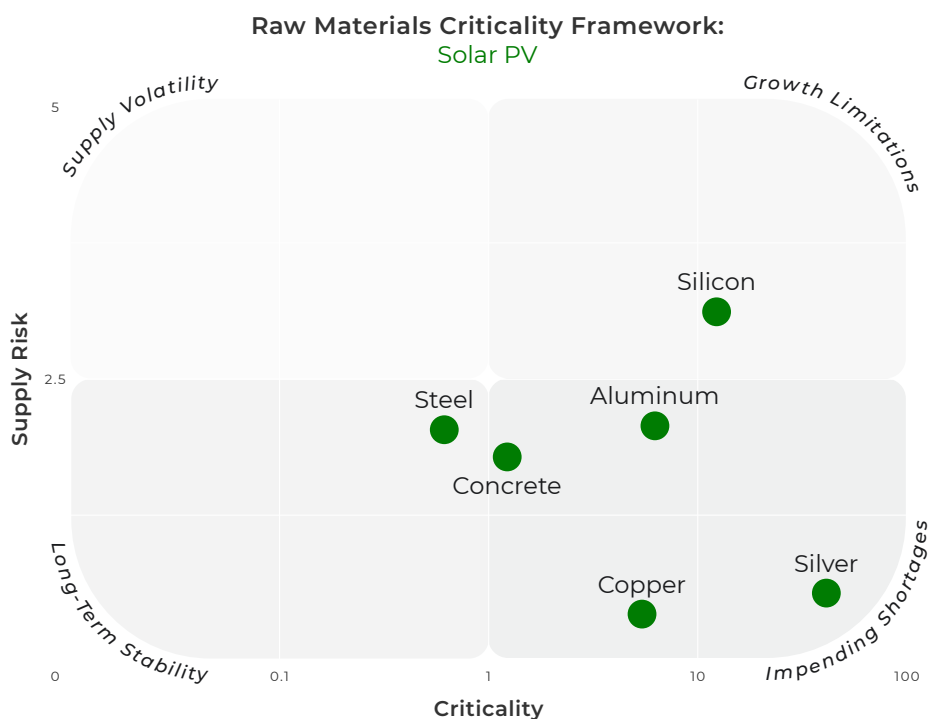


Figure 6. The Lux Raw Materials Criticality Framework assessing the supply risk and criticality of raw materials for crystalline silicon (c-Si) solar photovoltaics (PV). In this analysis, Lux assumes that c-Si solar PV accounts for all the 18,753 GW of total installed solar capacity in the IEA's NZE in 2050. Lux recognizes that c-Si solar currently holds an approximate 98% of the global solar PV market, and next-generation cells are likely to enter the market between now and 2050.

## Example Innovations

### CHEMICAL SOLAR PV RECYCLING

Solvent extraction of high-quality and -purity copper, silver, and solder (an alloy of lead and tin) from the solar cell

### ADVANCED HYDROMETALLURGY

Copper, nickel, lithium, manganese, cobalt, and aluminum extraction and purification from end-of-life Li-ion batteries using aqueous chemistry

### PLASMA AND MICROWAVE-ASSISTED IRRADIATION

Improves energy and extraction efficiency over traditional smelting for recovery of platinum group metals from electrolyzer and fuel cell catalysts

Rosi Solar develops a hybrid thermal and chemical recycling process for end-of-life solar modules and silicon waste produced during solar cell manufacturing. For decommissioned solar panels, the aluminum frame is mechanically removed and pyrolyzed to evaporate the ethylene vinyl acetate to remove the glass. Once the glass is separated from the panel, Rosi Solar uses solvents to reclaim 5N purity silicon, 80% purity copper, and 90% purity silver from the remaining solar cells.

HyProMag uses hydrogen gas to demagnetize neodymium iron boron (NdFeB) magnet scrap into a fine powder, which is mechanically separated. The recovered magnet powders are directly reprocessed into new magnets or rare earth alloys, closing the manufacturing loop and reducing the need for virgin materials.



# Alternative Materials

Fully replacing incumbent materials with novel and existing alternatives

## Opportunities

The development of alternative materials may become a strategic necessity as supply shortages and geopolitical instability present limiting factors for continued growth. Organizations must proactively mitigate these risks and unlock competitive advantages by identifying materials substitutes for these high-risk critical minerals. Focusing on regionally sourced raw materials reduces exposure to global logistics and supply chains susceptible to disruptions. In addition, the development of a localized supply chain for the alternative material provides long-term stability and potential cost predictability as it matures.

## Challenges

Despite strategic advantages, alternative materials face several challenges in terms of performance, technology, and integration. Performance tradeoffs are a key concern, often lagging those of incumbent materials. At the same time, these new materials are typically in early stage developments that are yet to be technically mature with uncertain market adoption outlooks as industries will be hesitant to adopt unproven materials. Novel materials often come with immature supply chains, and the transition away from legacy manufacturing processes often is costly.

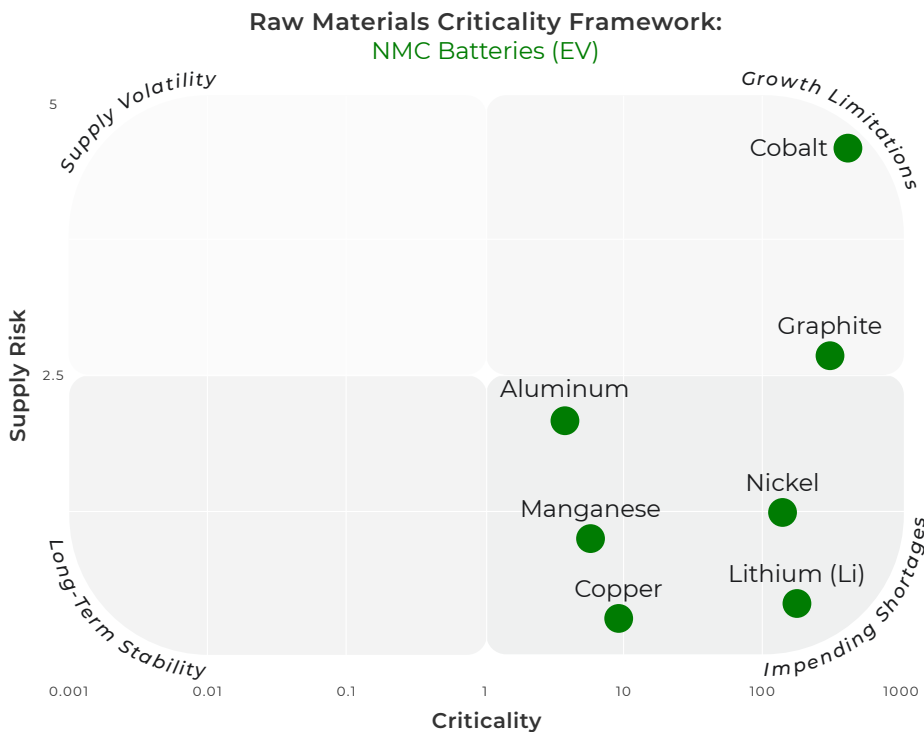


Figure 7. The Lux Raw Materials Criticality Framework assessing the supply risk and criticality of raw materials for Li-ion nickel-manganese-cobalt (NMC) batteries. In this analysis, Lux assumes a share of 8.4 TWh of NMC batteries in the IEA's NZE of 14 TWh of total battery capacity for EVs deployed in 2050. Lux recognizes that the impending changes in the share of battery chemistries for EVs such as lithium-iron-phosphate batteries, solid-state batteries, and others are entering the market between now through 2050.

## Example Innovations

### PEROVSKITE SOLAR CELLS

Halide-based solar cells, most commonly methylammonium lead halide, as the active material to replace silicon

### SODIUM-ION BATTERIES

Sodium-based cathode, anode, and liquid electrolyte containing dissociated sodium salts

### IRIDIUM-FREE ELECTROCATALYSTS

Iridium alternative electrocatalysts viable for use in electrolyzers, fuel cells, and other electrochemical processes

Mattiq combines real-world, high-throughput experimentation materials science and AI to accelerate the exploration and discovery of new electrocatalysts for desired characteristics such as cost, performance, degradation, and stability. The startup developed a portfolio of three durable alternatives to iridium oxide, a common catalyst used in proton-exchange membrane electrolyzers, citing it meets or exceeds performance of iridium-based incumbents.

Iron nitride-based magnets demonstrate excellent magnetic properties but lack the mechanical stability of rare earth-based magnets like NdFeB. Niron Magnetics claims its manufacturing process can precisely control the crystal structures of iron oxide nanoparticles to form strong chemical bonds that result in a stronger magnet. Niron plans to commercially produce its rare earth-free magnets at its U.S. facilities beginning in 2026.



# How to Leverage the Lux Raw Materials Criticality Framework

A global pandemic, regional conflicts, and overdependence on a handful of countries has exposed the vulnerabilities in the once-stable supply chain for raw materials.

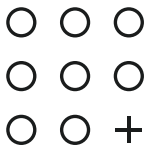
This volatility has been further exacerbated as countries use trade and economic policy to bolster their positions in the raw materials supply chain, reshaping global access to essential materials and

creating tangible business risks. This framework helps organizations assess raw materials supply risks and identify innovation strategies to enhance operational stability, resilience, and long-term growth.



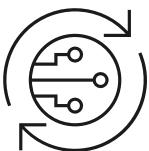
## Future-proof resilience through innovative measures

A robust strategy for raw materials security hinges on the development of local and alternative inputs. Organizations remain susceptible to risk due to the inherent nature of the global raw materials supply chain and events outside of their control — conflicts and trade bans can be unpredictable and happen swiftly. While localization reduces some supply risks, it remains constrained by regional resource availability. Exploring alternative materials that optimize domestic resources will be a key innovation lever for long-term resilience.



## Understand the importance of noncritical materials

While key materials and minerals such as rare earth elements and platinum group metals are critical to the core functionality of technologies, commodity materials such as basic metals, polymers, composites, and steel also play essential roles. These materials are key in infrastructure and structural components to enable the full functionality of the technology. Overlooking these components can create bottlenecks in production and deployment. A comprehensive raw materials strategy must account for both critical and noncritical materials to ensure future deployment.



## Observe shifting demand due to evolving technology variations

Rapid technological advances and the rise of regionally specific innovations are diversifying the technology landscape. As different variations of technologies (e.g., carbon capture materials) gain market share, raw materials demand will vary significantly. Analyzing technology variations and predicting the winners are key to anticipating demand changes and refining innovation strategies accordingly.



## Monitor changing dynamics in the global landscape

Supply risk and criticality are dynamic metrics, evolving alongside geopolitical shifts, industry expansion, technology development, and updated market projections. The framework provides a snapshot in time and should serve as a tool for monitoring indicators of change. Parallel technological advances and shifts in consumer behavior may either alleviate raw materials constraints or create new supply challenges, underscoring the importance of continuous assessment.



## Exploit unmet material demand for existing products

Analyzing the raw materials requirements for emerging technologies help guide long-term innovation strategies, but the framework should also be applied to current technologies utilizing existing products in an organization's portfolio. By adapting the framework to existing business sectors and applications, organizations can apply a quantitative, materials-driven approach to guide production capacity expansion, identify new market opportunities, and develop mitigation strategies for saturated markets.



# About Lux

Lux Research fuels innovators to not only imagine what's possible in the future but also operationalize innovation success in the near term. We deliver research and advisory services to inspire, illuminate, and ignite innovative thinking that reshapes and grows businesses. Using quality data derived from primary research, fact-based analysis, and opinions that challenge traditional thinking, our experts focus on finding truly disruptive innovations that are also realistic and make good business sense.

The “Lux Take” is trusted by innovation leaders around the world, many of whom seek our advice directly before placing a bet on a startup or partner — our clients rely on Lux insights to make decisions that generate fantastic business outcomes. We pride ourselves on taking a rigorous, scientific approach to avoid the hype and generate unique perspectives and insights that innovation leaders can't live without.

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