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The architecture behind renewable energy

Awareness of the landscape, strengthening supply chains and scaling responsibly

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The renewable energy transition is accelerating at extraordinary pace. As global deployment scales, a new dimension of leadership has emerged: ensuring the integrity, resilience and responsibility of the supply chains that enable it.

This acceleration is occurring alongside a broader structural shift – the electrification of transport, industry and infrastructure, and the growing 'batterisation' of the global economy. From grid-scale storage to electric vehicles, data centres and defence applications, batteries and power electronics have become foundational technologies across multiple sectors. Battery energy storage systems have emerged as one of the fastest-growing sources of demand for critical minerals, reflecting the increasing importance of grid flexibility and energy security alongside decarbonisation objectives. This convergence is driving sustained and significant demand for a shared set of critical minerals, components and processing capabilities – amplifying both opportunity and risk across global supply chains.

Lithium demand rose by nearly 30% in 2024, significantly exceeding the 10% annual growth rate recorded during the 2010s. Demand for nickel, cobalt, graphite and rare earth elements increased by 6–8% over the same period, largely driven by energy applications including electric vehicles, battery storage, renewables and grid networks.[1] The trajectory over the coming decades is steeper still – with lithium demand projected to grow by up to 86% between 2024 and 2040 under a net zero scenario.[1]

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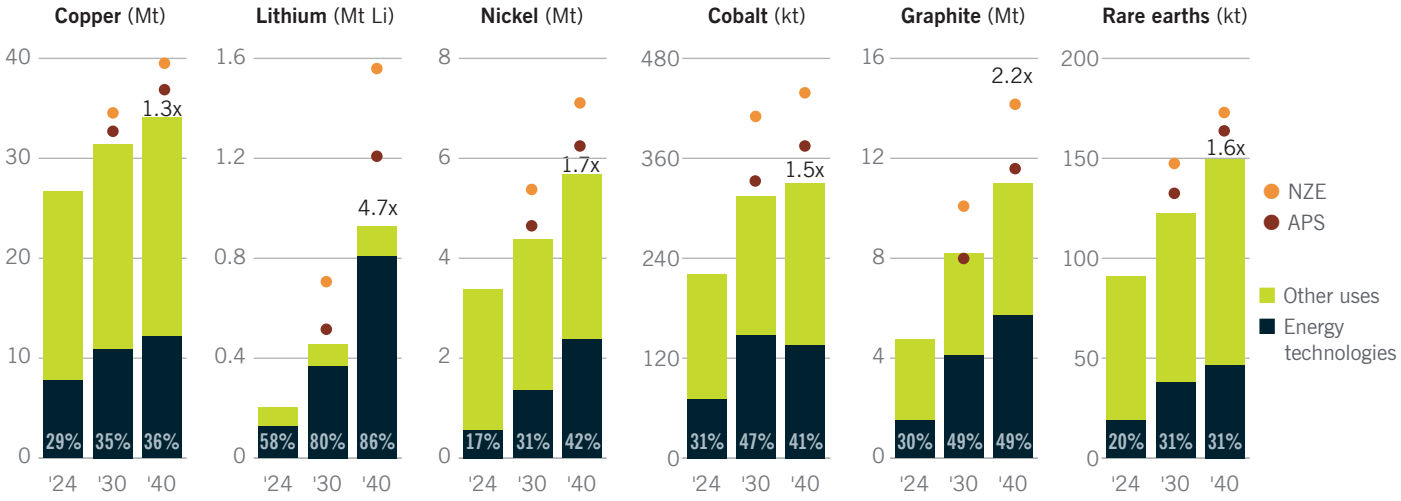
Figure 1: Demand for critical minerals continues to rise across all scenarios, driven by the rapid deployment of energy technologies

Global critical minerals demand in the STEPS



Notes: STEPS = Stated Policies Scenario; Mt = million tonnes; kt = kilotonnes; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. The figures for copper are based on refined copper (excluding direct-use scrap). Those for rare earth elements are for magnet rare earth elements only. Growth rates (in blue) are between 2024 and 2040.

Source: IEA Global Critical Minerals Outlook 2025. IEA. CC BY 4.0.[2]

Solar, wind and battery storage rely on critical minerals sourced from long-established international supply chains – networks that serve electronics, automotive, manufacturing and technology simultaneously. These systems pre-date the renewables sector. However, given the scale of clean energy deployment, the long-term nature of infrastructure capital and the increasing rigour of procurement standards, the sector is well-positioned to contribute meaningfully to how these global systems evolve.

Looking beyond a narrow lens

Much of the public conversation to date has focused on a single area: China's polysilicon production and the potential presence of forced labour in parts of the solar supply chain. That scrutiny has generated tangible improvements – from enhanced auditing protocols to more robust procurement standards and deeper supplier engagement across the industry.

However, the landscape is considerably broader. Attention has rightly expanded to battery energy storage systems and the minerals that underpin them: lithium, cobalt, nickel, graphite and rare earth elements. These materials travel through global networks that long pre-date the renewables industry and serve multiple high-demand sectors simultaneously. The supply chain challenges associated with these minerals are cross-industry in nature and cannot be resolved by any single sector acting in isolation.

Since publication of many of the underlying studies, geopolitical competition, export controls and industrial policy interventions have further reinforced the importance of supply chain diversification and supply chain transparency. These developments have highlighted the strategic significance of critical minerals beyond their role in the energy transition alone.

The appropriate response is not to assign responsibility, but to identify where influence is most material – and to deploy it deliberately.

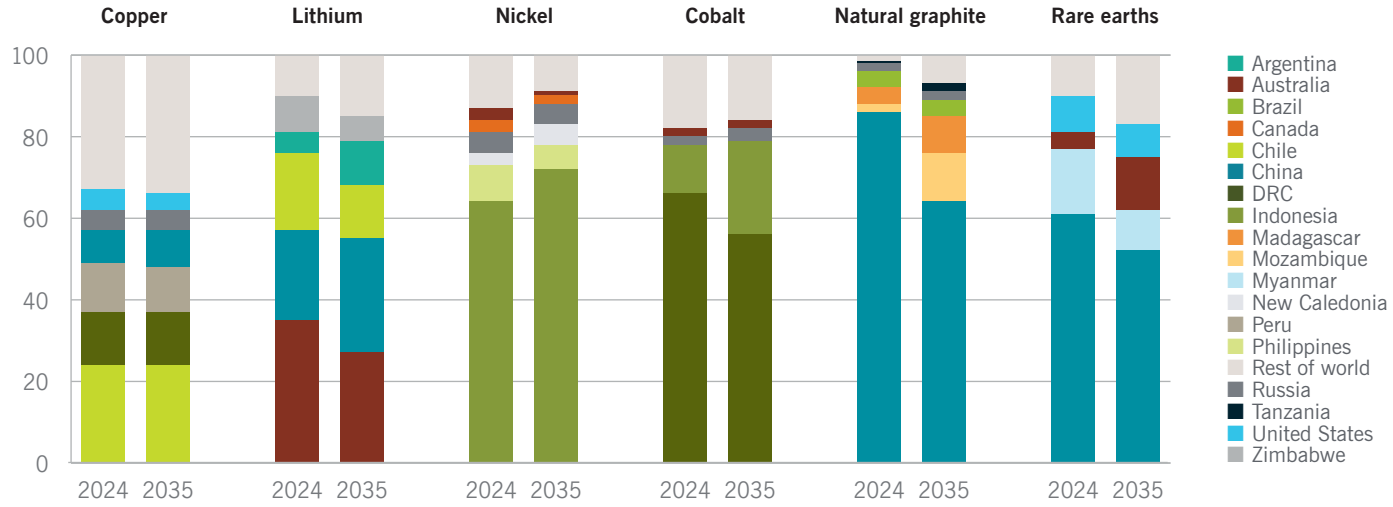
Whilst the renewable energy sector did not design these global supply chains, its scale, long-term capital allocation and evolving procurement practices position it to contribute meaningfully to their improvement – particularly by extending expectations beyond Tier 1 suppliers – those with a direct contractual relationship with the buyer – and prioritising the minerals where human rights and environmental risk is greatest.

A further dimension of concern is geographic concentration. The average market share of the top three refining nations for key energy minerals rose from 82% in 2020 to 86% in 2024, with approximately 90% of supply growth emanating from a single dominant supplier in each category – Indonesia for nickel, and China for cobalt, graphite and rare earths.[1] This concentration increases the sector's vulnerability to supply disruption and reinforces the urgency of diversification efforts.

Figure 2: Critical mineral supply chains are highly concentrated geographically, particularly at refining and processing stages

Mining of critical minerals is set to become more concentrated for copper, nickel and cobalt while more diversified for lithium, graphite and rare earth elements"

Geographical distribution of mined or raw material production for key energy minerals in the base case



Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. The figures for rare earth elements are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Source: IEA Global Critical Minerals Outlook 2025. IEA. CC BY 4.0.[1]

It is important to note that only a subset of rare earth elements is critical to the energy transition – primarily those used in high-performance permanent magnets for wind turbines, electric vehicle motors and grid applications.[1] A precise understanding of which minerals are material, and where they originate, is the foundation of credible supply chain governance.

CASE STUDY 1 – SOLAR: A COMPLEX CHAIN BEHIND A SIMPLE PRODUCT

A solar panel presents as a straightforward technological product. Behind it lies a considerably more complex manufacturing journey – from raw quartz through metallurgical-grade silicon, polysilicon production, wafer processing, cell manufacture and final module assembly – each stage characterised by its own geography, supplier base and transparency challenges.[3]

In a recent assessment conducted for a European solar procurement, Tier 1 suppliers demonstrated strong compliance, detailed audit trails and increasing alignment with responsible sourcing stewardship initiatives. However, several tiers upstream – particularly at the metallurgical-silicon stage – suppliers had no established requirement to track mine-level origin. This is not indicative of malpractice. It reflects a broader structural reality: global transparency norms are still developing in step with global demand.

This challenge echoes what Siddharth Kara highlights in his book Cobalt Red more broadly: "Most global supply chains lose visibility long before the raw material reaches the factory gate."*[4]

The solar supply chain was not designed with end-to-end traceability in mind. Under sustained pressure from clean energy buyers and evolving regulatory frameworks, that is beginning to change. Visibility continues to diminish further upstream, but the direction of travel is clear – and the renewables sector is helping to accelerate it.

Figure 3: Solar PV manufacturing value chain

CRYSTALLINE SILICON

MINERAL EXTRACTION

Silica (SiO2) : quartzite, quartz pebble, quartz vein
Carbothermic reduction
(carbon arc welding [CAW]), removal of impurities

Metallurgical-grade silicon (MG-Si >98% purity)
Hydrochloration

Trichlorosilane gas (HSiCl3)
Siemens process

Silane gas (SiH4)
Fluidised bed reactor (FBR)

Polysilicon (6-13N purity)

Czochralski (CZ) process	Float zone (FZ) technique	Molding (heat exchange method / electro-magneto casting / directional solidification system), doping

Monocrystalline silicon ingot

Multicrystalline, mono-like or quasi-mono silicon ingot
Sawing and slicing

Wafers
Cleaning, texturing, doping (diffusion), etching, anti-reflective coating deposition, contact printing and sintering, testing

Cells
Backsheet, contacts, encapsulation, glass and frame assembly and sealing, junction box connection, testing

Module
Mounting, inverter connection, connection to the grid

PV system

THIN-FILM (CDTE)

MINERAL EXTRACTION AND REFINING

Cadmium (Cd), Tellurium (Te), etc.

- Deposition of a transparent conducting oxide (TCO) (e.g. fluorine-doped tin oxide or indium-tin oxide) front contact layer on a substrate (e.g. glass, polymer)
- Deposition of a n-type cadmium sulfide (CdS) buffer or window layer
- Deposition of a p-type cadminum telluride (CdTe) absorber layer
- Junction-activation heat treatment
- Deposition of the back contact metal layers (e.g. zinc telluride [ZnTe], molybdenum [Mo])
- Definition of cells by laser scribing, interconnection bussing

Cells
Encapsulation, electrical lead attachement, junction box connection, testing

Module
Mounting, inverter connection, connection to the grid

PV system

Source: IEA (2022), Solar PV Global Supply Chains, IEA, Paris. Licence: CC BY 4.0.[3]

CASE STUDY 2 – BATTERY STORAGE: THE HUMAN REALITY BEHIND COBALT

Battery energy storage systems are central to a resilient and flexible grid. Many rely on cobalt, a mineral sourced predominantly from the Democratic Republic of Congo, where artisanal mining is widespread and economic vulnerability is acute.

Siddharth Kara's Cobalt Red provides a detailed account of conditions in the artisanal mining sector – children carrying sacks of ore, miners working with basic hand tools in open pits, and communities living in immediate proximity to extraction sites. As Kara writes: "The world's renewable future depends on individuals whose names we will never know, working in conditions we would never accept."*[4]

A 2025 University of Nottingham Rights Lab study provides empirical context: 36% of artisanal cobalt miners surveyed were found to be in forced-labour conditions, and 9% were children.[5]

These conditions are neither unique to the renewable energy sector nor confined to it. Cobalt serves a global range of industries – consumer electronics, electric vehicles, aerospace and technology among them. However, because battery storage depends on these minerals, the sector has both a direct stake and a clear responsibility in advocating for improved governance and more responsible sourcing practices across the value chain.

Evolving Practice: BESS Manufacturer Traceability and Asset Owner Visibility

In response to increasing scrutiny of battery supply chains, a number of BESS manufacturers and system integrators have begun to improve transparency and traceability across battery components. In practice, this includes component-level supply chain mapping, enhanced supplier disclosure requirements and the deployment of digital tracking systems that enable asset owners to trace key materials upstream.

These measures do not eliminate upstream risk in complex global mineral supply chains. However, they represent a substantive governance improvement – moving beyond high-level assurances towards structured accountability and clearer oversight across the BESS value chain. For asset owners, embedding explicit expectations on traceability and responsible sourcing within competitive procurement processes remains one of the most direct and impactful levers available.

CASE STUDY 3 – WIND: MYANMAR'S RARE-EARTH EXPANSION AND THE MAGNET SUPPLY CHAIN

Permanent magnets sit at the intersection of clean energy, geopolitics and industrial policy – and represent one of the more complex supply chain challenges currently facing the wind sector.

Neodymium-iron-boron (NdFeB) magnets are essential components of the direct-drive turbines deployed across modern onshore and offshore wind projects. These magnets depend on rare earth elements – principally neodymium and dysprosium[2] – the refining of which remains highly concentrated in China, which controls nearly 90% of global rare earth processing capacity.[6] A growing proportion of upstream ore now originates from northern Myanmar, where informal extraction expanded rapidly after 2018.

Global Witness – in its May 2024 investigation, Fuelling the future, poisoning the present: Myanmar's rare earth boom – documents extraction in Kachin State characterised by unregulated chemical leaching, minimal environmental oversight and limited visibility into labour conditions.[6] Between 2021 and 2023, mining sites in the region increased by more than 40%, with imports of heavy rare earth oxides to China more than doubling to 41,700 tonnes – exceeding China's own domestic mining quota.[6] The vast majority of this extraction is explicitly illegal, operating without regulatory frameworks in an active conflict zone.

As with cobalt and polysilicon, this is not a risk created by the wind sector. However, because turbine magnets depend on these materials, wind manufacturers and developers are increasingly engaging in responsible sourcing dialogue, participating in industry stewardship frameworks and exploring alternative magnet chemistries and recycling pathways.

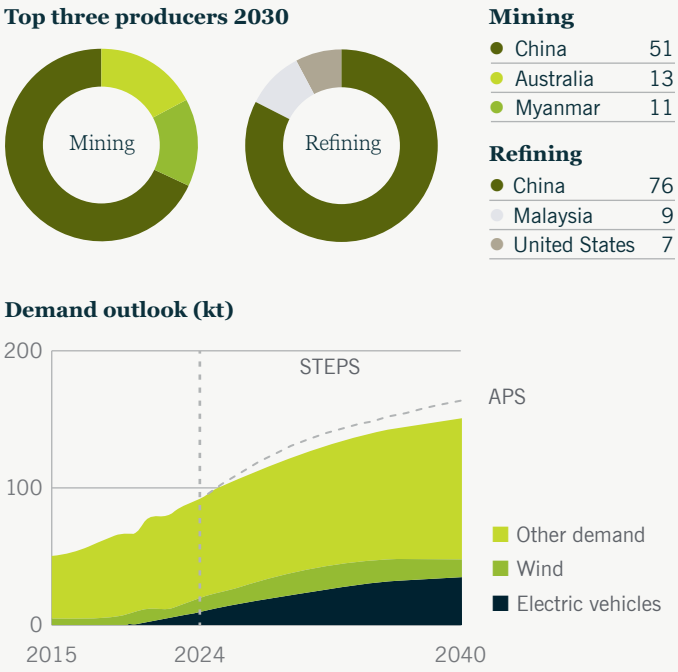
The pattern across all three case studies is consistent: strong transparency and compliance at Tier 1 – those suppliers in direct contractual relationship with the buyer – with visibility diminishing progressively further upstream, and a clear opportunity for the sector to drive systemic improvement beyond its direct footprint.

Closing the Historic Data Gap

A question frequently raised by investors and stakeholders concerns the limited availability of upstream data – particularly prior to 2020. The reasons are structural and industry-wide rather than sector-specific.

Figure 4 – Rare earth elements (Nd Pr Dy Tb)

Wind energy relies on only 4 out of the 17 rare earth elements. This subset faces rapidly growing demand and highly concentrated supply.



Source: IEA Global Critical Minerals Outlook 2025. IEA. CC BY 4.0.[1]

Upstream refiners and brokers operated without formal disclosure requirements. Traceability systems were still emerging and unevenly implemented across global supply chains. Artisanal mining was often poorly documented, and international due diligence expectations were only beginning to scale. These were characteristics of the global system as a whole – not failings unique to the renewable energy sector.

Acknowledging the boundaries of historical data is not a sign of weakness. It reflects the transparency expected of a credible and maturing industry – one that is clear-eyed about where influence is indirect, where legacy data is incomplete and where progress must be incremental rather than immediate.

Since then, the landscape has improved materially. Approximately 85% of the 25 major mining companies disclosed performance across 10 key environmental and social indicators in 2023, rising from 60% in 2020.[1] Many solar and storage manufacturers now participate in responsible sourcing programmes, and data quality across critical mineral supply chains continues to advance. This trajectory – measured, practical and sustained – is what responsible industry evolution looks like.

Our path forward – pragmatic, responsible, constructive

1. **Build on strong foundations**
   The renewable energy sector already occupies a leading position globally on responsible sourcing. The priority now is to extend that leadership upstream – expanding visibility beyond Tier 1 and directing focus towards the highest-impact minerals. Recent geopolitical developments have further underlined the value of resilient and diversified supply chains, making responsible sourcing not only an ESG consideration but also a strategic business imperative. For asset owners such as Nuveen, supply chain contracting and procurement processes represent a direct and underutilised lever for raising ESG standards across the BESS value chain. Embedding clear expectations on traceability, disclosure and responsible sourcing within competitive bidding and supplier selection processes enables asset owners to drive greater accountability among battery providers.

2. **Broaden the definition of community engagement**
   Many developers maintain strong community engagement practices around project sites. Extending that approach to upstream communities – even where influence is indirect – is where supply chain ESG integrity is most meaningfully tested and demonstrated.

3. **Support and participate in credible industry initiatives**
   The Solar Stewardship Initiative (SSI),[7] Global Battery Alliance (GBA)[8] and Responsible Minerals Initiative (RMI)[9] exist to harmonise expectations and create consistency across fragmented global supply chains. Active participation in these frameworks is central to any credible claim of supply chain leadership.

4. **Integrate human rights due diligence into procurement**
   Robust due diligence requires clear supplier expectations, independent audit mechanisms, corrective action frameworks and responsible exit pathways. These are the practical instruments of accountability – ensuring that supply chain partners are held to consistent standards without compromising delivery performance or commercial relationships.

5. **Advocate for proportionate and effective regulation**
   Policy frameworks that protect workers whilst supporting renewable energy deployment create the conditions for responsible companies to compete on a level basis. The sector has a material and credible voice in shaping regulatory development – and a responsibility to use it constructively. Notably, capital costs for projects in diversified regions are typically around 50% higher than for incumbent producers,[1] reinforcing the case for well-designed public financing support and price stabilisation mechanisms alongside regulatory advocacy.

Conclusion

Strengthening supply chain transparency is not a critique of the renewable energy sector – it is the logical next stage in its evolution.

As deployment scales globally, there is a genuine opportunity to establish a benchmark for ethical, transparent and socially responsible supply chain management. The standards set now will shape the long-term credibility of the transition – for investors, regulators and the communities whose labour and resources make it possible.

In an era where energy security, industrial policy and sustainability are increasingly inseparable, leadership is not defined by the absence of complexity. It is defined by transparency, rigorous collaboration and a willingness to engage decisively where influence is greatest.

For more information, please visit nuveen.com/cleanenergy.

1 IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021. IEA. Available at: iea.org
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4 Siddharth Kara, Cobalt Red: How the Blood of the Congo Powers Our Lives, St. Martin's Press, 2023
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7 solarstewardship.org
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Endnotes

Sources

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