International Labour Organization

▶ ILO brief

ILO Brief

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Powering the future:
Critical energy transition minerals and the workforce of tomorrow

Key points

- **Demand for critical energy transition minerals (CETM) is increasing**: CETM underpin clean-energy technologies and infrastructure, including wind and solar photovoltaic power generation, green hydrogen production, electric vehicles, electricity grids and energy storage systems. The rapid expansion of renewable energy technologies is driving increased demand for minerals such as lithium, cobalt, copper, nickel and rare earth elements, leading to intensified global exploration and extraction activities.

- **There is considerable scope for industrial capacity upgrading in resource-rich countries**: While deposits of CETM are geographically widespread, extraction and processing remain highly concentrated. At the same time, there are significant opportunities for international cooperation, including technology transfer, industry stakeholders' engagement, skills development programmes and capacity-building for resource-rich countries, including training of trainers.

- **CETM skills gaps must be urgently addressed**: Rapid technological change, the outward migration of skilled workers and the perceived unattractiveness of the mining sector continue to undermine the ability of resource-rich countries to build the skilled workforce needed across CETM value chains. National CETM frameworks should include explicit skills pillars and strengthen CETM-specific skills, while linking training programmes to national development goals.

- **Alignment of CETM workforce planning with occupational and skills shifts is increasingly important**: Value chain analysis across upstream, midstream and downstream segments shows rapidly growing skills demand at all skill levels. Given the rapid growth in demand for CETM and ongoing technological change, skills intelligence, focusing on CETM-specific needs, should be generated on a continuous basis to inform the development and implementation of curricula, training programmes and qualification and certification frameworks.

- **CETM skills ecosystem should be strengthened to promote employability, decent work and local value addition through social dialogue**: Governments, social partners, training institutions and industry stakeholders should co-design and implement relevant curricula and competency standards; promote work-based learning and quality apprenticeships and recognition of prior learning and other supporting employability measures while facilitating the transition to formality of workers, including artisanal and small-scale mining workers; design targeted programmes for women and young people; organise campaigns to raise awareness of opportunities in the CETM sector; and leverage South–South and triangular cooperation to facilitate technology and skills transfer.

▶ 1. Introduction

Critical energy transition minerals (CETM),[1] which include copper, cobalt, nickel, lithium, graphite, rare earth elements and other minerals, are key inputs for rapidly expanding clean-energy technologies and infrastructure, including wind turbines, solar photovoltaic panels, electric vehicles and battery storage systems. As the world shifts from its dependence on fossil fuels to cleaner energy in pursuit of the goal of net zero carbon emissions by 2050, demand for CETM is likely to almost triple by 2030 and quadruple by 2040 (UN 2024).

While this rising demand is closely linked to their economic and strategic role in defence, aerospace, electronics and digital technologies and in enabling the energy transition, it also underscores a broader opportunity to address the environmental challenges associated with mineral extraction and processing. Land degradation, significant water use, biodiversity loss and the generation of waste through mining and refining activities are becoming central concerns across many countries, while global biodiversity instruments increasingly call for the adoption of nature-positive mining practices. For the mining industry, these environmental imperatives are emerging not only as sustainability priorities but also as important compliance considerations.

At the same time, if not properly managed, rising demand for CETM could reinforce commodity dependence, intensify geopolitical tensions and exacerbate environmental and social challenges. Those challenges include adverse effects on livelihoods, ecosystems, public health, and human rights, potentially undermining progress towards a sustainable energy transition. In this context, adopting nature-positive and environmentally responsible mining practices is essential to ensure that the expansion of CETM supports environmental objectives, economic diversification and social inclusion goals.

As the extraction of CETM accelerates to meet the demands of the global energy transition, it is vital to make sure that resource-rich countries and local communities benefit fully from the expansion of the CETM sector. In addition to renewable energy deployment, the adoption of clean energy and energy efficiency solutions, and other climate change mitigation efforts, mineral-rich countries should prioritize adaptation needs, such as climate-resilient infrastructure and services, taking into account country-specific vulnerabilities. The expanding market for CETM should not only be viewed as an entry point into clean-energy value chains, but also as a broader opportunity to catalyse structural transformation, expand access to energy and advance just transition that promote social justice and decent work.

By leveraging CETM value chains, countries can build or strengthen their domestic manufacturing capacity, expand industrial applications beyond renewable energy technologies and support more diversified and resilient economic growth. Such transitions have the potential to generate quality employment, support the development of new industries and create demand for a wide range of skills. In this sense, the production of CETM resources can support the achievement of both global climate goals and national development priorities, including poverty reduction and improved access to modern, sustainable and affordable energy (IRENA 2023; UN 2024).

The Principles to Guide Critical Energy Transition Minerals towards Equity and Justice, set out in the report of the Secretary-General's Panel on Critical Energy Transition Minerals, highlight the importance of expanding the skills base in mineral-producing countries (UN 2024). Against that backdrop, the aim of this policy brief is to identify the occupational and skills shifts likely to arise from the transition to cleaner energy across each segment of the CETM value chain and to outline the implications of that transition for skills development policies and programmes.

[1] In this brief, CETM refer to the minerals necessary to construct, produce, distribute and store renewable energy. They include the copper, cobalt, nickel, lithium, graphite, rare earth elements and aluminium required for electric vehicles and battery storage; the silicon, cadmium, tellurium and selenium (to name a few) that build solar panels. In addition, wind power requires copper. Hydropower also uses copper, and chromium, zinc and more aluminium (UN 2024).

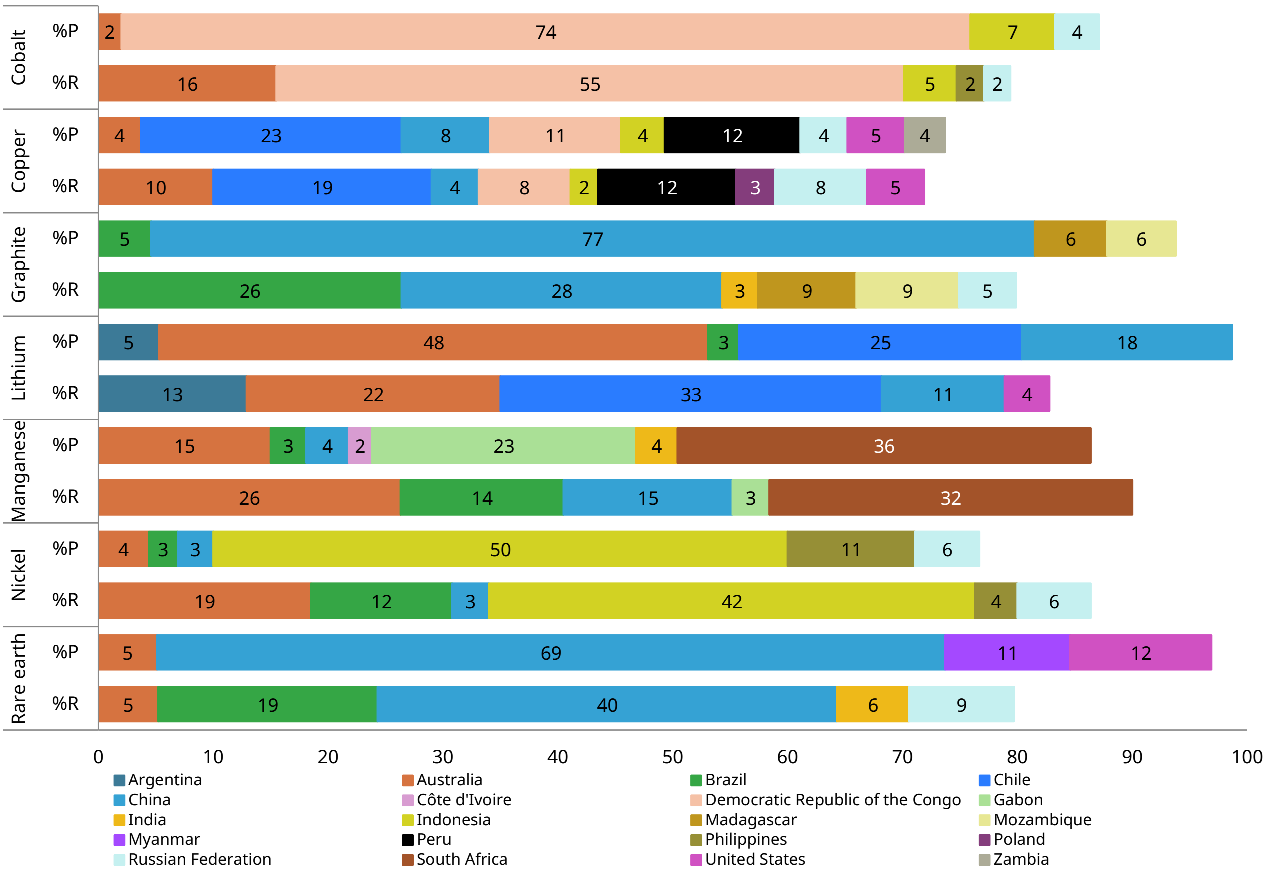
▶ 2. CETM and their role in the energy transition

2.1. Main global producers of CETM

Global CETM reserves are relatively evenly distributed, with geological deposits widespread and not characterized by scarcity (IRENA 2023). However, countries holding the largest reserves are often not those leading extraction, processing or refining. Bolivia, for example, holds one of the world's largest lithium resources, estimated at approximately 23 million metric tons (USGS 2024), yet produced less than 1 per cent of global supply in 2021 (Idoine et al. 2023).

As illustrated in figure 1, there is a marked disparity between the geographical distribution of reserves (%R) and production (%P) across critical energy transition minerals. While reserves are often more widely spread across countries, production tends to be highly concentrated in a small number of producers. For example, the mining of minerals used in battery production is particularly highly concentrated, with cobalt extraction led by the Democratic Republic of the Congo (around 74 per cent of global production), nickel production by Indonesia (around 50 per cent) and lithium production concentrated in Australia (48 per cent) and Chile (25 per cent) (USGS 2023, 2024; Gordon 2023). A similar pattern can be observed across other minerals, where a limited group of countries accounts for a disproportionate share of production.

▶ **Figure 1. Lead producers and reserve holders of critical energy transition minerals**



Note: %R = percentage of global reserves; %P = percentage of global production
Sources: USGS 2023, 2024; Gordon 2023.

Global refining and processing capacity is even more concentrated than mineral production, and the trend is that of further “concentration” rather than “diversification”. IEA analysis shows that the average market share of the top three countries for refining CETM increased from about 82 per cent in 2020 to 86 per cent in 2024. In some cases, single dominant producer drove this trend – Indonesia for nickel and China for cobalt, graphite and rare earths (IEA 2025a).

This global context highlights a fundamental disconnect between resource endowment and value capture. Structural barriers prevent many resource-rich countries from leveraging their mineral wealth for industrial development and job creation. While opportunities exist to diversify supply through untapped terrestrial deposits and deep-sea resources, these options are accompanied by regulatory uncertainty and environmental risks (IRENA 2023).

The organization of global CETM value chains, characterized by concentration of extraction, processing and refining among a small number of firms and countries creates significant challenges for developing economies (IEA 2025a; IRENA 2023; UN 2024). They face persistent constraints, including limited infrastructure, costly or unreliable energy systems, weak regulatory frameworks, and insufficient transport and logistics capacity (UN DESA 2025a). In addition, a lack of a robust domestic industrial base such as processing plants, refining operations and manufacturing facilities limits their ability to move up the value chain (UNCTAD 2026). As a result, these countries often remain confined to low-value segments of production, while higher-value activities such as refining, component manufacturing and technology development take place elsewhere (IRENA 2023; UN 2024).

These structural constraints have direct implications for employment. Many developing resource-rich economies often experience high unemployment and widespread informal work, particularly among low-skilled workers (IISD 2025). Informality is especially prevalent in artisanal and small-scale mining, where workers face unsafe conditions, low pay, limited access to social protection and significant occupational hazards (ILO 2026). Gender inequalities further exacerbate these challenges: women are disproportionately concentrated in the most precarious segments of mining while remaining underrepresented in technical and leadership roles (ILO 2026; IISD 2023).

At the same time, rapid technological change, including automation, digitalization and advanced processing techniques is reshaping skill requirements in the mining sector. Without adequate investment in training, reskilling and labour protections, workers risk exclusion from emerging opportunities (IISD 2025). Existing opportunities for upskilling and reskilling remain limited and require coordinated investment alongside efforts to create new employment pathways both within mining-related activities and in more diversified sectors.

Addressing these interconnected challenges requires integrated strategies that combine skills development with coherent industrial policies, environmental regulation, enterprise development and social dialogue. Resource-rich countries must adopt coordinated approaches to formalize artisanal mining, reduce gender disparities, strengthen occupational safety and health systems, and anticipate evolving skills needs. At the same time, value chain upgrading must align with environmental safeguards, including nature-positive mining practices that minimize land degradation, water stress, biodiversity loss and waste impacts.

Ultimately, the expansion of CETM supply chains will contribute to sustainable development only if it supports decent work, strengthens domestic industrial capacity, and enables more equitable and resilient participation of resource-rich countries in global value chains.

2.2. Current and projected global demand for CETM

The rapid expansion of renewable energy systems, alongside the electrification of transport and industry, is reshaping global demand for CETM. Achieving global net-zero emissions by 2050 will depend not only on scaling up such technologies as batteries, solar photovoltaic panels and wind turbines, but also on securing the large quantities of CETM that underpin those technologies. Understanding current and projected demand for those minerals is therefore essential if stakeholders are to anticipate shifts in supply, demand and prices, investment needs and associated socio-economic implications across mineral value chains.

The global stock of electric light-duty vehicles is expected to reach 245 million by 2030 (IEA 2024a), driving a significant increase in demand for key battery minerals, including graphite, lithium, cobalt, copper, phosphorus, manganese and nickel. Current electric vehicles require substantial quantities of energy transition minerals. An electric vehicle uses around six times more mineral inputs than a conventional internal combustion engine (IEA 2021). By 2030, electric vehicles are expected to account for between 78 and 85 per cent of global lithium demand, up from approximately 62 per cent in 2022 (IRENA 2024a).

While batteries are expected to play an increasingly central role in the transport sector by powering electric vehicles, they also support the deployment of wind and solar energy technologies. In the IEA Net Zero Emission by 2050 scenario, global energy storage capacity needs to increase sixfold by 2030, reaching 1,500 gigawatts, with batteries accounting for about 90 per cent of the increase, and battery storage reaching around 1,200 gigawatts (IEA 2024b).

Global solar photovoltaic energy generation capacity has expanded rapidly as a result of falling costs and strong policy support, making it one of the most cost-effective energy technologies worldwide. Solar photovoltaic technologies accounted for just over 5 per cent of global electricity generation in 2023-24, but that share is expected to rise to approximately 17 per cent by 2030, positioning the solar photovoltaic sector as a key contributor to achieving the renewable energy targets agreed at the twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) (IEA 2024c). That expansion is expected to drive increased demand for key minerals, including copper and aluminium.

The continued expansion of onshore and offshore wind energy is also driving rising demand for important minerals, including copper, zinc and rare earth elements. Onshore wind plant, for example, require around 9 times more minerals than gas-fired power plants of comparable capacity (IEA 2021). Under the IRENA 1.5 °C Scenario,[2] renewables could account for some 91 per cent of global electricity generation by 2050, with solar photovoltaic and wind contributing around 70 per cent of the total (IRENA 2024b).

In 2024, global wind power generation capacity reached a cumulative total of 1,133 gigawatts (IRENA 2026). While onshore installations set a new record, the offshore pace was far slower than in the previous four years. Growth in offshore wind power generation is constrained by high material costs, permitting delays, policy uncertainty and supply chain challenges (IRENA 2024b). Overall, annual growth rate of total installation (onshore and offshore) between 2020 and 2025 stood at around 12 per cent (GWEC 2026).

At the same time, turbine designs have evolved, with larger turbines featuring taller towers and lighter drivetrains contributing to higher capacity factors, which increased from around 27 per cent in 2010 to some 34 per cent in 2018. Those efficiency gains can result in higher energy output per unit of installed capacity, thereby reducing the mineral intensity of such key materials as copper, zinc and rare earth elements over time (IEA 2021).

Overall, projected demand for CETM is expected to increase across all major renewable energy and electrification technologies, although the pace and scale of that growth remain uncertain. Key sources of uncertainty include policy choices, the commercial viability of mineral deposits, the development of alternative technology pathways and the expansion of recycling within a circular economy framework. For example, advances in battery technologies suggest that future demand for lithium, cobalt and nickel could shift, as alternative battery chemistries are developed and deployed (IRENA 2023). Such technological changes would have implications for countries that currently produce those minerals.

At the same time, the concentration of raw material supply and processing presents systemic risks across clean-energy value chains. Heavy reliance on a limited number of producer and processor countries increases vulnerability to supply disruptions, price volatility and geopolitical tensions (Energy Transitions Commission 2023; IRENA 2023). Geopolitical factors further intensify uncertainty by generating competition over access to and control of critical minerals, making supply chains increasingly contested and raising the risk of higher costs and delays in the energy transition (IRENA 2023; IEA 2025a).

These evolving dynamics present both risks and opportunities for resource-rich countries. On the one hand, they create opportunities to capture greater value and broader development benefits through local processing, manufacturing and

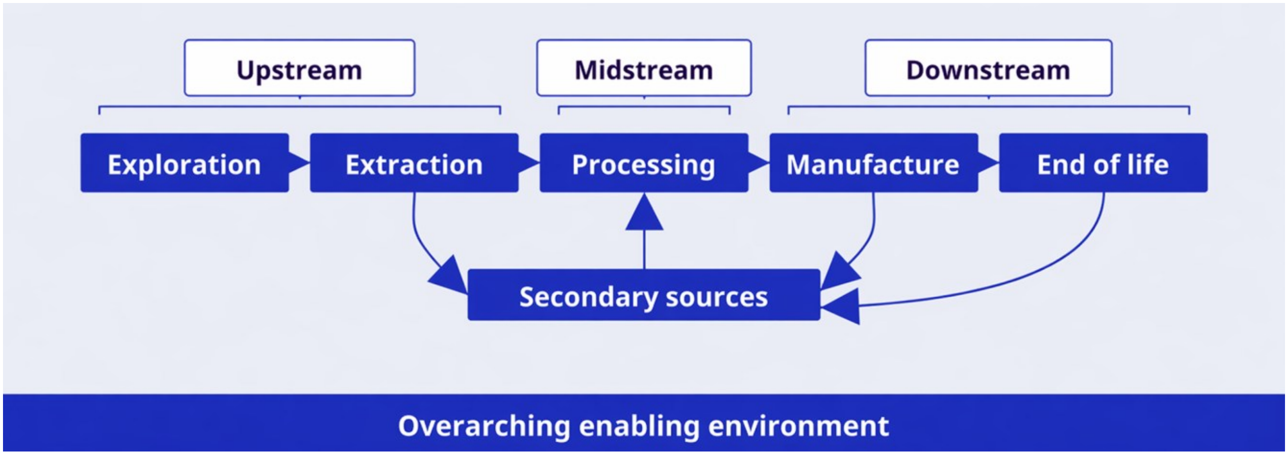
[2] The 1.5 °C scenario outlines a pathway consistent with limiting the increase in global average temperatures to 1.5 °C by 2050. It identifies electrification and energy efficiency as key drivers of the transition, supported by the large-scale deployment of renewable energy, clean hydrogen and sustainable biomass (IRENA 2024b).

green industrialization. On the other hand, they expose countries to heightened risks associated with market volatility, political pressures and technological displacement, which may result in uneven distribution of development benefits. Occupational changes and skills needs will be shaped to a large extent by the policy choices that countries make throughout this transition.

3. Occupations and skills demand: Who is needed in the CETM sector?

To assess occupational and skills needs in the CETM sector, an analysis was conducted from a value chain perspective. Figure 2 presents a structured representation of the CETM value chain, organized into three main segments—upstream, midstream and downstream—alongside those related to the overarching enabling environment. The upstream segment comprises exploration and extraction which are typically labour-intensive. The midstream segment focuses on processing, where raw materials are transformed into refined inputs suitable for industrial use. The downstream segment includes manufacturing and end-of-life management. A distinctive feature of the value chain illustrated is the role of secondary sources, which are integrated across multiple stages. Materials recovered from end-of-life products and manufacturing processes are reintroduced into the processing stage, highlighting the growing importance of circular economy practices and their implications for emerging occupations in recycling, refurbishment and resource recovery. The entire value chain is embedded within an overarching enabling environment, which supports all stages. This includes regulatory frameworks, research and development, finance and procurement, among others. These cross-cutting elements shape how effectively the value chain operates. The analysis of this section identifies key activities, occupations and skills required across each segment of the value chain, as well as those related to the overarching enabling environment.

▶ **Figure 2. The CETM value chain**



Source: Author's elaboration on the basis of Institute of Materials, Minerals and Mining 2023

Table 1 provides an overview of key occupations across CETM value chains, drawing on a review of relevant literatures. Shifts in demand are anticipated for current occupations and emerging job roles across different value chain segments, reflecting the impact of clean energy technology deployment and increasing automation. Occupational change may also be driven by efforts to diversify local economies and to promote environmentally sustainable practices in mining and refining, including measures to address land degradation, water use, biodiversity loss and waste management. Changes in occupational profiles are likely to have significant implications for skills requirements throughout the value chain.

▶ Table 1. Overview of occupational needs across CETM value chains

Value chain segments		Occupations (Examples)
Core value chain segments	**Upstream**: Exploration and extraction	Exploration geologist, metallurgist, remote sensing specialist, mineral surveyor, geographic information system (GIS) analyst, field technician, geochemist, core logger, mapping specialist, environmental specialist, mineral economist, hydrogeologist, geotechnical engineer, exploration manager, mining engineer, geotechnical engineer, environmental engineer, electrical engineer, mechanical engineer, blasting engineer, maintenance technician, mine supervisor, drill and blast operator, heavy-duty equipment operator, surveyor, shift supervisor, process technician, transport and truck driver, automation engineer, data scientist, water treatment specialist, construction millwright, industrial mechanic, mine labourer, heavy-duty equipment mechanic, underground production and development miner, underground mine service and support worker, data scientist, software expert, data analyst, mechatronics engineer, systems engineer, systems integrator, cybersecurity specialists, mining robotics specialists, geological engineer, processing engineer, mine closure planning expert, water and waste management specialists.
	Midstream: Primary and secondary source processing	Metallurgical engineer, process technician, process operator, chemical engineer, hydrometallurgist, pyrometallurgist, quality control analyst, environmental engineer, environmental consultant, plant manager, plant supervisor, maintenance manager, maintenance technician, supply chain manager, regulatory compliance specialist, materials engineer, process control engineer, analytical chemist, energy efficiency specialist, water treatment engineer, mineral processing operator, mill operator, ore sorting operator.
	Downstream: Manufacturing and end-of-life circularity management	Metallurgist, materials engineer, manufacturing engineer, production supervisor, electrochemist, automation engineer, supply chain manager, quality control manager, process improvement specialist, industrial designer, packaging engineer, materials scientist, research and development engineer, formulation scientist, product manager, sales and marketing manager, process engineer, life cycle assessment practitioner, materials modeller, ecotoxicologist, battery production workers, electrical electronic and electromechanical assembler, chemical engineers, electronics engineers, recycling specialist, chemical engineer, chemist, waste management engineer, circular economy analyst, sustainability manager, quality control analyst, product stewardship manager, materials recovery technician, energy efficiency specialist, environmental consultant, data analyst.
Overarching enabling environment	**Regulations**	Mine overseer, regulatory compliance officer, planning and permitting officer, safety and environmental compliance manager, compliance auditor, safety and environmental compliance officer, quality control analyst, regulatory compliance specialist, regulatory compliance officer, environmental specialist, process control engineer, product specification specialist, environmental sustainability manager, occupational safety and health officer, quality assurance manager.
	Procurement and supply chains	Supply chain manager, logistics coordinator, reverse logistics coordinator.
	Research and development	Research and development scientist, product development engineer, electrical engineer, mechanical engineer, chemical engineer, systems engineer.
	Economics and finance	Mineral viability assessment specialist.
	Marketing	Technical writer, technical communicator, sales and marketing manager.
	Administration	Project manager, logistics coordinator, supervisor in mining and quarrying, manager in natural resources production and fishing
	Public awareness-raising and advocacy	Community engagement officer, technical writer, community mobilization specialist, public relations officer.

Sources: Institute of Materials, Minerals and Mining 2023; Mining Industry Human Resources Council 2023; Mining Industry Human Resources Council 2024; ILO 2019; Rogers et al. 2019; OECD 2025; Colato and Ice 2023.

3.1. Upstream: mineral exploration and extraction

The upstream segment of the CETM value chain encompasses both the identification and extraction of mineral deposits. Key activities include geological mapping, remote sensing, geophysical surveys, sampling, assaying and resource estimation. Those activities are followed by extraction processes, which typically involve operations such as drilling, excavation, blasting, cutting, rock hauling, the operation of heavy equipment, shaft equipping and tunnel development (Gaokgorwe 2023; Long et al. 2024). These operations make education and training in the areas of occupational safety and health, environmental management, risk assessment, as well as worker participation in prevention systems core requirements (ILO 2018).

As CETM mining expands, demand is increasing for low- and medium-skilled workers to support extraction activities, while workers in higher-skilled occupations are assuming an increasingly strategic role. Those workers include mining engineers, geologists, metallurgists, operations managers and environmental engineers, as well as specialists in mine closure, occupational safety and health and commodity management. The expansion of automation and sustainability-oriented practices is also generating demand for professionals from related engineering disciplines, including mechatronics, electrical engineering and software engineering (CSIRO 2023). In addition, the integration of data science, artificial intelligence and machine learning into mining workflows is creating demand for process automation specialists and digitally skilled technical mining workers (OECD 2025; Shimaponda-Nawa and Nwaila 2024).

Upskilling in geological mapping, remote sensing, geophysical techniques and mine rehabilitation is becoming increasingly important, particularly as some mines approach the end of their operational life cycles. At the same time, the expansion of automation and artificial intelligence may displace workers, especially in low- and medium-skilled roles. Tasks such as drilling, blasting and haulage, which together account for more than 70 per cent of typical mine operations, are particularly exposed to automation-related risks (Rogers et al. 2019), as are workers performing repetitive or physically demanding tasks, including administrative clerks, truck drivers and drill operators. Autonomous vehicles and intelligent systems are already being deployed at many mining sites (De Rose 2025).

Despite those disruptions, automation is also generating new opportunities, particularly in areas requiring advanced digital and cognitive skills. Emerging roles include supervisory and maintenance personnel, cybersecurity specialists, remote operations centre staff and mining robotics specialists (OECD 2025; Shimaponda-Nawa and Nwaila 2024). As the industry shifts from manual to increasingly digital modes of operation, the workforce will need to develop capabilities in programming, system oversight and real-time data analysis. Skills such as complex problem-solving, systems thinking and critical analysis are becoming increasingly important, particularly for working effectively in collaborative human–machine environments (CSIRO 2023; Hyder, Siau and Nah 2019; OECD 2025).

Automation in CETM mining not only addresses efficiency and safety concerns but can also help mitigate projected labour shortages in the context of expanding mining activity. For example, mining companies in Australia are already deploying autonomous haulage systems, automated drilling technologies and driverless trains in iron ore operations (CSIRO 2023; Hajkowicz et al. 2019; Rogers et al. 2019). Those developments reflect the emergence of what is known as Mining 4.0 (See Box 1), a new phase in the mining sector characterized by the integration of advanced digital technologies such as artificial intelligence, the Internet of Things, autonomous machinery, digital twins, machine learning and cyber-physical systems. If managed well, rather than eliminating human input, this paradigm could augment human capabilities by enabling machines to analyse large volumes of data and support engineers and operators in making timely and data-informed decisions (Zhironkin and Ezdina 2023).

▶ Box 1: Mining 4.0 and skills

Mining 4.0 refers to the digital and automated transformation of mining operations through the integration of advanced technologies such as robotics, artificial intelligence, sensors and data analytics. Examples include the use of autonomous haulage systems to transport ore without drivers and predictive maintenance tools that identify equipment faults before they lead to operational downtime. The adoption of those technologies is generating demand for new and evolving skill sets, including data analysis, equipment programming and digital monitoring. To benefit fully from Mining 4.0, workers require targeted training and reskilling to enable them to operate, supervise and maintain advanced machinery safely and efficiently. Ensuring that such skills development keeps pace with technological change is critical if productivity gains are to translate into higher-skilled, better-quality jobs.

Source: Zhironkin and Ezdina 2023.

As the mining sector integrates increasingly advanced technologies, the profile of the mining workforce is expected to evolve. Future mining jobs are likely to require a greater number of mechatronics specialists, software engineers and robotics technicians with the capacity to programme, maintain and enhance automated systems (CSIRO 2023; Long et al. 2024; OECD 2025; Zhironkin and Ezdina 2023).

3.2. Midstream: processing of primary and secondary mineral sources

The midstream segment covers the processing and refining stages through which extracted materials are transformed into products that meet specific quality, purity and technical specifications, such as the conversion of lithium ore into lithium carbonate or lithium hydroxide. Activities include the crushing and grinding of rock ores, as well as the evaporation or chemical extraction of brines. Value is added at this stage by converting raw mineral inputs into refined products with higher economic and industrial utility. In this context, an increasing number of mineral-producing countries are pursuing strategies to promote local beneficiation in order to capture greater value from their mineral resources.

Local beneficiation of CETM in the midstream segment has the potential to generate employment and increase demand for occupations such as hydrometallurgists, pyrometallurgists, quality control analysts, research and development scientists, environmental engineers, plant supervisors and supply chain managers. These occupations often require skill sets that extend beyond those associated with traditional mining activities, involving advanced chemical processing and materials engineering (Institute of Materials, Minerals and Mining 2023; UN DESA 2025b). As such skills are not always adequately developed through training programmes oriented towards traditional mining activities, acute skills shortages persist in many contexts (OECD 2025). Moreover, careers in midstream processing and refining tend to have lower visibility, while public awareness of their role in the mining industry is often limited, further constraining the development of a sufficiently skilled workforce (Institute of Materials, Minerals and Mining 2023).

In addition, and as noted earlier, many developing resource-rich countries currently lack the industrial capacity required for the manufacturing, processing and refining of CETM, which limits their participation in the midstream segment of the value chain (UNCTAD 2026). Local beneficiation strategies therefore require an integrated approach. Producer countries need coherent industrial policies and regulatory frameworks, reliable and affordable energy, water and transport infrastructure, permitting capacity, access to finance, technology partnerships, supplier development and environmental safeguards, together with skills development. Without those enabling conditions, training investments alone may not translate into midstream or downstream jobs (UN 2024).

3.3. Downstream: manufacturing and end-of-life circularity management

The downstream segment encompasses the manufacturing stages through which refined CETM are transformed into intermediate or final products. Activities in this segment include material formulation, chemical processing, shaping and forming, heat treatment, machining and fabrication, surface treatment and coating, assembly and integration, quality control and testing, as well as innovation, supply chain coordination and logistics (Institute of Materials, Minerals and Mining 2023). For example, lithium carbonate or lithium hydroxide is used in the production of battery components, including cathodes and electrolytes, which are assembled into battery cells and packs (Igogo et al. 2019) and subsequently integrated into final products such as electric vehicles and electronic devices for distribution and sale.

Expanding manufacturing and product development in the context of renewable energy technologies has become a policy priority in many countries. In South Africa, for example, the Just Energy Transition Implementation Plan 2023–2027, formulated in line with the South African Renewable Energy Masterplan, highlights the need to develop domestically-manufactured renewable energy and battery storage components. (South Africa, Presidency of the Republic 2023).

The manufacture of batteries and other components and final products that rely on CETM entails a shift from traditional mechanical production processes towards more complex electrochemical and high-technology manufacturing operations (Cotterman et al. 2024). Furthermore, rapid technological change across downstream industries is increasing demand for workers with advanced technical and digital skill sets. In the electric vehicle sector, for example, demand is rising for workers who can perform such tasks as the application of specialized technical knowledge to advanced manufacturing processes (ILO 2024).

The expansion of battery manufacturing and charging infrastructure is expected to increase demand for assemblers and technicians with computer and engineering expertise, as well as for workers skilled in designing, testing and managing automated tools and data-driven process control systems (ILO 2024; Bui and Slowik. 2025). Engineers and technicians specialized in internal combustion engines will require reskilling, while automotive assemblers will need to acquire competencies in electric vehicle-specific components and technologies, including battery production and software for vehicle automation (ILO 2024).

Recycling end-of-life products and downstream by-products will play an increasingly important role in feeding materials back into the midstream segment of the CETM value chain, helping to mitigate supply disruptions, support economic diversification and reduce environmental impacts (IEA 2024b). In the solar photovoltaic sector, the potential for developing circular value chains is particularly significant in countries and regions where renewable energy deployment has occurred at scale (IRENA and IEA-PVPS 2016). The importance of end-of-life management in the solar photovoltaic sector is expected to grow as increasing numbers of installations reach the end of their operational life (IRENA and IEA-PVPS 2016). Circularity requires operational tasks such as end-of-life collection, disassembly, sorting, panel transport, materials recovery, disposal and environmental compliance (IRENA and IEA-PVPS 2016).

▶ 4. Skills supply: What are the key challenges impeding the CETM skills supply?

Ensuring a robust talent pool and a reliable supply of skilled workers is essential to unlocking the full value of CETM in the transition to cleaner energy. The occupational and skills needs analysis presented in the previous section makes it clear that an adequate supply of workers capable of performing specialized and emerging tasks is required across the CETM value chain. However, the sector is facing increasingly severe skills shortages and gaps (OECD 2025). Skills development systems in many mineral-producing countries, particularly low- and middle-income countries, are not sufficiently equipped to meet current and emerging industry needs. As shown in table 2, the challenges in this area are manifold: some are specific to CETM, while others are common across the broader mining and energy sectors.

▶ Table 2. Main challenges facing skills development in the CETM sector

Challenge	Description
Specialized skills requirements and rapid technological change	Processing and refining techniques for CETM require specialized skills that are often not covered in traditional mining-related training programmes. In addition, the pace of technological change frequently outpaces curriculum review and development cycles, making it difficult for education and training programmes to keep pace with evolving skills needs in the CETM sector (Institute of Materials, Minerals and Mining 2023; OECD 2025).
Informality	Informality remains widespread in parts of CETM value chains, particularly in artisanal and small-scale mining (ILO 2026). Many artisanal and small-scale miners lack formal qualifications and rely on informal methods of skills development and transmission, including informal apprenticeships. The absence of formal certification and recognition of prior learning limits access to structured upskilling and reskilling opportunities.
Gender-based barriers	Gender disparities persist across the CETM sector, with women accounting for only around 15 per cent of mining workers globally (OECD 2025). The supply of female workers remains weak, with enrolment of women in mining-related education and training programmes consistently low or stagnant (Consejo de Competencias Mineras and Eleva 2023). Contributing factors include the lack of female role models, gender-based violence and harassment, and male-dominated workplace cultures (OECD 2025).
Outward migration of skilled workers	Trained professionals and recent graduates in developing resource-rich countries often seek employment opportunities abroad in search of higher wages and better working conditions, contributing to skills outflows. Rising global demand for CETM has intensified international competition for talent, with some higher-income countries introducing or considering targeted immigration pathways for CETM-related occupations (Tritt 2025).
Limited public awareness of opportunities and negative perceptions	The CETM sector, particularly exploration, extraction and end-of-life recovery, is often associated with negative environmental impacts, occupational safety and health risks and poor working conditions. Such perceptions are particularly prevalent among young people. (McKinsey & Company 2023; Australian Mining and Automotive Skills Alliance 2024; OECD 2025). At the same time, value-addition opportunities in midstream and downstream segments of CETM value chains remain poorly understood, with limited public awareness of the availability and potential uses of critical mineral resources (Institute of Materials, Minerals and Mining 2023).
Aligning workforce planning with investment and industrial policies	Aligning workforce planning with broader investment and industrial policies becomes a complex challenge. The timing and sequencing of skills development efforts must be carefully coordinated with infrastructure development, industrial expansion and market creation to ensure that training translates into real employment opportunities.

Circularity and recycling capacity gaps	End-of-life recovery of batteries, photovoltaic modules and other mineral-intensive products requires new skills in safe collection, transport, diagnostics, disassembly, sorting, materials recovery, quality assurance, environmental compliance and traceability (IRENA and IEA-PVPS 2016). Informal and unsafe recycling can create decent work deficits if formalization and OSH controls are absent (ILO 2025).

Source: Author's elaboration.

▶ 5. National CETM policies and skills development initiatives

While relatively few policies explicitly target skills development for the CETM sector, an emerging group of producer countries is beginning to embed skills, employment and inclusion objectives more systematically within their CETM strategies. National frameworks in Australia, Canada, India and South Africa increasingly link CETM supply security and value-addition objectives with dedicated skills components aimed at building skilled workforces across value chain segments. Those approaches often draw on established technical and vocational education and training and higher education programmes and strengthening CETM-specific skills intelligence. They also address gender gaps and the low attractiveness of mining careers among young people through targeted public awareness-raising initiatives.

▶ Table 3. Selected national CETM strategies: skills development initiatives and insights

Country	Strategy overview	Key skills development objectives	Insights for skills development
Australia	**Critical Minerals Strategy 2023-2030**: A federal strategy aimed at securing Australia's position as a major, high-value producer of critical minerals and downstream products.	• Establish a dedicated focus on building a skilled, diverse and growing workforce. • Deploy large-scale national skills programmes that can be leveraged to support the critical minerals sector. • Leverage Jobs and Skills Australia, a national government agency to provide independent, tripartite labour market and skills analysis relevant to mining, processing and manufacturing. • Advance gender equality objectives in clean energy and science, technology, engineering and mathematics, supported by workplace safety and cultural reforms to attract and retain women and First Nations workers.	• Skills shortages are treated as a systemic risk to critical minerals sector development, with responses deployed through coordinated, multi-level policy instruments. • There is an explicit focus on downstream battery and manufacturing industries, promoting skills development beyond upstream exploration and extraction. • Diversity, gender equality and engagement with First Nations communities are mainstreamed as part of efforts to address gender barriers and the low attractiveness of mining-related careers, particularly for women and young people. • Anticipatory skills intelligence is embedded within the critical minerals strategy to inform workforce planning and skills development
Canada	**Canadian Critical Minerals Strategy**: A national strategy aimed at securing critical mineral supply, promoting value-added processing, manufacturing and waste reduction, and supporting a just transition, with a strong emphasis on building a diverse workforce and prosperous communities.	• Leverage established federal programmes to train and reskill workers for employment in critical mineral value chains. • Forecast future skills needs in the critical minerals sector and use that analysis to inform skills development programmes. • Establish the Sustainable Jobs Training Fund and the Sustainable Jobs Secretariat to support workforce transitions in the critical minerals sector. • Mobilize the Youth Employment and Skills Strategy (YESS) and Canada Summer Jobs to provide young people with work experience relevant to critical minerals. • Increase the participation of women and other underrepresented groups in critical minerals-related occupations. • Promote partnerships to raise awareness of opportunities offered by CETM and encourage enrolment in education and training programmes relevant to critical minerals.	• Established national programmes are leveraged to reskill workers for the critical minerals sector, offering a useful model for countries whose technical and vocational education and training systems are not yet tailored to CETM-related skills needs. • A strong and explicit emphasis on Indigenous Peoples reflects the need to ensure that local communities benefit from critical mineral value chains. • The strategy directly addresses gender gaps as part of efforts to tackle the persistent male dominance of the sector. • Awareness raising about the opportunities offered by CETM represents a distinctive approach to addressing negative perceptions associated with the CETM sector.

India	**National Critical Mineral Mission (NCMM):** A national initiative under the Ministry of Mines aimed at securing the supply of 30 identified critical minerals, supporting domestic exploration and processing, and enabling clean energy deployment across solar, wind, electric vehicles and energy storage.	• Foster innovation, skills development and competitiveness across mineral exploration, extraction, beneficiation, processing and recycling. • Develop and introduce specialized modules on critical minerals within established degree programmes in mining, metallurgy and recycling technologies by 2026. • Establish skills development centres in collaboration with the Ministry of Skill Development and Entrepreneurship and provide dedicated funding. • Train and upskill approximately 10,000 individuals in critical minerals-related occupations by 2031. • Offer capacity-building programmes for other resource-rich countries.	• Skills targets are embedded within the broader national strategy to enhance the competitiveness of the critical minerals sector. • The skills development pillar is jointly steered by the Ministry of Mines and the Ministry of Skill Development and Entrepreneurship, providing a strong example of interministerial coordination. • Time-bound, quantitative targets for training and upskilling are embedded in the national framework. • International cooperation is explicitly envisaged through the provision of capacity-building programmes for other resource-rich countries, leveraging the national training infrastructure of India, including its industrial training institutes and universities.
South Africa	**Critical Minerals and Metals Strategy**: A national framework aimed at leveraging the country's mineral endowments to support green industrialization. The Strategy is structured around nine pillars, including Pillar III, entitled "Research and Development and building a Skilled Workforce".	• Align occupational demand with the supply of graduates from higher education institutions to ensure that skills profiles meet the needs of established and emerging critical minerals sectors. • Establish accredited education and training programmes, in cooperation with international institutions and training providers, to build skills related to energy storage technologies. • Introduce critical minerals workforce planning to develop a shared understanding of skills demand, gaps and future needs across the sector. • Prioritize government- and industry-led awareness initiatives to strengthen relations with host communities and improve understanding of the direct and indirect employment opportunities associated with critical minerals, including those linked to climate impact mitigation and industrial expansion.	• The Strategy articulates a value chain-wide skills vision that explicitly links critical minerals to batteries, fuel cells, electric vehicles and titanium-based aerospace components, extending skills development beyond upstream extraction to midstream and downstream segments. • The adoption of a "multiple helix" approach, bringing together universities, technical and vocational education and training institutions, industry and government, directly addresses curriculum misalignment and increases the availability of up-to-date training programmes for the critical minerals sector. • A strong emphasis on community engagement reflects efforts to respond to challenges faced by local communities and to strengthen local participation in CETM value chains.

Sources: Australia, Department of Industry, Science and Resources 2023; Canada, Natural Resources Canada 2022; India, Ministry of Mines 2025; South Africa, Department of Mineral and Petroleum Resources 2025.

Governments, in collaboration with social partners, are beginning to implement targeted skills measures in support of CETM strategies. In Australia, the Critical Minerals Strategy 2023–2030 is being implemented through large-scale national initiatives such as the Apprenticeships Incentive System and New Energy Apprenticeship and Skills Programmes, complemented by state-level skills plans that promote science, technology, engineering and mathematics and the provision of tailored training related to critical minerals. In Canada, the Canadian Critical Minerals Strategy leverages a wide range of federal instruments, including the Sectoral Workforce Solutions Program, the Indigenous Skills and Employment Training Program and the Youth Employment and Skills Strategy, as well as Canada Summer Jobs and partnerships with provincial governments, Indigenous organizations, universities and colleges. In India, the skills pillar of the National Critical Mineral Mission is being operationalized through the establishment of skills development centres, the integration of critical minerals modules into established mining, metallurgy and recycling programmes, with time-bound targets to train and upskill 10,000 individuals by 2031, alongside international cooperation aimed at providing capacity-building support for other resource-rich countries.

In Latin America, countries with large reserves of minerals such as copper and lithium are now modernizing their mining education and training programmes in order to support emerging job roles across CETM value chains. In Chile, for example, the Eleva initiative, implemented in coordination with the Mining Skills Council, is focused on reviewing and updating curricula in technical secondary schools and training institutions, with the aim of ensuring that training programmes reflect current technologies and industry practices. A core component of the Eleva initiative is work-based learning, under which students participate in structured workplace training based on the Eleva–Mining Skills Council work practices model, delivered in collaboration with leading mining companies (Fundación Chile, n.d.). In Bolivia, policy efforts have focused on the development of advanced skills related to lithium-based battery technologies, including through international cooperation initiatives, such as a partnership with an institute of higher education in the United Kingdom (University of Warwick 2023).

In Southeast Asia, Indonesia is scaling up skills development programmes to support domestic processing of nickel, which is used in the production of stainless steel and in certain lithium-ion battery technologies. In 2017, the Ministry of Industry established a polytechnic to provide young people with the training they require to assume technical roles in nearby smelters and battery precursor plants. The curriculum is structured around a strong practical component, with 60 per cent of training delivered through hands-on learning, following a "4+2" model under which students spend four semesters on campus and two semesters in industry internships at metallurgical facilities (Swisscontact 2024).

▶ 6. Conclusions and recommendations

The transition towards cleaner energy is driving rising demand for CETM, which are indispensable for the development and deployment of clean-energy technologies. The expansion of CETM markets presents important opportunities for resource-rich countries to foster economic growth and industrial development. At the same time, it poses significant challenges, including the risk of over-reliance on commodity exports, environmental pressures, informality, gender inequality and persistent decent work deficits. Skills development is a key enabler of industrial capacity-building, supporting the effective participation of resource-rich countries in CETM value chains and facilitating a more equitable sharing of gains from the energy transition. However, in many resource-rich developing countries, skills development systems remain constrained by a range of structural challenges. These challenges include: weak alignment between traditional mining curricula and CETM industry needs, limited and unequal access to training opportunities, persistent gender-based barriers, outward migration of skilled workers, and limited public awareness of employment opportunities alongside negative perceptions of CETM-related activities, OSH-related risks, low capacity to promote circularity of CETM value chains, among others. To address these challenges, this policy brief puts forward the following recommendations:

- **Integrate CETM skills development into industrial strategies**: Emerging experience of countries reviewed for this brief suggests that several countries already recognize a strong synergy between national strategies aimed at strengthening industrial capacity in the CETM sector and skills development policies. Skills strategies should be linked to the conditions required for local beneficiation and industrial upgrading. Embedding skills development as a dedicated pillar within CETM strategies is a step forward in facilitating interministerial coordination among ministries responsible for mines and energy, employment, and technical and vocational education and training, while also engaging social partners and stakeholders from industry through structured initiatives. Tripartite arrangements, such as mining sector skills councils, as well as dedicated task forces on CETM sector development, should be leveraged as platforms for social dialogue to promote policy coherence and coordinated implementation.

- **Build dedicated and robust skills intelligence for the CETM sector**: In the context of rapidly evolving occupational and skills requirements and accelerating technological change in the CETM sector, there is an urgent need to establish robust labour market information systems for generating forward-looking skills intelligence. Such intelligence is essential to inform reforms of education and training systems from a forward-looking perspective. CETM sector-specific skills foresight should be developed in line with national CETM strategies, technology pathways and investment plans. Active industry engagement, supported by dedicated institutional mechanisms such as sector skills councils, should play a central role in the generation of timely, detailed and relevant skills intelligence, and the translation of such intelligence into practical outputs to inform policies and programmes.

- **Align education and training programmes with the skills needs along CETM value chains**: Many traditional mining education and training programmes often struggle to adequately develop the specialized skills required in the CETM sector, particularly in the midstream (processing) and downstream (manufacturing and end-of-life) segments. That misalignment constitutes a major bottleneck for many resource-rich countries that have established mining training systems but lack programmes tailored to the specific requirements of CETM value chains. Technical and vocational education and training and higher education authorities should therefore review, update and, where necessary, develop new occupational and competency standards, curricula, and quality apprenticeships and other forms of work-based learning, in close partnership with social partners and industry stakeholders, and in line with national CETM strategies and the international labour standards, including the Human Resources Development Convention, 1975 (No. 142) (ILO 1975), the Human Resources Development Recommendation, 2004 (No. 195) (ILO 2004) and the Quality Apprenticeships Recommendation, 2023 (No. 208) (ILO 2023).

- **Promote gender equality and social inclusion**: Persistent gender gaps and limited access to formal training and social protection for informal workers, including artisanal and small-scale miners and informal recycling workers, remain major challenges that continue to undermine the potential of CETM to contribute to a just energy transition. Skills strategies and initiatives related to CETM should explicitly promote the participation, retention and progression of women, young people, informal workers and other groups of people in vulnerable situations through targeted measures. These should include dedicated training programmes for women and underrepresented groups; recognition of prior learning for artisanal and small-scale mining and recycling workers; childcare, maternity and parental protection; safe transport and prevention of violence and harassment; accessible training facilities; income support, unemployment protection and paid training time during reskilling; and measures to extend social insurance and labour protection to informal and newly formalized workers, among others. Active labour market policies, skills development, job placement services and social protection should be designed and implemented together through social dialogue so that workers can transition into emerging CETM occupations without losing income security, care protections or access to essential health services.
- **Put skills for Occupational Safety and Health at the centre**: Embed occupational safety and health competence across CETM training programmes. CETM skills programmes should include modules on hazard identification, risk assessment, emergency response, worker participation in OSH systems, aligned with the Safety and Health in Mines Convention, 1995 (No. 176) (ILO 1995) and national OSH legislation.
- **Strengthen skills for circular economy**: Skills policies should address skills needs in the circular economy across the value chain, including R&D, product design for recycling, repair, safe dismantling, end-of-life and second-life management, hazardous-waste management, regulations, environmental compliance and quality assurance, among others.
- **Raise awareness of the opportunities offered by CETM in order to enhance the attractiveness of CETM careers among young people**: In many countries, limited public awareness of employment opportunities in the CETM sector and persistent negative perceptions of mining, particularly among young people, continue to weaken the future skills pipeline. Targeted communication campaigns and career guidance programmes should therefore be implemented to promote awareness of the opportunities offered by CETM sector, particularly among young people, by improving understanding of CETM value chains, the role of minerals in green technologies, and the full range of related occupations and career pathways.
- **Strengthen international cooperation**: As global competition for skilled workers intensifies, South–South and triangular cooperation will be increasingly important to help address skills gaps and support talent development and retention in resource-rich countries. Structured South–South and triangular cooperation initiatives should be implemented in collaboration with industry stakeholders willing to support skills development in CETM-producing countries and should combine technology transfer, the training of trainers and broader skills development efforts.

Effective skills development and lifelong learning are essential enablers of industrial transformation, decent work and the sustainable development of CETM value chains. A holistic skills ecosystem should be aligned with industrial strategies and policy frameworks, anticipate future labour market needs, and integrate technical, social and environmental competencies across the value chain. Key elements of that ecosystem should include collaboration among stakeholders, regularly updated curricula and clear career pathways so as to ensure that the socio-economic dimensions of the energy transition are adequately addressed. In line with the *ILO Guidelines for a just transition towards environmentally sustainable economies and societies for all* (ILO 2015), CETM skills strategies should be designed through social dialogue and aligned with decent work, occupational safety and health, social protection, equality of opportunity and treatment, and respect for fundamental principles and rights at work.

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