CRITICAL MINERALS

The physical foundations of the transition

In the NEXT PHASE *of the energy* TRANSITION, *minerals and materials have become as strategic as generation itself. As global electricity demand surpasses 33,000 TWh by 2026, the renewable build-out is embedding unprecedented volumes of copper, lithium, nickel, rare earths, aluminium & steel into the physical economy. Critical minerals have emerged as increasingly* FOUNDATIONAL *to the economics of* DECARBONISATION.

IN BRIEF:

- Demand is accelerating: Clean energy pathways require 2–4x more critical minerals by 2030, yet new mines take 7–15 years to develop and capital intensity per tonne has risen 2–3x since the early 2000s.
- Downstream processing is the sharpest bottleneck: 60–90% of global processing in lithium, cobalt, rare earths and graphite is concentrated in a single jurisdiction, often more than mining itself.
- High material intensity: A 3MW wind turbine requires ~335t of steel, 4–5t of copper and up to 2t of rare earths; offshore wind is ~2x more mineral-intensive per MW than utility-scale solar.
- Capital formation gap: ~US$500–600bn is needed in mining and ~US$600–750bn in processing by 2040, highlighting a structurally undercapitalised supply chain.

As established in éthica Capital's previous Energy Transition industry report, global energy demand is entering a period of sustained structural growth. Industrial electrification is accelerating, while new sources of load are emerging from technological innovation- data centres, AI computation, and digital infrastructure. Global electricity consumption alone is projected to exceed ~33,000-33,500 terawatt-hours by 2026[1], growing at close to 3.7% per annum, more than twice the rate of total energy demand growth[2]. This divergence underscores the scale and durability of the shift and reflects a permanent expansion in the energy intensity of the global economy.

Within this context, renewable energy has become the dominant source of new power supply by economic and system logic. Wind & solar account for the vast majority of new generation capacity added globally, reflecting their position as the lowest-cost sources of incremental power across most regions[3]. Once constructed, these assets operate with minimal variable costs and limited supply-chain risk relative to fuel-dependent generation[4].

By contrast, new fossil generation faces rising capital intensity, longer development timelines, and increasing uncertainty around utilisation in an electrifying system[5]. As a result, global capital

[1] Del Bianco, S. (2025) Global electricity demand rising fast through 2026. Rinnovabili, 1 August.Available at: https://www.rinnovabili.net/business/energy/global-electricity-demand-forecast-2025-2026/
[2] International Energy Agency (2025) Electricity 2025: Analysis and forecast to 2026. Paris: IEA. Available at: https://www.iea.org/reports/electricity-2025
[3] BloombergNEF (2025) New Energy Outlook 2025. Bloomberg Finance L.P. Available at: https://about.bnef.com/insights/clean-energy/new-energy-outlook/;
[4] International Renewable Energy Agency (2023) Renewable Power Generation Costs in 2022. Abu Dhabi: IRENA. Available at: https://www.irena.org/publications
[5] Energy Transitions Commission (2023) Making the Power Sector Fit for Net Zero. London: ETC. Available at: https://www.energy-transitions.org/publications/; Wood Mackenzie (2023) Global Power Markets Outlook. Edinburgh:

allocation has shifted decisively, with incremental investment flowing toward renewables due to superior cost visibility, scalability, and durable economics[6].

The effect of this shift is that the energy transition has become fundamentally a problem of physical build-out rather than optimisation.

Unlike fossil systems, where costs are spread over time through fuel consumption, renewable systems concentrate cost and risk at the point of construction & integration of new generation assets, transmission and distribution networks, and storage capacity[7]. Each unit of installed capacity embeds a substantial upfront material requirement, with all low-carbon systems demanding significant volumes of minerals per megawatt deployed despite variation in technology-specific intensity[8]. As a result, progress in the transition is increasingly inseparable from physical systems.

CRITICAL MINERALS: DEFINITION AND SYSTEM ROLE

Critical minerals are defined by their function and vulnerability rather than by geological rarity alone. A material becomes "critical" when it is essential to the performance of energy systems and its supply chain is exposed to disruption–through concentration, long development timelines, processing bottlenecks, or limited substitutes[9].

This framing aligns with criticality literature, which treats criticality as a multi-dimensional system property- typically combining supply risk and vulnerability to restriction, rather than focusing on scarcity in the ground[10].

Operationally, criticality tends to emerge when three conditions coincide[11].

- The material is functionally essential to generation, storage, transmission, or electrification.
- It is slow to scale, because expanding supply requires capital-intensive projects, long approvals, and complex industrial processing.
- It is hard to substitute without redesigning infrastructure or accepting performance penalties.

Where these conditions hold, shortages cannot be engineered away quickly; they propagate directly into infrastructure timelines and cost bases[12]. Accordingly, critical minerals are not a standalone "transition sector". They are embedded inputs to physical infrastructure, and their relevance rises as the

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> *U.S. Department of the Interior*

transition becomes a construction and manufacturing problem rather than one of technology adoption[13].

Critical minerals remain structurally important to the energy transition because their role is defined at the system level and not by short-term price cycle[14]. Criticality is driven by the industrial pace of build-out and the practical frictions in scaling mining and processing capacity[15]. In this capacity, critical minerals function as part of the transition's physical foundation, shaping execution risk, sequencing, and ultimately investment outcomes across the energy value chain[16].

UPSTREAM SUPPLY: EXTRACTION, LEAD TIMES, AND CAPITAL INTENSITY

The upstream segment of the critical minerals value chain is characterised by long lead times, high capital intensity, and structurally low supply elasticity[17]. The energy transition is expected to require a doubling to quadrupling of mineral demand for clean energy technologies by 2030 under net-zero pathways, far exceeding historical rates of mineral supply growth[18].

Across most minerals embedded in energy systems, the interval between discovery and first production typically spans seven to fifteen years, extending further where permitting or infrastructure access is complex. These timelines are largely invariant to short-term demand signals, reflecting the physical and regulatory realities of mining rather than market conditions[19].

Capital requirements reinforce this rigidity. Capital intensity per tonne of minerals has risen two to three times for many metals since the early 2000s as ore grades decline and new deposits are developed at greater depth[20]. New copper, nickel, lithium, and rare earth projects now routinely require hundreds

[6] International Energy Agency (2025) Electricity 2025 [7] Wilson, C., Shrimali, G. and Caldecott, B. (2025) 'Financing costs and the competitiveness of renewable power', iScience, 28(12). https://doi.org/10.1016/j.isci.2025.113777 [8] International Energy Agency (IEA) (2025) The Role of Critical Minerals in Clean Energy Transitions [9] U.S. Geological Survey (2025) What are critical minerals? U.S. Department of the Interior. https://www.usgs.gov/programs/mineral-resources-program/science/what-are-critical-minerals-0;Graedel, T.E. et al. (2011) 'Methodology of metal criticality determination', Environmental Science & Technology. https://pubs.acs.org/doi/10.1021/es203534z [10, 11, 14,16] Graedel, T.E. et al. (2015) 'Criticality of metals and metalloids', Proceedings of the National Academy of Sciences (PNAS), 112(14). https://www.pnas.org/doi/10.1073/pnas.1500415112 [12] World Bank (2023) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. Washington, DC: World Bank. https://openknowledge.worldbank.org/entities/publication/4dd08d0c-ab51-4955-a464-35a95201a5eb; Organisation for Economic Co-operation and Development (2024) Raw Materials and Industrial Policy in the Energy Transition. Paris: OECD Publishing. https://www.oecd.org/industry/raw-materials-energy-transition.htm [13] Yu, D. et al. (2025) 'Critical mineral bottlenecks constrain sub-technology pathways…', iScience. Available at: https://www.cell.com/iscience/fulltext/S2589-0042%2825%2901528-7 [15] International Energy Agency (IEA) (2025) The Role of Critical Minerals in Clean Energy Transitions [17] Global Investor Commission on Mining 2030 (2024) Mining Landscape Report: The Role of Investors in Realising an Environmentally and Socially Responsible Mining Industry. London: Global Investor Commission on Mining 2030. https://mining2030.org/wp-content/uploads/2024/10/Mining2030-Report-v9.pdf [18] World Economic Forum (2025) Why we need critical minerals for the energy transition. Available at: https://www.weforum.org/stories/2025/05/critical-minerals-energy-transition-supply-chain-challenges/ [19] Schneider et al., 2014; International Energy Agency (IEA) (2025) The Role of Critical Minerals in Clean Energy Transitions [20] Global Investor Commission on Mining 2030, 2024, Mining Landscape Report; Calvo, G., Mudd, G.M., Valero, A. & Valero, A. (2016) Decreasing ore grades in global metallic mining: a theoretical issue or a global reality? Resources 5(4), https://doi.org/10.3390/resources5040036

TABLE 1: STRUCTURAL CHARACTERISTICS OF UPSTREAM CRITICAL MINERAL SUPPLY						
Critical mineral (upstream)	**Typical lead time to new supply (years)**	**Capital intensity**	**Substitutability in energy systems**	**Where constraint appears (upstream)**	**Highest concentration of supply – mining only (global share)**	**Australia's position**
Copper ores	10–15	High	Low	Declining ore grades; long permitting timelines	Chile ~27%, Peru ~13% (top 2 ~40%)	Major producer; limited domestic refining
Lithium-bearing minerals (e.g. spodumene)	7–10	High	Low	Project development timelines; conversion readiness	Australia ~51%, Chile ~26% (top 2 ~77%)	World's largest miner; processing largely offshore
Nickel ores	8–12	Very high	Medium–Low	Capital intensity; ore quality for battery-grade	Indonesia ~40–45%, Philippines ~10–15%	Significant producer; mixed battery-grade exposure
Cobalt ores	8–12	High	Low	Extreme geographic concentration; ESG risk	DRC ~70–75%	Minor producer; limited strategic leverage
Graphite (natural & synthetic)	5–8	Medium	Low	Mine-to-market bottlenecks; quality constraints	China ~60–65%	Emerging producer; processing offshore
Rare earth minerals	10–20	Very high	Low	Complex geology; long development and permitting	China ~60%, Australia ~5%	Meaningful reserves; limited separation capacity
Iron ore	7–10	Very high	Medium	Scale requirements; decarbonisation of mining	Australia ~36%, Brazil ~34% (top 2 ~70%)	World's largest exporter; upstream strength
Bauxite	6–10	Very high	Medium	Mine development; logistics	Australia ~28%, Guinea ~24%	Major producer; downstream energy-intensive
Silica (quartz)	5–7	High	Medium	High-purity resource qualification	Widely distributed (no dominant miner)	High-grade resources; limited high-purity development
Manganese ores	6–10	Medium–High	Medium	Battery-grade suitability	South Africa ~30%, Australia ~16%	Strong reserves; limited downstream scale

TABLE 1; U.S. GEOLOGICAL SURVEY (2025) MINERAL COMMODITY SUMMARIES 2025

of millions to several billions of dollars in upfront capital before revenues are realised[21].

These cost pressures reflect structural changes in resource quality and mine design. Average copper ore grades have fallen from approximately 1.6% Cu in the early twentieth century to around 0.6% today, a decline of roughly 60-65%, increasing the volume of material that must be mined and processed per unit of output[22]. At the same time, new copper & base metal supply increasingly depends on underground operations at depths of 500-1,000 metres, compared with less than 300 metres for many legacy open-pit mines[23]. As a result, even sustained price incentives translate only gradually into additional supply, reinforcing the structural inelasticity of upstream mineral production[24].

Environmental approvals, land & water availability, and community consent have become material

[21] World Bank (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition [22, 23] Sy, D., Liwanag, A. K., & Manubag, N. M. (2025, December 12). Capital demands soar for new copper supply. S&P Global Commodity Insights. https://www.spglobal.com/market-intelligence/en/news-insights/research/2025/12/capital-demands-soar-for-new-copper-supply [24] World Bank (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. FOR FOLLOWING PAGE: [27, 28] U.S. Geological Survey (2025) Mineral Commodity Summaries 2025 [29] Ibid; International Energy Agency (2023) Critical Minerals Market Review 2023. Paris: IEA. https://www.iea.org/reports/critical-minerals-market-review-2023; [30, 31] International Energy Agency (IEA) (2025) The Role of Critical Minerals in Clean Energy Transitions; OECD (2025) Economic security in a changing world: Special focus – Critical raw materials supply chains. OECD Publishing, Paris. https://www.oecd.org/en/publications/2025/09/economic-security-in-a-changing-world_78f3b129/full-report/special-focus-critical-raw-materials-supply-chains_daf99c07.html; U.S. Geological Survey (2025)

considerations in the development of new mining projects across many jurisdictions[25]. These determinations reflect the reality that critical minerals are extracted within social & ecological systems that the energy transition itself seeks to protect.

For several minerals- most notably copper, cobalt, and rare earths- social licence and environmental risk have become as decisive as geology in determining whether projects proceed[26]. Rather than negating the case for renewables, these limitations shape the pace and form of their deployment. They limit how quickly supply can expand, regardless of capital availability, and in doing so make execution, sequencing, and system design central to transition outcomes.

Table 1 illustrates how these characteristics manifest across major upstream minerals. Lead times remain long even in well-established mining jurisdictions. Capital intensity is consistently high. Substitutability within energy systems is limited, particularly for copper, lithium, cobalt, and rare earths, where material properties are difficult to replicate without redesigning infrastructure. Supply concentration at the mining stage further amplifies risk, with a small number of countries accounting for a dominant share of global output across several critical minerals[27].

> “AUSTRALIA IS A *LEADING GLOBAL PRODUCER* OF CRITICAL MINERALS, *1ST* IN LITHIUM MINING, & A *TOP 3* IN IRON ORE, BAUXITE &MANGANESE”
>
> *U.S. Geological Survey*

Australia occupies a distinctive position in the upstream energy transition as a leading global producer of critical minerals, ranking first in lithium mining, among the top three producers of iron ore, bauxite and manganese, and among the world’s significant producers for copper and rare earths[28].

In volume terms, Australia supplies roughly half of global lithium ore and more than one-third of global iron ore, giving it a central role in the raw material foundations of electrification and infrastructure build-out[29]. However, upstream scale does not equate to system flexibility. Australian mining projects face the same structural realities observed globally. As a result, even in a resource-rich jurisdiction, upstream supply cannot be accelerated quickly enough to absorb rapid surges in demand from electrification and infrastructure deployment. Australia’s position is therefore best understood as upstream-rich rather than upstream-fast - significant in global supply, but governed by the same physical and regulatory pace that defines the mining sector more broadly[30]. Collectively, these characteristics explain why upstream mineral supply responds slowly to structural demand growth. The bottleneck is in the physical reality of bringing new mines into production within existing industrial, regulatory, and social limits. This low elasticity at the upstream stage is the first point at which execution risk enters the energy transition.

DOWNSTREAM CONVERSION: FROM MINERALS TO METALS AND MATERIALS

As the energy transition moves into its execution phase, the locus of control increasingly shifts downstream. Energy infrastructure is constructed from processed metals and materials from raw minerals that are refined and fabricated before they can be deployed into infrastructure. While upstream supply defines the outer bounds of availability, downstream capacity governs the pace at which physical assets can actually be delivered[31].

Downstream conversion introduces a distinct set of physical and economic characteristics. Processes that convert minerals into functional materials are typically more energy-intensive than extraction[32]. They require continuous high-temperature[33] or chemically complex operations and depend on long-lived industrial assets[34].

The production of aluminium[35] and battery-grade lithium hydroxide or carbonate[36] both illustrate this dynamic; These processes are capital-intensive, slow to scale, and necessarily dependent on access to cheap, reliable power. In addition, downstream facilities exhibit strong path dependence once established, with limited flexibility to respond quickly to shifts in demand.

Geographic concentration further reinforces this dependence. Across metal and material production, processing capacity is densely clustered in a small number of jurisdictions. Assessments of material criticality consistently show that downstream concentration often exceeds upstream mining concentration, increasing systemic vulnerability even where mineral reserves are geographically diverse[37]. This concentration reflects decades of cumulative investment, industrial clustering, and energy-system alignment, rather than short-term policy choices.

[32] Norgate, T. and Haque, N. (2010) ‘Energy and greenhouse gas impacts of mining and mineral processing operations’, Journal of Cleaner Production, 18(3), pp. 266–274. https://doi.org/10.1016/j.jclepro.2009.09.020; Petrakis, E. (2025) ‘Advances in mineral processing of hard-rock lithium ores’, Mineral Processing and Extractive Metallurgy Review. Available at: https://link.springer.com/article/10.1007/s42461-025-01227-y [33] Pauliuk, S., Arvesen, A., Stadler, K. and Hertwich, E.G. (2017) ‘Industrial ecology in integrated assessment models’, Nature Climate Change, 7(1), pp. 13–20. https://doi.org/10.1038/nclimate3148. [34] Allwood, J.M., Ashby, M.F., Gutowski, T.G. and Worrell, E. (2011) ‘Material efficiency: A white paper’, Resources, Conservation and Recycling, 55(3), pp. 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002; U.S. Geological Survey (2025) Mineral Commodity Summaries 2025; [35] International Aluminium Institute (2019) Aluminium recycling saves 95% of the energy needed for primary aluminium production. International Aluminium Institute. Available at: https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/; [36] Kelly, J.C., Wang, M.Q., Dai, Q. and Winjobi, O. (2021) ‘Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries’, Resources, Conservation and Recycling, 174,

DOWNSTREAM PROCESSING CHARACTERISTICS OF CRITICAL MINERALS							
Upstream mineral	**Metal / material produced**	**Embedded infrastructure use**	**Processing energy intensity**	**Dominant processing capability & global share**	**Typical processing lead time**	**Relocation potential**	**Why this matters**
Copper ores	Refined copper (cathode, wire rod)	Grids, transmission, motors, EV wiring, data centres	Medium	**Refining & fabrication:** China ~45%	3–5 years	Medium	Grid build speed is governed by refining and fabrication capacity
Lithium-bearing minerals	Lithium carbonate / hydroxide	EV batteries, grid-scale storage	Medium	**Chemical conversion:** China ~60–65%	3–6 years	Medium	Conversion, not mining, determines battery supply
Nickel ores	Class 1 nickel, nickel sulphate	Battery cathodes, energy alloys	High	**Battery-grade refining:** China + Indonesia ~65–70%	4–7 years	Low–Medium	EV scaling depends on battery-grade nickel availability
Cobalt ores	Cobalt sulphate	Battery cathodes	Medium	**Chemical refining:** China ~70–75%	3–5 years	Low	Downstream concentration creates single-point failure risk
Graphite (natural & synthetic)	Battery-grade graphite (anodes)	EV and storage batteries	High	**Purification & shaping:** China ~85–90%	2–4 years	Low	Processing dominance captures most value
Rare earth minerals	Rare earth oxides → rare earth metals (NdPr)	Wind turbines, EV motors, generators	High	**Separation & metallisation:** China ~85–90%	5–10 years	Very low	Separation is the strategic choke point
Iron ore	Steel (plate, beam, rebar)	Wind towers, transmission, foundations	Very high	**Steelmaking:** China ~55%, Japan & South Korea significant	5–10 years	Low	Infrastructure scale depends on steelmaking capacity
Bauxite	Alumina → aluminium metal	Solar frames, transmission, lightweight structures	Very high	**Smelting:** China ~58%; West Asia (Saudi Arabia, UAE, Oman, Bahrain, Qatar) ~10–12%	5–8 years	Low	Smelting follows cheap, reliable power
Silica (quartz)	Silicon → polysilicon	Solar PV, semiconductors	High	**Silicon metal:** China ~65–70% Polysilicon: China ~70–75% Solar-grade: China ~80%+	3–6 years	Low–Medium	Solar supply chains hinge on high-purity processing
Manganese ores	Manganese sulphate	Battery cathodes, steel alloys	Medium	**Battery-grade refining:** China ~90%	3–5 years	Low	Battery-grade capacity is scarce and concentrated

TABLE 2 : DOWNSTREAM PROCESSING CHARACTERISTICS OF CRITICAL MINERALS, IEA 2025[39]

Table 2 illustrates how downstream conversion concentrates both control and value. Across copper, lithium, nickel, cobalt, graphite, rare earths, aluminium, steel, and silicon, dominant processing shares frequently exceed 60-80% in a single country or tightly linked group of countries[38]. Typical lead times to establish new refining or conversion capacity range from three to ten years, even where technologies are mature, reflecting energy-infrastructure requirements[39].

[38] International Energy Agency (IEA) (2025) Change in refined copper, lithium, nickel, cobalt, graphite and rare earths production by country, 2020–2024. Paris: IEA. Available at: https://www.iea.org/data-and-statistics/charts/change-in-refined-copper-lithium-nickel-cobalt-graphite-and-rare-earths-production-by-country-2020-2024; Ernst & Young (EY) (2024) Critical raw materials for the energy transition – how to achieve the targets? EY CESA Energy Center. https://www.ey.com/en_gl/insights/energy-resources/critical-raw-materials-for-the-energy-transition; Goldman Sachs Global Institute (2023) Resource realism: The geopolitics of critical mineral supply chains. Goldman Sachs, 13 September. Available at: https://www.goldmansachs.com/insights/articles/resource-realism-the-geopolitics-of-critical-mineral-supply-chains [39] U.S. Energy Information Administration (EIA) (2025), China dominates global trade of battery minerals, 21 May 2025, available at: https://www.eia.gov/todayinenergy/detail.php?id=65305; International Renewable Energy Agency (IRENA) (2025), Geopolitics of the Energy Transition: Critical Materials, available at: https://www.irena.org/Digital-Report/Geopolitics-of-the-Energy-Transition-Critical-Materials

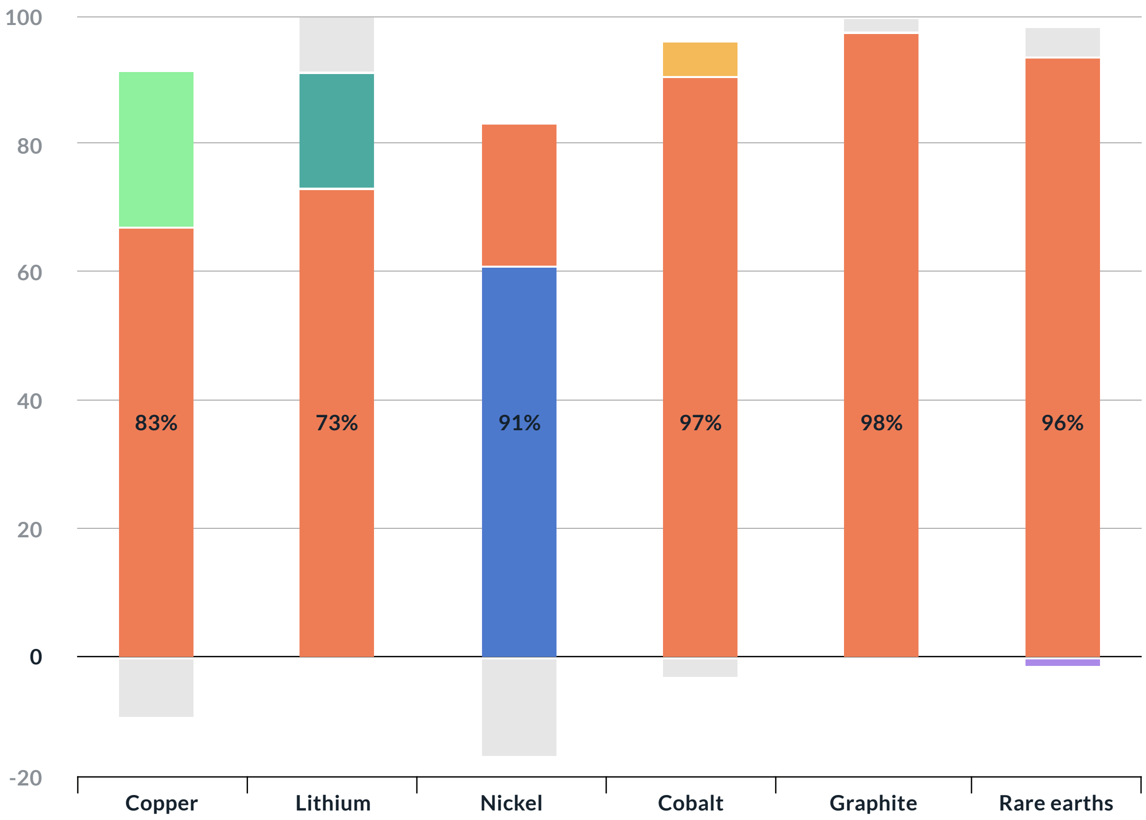

FIGURE 3: CHANGE IN REFINED COPPER, LITHIUM, NICKEL, COBALT, GRAPHITE AND RARE EARTHS PRODUCTION BY COUNTRY, 2020-2024[40]

The physical materialness and dependencies make relocation potential limited. High-energy processes such as aluminium smelting[41], polysilicon purification[42], and rare earth metallisation[43] follows power availability rather than mineral endowment. Once facilities are built, replication elsewhere creates lag and capital-churn, reinforcing downstream bottlenecks as durable features of the system rather than temporary frictions.

MATERIAL INTENSITY OF ENERGY INFRASTRUCTURE TECHNOLOGIES					
Technology	Steel (t/MW)	Copper (t/MW)	Aluminium (t/MW)	Critical Minerals (t/MW)	Other Material Notes
Onshore Wind	~110–120 (structural)*	~2.9 (wiring/generators)	~3–5	**~10**	Includes tower & hub components (smenet.org)
Offshore Wind	~150+ (structural)*	~8.0	~5–10	~15.5	Larger foundations, subsea cabling (TM Partners Group)
Solar PV	n/a (module frame)	~5.5	~8–13 (frame)	~6.8	Panels: glass ~70 % of mass (Anern)
Grid Infrastructure	-	-	-	n/a	Cumulative metal demand in tens of Mt globally (PMC)

FIGURE 4 : MATERIAL INTENSITY OF ENERGY INFRASTRUCTURE TECHNOLOGIES

[40] International Energy Agency (IEA) (2025) Change in refined copper, lithium, nickel, cobalt, graphite and rare earths production by country, 2020–2024 [41] World Economic Forum (2023) Net-Zero Industry Tracker 2023: Aluminium industry net-zero tracker. World Economic Forum. Available at: https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/aluminium-industry-net-zero-tracker/; International Energy Agency (IEA) (2023) Aluminium [42] International Energy Agency (2022) Solar PV global supply chains: Executive summary. Paris: IEA. [43] Rzad, M. (2026) Market concentration of rare earth elements: China's dominance and the global response. Michigan Journal of Economics, 9 January. Available at: https://sites.lsa.umich.edu/mje/2026/01/09/market-concentration-of-rare-earth-elements-chinas-dominance-and-the-global-response/; International Energy Agency (2025) With new export controls on critical minerals, supply concentration risks become reality. IEA Commentary, 23 October. Paris: IEA. Available at:https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality

*(Note: Steel for wind is implicit from turbine structural mass data; specific ratios vary by design.)

Material intensity data reinforces why downstream capacity has become decisive. Renewable and electrified energy systems embed large volumes of processed materials at the point of construction. Wind, solar, storage, and transmission infrastructure require substantial quantities of steel, copper, aluminium, alongside smaller but strategically critical volumes of rare earths, battery minerals, and high-purity silicon[44].

Across technologies, copper intensity provides a useful benchmark for material demand. Renewable energy systems typically require four to six times more copper per megawatt than conventional thermal power generation, reflecting extensive cabling, power electronics, and grid integration requirements. This reflects the shift from fuel-centric systems to electricity-centric systems, rather than an increase in total lifecycle resource dependence[45].

A single utility-scale onshore wind turbine illustrates this intensity. A modern 3 MW turbine typically requires approximately 300-350 tonnes of steel, 4-5 tonnes of copper, 2-3 tonnes of aluminium, up to 2 tonnes of rare earth elements, and more than 1,000 tonnes of concrete for foundations[46]. Offshore wind installations are even more material-intensive due to larger turbine sizes, subsea cabling, and reinforced foundations, with critical mineral requirements estimated at ~15.5 tonnes per MW, compared with ~10 tonnes per MW for onshore wind[47].

Solar photovoltaic (PV) systems similarly embody large material inputs. Crystalline silicon PV modules consist predominantly of glass, accounting for approximately 70-76 % of module mass[48]. At the system level, utility-scale solar installations are estimated to require ~6.8 tonnes of critical minerals per MW of installed capacity[49].

Material demand extends beyond generation assets to the broader electricity system. Transmission and distribution expansion requires 27-81 million tonnes of copper, 20-67 million tonnes of steel, and 11-31 million tonnes of aluminium globally over the course of the energy transition, depending on deployment pathways and grid architectures[50]. Even digital layers - including grid management systems, data centres, and AI-enabled optimisation - rely on mineral- and energy-intensive hardware, reinforcing the material nature of modern energy systems[51].
Together, these figures highlight a structural reality: decarbonisation is a large-scale material transformation[52]. The pace, cost, and feasibility of infrastructure deployment is inextricably linked from the resilience of the mineral supply chains structurally integrated within these systems.

CAPITAL IMPLICATIONS ACROSS THE VALUE CHAIN

From a capital perspective, the upstream-downstream distinction clarifies where execution risk now resides. While upstream mining requires substantial investment and long development timelines, downstream conversion is more acutely capital- and energy-constrained. The International Energy Agency estimates that US$500-600 billion in cumulative investment will be required in mining between 2023 and 2040 to support the energy transition[53].

By contrast, BloombergNEF's tracking shows that the downstream buildout is already absorbing very large annual capital flows: US$483bn went into grids in 2025, and a further US$127bn into clean-energy supply chains (including factories and battery-metals processing assets[54].

Individual downstream facilities typically require significant upfront capital while relying on sustained access to low-cost power over long development and commissioning timelines. In this environment, returns increasingly accrue to those able to finance, sequence, and operate physical systems across constrained value chains. Capital structure, execution capability, and access to energy and processing infrastructure are therefore central determinants of investment outcomes[55].

SYSTEM PRESSURES AND STRUCTURAL FRICTIONS

Stress within mineral and materials systems has become increasingly visible[56].These pressures are a predictable outcome of attempting to scale capital-intensive, energy-dependent supply chains at unprecedented speed. The system is adapting, but incrementally and unevenly[57].

System Pressures

Processing concentration remains the most acute source of vulnerability. While mineral reserves are geographically dispersed, downstream conversion

[44] Graedel, T.E. et al. (2015) 'Criticality of metals and metalloids; World Bank (2023) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.
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capacity is heavily clustered. Criticality assessments consistently show that supply risk increases materially once processing and refining stages are considered, often exceeding the concentration observed at the mining stage itself[58]. This concentration limits redundancy, amplifies geopolitical exposure, and constrains the pace at which infrastructure can be deployed, even where upstream supply is available[59].

Energy intensity compounds this challenge. Many downstream processes are among the most energy-intensive industrial activities in the economy. Their economics depend on continuous access to low-cost, reliable power. This creates a consequential feedback loop in which the energy transition depends on industrial processes that are themselves constrained by energy availability.

Similarly, **coupled mineral–energy constraints** reinforce system rigidity. Processing capacity requires power; power infrastructure requires processed materials. This interdependence means that bottlenecks rarely resolve independently. Progress in one part of the system often shifts pressure elsewhere rather than eliminating it[60].

Long build timelines further limit responsiveness. New refining, smelting, and processing facilities typically require several years to permit, finance, construct, and commission. These timelines are slow relative to growth in electricity demand and electrification, and they do not compress meaningfully in response to price signals or policy ambition[61].

> "*US$500-600B* INVESTMENT WILL BE REQUIRED IN MINING BY 2040 TO *SUPPORT* THE ENERGY TRANSITION"
>
> *The International Energy Agency*

Emerging System Responses

The system response to these pressures is evolutionary, shaped by industrial timelines and capital requirements rather than rapid substitution[62].

Incremental diversification of processing capacity is underway, particularly in battery materials, aluminium, and rare earths. Governments and institutions are supporting new refining, smelting, and conversion facilities across Australia, North America, and parts of Europe and Southeast Asia[63]. The International Energy Agency estimates that cumulative investment of US$600-750 billion will be required globally for critical mineral processing and refining by 2040 under stated policy and net-zero scenarios[64]. Individual facilities typically require US$300 million to over US$1.5 billion in upfront capital and multi-year development[65]. As a result, diversification remains additive rather than substitutive: it reduces marginal concentration but does not displace incumbent capacity at scale in the near term.

Recycling and secondary supply are gaining importance, particularly for batteries and base metals. Secondary material flows offer lower energy intensity and reduced environmental footprint relative to primary extraction, and are increasingly integrated into industrial strategies for lithium, nickel, cobalt, copper, and aluminium[66].

The World Bank and OECD estimate that scaling recycling and secondary supply to a meaningful share of demand will require US$150-250 billion in cumulative global investment by 2040[67].However, volumes remain constrained by the existing stock of deployed infrastructure. Recycling can ease pressure over time, but it cannot supply the first wave of large-scale electrification, when material demand is front-loaded and end-of-life feedstock remains limited.

Platform-scale processing has emerged as a dominant investment strategy in response to execution risk[68]. Rather than single-asset projects, capital is increasingly directed toward integrated platforms that aggregate throughput across multiple sites, secure long-term offtake agreements, and justify co-investment across infrastructures.

BloombergNEF estimates that US$400-600 billion in cumulative capital will be required globally by 2040 for integrated processing, materials manufacturing, and conversion platforms linked to the energy transition[69]. These platforms improve execution certainty and attract infrastructure-style capital, but they remain capital-intensive, with multi-phase build-outs often exceeding US$1-5 billion and development timelines extending over a decade [70].

Co-location with power is increasingly shaping downstream investment decisions. Energy-intensive facilities such as aluminium smelters, polysilicon plants, battery-grade chemical conversion, and rare earth separation are increasingly sited where access to low-cost, reliable electricity can be secured, whether from renewables, hydro, or nuclear generation[71]. The IEA estimates that supporting energy-intensive industrial processing associated with the transition will require an additional US$300-500 billion in power generation and grid investment

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globally by 2040[72], embedded within broader electricity network expansion[73].While co-location improves operating economics and emissions profiles, it reinforces geographic clustering and limits the pace at which processing capacity can be relocated.

Capital Allocation and Execution Dynamics

Cumulatively, these responses demonstrate that adaptation is occurring, but within tight physical and financial bounds. Capital is flowing at scale, yet timelines remain long, concentration persists, and solutions relieve pressure incrementally rather than eliminating it. The transition's material systems are adjusting - but at industrial speed, not at the pace implied by demand growth. Capital is currently being deployed to relieve obstacles in a targeted and layered manner, reflecting the industrial and capital-intensive nature of the challenge.

Public capital and policy-backed finance are concentrated at the early stages of the value chain[74], where risk is highest and private capital is least responsive. This includes support for permitting, first-of-a-kind processing facilities, and conversion of assets through grants, concessional loans, export credit, loan guarantees, and long-term offtake agreements[75].

Private capital, by contrast, is flowing predominantly into downstream and midstream assets where throughput can be secured, access to low-cost power is reliable, and revenues can be contracted over long durations. Infrastructure funds, strategic corporates, and sovereign investors are increasingly targeting processing platforms, refining capacity, recycling facilities, and energy-intensive materials manufacturing, often through phased build-outs that allow capital to be committed progressively as execution risk declines[76].

Across the stack, capital structures have become more complex, combining equity, project finance, structured debt, and credit enhancement to manage high upfront costs and long development timelines typical of industrial assets. In this environment, barrier relief is driven by the ability to sequence capital with physical delivery milestones, and underwrite assets through construction and early operations- capabilities that increasingly differentiate outcomes across the transition economy.

OUTLOOK

As the energy transition progresses, Australia's role increasingly centres on execution capacity and capital coordination rather than rapid volume expansion. The focus is shifting toward aligning generation, transmission, storage, and energy-intensive industrial assets within coordinated development corridors [77], supported by long-dated access to power and infrastructure. This approach reflects the reality that material and energy systems scale through sequencing and integration, not acceleration alone.

From a capital perspective, this favours platform-style development over isolated asset deployment. Integrated approaches that combine upstream supply, processing capacity, energy infrastructure, and contracted offtake improve delivery certainty and reduce bottleneck risk across long investment cycles. In this context, Australia functions as a stable execution platform for large-scale transition infrastructure rather than a flexible marginal supplier responding to short-term demand signals.

éthica Capital & Green Bond Corporation Group

As the energy transition becomes increasingly defined by material constraints and execution risk, capital deployment is shifting toward assets and platforms capable of managing long development timelines, high upfront capital requirements, and interdependent infrastructure delivery. In constrained systems, value accrues to structures that align financing with physical sequencing rather than standalone asset exposure.

éthica Capital and Green Bond Corporation Group operate at the intersection of physical infrastructure and capital structuring across the transition economy. The group focuses on financing solutions that support execution-critical assets, including renewable generation, grid infrastructure, processing capacity, and energy-intensive industrial systems, where delivery risk and system integration materially influence outcomes.

The focus is on capital sequencing, platform finance and asset-backed structures that move projects from development through construction to operation, using equity, project finance, structured debt and contracted revenues aligned to delivery milestones.

éthica Capital, Carbon Capital Corporation & Green Bond Corporation form part of the Green Bond Corporation Group.

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