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Metals, markets, and megawatts

The critical raw materials challenge facing the energy sector

1. Introduction

The rapid expansion of renewable energy infrastructure is reshaping global energy systems and supply chains. Offshore wind, solar photovoltaics (PV), battery energy storage systems (BESS), and supporting grid infrastructure are deploying at unprecedented speed.

However, this transformation depends on secure access to a small set of critical raw materials including copper, rare earth elements, lithium, nickel, and cobalt whose production and refining are highly concentrated, environmentally intensive, and increasingly geopolitically senstiive.

This whitepaper examines the material dependencies of renewable technologies, the systemic risks emerging from constrained supply, and the opportunities presented by circularity, innovation, and foresight-based strategies..

If the material basis of the energy transition remains fragile, the pace of deployment will falter. But if vulnerabilities are addressed through foresight and coordinated strategy, the transition can become not only faster and more affordable but also more resilient, equitable, and sustainable. This paper aims to support that outcome.

At a glance
Materials and the energy transition

The scale of deployment	The material intensity
• Global renewable power capacity additions reached 510 GW in 2023 (50% year-on-year growth). • By 2030, additions are expected to triple again, led by solar, wind, and storage.	• An electric car requires 6× more minerals than a conventional car. • A single offshore turbine contains 800 t steel, 30 t copper, 600 kg REEs. • Lithium demand has risen 700% since 2010.

The energy transition is reshaping the foundations of global industry, infrastructure and society. Achieving net-zero by mid-century requires an unprecedented scale of deployment in renewables, storage and electrification. Wind, solar, batteries and grid infrastructure have become central to national energy strategies and industrial policy.

Beneath this visible build-out lies a less visible dependency. The transition is critically reliant on metals and minerals extracted, processed and traded through highly concentrated global supply chains with significant environmental and social impacts. Unlike fossil systems, which depend on continuous fuel flows, renewable systems depend on large upfront material investments. This structural shift means that access to critical raw materials will shape the speed, cost and resilience of the transition as much as policy ambition or capital availability.

These risks are compounded by systemic vulnerabilities. Refining and processing of many critical materials is concentrated in a small number of regions, creating strategic chokepoints. Markets for copper, lithium and nickel are volatile, complicating project finance.

Manufacturing capacity for grid components and turbines is already stretched, generating multi-year lead times. ESG risks in cobalt, nickel and lithium supply chains further constrain access to resources and capital. At the same time, many clean technologies are locked into specific material choices, limiting adaptability.

Governments have responded by formally designating critical or strategic raw materials. The EU, US, UK, Canada, Australia and South Korea have all introduced frameworks identifying materials that combine high economic importance with high supply risk. While terminology differs, these frameworks converge on a shared logic. Critical materials are indispensable for clean energy systems, yet their supply chains are concentrated and vulnerable. Across jurisdictions, lithium, nickel, cobalt, copper, graphite and rare earths are consistently prioritised.

Recent supply disruptions, price spikes and project delays have already tested the resilience of clean energy systems. Without intervention, these constraints risk becoming structural, slowing decarbonisation, raising consumer costs and weakening industrial competitiveness.

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2. Materials dependence of renewable energy

The clean energy transition is fundamentally a materials transition. The scale of deployment required for net-zero targets means that metals such as copper, lithium, nickel, cobalt, and rare earth elements (REEs) become as strategically important to future energy security as oil and gas were in the past. Understanding the intensity of these dependencies is essential for assessing supply risks and resilience needs.

The global energy transition relies on a narrow set of metals that sit at the heart of renewable energy technologies, yet these materials are becoming increasingly scarce, geopolitically sensitive, and economically volatile.

Offshore wind, solar PV, battery storage, and transmission systems all depend on highly concentrated supply chains where a handful of countries control the majority of mining and refining capacity.

This creates structural vulnerabilities for renewable energy developers, investors, and policymakers. Project timelines, CAPEX stability, and the viability of long-term decarbonisation pathways are now directly linked to the availability and price stability of critical raw materials. Understanding the specific exposure, constraints, and risks associated with each metal is essential for building strategies that ensure scalability, affordability and resilience in the transition to net zero.

Copper: The backbone of electrification

Copper is the foundation of renewable energy systems, used extensively in turbines, solar PV arrays, HVDC cables, transformers, and storage technologies. Copper's criticality lies in the convergence of surging demand, concentrated refining, and substitution constraints.

Looking ahead, total global refined copper demand is expected to grow substantially, rising from almost 27 million tonnes in 2024 to almost 33 Mt in 2035 and approximately 37 Mt in 2050, representing a projected 30% growth from today through 2040. Within this growth, demand from electric vehicles is the fastest-growing source, projected to increase sevenfold from just 2% of global demand in 2024 to 10% by 2050.

Copper supply is facing significant challenges, with projections pointing to a potential 30% supply shortfall by 2035 due to factors such as declining ore grades, rising project costs, limited resource discoveries and long lead times for new mines.

While mined copper is considered relatively diversified compared with other key energy minerals, its geographical concentration is expected to intensify, with the top three mining countries accounting for 48% of global output in 2024 and projected to reach 53% by 2040. Copper refining is significantly more concentrated, with China maintaining dominance, responsible for 45% of production in 2024 and set to grow its share to 50% by 2040.

Copper has an infinite recyclable life and can be reused indefinitely without quality loss. Scaling up copper recycling is therefore deemed one of the most critical actions to help close the projected supply gap.

Copper snapshot	Value
Forecast demand growth	+30% by 2040
Top uses	Electric vehicles, solar, wind
Refining concentration 2030	~50% in China, Chile, and the DRC
Recycling potential	High

Rare earth elements: Turbine magnets and systemic exposure

Rare earth elements (REEs) such as neodymium, praseodymium, dysprosium, and terbium are essential for permanent magnets used in offshore and increasingly onshore wind turbines. Demand for the materials for electric vehicles (EV) motors will also increasingly challenge market availability.

In 2024 alone, demand for rare earths increased by 6-8%. Permanent magnets already account for approximately 60% of magnet REE demand today. Looking ahead, global demand for magnet REEs is projected to increase substantially, increasing by 50-60% by 2040, driven primarily by EV motors, whose contribution is expected to rise from 9% of global demand in 2024 to 22% by 2050.

The REE supply chain is recognised as among the least geographically diversified of all critical minerals. In 2024, the top three producing countries accounted for 86% of global mined supply. This concentration is even more extreme in refining, where the top three countries controlled 97% of refined output in 2024. As a result, rare earth dependency represents one of the most significant single-point criticalities in the renewable energy value chain.

Rare earth snapshot	Value
Forecast demand growth	+50% by 2040
Top uses	Turbine magnets, EV motors
Refining concentration	~90% in China
Recycling potential	Emerging (<5% today)

1.The description and projections of material demand and supply are drawn from the International Energy Agency's Global Critical Minerals Outlook 2025. All projections are using the Stated Policies Scenario (STEPS). Information about the recycling potential is drawn from the Recycling of Critical Minerals report, also from the IEA.

Nickel and cobalt: Chemistry trade-offs and ESG challenges

Nickel and cobalt are critical for high-density lithium-ion chemistries, used in both EVs and grid-scale batteries to deliver longer-duration storage and improved performance. Demand for both materials is expected to increase by about 50% by 2040, primarily driven by batteries.

Nickel and cobalt introduce dual risk dimensions via supply concentration and ESG exposure. In mining, the top three producing countries accounted for 81% of cobalt supply in 2024 and 77% of nickel supply in 2024, with both projected to see increasing geographical concentration by 2035. Cobalt sourcing is further complicated by its reliance on artisanal mining in the Democratic Republic of Congo, where severe and well-known environmental and human rights impacts persist. Approximately 70% of refining capacity is concentrated in a handful of countries, creating vulnerability to geopolitical instability and export restrictions.

While the growing adoption of lithium iron phosphate chemistries reduces dependence on nickel and cobalt, they introduce new dependencies on lithium and graphite, trading one constraint for another. Without diversification, storage portfolios risk locking into volatile supply chains that undermine cost predictability.

Nickel and cobalt snapshot	Value
Forecast demand growth	+50% by 2040
Top uses	Batteries
Refining concentration	~70% in China
Recycling potential	Moderate (~50% achievable)

Lithium: The storage and mobility bottleneck

Lithium is at the heart of the battery storage revolution, powering grid-scale BESS, residential storage systems and electric vehicles. Looking forward, lithium demand is expected to triple over the next decade. Total demand is projected to grow fivefold from today to 2040, reaching 700 kilotonnes by 2035, with the EV sector responsible for 90% of this additional demand. Lithium supply is currently rising rapidly, with mining in particular diversifying. However, lithium refining remains highly geographically concentrated, with the top three refining nations holding a 96% market share in 2024. Regarding recyclability, lithium recycling is an emerging commercial opportunity showing rapid growth, with the recycling rate relative to available feedstock having risen steadily to 20% in 2023.

Despite these positive developments, projected demand growth is expected to push the market into a deficit by the 2030s, with expected mined supply falling short of projected demand in 2035

Lithium snapshot	Value
Forecast demand growth	+500% by 2040
Top uses	BESS, EV batteries
Refining concentration	~96% in China, Argentina, and Chile
Recycling potential	High

A day in the life of a turbine: Tracing the global supply chains behind offshore wind

An offshore wind turbine standing in the North Sea is the endpoint of dozens of interwoven global supply chains. From the moment raw materials are mined to the day the turbine is decommissioned, its lifecycle illustrates how dependent renewable energy is on critical minerals, and how many countries are involved in its construction.

1 Mining and extraction

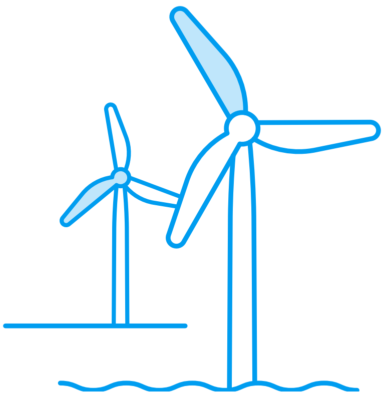
- **Steel & concrete:** Iron ore from Brazil or Australia, coal for steelmaking from South Africa, and limestone from Europe form the backbone of the turbine tower and foundations.
- **Aluminium:** Bauxite mined in Guinea, Brazil, or Jamaica.
- **Copper:** Extracted in Chile, Peru, or Zambia, later refined in China, for use in cabling, transformers, and generators.
- **Rare earth elements:** Neodymium and dysprosium from mines in Inner Mongolia, Myanmar, or Australia, processed largely in China, for permanent magnet generators.

2 Processing and refining

- **Aluminium:** Bauxite refined into alumina and smelted in Iceland or Canada using electricity, then rolled into turbine components.
- **Steel:** Converted in European or Asian mills, requiring vast amounts of coking coal or increasingly green hydrogen for decarbonised production.
- **Rare earth elements:** Refined and magnetised primarily in China before shipment to generator manufacturers in Europe or Japan.

3 Component manufacturing

- **Turbine blades:** Composite materials (fibreglass, epoxy resins) produced in Denmark, Spain, or India.
- **Nacelle and gearbox:** High-precision engineering in Germany, Spain, or the US, embedding rare earth magnets.
- **Subsea Cables:** Copper-intensive HVDC cables manufactured in limited facilities in Europe and Asia with lead times of 3–5 years.



4 Assembly and installation

- Turbines shipped by specialised vessels from ports in Denmark, the Netherlands, or the UK.
- Offshore foundations installed using steel monopiles or jacket structures fabricated in Europe or Southeast Asia.
- Supply chains converge at coastal hubs where nacelles, towers, and blades are integrated before offshore deployment.

5 Operation and maintenance

- Each turbine requires continuous monitoring through digital platforms and replacement of parts over a 25–30 year lifespan.
- Copper and aluminium cabling connects turbines to offshore substations and back to onshore grids, requiring regular upgrades.
- Maintenance crews rely on a global ecosystem of spare parts, often sourced from the same concentrated supply hubs as the original build.

6 End-of-life and recycling

- **Steel and aluminium:** High recycling potential, with recovery rates above 90%.
- **Copper:** Recoverable through established scrap markets, although subsea retrieval remains costly.
- **Rare earths:** Currently <5% recycled, leaving most magnet material unrecovered.
- **Blades:** Among the most challenging components, with few scalable recycling options, although pilot projects in Europe are exploring co-processing and repurposing

3. Systematic supply vulnerabilities

As the previous pages have illustrated, technologies such as wind turbines, solar photovoltaics, batteries, and electric grids all rely on material inputs that are far more intensive than conventional energy systems. Copper, lithium, nickel, cobalt, rare earth elements, and other critical materials form the hidden backbone of decarbonisation. Without them, deployment targets for renewables, storage and electrification cannot be met.

Yet while policy momentum and capital flows are accelerating deployment, the underlying materials system shows structural fragilities that could derail progress. Supply chains for these resources are geographically concentrated, often dominated by a small number of countries or even individual companies. Production is both energy and water-intensive, exposed to climate stress and frequently associated with governance challenges, labour risks and environmental impacts. At the same time, demand projections are rising sharply, creating a widening gap between ambition and secure availability.

These vulnerabilities are systemic in nature. They cut across geographies, markets, technologies, and governance frameworks. They are not isolated risks but interconnected factors that can amplify one another in that a climate event disrupting mining operations, for example, may intersect with geopolitical tensions or trade restrictions to create cascading impacts on global markets. Such compound vulnerabilities make the system more fragile and less able to support a stable transition pathway.

Understanding the depth and complexity of these vulnerabilities is the essential first step before moving to solutions. By identifying where and how the system is most exposed, we can assess the degree of risk for different technologies, sectors and regions and begin to design responses that strengthen resilience, diversify supply, and align material use with long-term sustainability goals.

1. Geographic concentration

One of the most significant vulnerabilities lies in the extreme geographic concentration of refining and processing capacity for critical raw materials. While extraction may occur in multiple countries, the value-adding stages of refining and separation are typically monopolised by one or two countries. This creates a chokepoint risk in that even if raw ore is sourced globally, almost all material must flow through a narrow processing channel before it becomes usable for industry.

Rare earth elements (REEs), essential for permanent magnets in wind turbines and EVs, are more than 80% refined in a single country i.e. China. Lithium refining is dominated by three countries (China, Chile, Australia) that together accounted for in excess of 90% of global capacity in 2024.

Such concentration makes industries highly exposed to trade restrictions, geopolitical tensions, or industrial accidents in just one geography. For developers and OEMs, it translates into potential project delays and higher costs and for investors it raises premium.

2. Price volatility and CAPEX instability

Volatility in commodity markets is another systemic vulnerability. Critical raw materials are traded globally, often with relatively thin markets and speculative dynamics that amplify price swings. When demand surges collide with slow supply expansion, sharp price movements follow.

Copper, the backbone of electrification, has risen by more than 70% since 2018, directly impacting grid reinforcement and cabling costs. Cobalt experienced a dramatic surge in early 2025 after the DRC announced a four-month suspension of cobalt exports, whereafter prices increased by more than 60%.

Overall, the International Energy Agency estimates that, across 20 energy-related minerals, prices have historically been more volatile than oil prices.

For developers, such volatility creates budgeting uncertainty in that projects planned at one cost baseline may overshoot before execution. For investors, it undermines confidence in project economics and increases the cost of capital. For governments, it makes subsidy and support scheme design more difficult, as baseline assumptions on technology costs may no longer hold. Ultimately, volatility erodes predictability, a critical requirement for scaling investment in long-term infrastructure.

3. Lead-time bottlenecks

Even where materials are available and affordable, bottlenecks in component manufacturing present another layer of vulnerability. Unlike commodities, where additional supply can eventually flow from new mines, manufacturing capacity for highly specialised components takes years to scale.

High voltage direct current (HVDC) subsea cables, which are essential for offshore wind interconnections, already face lead times of three to five years. Large power transformers (vital for grid reinforcement) are in short supply, with utilities reporting procurement delays of up to two years.

Wind turbine manufacturing itself has grown, but the trend toward ever-larger offshore turbines requires highly specialised casting, logistics and assembly, stretching production timelines.

These constraints are structural in that building new factories requires high upfront capital, long permitting processes and specialised labour. Developers face delays in project completion, investors encounter stranded capital waiting for components and governments risk missing electrification targets even when projects are fully financed. In this sense, bottlenecks are not just a commercial issue but a constraint on the speed of the entire transition.

4. Sustainability and reputational risks

The availability of critical materials is also limited by environmental and social challenges at extraction and processing sites. Unlike traditional industrial risks, environmental and human rights risks can directly restrict access to resources by undermining the social licence to operate or by triggering regulatory and investor intervention.

Cobalt mining in the Democratic Republic of Congo, which supplies more than 70% of global demand, has been associated with unsafe working conditions, artisanal mining practices and child labour. Lithium extraction in South America's "lithium triangle" consumes large volumes of water in arid regions, intensifying conflicts with local communities, and competing land uses. Nickel mining, particularly in laterite deposits, can create severe ecological damage if waste streams are poorly managed.

For companies, these issues present more than reputational concerns. They can delay projects, restrict access to financing, or result in exclusion from supply contracts. Investors face growing scrutiny of portfolios linked to high-risk mining practices. Regulators are tightening due diligence obligations mandating transparency across supply chains while policymakers must balance the urgency of scaling supply with the need to enforce robust protection of the environment and human rights, often slowing expansion where governance capacity is weak.

5. Technology lock-ins

Finally, the technologies that underpin the energy transition are themselves a source of vulnerability. Design choices made for reasons of efficiency or cost-effectiveness have created deep lock-ins to specific materials, making industries less flexible when shortages occur.

Offshore wind turbines increasingly rely on permanent magnet generators, which lock the sector into rare earths such as neodymium and dysprosium. Battery technologies, particularly for EVs and stationary storage, are built around lithium, cobalt and nickel chemistries, even as alternatives are under development. Transitioning to new chemistries or generator designs requires retooling entire manufacturing ecosystems and supply chains, a process that can take many years.

Technology lock-ins reduce system resilience. If a key input becomes scarce or expensive, industries cannot pivot quickly. Developers face cost inflation or stalled projects and investors are exposed to stranded technology pathways and policymakers must contend with industries that cannot adapt fast enough to changing supply conditions. Lock-ins, therefore, are not just technical challenges but systemic risks that amplify the effects of other vulnerabilities such as concentration, volatility and ESG exposure.

Five warning signals to watch
Anticipating vulnerabilities in critical raw materials supply chains

Resilience depends on the ability to detect stress points before they escalate into crises. Critical raw materials often show warning signs of systemic vulnerabilities. Monitoring these indicators enables companies, investors and policymakers to act pre-emptively rather than reactively.

The five signals below point to growing fragility in supply chains and highlight where strategic intervention is needed. Proactive companies should set internal thresholds to identify their own set of critical raw materials and develop strategies to manage criticality.

1

Geographic concentration

When refining capacity for a given metal is controlled by a single country or region, the risk of supply disruption becomes acute e.g. rare earth elements, where ~90% of global refining occurs in China.

Why it matters: Creates vulnerability to geopolitical shocks, export restrictions and policy leverage.

2

Price volatility

Commodity price surges signal structural tightness in supply e.g. cobalt prices rising by more than 67% over a four-month period in early 2025 due to an export ban in the DRC.

Why it matters: Erodes CAPEX stability, increases project cancellations and signals that supply pipelines are lagging demand.

3

Lead times

When procurement of essential components (e.g., HVDC cables, transformers, nacelles) exceeds three years, bottlenecks are already constraining deployment e.g. subsea cable lead times of 3–5 years delaying offshore wind projects.

Why it matters: Threatens project timelines, slows renewable integration and locks in higher financing costs.

4

Severe environmental or human rights impacts affecting

If a significant portion of global supply is linked to environmental or social risks, reputational exposure escalates e.g. cobalt, with ~70% sourced from the DRC, where child labour and governance issues are prevalent.

Why it matters: Can restrict financing, trigger regulation and force abrupt shifts in sourcing strategies.

5

Single-chemistry dominance

Heavy reliance on one technology pathway creates systemic rigidity e.g. over 70% of battery production remains dependent on lithium-ion chemistries (NMC and LFP), despite research into alternatives.

Why it matters: Limits flexibility to adapt, locks industries into vulnerable supply chains, and magnifies shocks

Why these signals matter

Taken individually, each indicator highlights a vulnerability. Taken together, they form a dashboard of systemic risk. Companies that monitor these signals, set internal thresholds for criticality and act early by diversifying supply, accelerating recycling, or adopting alternative technologies are better positioned to withstand shocks.

4. Addressing vulnerabilities
From risk to resilience

The vulnerabilities outlined in the previous section demonstrate that critical raw materials are not simply a technical supply issue but a systemic risk that spans technology design, global trade, environmental sustainability, and governance. Left unmanaged, these vulnerabilities will slow renewable deployment, increase project costs and create new forms of dependency even as the world seeks greater energy security.

Addressing them requires a deliberate shift in strategy from linear, reactive, and fragmented approaches to ones that are circular, anticipatory, diversified, compliant and collaborative. This section outlines five strategic pathways that provide practical guidance for companies and investors seeking to navigate these risks and build resilience into the material foundations of the energy transition.

1. Circular economy integration

Renewable technologies have been optimised for rapid cost reduction and deployment speed, with far less attention given to recoverability or recyclability. This results in designs that are difficult to disassemble, recover or reuse, leaving high-value materials such as rare earths, lithium, silver, and copper locked in obsolete infrastructure. With tens of millions of tonnes of wind blades, PV modules and batteries, industries face growing waste liabilities and continued dependence on virgin extraction concentrated in a few countries. Without circular solutions, these materials will remain stranded in waste facilities or in under-utilised secondary markets, amplifying supply risks and regulatory exposure.

Developers and OEMs sit at the centre of this challenge. Their design, sourcing and product-end strategies decide whether materials remain stranded or become recoverable. Turbines designed with rare earth magnets or batteries without disassembly in mind lock in exposure for decades. Conversely, modular, repairable and traceable designs embed resilience across entire systems. Investors can accelerate this shift by financing early-stage pilots, recycling demonstrations and substitution R&D. Catalytic capital deployed in the next few years can de-risk emerging technologies and generate proof points for future scaling. Key initiatives include but are not limited to:

- Design-for-disassembly protocols: adopt engineering standards that mandate mechanical fastening, reversible adhesives and modular component structures to allow rapid dismantling of turbines, panels, and battery packs.
- Extended component lifetimes: create repair, refurbishment and remanufacturing ecosystems, for example refurbishment of turbine gearboxes or repowering of PV panels to defer raw material demand.
- Digital product passports: implement mandatory tagging of turbines, panels and batteries with digital records of material composition, origin, and recyclability, in line with EU Digital Product Passport requirements.
- Circular procurement requirements: embed measurable KPIs into supply contracts, such as minimum secondary material content, recoverability percentages, or recyclability thresholds.
- Extended producer responsibility (EPR): require OEMs to manage structured take-back schemes and demonstrate closed-loop recovery for critical metals.

The outcome

Circularity transforms waste into resource security. Developers and OEMs gain stable access to critical inputs, investors de-risk portfolios by backing companies with closed-loop strategies and secondary markets emerge as viable supply sources. By 2040, circular flows could meet up to 40% of demand for key metals, reducing geopolitical and environmental risk.

2. Foresight and scenario planning

Global demand for critical materials is growing at unprecedented rates, yet supply remains constrained by long lead times, geopolitical concentration and uncertain substitution pathways. Without foresight, companies risk locking in stranded strategies that collapse under alternative futures, leaving portfolios exposed to cost spikes and project delays. For developers, OEMs and investors alike, these dynamics translate directly into project cost risk, stranded assets and valuation instability. Key initiatives include but are not limited to:

- Systematic scenario analysis: conduct multi-scenario modelling of material availability, testing project pipelines under constrained, balanced and accelerated demand futures.
- Cross-sector foresight integration: analyse overlaps between renewables, EVs, defence and digital sectors to understand where material competition could intensify.
- Digital twin modelling: use system models to simulate how disruptions in one material (e.g. lithium) cascade into other sectors (e.g. EV adoption, stationary storage and grid stability).
- Early-warning indicators: build real-time dashboards tracking commodity price spikes, mine development delays, refining expansions, and policy shifts.
- Adaptive supply contracts: negotiate agreements with built-in flexibility (e.g. alternative sourcing clauses, substitution allowances) informed by foresight outputs.

The outcome

Foresight converts uncertainty into preparedness. Developers and OEMs can pivot designs ahead of disruptions, investors can rebalance portfolios before price spikes or shortages materialise. At the system level, coordinated foresight aligns capital, policy, and industrial strategy to avoid cascading crises.

3. Regulatory alignment

Regulation of critical raw materials is intensifying, with significant implications for industry. The EU's Critical Raw Materials Act mandates resilience monitoring and minimum recycled content thresholds. Divergent approaches between the EU, U.S. and Asia add further complexity. Misalignment risks financial penalties, reputational harm, restricted access to sustainable finance, and exclusion from procurement frameworks.

Developers and OEMs sit at the compliance front line, yet many still operate with fragmented governance and incomplete data. Investors increasingly view regulatory maturity as a proxy for management quality and a prerequisite for capital allocation.

Compliance cannot be treated as an afterthought but must be integrated into governance, procurement and reporting systems. Companies can strengthen regulatory readiness by:

- Critical Raw Materials Act (CRMA) compliance programmes: map product portfolios against recycled content quotas, establish annual resilience monitoring, and implement supplier disclosure systems.
- Carbon Boarder Adjustment Mechanism (CBAM): build data infrastructure to calculate embodied carbon in steel, copper and aluminium imports, align supplier reporting with EU requirements.
- Adoption of best-practice standards: implement Organisation for Economic Co-operation and Development (OECD) Due Diligence Guidance and Initiative for Responsible Mining Assurance (IRMA) frameworks to exceed minimum compliance thresholds and streamline across jurisdictions.
- Investor disclosure: require investees to report material dependencies, concentration risks and recycling performance under Corporate Sustainability Reporting Directive (CSRD) or International Sustainability Standards Board (ISSB)-aligned frameworks.

The outcome

Regulatory alignment transforms compliance into a differentiator. Developers and original equipment managers (OEMs) gain access to sustainable finance and procurement frameworks, investors gain transparency, and confidence in risk management. Systemically, alignment harmonises standards and embeds accountability across supply chains.

4. Supply chain diversification

Critical material refining and processing is heavily concentrated, leaving industries vulnerable to single points of failure. OEMs often exacerbate this risk by relying on single-source Tier-1 suppliers with limited visibility into Tier-2 or Tier-3 risks. Without diversification, global energy transition targets are hostage to a fragile upstream system. Building resilient supply chains requires diversification across geography, suppliers and materials. This reduces exposure to single-source risks and creates redundancy across procurement portfolios. Key initiatives include but are not limited to:

- Multi-regional sourcing strategies: build supply networks across multiple continents, deliberately balancing exposure to different jurisdictions and political risk profiles.
- Long-term offtake agreements: secure supply stability by negotiating multi-year contracts with miners and refiners, including price-indexed clauses to reduce volatility.
- Equity investments in supply chains: acquire minority stakes in upstream operations (mines, refineries, recyclers) to guarantee allocation during shortages.
- Substitution pathways: pilot alternative material solutions such as aluminium conductors for copper or sodium-ion and zinc-air batteries as partial substitutes for lithium-based chemistries.
- Supplier base expansion: engage with Tier-2 and Tier-3 suppliers, diversifying beyond Tier-1 and conducting ESG risk audits across all tiers.

The outcome

Diversification turns systemic fragility into flexibility. Developers and OEMs maintain continuity through disruption, while investors back companies with multi-region exposure and forward-purchase agreements. At the system level, capital reallocation towards regional refining and recycling rebalances global supply networks and strengthens strategic autonomy.

5. Cross-sector collaboration

Critical raw materials are not unique to renewables but are equally central to EVs, digital infrastructure, consumer electronics and defence. These sectors compete for the same scarce inputs but their recovery efforts remain fragmented. Recycling facilities are typically sector-specific and subscale, product passport standards are inconsistent, and data sharing is limited. This fragmentation undermines economies of scale, leaves large end-of-life material streams underutilised and weakens the commercial case for advanced recycling technologies.

Collaborative action is essential to unlock scale, efficiency and innovation in material recovery and substitution. Developers and OEMs can convene industrial ecosystems and investors can provide the long-term, blended capital required to scale shared infrastructure. Key initiatives include but are not limited to:

- Joint recycling infrastructure: pool capital across renewables, EV and electronics sectors to build shared recovery hubs capable of processing large volumes of panels, magnets and batteries.
- Industrial symbiosis: create cross-sector platforms where waste streams from one industry (e.g. EV batteries) are repurposed for another (e.g. stationary storage).
- Standardised product passports: develop interoperable digital passports for all critical material-intensive technologies, ensuring traceability across multiple industries.
- Aggregated procurement pools: combine demand for recycled metals across sectors to stabilise markets and guarantee recovery economics.
- Policy engagement coalitions: form joint industry–policy taskforces to shape regulatory frameworks that incentivise shared infrastructure and recovery standards.

The outcome

Collaboration transforms fragmentation into systemic efficiency. Shared infrastructure and interoperable data reduce costs, improve traceability, and accelerate recycling. Investors benefit from stable returns in new circular markets, while developers and OEMs secure resilient supply chains that support parallel growth across renewables, mobility and digital sectors.

Foresight at work

Stress testing the energy transition - Lithium supply shock in 2035

Foresight is not about prediction. It is about testing resilience under conditions that could plausibly occur. Stress tests are one way to do this. By simulating shocks to critical raw material (CRM) supply, companies and policymakers can explore vulnerabilities, anticipate cascading effects, and identify adaptive strategies before disruption occurs.

Imagine that by 2035, lithium refining capacity fails to scale with demand, while localised restrictions tighten access to brine resources in South America. Global lithium supply falls to 50% of expected levels, creating a structural deficit just as demand peaks from EV adowption and grid-scale storage.

Consequences for the energy system

- **Price escalation:** lithium carbonate prices surge five-fold, destabilising EV and BESS procurement.
- **Project delays:** utilities cancel or defer large-scale storage projects, EV manufacturers reduce production targets.
- **Cascading effects:** grid balancing costs rise as storage lags, slowing renewable integration and consumer adoption of EVs falters.
- **Competitiveness risk:** regions with domestic lithium refining (e.g. China, Australia) gain strategic advantage while import-dependent regions face supply insecurity.

Scenario pathways

1 Delayed EV rollout

- EV penetration slows, extending the life of internal combustion engines.
- Additional emissions reduction must come from accelerated renewable generation, modal shifts in transport, and energy efficiency.

2 Pivot to sodium-ion and alternative chemistries

- OEMs accelerate commercialisation of sodium-ion and solid-state chemistries.
- Sodium-ion gains traction in short-duration storage and entry-level EVs.
- Trade-offs include lower energy density and slower market scaling.

3 Massive recycling drive

- End-of-life EV batteries become a critical “urban mine.” Closed-loop recycling rates for lithium increase from <5% today to >70% by 2040.
- Policy accelerators: mandatory product passports, recovery targets, and investment in advanced hydrometallurgical recycling.

Why it matters

Stress tests like this reveal how a single chokepoint material can ripple through entire energy systems. They demonstrate the need to build flexible technology portfolios, invest in recycling infrastructure now, before volumes peak and diversify supply and chemistry options to avoid systemic lock-in. By embedding foresight exercises into strategy and governance, organisations can move from reactive crisis management to proactive resilience building.

5. Conclusion

From metals crunch to materials resilience

The global energy transition is accelerating, but its foundation rests on a fragile system of metals and minerals. Renewable energy technologies rely on critical materials such as copper, lithium, nickel, cobalt, and rare earth elements. These resources are as critical to the future as oil and gas were in the past. Yet, as this paper has shown, the supply chains that deliver them are highly vulnerable in that they are geographically concentrated, slow to scale, environmentally and socially contested and prone to price instability.

If left unaddressed, these vulnerabilities will shape the trajectory of the transition. They will delay projects, inflate costs, increase financing risks, and undermine public and investor confidence. In a system that depends on rapid deployment at unprecedented scale, fragility in the materials base is the risk multiplier that could make or break the transition. At the same time, supply risk does not equate to inevitability of failure. This paper demonstrates that there are multiple pathways towards resilience. Three overall messages stand out, namely:

Vulnerabilities are systemic, not isolated.

The risks around critical raw materials rarely occur in isolation. Geographic concentration makes supply chains fragile, price volatility amplifies cost uncertainty, long equipment lead-times delay project delivery, and ESG controversies threaten financing. These factors interact and reinforce one another, creating compound risks that ripple across technologies and geographies. Addressing them requires moving away from siloed approaches to integrated, foresight-driven risk governance. Only by viewing vulnerabilities systemically can companies and investors anticipate cascades rather than being surprised by them.

Resilience is a function of collaboration.

No single actor can solve the materials challenge. Developers and OEMs can redesign technologies, but they cannot scale recycling markets without investors. Investors can allocate capital, but they depend on policymakers to create regulatory certainty. Policymakers can set standards, but they need industry to provide data and practical solutions. The result is that resilience is fundamentally collective requiring cross-value-chain coordination, joint investment in recycling and refining, and shared data systems such as product passports.

Time is the critical factor.

The 2020s are the decisive decade. Short-term actions such as exposure mapping, supplier diversification, and pilot recovery schemes need to be completed as a priority if organisations are to be prepared for scaling. The aspiration must be that by the early 2030s, diversification, substitution, and commercial-scale recycling are operational or the 2030s will become a decade of bottlenecks instead of expansion. Resilience cannot be retrofitted at the point of crisis but be built now, in parallel with rapid deployment. Time, more than technology or capital, is the scarcest resource in building resilient materials systems.

The path forward, however, is not without friction. Circularity requires upfront investment before returns are visible.

Diversification requires longer and more complex supply agreements that may initially raise costs. Substitution often involves short-term performance trade-offs. These are not trivial barriers. Yet the alternative of remaining dependent on fragile and concentrated supply chains is far riskier.

The choice is not between cost and no cost, but between manageable investments today and disruptive losses tomorrow. What emerges is a dual reality.

Supply risks are unavoidable. The materials intensity of renewable technologies is non-negotiable. For example wind turbines will require steel and copper, solar panels will require aluminium, silicon and silver, batteries will require lithium and other active materials.

Equally non-negotiable are the geographic and economic constraints of their supply. Concentration ratios, long mine development cycles and ESG issues mean volatility will remain a structural feature of these markets.

Despite these constraints, resilience is within reach. Through foresight, circularity and collaboration, vulnerabilities can be anticipated, buffered and mitigated. Transparency in supply chains, investment in recycling diversification of procurement and cross-sector cooperation can stabilise costs and distribute risks more evenly.

Final reflection

The energy transition is often described as a technological race, building turbines, PV modules and storage at speed and scale. Yet beneath the visible hardware lies an invisible foundation of metals and minerals. The transition will not be defined solely by innovation in renewable technologies, but also by our ability to secure, manage and recover the materials that make them possible.

The metals crunch is foreseeable. It is not a surprise waiting to happen, but a risk already visible in concentration ratios, demand forecasts and price trajectories. The question is not whether vulnerabilities exist, but whether the actors who depend on these materials will act on the foresight now available to them.

The conclusion is unambiguous in that the supply risks of the energy transition are real, systemic and urgent but they are not insurmountable. Developers, OEMs, investors and policymakers have the tools, the knowledge and the foresight to act. If they embed resilience today, the transition can proceed on stable foundations. If they delay, the costs of inaction will not only be financial but strategic, threatening the credibility of net-zero pathways themselves.

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