Mining Future Skills

MINING QUALIFICATIONS AUTHORITY

FINAL REPORT

FINAL REPORT

FOR

STUDY ON DEVELOPING FUTURE-READY SKILLS FOR THE CRITICAL MINERALS VALUE CHAIN IN SOUTH AFRICA

Prepared by: Wits Mining Institute

EXECUTIVE SUMMARY

Background and Purpose

South Africa's mining and minerals sector is being reshaped by the global drive for critical minerals. Driven by the transition to cleaner energy and the advancement of digital and green technologies, competition for these minerals is intensifying worldwide. Given South Africa's significant endowment of several minerals classified as critical, there is growing interest in understanding how the country can position itself as an active and competitive participant in these emerging value chains. In response, the Mining Qualifications Authority (MQA), in partnership with the Wits Mining Institute (WMI), has initiated a research project to examine the skills landscape within the South African critical minerals sector. This work is aimed at supporting the implementation of the country's Critical Minerals and Metals Strategy, which has identified a skilled and future-ready workforce as a key enabler for advancing local value addition, industrial competitiveness, and ensuring inclusive participation in global critical minerals value chains.

Aim and Objectives

The study aims to inform the development of future-ready skills needed to support South Africa's participation in critical minerals value chains. It focuses on identifying skills gaps, understanding current and future human capital requirements, and making evidence-based recommendations for targeted skills development interventions. The specific objectives of the study were to:

- Assess the resource base and geological distribution of critical minerals in South Africa.
- Provide an overview of current and planned exploration and mining projects involving critical minerals.
- Map the critical minerals value chain from upstream extraction through to downstream manufacturing.
- Evaluate the strategic importance of critical minerals nationally and globally, including their role in the green and digital economies.

- Identify current and future human capital needs across the different stages of the value chain.
- Examine the capacity of TVET colleges, universities, and industry to build the required human capital.
- Review the regulatory environment governing critical minerals and assess alignment with national frameworks including the NDP, NSDP, and Just Energy Transition strategy.
- Identify strengths, weaknesses, opportunities, and challenges in South Africa's critical minerals landscape, and define the MQA's strategic role in addressing them.

Methodology

The study used a mixed methods research design, combining quantitative and qualitative approaches to provide a comprehensive understanding of skills requirements. A systematic literature and policy review was conducted first, covering global and South African critical minerals research, policy frameworks (including the CMMS, NDP, JET-IP, and AGMS), and existing skills development literature. This provided the conceptual and evidence base for the primary data collection. An online stakeholder survey was administered to stakeholders across the critical minerals' ecosystem. Responses were received from executives, researchers, technical specialists, educators, industry associations, civil society organisations, and government. The surveys were complemented by key informant interviews conducted with participants drawn from academia, industry and professional bodies, research institutions, government, and community representatives. Additional data was collected through a stakeholder validation webinar which was attended by participants from across industry, academia, government, and civil society. The webinar served both to validate preliminary findings and to generate additional qualitative data through live discussion.

Key Findings

Nine key findings emerged consistently across all three data sources:

Finding 1: Emerging Skills for South Africa's Critical Minerals Sector

Skills required for the critical minerals sector extend beyond traditional mining. They include advanced processing, digital technologies (AI, automation), and sustainability. These are supported by strong foundations in STEM, adaptability, and industry collaboration. Both advanced digital skills and strong basic competencies are needed together.

Finding 2: The Skills Gap Is Deep and Structural

South Africa's skills base is not aligned with the needs of a beneficiation- and manufacturing-driven economy. The workforce remains strong in traditional upstream areas but weak in key future capabilities such as automation, data analytics, and advanced processing.

Finding 3: The Gap Between Industry and Education Is the Most Critical Fault Line

The biggest constraint to skills development is the disconnect between industry and the education system. Graduates lack practical experience, curricula are not sufficiently industry-informed, and work-integrated learning is ineffective. At the same time, the labour market is not growing fast enough to absorb graduates.

Finding 4: Future Skills Requirements for the Critical Minerals Sector

Stakeholders held both converging and diverging views on future skills requirements. Some called for a national skills inventory to identify existing capabilities, underutilised skills and reskilling needs, while others argued for a forward-looking focus on targeted reskilling, research and development, and future-ready competencies. The required shift is from legacy capabilities in bulk extraction and siloed processes towards complex beneficiation, AI-enabled systems and circular resource use.

Finding 5: Strategic Roadmap for Activation: A Unified Sectoral Mandate

Beyond technical skills, the sector requires cross-cutting capabilities such as systems thinking, multidisciplinary collaboration, digital literacy, commercial awareness, and adaptability. These "power skills" are essential for linking technical knowledge to real-world application.

Finding 6: Community and Environmental Skills Are Being Left Behind

Skills related to community engagement, environmental management, and ESG are weak and under-prioritised, despite being critical for the sector's long-term sustainability and social licence to operate.

Finding 7: One Plan Cannot Fit All Minerals or All Contexts

There is no one-size-fits-all skills plan. Different minerals, value chain stages, and types of operators require different skills. Skills development must be tailored to specific value chains and operational contexts.

Finding 8: The Country Needs Action, Not More Analysis

South Africa has strong research on skills challenges, but limited action. Stakeholders emphasised the need for practical implementation, including industry-linked training, value chain development, and coordinated programmes that deliver tangible outcomes.

Finding 9: The Quadruple Helix Model: The MQA as Strategic Coordinator

The MQA is well positioned to act as a strategic coordinator across industry, academia, government, and society (the Quadruple Helix). This includes aligning stakeholders, driving targeted skills development, and ensuring that skills planning translates into real outcomes.

Recommendations

A set of stakeholder-informed recommendations have been proposed, and these are structured in accordance with the SMART framework to ensure they are specific, measurable, achievable, relevant, and time-bound.

Recommendation 1: Strategic Coordination via the "Quadruple Helix" Model

The study identifies a clear "activation gap", with stakeholders aligned in their thinking but not working in a coordinated way. To address this fragmentation, the MQA needs to reposition itself as a central coordinating body that connects government, industry, academia, and society, ensuring that policy priorities are translated into action. A critical starting point for this role is the development of a joint implementation roadmap for critical minerals skills, agreed upon by all key stakeholders. This roadmap should define shared

priorities, roles, timelines, and accountability mechanisms to ensure coordinated and effective execution.

Activity	**Reposition the MQA as a strategic "puzzle-solver" and sectoral bridge between the DMPR, DHET, and the mining value chain to activate critical minerals strategies.**
Timeline	This project can be earmarked for the **2026/27 financial year**, with engagements scheduled on a periodic basis thereafter.

Recommendation 2: Develop Commodity- and Value-Chain-Specific Skills Profiles

The MQA will develop detailed skills profiles for each of the 21 priority minerals, specifying the exact competencies required at each stage of the value chain (exploration, extraction, midstream processing, manufacturing, and circular economy/recycling). Each profile will distinguish between short-term (existing technology) and long-term (emerging technology) requirements.

Activity	**Develop Commodity- and Value-Chain-Specific Skills Profiles**
Timeline	Four profiles per quarter beginning Q2 of 2026/27, completing all 21 within 18 months. High-criticality minerals (PGMs, manganese, chrome, coal, platinum) to be completed first within 6 months.

Recommendation 3: Launch a Flagship Value-Chain Skills Initiative

The MQA will co-develop and fund a flagship end-to-end skills initiative anchored in a complete domestic critical minerals value chain. The initial flagship will focus on vanadium redox flow battery (VRFB) manufacturing, partnering with Mintek, the Department of Science and Innovation (DSI), and the East London SEZ. This initiative will simultaneously develop specific technical skills (electrolyte chemistry, cell assembly, battery engineering, materials science), generate a demonstrable industrial product, and create a replicable template for other minerals.

Activity	**Launch a Flagship Value-Chain Skills Initiative**
Timeline	2026/27: sign MOUs with Mintek, DSI, and East London SEZ; begin curriculum design. 2027/28: pilot training cohort of 50 learners. 2028/29: full programme operational with 200 learners per year. 2029/30: replicate for second mineral value chain.

Recommendation 4: Modernise Unit Standards and Qualifications

The MQA should work closely with universities, TVET colleges, and industry partners to review and update existing curricula and qualifications. This includes funding and accrediting short courses and micro-credentials in areas such as AI, automation, and advanced mineral processing.

Activity	**The MQA should lead an industry-wide modernisation of curricula and qualifications by working with education and training institutions to integrate key future skills, including mechatronics, AI literacy, prompt engineering, and advanced mineral recognition, into the national PSET framework**
Timeline	Year 1 (2026/27): complete curriculum gap analysis and identify 15 priority unit standards for revision. Year 2 (2027/28): submit revised standards to QCTO and begin pilot delivery with at least 3 TVET colleges and 2 universities.

Recommendation 5: Revitalise TVET Colleges Through the 'Nursing College' Competency Model

To address the "broken pipeline" where graduates lack practical capability, stakeholders recommend a shift toward competency-based training. This model ensures graduates possess the hands-on ability to perform technical tasks from day one. It is recommended that MQA design and fund structured Work-Integrated Learning (WIL) pathways that guarantee every learner in an MQA-registered qualification gains documented, assessed practical experience in a real mining or minerals processing environment before graduating. This includes apprenticeships, learnerships, and graduate placement programmes.

Activity	**Shift funding focus from purely academic bursaries toward vocational, hands-on training pathways where "doing" precedes "knowing".**
Timeline	2026/27: conduct TVET landscape assessment across mining corridors and identify 10 pilot colleges. 2027/28: pilot the corridor alignment model in 5 colleges. 2028/29: scale to all 10 colleges and register first competency-based qualifications.

Recommendation 6: Expand Workplace-Integrated Learning (WIL) and Apprenticeships

The transition from graduation to industry readiness is a major bottleneck. To expand workplace-integrated learning and apprenticeships, the MQA should introduce incentives for mining companies to host interns and apprentices. A centralised system should be developed to match graduates with available opportunities and track placements. Special attention

should be given to emerging subsectors such as tailings reprocessing and secondary mineral extraction.

Activity	**Target discretionary grants toward matching graduates with exploration juniors and operators specializing in secondary extraction from tailings and waste dumps.**
Timeline	This project can be earmarked for the **2026/27 financial year** where MQA design WIL framework and pilot with 5 mining companies and 3 TVET colleges.

Recommendation 7: Administer an Industry-Funded Community Skills Transition Fund

To ensure economic justice during the energy transition, local communities must be equipped for the green economy. A mandated fund, financed by large industry players, should support localised community skills development and training.

Activity	**Position the MQA as the administrative partner for a ring-fenced fund dedicated to upskilling host communities in green-economy extraction and advanced mineral recognition.**
Timeline	This project can be considered for establishment in the **2026/27 financial year**.

Recommendation 8: Institutional Regional Technical Councils

Stakeholders suggest that continuous knowledge sharing is required to respond to rapid technological change. These councils should host regular workshops, mentorship programmes, and peer-learning sessions. A supporting digital platform should also be developed to capture, share, and update technical knowledge and best practices.

Activity	**Co-establish regular regional technical councils to facilitate continuous skill sharing, mentorship, and the dissemination of operational best practices.**
Timeline	This project can begin in the **2026/27 financial year**, with database and database updates scheduled periodically thereafter.

Recommendation 9: Global Knowledge Transfer and Exchange Programmes

South Africa lags behind in certain complex beneficiation technologies. Funding international exchanges would allow professionals to learn midstream processing techniques and "bring the skills home". The MQA should develop partnerships with leading international institutions and mining hubs in countries such as Finland, Germany, and the United States. It should fund scholarships and professional exchange programmes in priority skills areas. Participants

should be required to transfer their knowledge locally through structured training, mentorship, or curriculum development initiatives upon their return.

Activity	**Fund exchange programmes where students and professionals spend time at advanced facilities in countries like Finland, Germany, or the USA.**
Timeline	This project can begin in the 2026/27 financial year, where the exchange programme framework is developed and MQA work towards signing one international MOU partnership.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/acronym	Description
4IR	Fourth Industrial Revolution
AfCFTA	African Continental Free Trade Area
AGMS	African Green Minerals Strategy
AI	Artificial Intelligence
AMDC	African Minerals Development Centre
AMV	African Mining Vision
ASM	Artisanal and Small-scale Mining
AU	African Union
BIC	Bushveld Igneous Complex
BRICS	Brazil, Russia, India, China, South Africa
CEAP	Circular Economy Action Plan
CMMS	Critical Minerals and Metals Strategy
CSIR	Council for Scientific and Industrial Research
DHET	Department of Higher Education and Training
DMPR	Department of Mineral and Petroleum Resources
DMRE	Department of Mineral Resources and Energy
DRC	Democratic Republic of Congo
DSI	Department of Science and Innovation
DTIC	Department of Trade, Industry and Competition
EITI	Extractive Industries Transparency Initiative
ESG	Environmental, Social, and Governance
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
GIS	Geographic Information Systems
HSRM	Hydrogen Society Roadmap

Abbreviation/acronym	Description
ICMM	International Council on Mining and Metals
IDZ	Industrial Development Zone
IEA	International Energy Agency
IGF	Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development
ILO	International Labour Organization
IoT	Internet of Things
IPAP	Industrial Policy Action Plan
JET-IP	Just Energy Transition Investment Plan
MMS	Mining and Minerals Sector
MQA	Mining Qualifications Authority
MSP	Minerals Security Partnership
NDP	National Development Plan
NSDP	National Skills Development Plan
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OHS	Occupational Health and Safety
OV	Operation Vulindlela
PEP	Project Execution and Methodology Plan
PGMs	Platinum Group Metals
R&D / RDI	Research and Development / Research, Development and Innovation
REEs	Rare Earth Elements
SADC	Southern African Development Community
SDGs	Sustainable Development Goals
SETA	Sector Education and Training Authority
SEZ	Special Economic Zone
STEM / STE(A)M	Science, Technology, Engineering, (Arts) and Mathematics
TVET	Technical and Vocational Education and Training

Abbreviation/acronym	Description
USGS	United States Geological Survey
VRFB	Vanadium Redox Flow Battery
WMI	Wits Mining Institute

1. INTRODUCTION

The Mining Qualifications Authority (MQA) has partnered with the Wits Mining Institute (WMI) to conduct a study aimed at informing the development of future-ready skills needed to support the critical minerals value chains in South Africa. The country has recently published its Critical Minerals and Metals Strategy, which recognises South Africa's strategic role in the global energy transition, digitalisation, and advanced manufacturing (Department of Mineral and Petroleum Resources, 2025). The strategy outlines a coordinated roadmap to leverage the country's vast mineral endowment to drive inclusive growth, industrialisation, job creation and transformation.

In view of the challenges facing the Mining and Minerals Sector (MMS) in the country, the strategy is centred on six pillars, one of which focuses on Research and Development and Building a Skilled Workforce. This pillar recognises the need for sector-orientated skills to ensure that South Africa can leverage the opportunities presented by the critical minerals value chains. As the Sector Education and Training Authority (SETA) for the MMS, the MQA is expected to lead skills development interventions in support of the country's strategy. To this effect, it is important that the MQA understand the critical minerals landscape in the country including the mineral resource base, value chain activities, emerging technologies, and evolving workforce requirements. This understanding will enable the MQA to design and implement fit-for-purpose skills strategies that support the strategic objectives of the country.

This chapter outlines the background and context supporting the study, defines the problem statement and presents the aim and objectives of the study. The chapter also highlights the significance of the study.

1.1 Background and Context

The worldwide acceleration of the green energy transition, fundamentally rooted in the urgent need to mitigate climate change and reduce greenhouse gas emissions, has been propelled by advances in renewable energy systems, electric vehicles, advanced manufacturing, and digital technologies. This shift has dramatically increased global demand for critical minerals (World Bank Group, 2018; Khanna et al., 2024). While the classification of

critical minerals varies across countries, common dimensions used to define them include their economic importance, supply risk, and strategic value in enabling low-carbon technologies and industrial competitiveness (United States Geological Survey (USGS), 2025; OECD, 2015; DMPR, 2025).

A wide range of minerals fall under this category, including platinum group metals (PGMs), rare earth elements, cobalt, lithium, chrome, and vanadium (DMPR, 2025; Nwaila et al., 2023). According to the 2025 USGS Critical Minerals List, the United States currently recognises 54 critical minerals, including lithium, cobalt, nickel, manganese, platinum group metals, rare earth elements, copper, and zirconium (USGS, 2025). The European Union's Critical Raw Materials Act (2023) similarly lists 34 materials, with heavy overlap around REEs, PGMs, lithium, cobalt, and tungsten (European Commission, 2024). Broadly, these globally recognised critical minerals can be grouped into several categories (see Table 1). Due to the wide applications of minerals, they appear in more than one category in the table.

Table 1: List of critical minerals and end-use industries

End-use industries	List of minerals
Battery and energy materials	Lithium, cobalt, nickel, graphite, and manganese
Renewable and digital technology materials	Rare earth elements (REEs) such as neodymium, dysprosium, terbium, and scandium
Catalytic and green hydrogen materials	Platinum group metals (platinum, palladium, rhodium, iridium, ruthenium)
Light alloys and structural materials	Aluminium (bauxite), magnesium, titanium, silicon, and chromium (chrome)*
Conductors and semiconductors	Copper, gallium, germanium, indium, and tellurium
Superalloys and specialised applications	Tantalum, niobium, tungsten, hafnium, zirconium, vanadium, and chromium*
Other supply-sensitive minerals	Antimony, fluorspar, bismuth, and natural graphite

**Note: Some critical minerals have applications across multiple end-use categories. Chromium is included under both Light alloys and structural materials and Superalloys and specialised applications due to its distinct metallurgical roles: it provides strength and corrosion resistance*

in structural stainless and alloy steels, while contributing high-temperature oxidation and corrosion resistance in nickel-, cobalt-, and iron-based superalloys.

In the South African context, critical minerals are defined as "minerals that are essential for the overall economic development, job creation, industrial advancement and contribution to national security" (DMPR, 2025). In alignment with this definition, South Africa has identified its critical minerals based on five key criteria: export significance, domestic economic relevance, industrial utility, alignment with national development priorities, and global market demand. Critical minerals in South Africa are classified according to three groups: "minerals with high criticality", "minerals with moderate to high criticality" and "minerals with moderate criticality". Table 2 provides the list of critical minerals in South Africa according to the three-tier system.

Table 2: South Africa's list of critical minerals

Criticality Level	Minerals and Metals
High Criticality	Platinum, Manganese, Iron Ore, Coal, Chrome Ore
Moderate to High Criticality	Gold, Vanadium, Palladium, Rhodium, Rare Earth Elements
Moderate Criticality	Copper, Cobalt, Lithium, Graphite, Nickel, Titanium, Phosphate, Fluorspar, Zirconium, Uranium, Aluminium

(Source: DMPR, 2025)

1.2 Problem Statement

The World Bank Group (2018) projects that global demand for critical minerals may rise by as much as 500 per cent over the next 25 years. This scenario underscores the need for a strategic shift away from traditional linear mining and export models towards a circular economy approach that prioritises beneficiation, responsible production, local manufacturing, and recycling (Khan et al., 2022). This shift is particularly relevant for South Africa, a country with a long-standing mining legacy yet one that continues to grapple with the triple challenges of poverty, unemployment, and inequality. Leveraging the opportunities presented by the critical minerals sector is important for South Africa not only because it puts the country in a better position to strengthen its industrial base but also advance its broader development objectives.

While mining in South Africa is well established across a diverse range of commodities, several persistent challenges continue to affect its overall performance and contribution to national development. The performance of the mining sector has been characterised by a decline in both its share of the Gross Domestic Product (GDP) and in employment figures. According to the Minerals Council South Africa (2025), the sector's contribution to GDP fell from 6.2% in 2023 to 6% in 2024, accompanied by a loss of approximately 5,744 jobs during the same period (Minerals Council South Africa, 2024).

This weakening performance is attributed to a range of interconnected factors which continue to affect production outputs and the sustainability of the MMS. Among these, skills shortages remain a significant barrier. According to the Mining Qualifications Authority (2023), approximately 35% of the mining workforce lacks a matric or equivalent qualification, pointing to a substantial gap in foundational education and technical competencies. This shortfall limits the sector's ability to transition toward advanced, technology-driven operations and to fully leverage opportunities presented by the critical minerals sector. Against these challenges, it is important to increase skills development efforts within the MMS. Achieving this requires evidence-based research to guide targeted and strategic interventions that support the implementation of the country's critical minerals and metals strategy.

1.3 Aim and Objectives

This research study aims to inform the development of future-ready skills needed to support the critical minerals value chains in South Africa. In so doing, the study makes recommendations on targeted interventions needed to enhance the contribution of critical minerals in South Africa's economy. The research is supported by the following objectives:

1) Assess the resource base and geological distribution of critical minerals in the country.
2) Provide an overview of current and planned exploration and mining projects involving critical minerals.
3) Map the critical mineral value chain for key minerals including upstream, midstream, downstream as well as supporting activities.
4) Evaluate the strategic importance of critical minerals both in South Africa and globally.

5) Assess the role of critical minerals in green and digital economies taking into account use in renewable energy, batteries, electric vehicles, green hydrogen, and advanced manufacturing.

6) Identify current and future human capital needs across the different value chains, assessing the adequacy of the existing skills base to support critical minerals value chains.

7) Examine the role of post-school education and training institutions such as TVET colleges and universities as well as industry stakeholders in building the human capital required to support the development of South Africa's critical minerals sector.

8) Examine the regulatory environment governing critical minerals, including the critical minerals strategy, and establish alignment with national frameworks such as the National Development Plan (NDP), National Skills Development Plan (NSDP), Green Hydrogen and Just Energy Transition strategies and other relevant frameworks in the country.

9) Identify the strengths, weaknesses, challenges, and opportunities within South Africa's critical minerals landscape, with a focus on informing the strategic role of the MQA.

1.4 Significance of the Study

This study on future-ready skills required to support participation in critical minerals value chains is both timely and essential for South Africa's mineral and mining sector. This is because the Department of Minerals and Petroleum Resources (DMPR) released the country's critical minerals and metals strategy which aims to position South Africa as "a dependable global supplier of raw and processed materials, and high-valued end products" (DMPR, 2025; 17). This vision is supported by several strategic objectives which include attracting investment in exploration, production, processing and beneficiation of critical minerals; providing targeted support for the expansion and localisation of critical mineral value chains; and lastly, fostering regional and global cooperation for sustainable supply of critical minerals. For South Africa to attain these goals, the strategy has several pillars and pillar III specifically speaks to research and development and building a skilled workforce.

In particular, the strategy recognises that South Africa's ability to capitalise on opportunities arising from the global energy transition and increasing demand for critical minerals will depend on the availability of appropriately skilled people. It further emphasises the need to ensure that South Africans have the requisite skills, opportunities, and support to participate meaningfully in the sector. There is therefore a need to have an understanding of the specific skills, competencies, and capabilities that will be required across emerging critical mineral value chains, as well as the extent to which these skills are currently available within the country and the gaps that exist. This study, as commissioned by MQA comes as dedicated research aimed at informing evidence-based skills planning and development.

Through this study, the specific skills and competencies required to ensure that South Africa's workforce is adequately prepared to meet the evolving demands of the critical minerals sector will identified enabling MQA and partner institutions (i.e., government, industry bodies, academic institutions) to develop targeted skills interventions for beneficiation, and advanced mineral processing increasing across critical minerals value chains (MQA, 2025).

1.5 Structure of the Study

The report is structured into eight sections, and these are elaborated below:

Section 1 provides introduction and background to the study. This is supported by the problem statement as well as aim and objectives of the study. The significance of the study is also included in the chapter.

Section 2 reviews the literature and policy frameworks applicable to the critical minerals sector. It provides an overview of critical minerals globally, with specific consideration of the South African context, and discusses their importance. It further unpacks critical minerals value chains and identifies the associated skills needs.

Section 3 discusses the research methodology that was employed in the study. The chapter outlines the data collection and analysis methods as well as ethical requirements and challenges and limitations of the study.

Section 4 presents the first set of study findings, based on data collected from stakeholder surveys. **Section 5** provides the second set of findings, drawing on insights from key informant

interviews. **Section 6** complements these by presenting insights from a stakeholder webinar, which was conducted to validate the preliminary findings and gather additional input from stakeholders. **Section 7** provides the overall discussion and draws the key findings from the study.

Section 8 provides the conclusion and recommendations, framed using the SMART framework, which provides a structured approach to ensure that the goals are specific, measurable, achievable, relevant, and time bound.

2. LITERATURE AND POLICY REVIEW

2.1 Introduction

The section presents the literature and policy review underpinning the study. The section begins by defining key concepts to ensure clarity and consistency throughout the study. The section then provides a global overview of critical minerals, followed by an examination of South Africa's critical minerals landscape. It further explores critical minerals value chains and details the associated activities across targeted industries. In addition, the section analyses the linkages between value chains and skills requirements. Finally, it reviews South Africa's policy environment and highlights key stakeholder efforts aimed at supporting critical minerals value chains.

2.2 Defining Key Concepts

2.2.1 Critical and Strategic Minerals

Critical minerals are generally defined as those that are economically and technologically essential yet vulnerable to supply disruptions (World Bank, 2020). While this definition fits into the categorisation of critical minerals by several countries, it has been advanced that the classification of "criticality" depends on perspective and countries' contexts. For importing countries, typically in the Global North, criticality is defined by supply risk and strategic dependence (i.e., minerals whose absence threatens industrial or national security). For example, the European Commission (2023) defines a mineral as critical when it is of high economic importance and faces high supply risk with limited substitutes. The United States and Japan adopt similar criteria, linking criticality to defence, energy security, and technological resilience (US Department of the Interior, 2022; Japanese Ministry of Economy, Trade and Industry, 2023).

For producer countries, particularly across Africa, the term often conveys developmental opportunity (i.e., minerals capable of catalysing industrialisation, diversification, and job creation). With this context, South Africa's 2025 Critical Minerals and Metals Strategy situates criticality within this broader developmental context, defining critical minerals as those essential for advancing industrialisation, energy transition, and technological innovation (Government of South Africa, 2025).

At the continental level, the African Green Minerals Strategy (AGMS, 2024) promotes value addition at source and regional cooperation to ensure that Africa's mineral wealth drives sustainable development rather than extraction-led dependency. Critical minerals are thus positioned not merely as geological assets but as instruments for sovereignty, inclusivity, and industrial transformation.

Although definitions vary, a common trend emerges which is that many minerals long mined for conventional uses have become newly critical due to their expanding roles in clean energy and digital technologies.

A consensus on the distinction between critical and strategic minerals has yet to be reached (Encyclopaedia Britannica, 2025). One view is that strategic minerals are those whose production and beneficiation are fundamental to achieving national development and security objectives, particularly for defence. Despite these nuances, many minerals appear on the critical and strategic lists of multiple nations, highlighting shared supply risks and the need to maximise benefits of mineral extraction for sustainable development. This report therefore adopts a broad definition of critical minerals, which are those that are of strategic importance to South Africa, which may also be regarded as strategic elsewhere.

2.2.2 Future-Ready Skills

The concept of future-ready skills is widely referenced in discussions on the Fourth Industrial Revolution (4IR), reflecting the growing emphasis on the capabilities required to navigate rapidly evolving technological and economic environments. Broadly, future-ready skills are dynamic competencies that enable individuals to navigate and thrive in rapidly evolving economic, technological, and social environments shaped by sustainability imperatives and ongoing industrial transformation. They encompass both technical abilities, such as digital literacy and AI proficiency, and deeply human capacities, including creativity, critical thinking, adaptability, ethical reasoning, and effective communication (Li, 2022; Chirgwin, 2021).

In the mining sector, these skills combine the core technical skills with digital and human-centred capabilities essential for modern operations. They include data analysis, automation and remote operations, sustainability leadership, advanced problem-solving, and effective collaboration. Such competencies allow the workforce to adapt to innovations associated

with 4IR technologies, mine-modernisation initiatives, and evolving socio-environmental expectations (MQA, 2024; EY, 2019; Chirgwin, 2021; Li, 2022; EY, 2020; Minerals Council South Africa, 2022).

Within the critical minerals value chain, future-ready skills span all stages of activity that are exploration, extraction, processing, refining, manufacturing, recycling, and innovation (EY, 2019; MQA, 2024; NSW Government, 2024). At the technical level, this includes geoscience, mining engineering, process engineering, metallurgy, manufacturing, and recycling. Within the digital domain, there are automation, robotics, and data analytics. These capabilities underpin the deployment of 4IR technologies that improve efficiency and sustainability across mining and manufacturing (EY, 2019; EY, 2020; MQA, 2024; Minerals Council South Africa, 2022).

At the cross-cutting level, they encompass environmental, social, and governance (ESG) literacy, occupational health and safety culture, systems thinking, and circular-economy principles such as waste minimisation and material recovery (MQA, 2024; EY, 2020; NSW Government, 2024; Minerals Council South Africa, 2022). Developing these capabilities throughout the critical minerals value chain will be pivotal for South Africa's ability to capture emerging industrial opportunities, close existing skills gaps, build a workforce that supports sustainable, inclusive growth while protecting its environment and people.

2.3 Global Overview of Critical Minerals

Building on the core concepts outlined above, this section examines the global distribution, demand drivers, and supply risks associated with critical minerals. Although definitions and strategic priorities vary across countries, there is broad convergence around a core group of minerals - including lithium, cobalt, nickel, platinum group metals (PGMs), graphite, and rare earth elements - that are widely recognised as essential for clean energy, advanced technologies, and modern manufacturing (UN DESA, 2025; IISD, 2023; U.S. Geological Survey, 2025).

Demand for these minerals has surged in response to the global energy transition, the expansion of digital infrastructure, and growing ambitions for climate mitigation (Government of South Africa, 2025; UN DESA, 2025). Most are used in renewable energy

systems, battery storage, electric vehicles, and high-technology manufacturing. However, their production remains highly concentrated in a few countries, creating supply-chain vulnerabilities and prompting international efforts to diversify sourcing, enhance transparency, and promote sustainable mining practices (UN DESA, 2025; IISD, 2023).

Table 3 provides a comparative summary of critical minerals identified by major economies, that are, China, the European Union (EU), Russia, the United States of America (USA), and South Africa, highlighting areas of overlap and divergence. This comparative perspective illustrates which minerals are considered globally critical and hold specific regional importance (The Assay, 2025; Voronoi, 2024).

Table 3: Cross-country comparison of critical minerals

Mineral	China	EU	Russia	USA	South Africa	Common Across All*
Aluminium/Bauxite	✓	✓	✓	✓	✓	✓
Antimony	✓	✓	✓	✓		
Cobalt	✓	✓	✓	✓	✓	✓
Fluorspar	✓	✓	✓	✓	✓	✓
Graphite	✓	✓	✓	✓	✓	✓
Lithium	✓	✓	✓	✓	✓	✓
Nickel	✓	✓	✓	✓	✓	✓
Rare Earth Elements[1]	✓	✓	✓	✓	✓	✓
Tungsten	✓	✓	✓	✓		
Chromium	✓		✓	✓	✓	
Tin	✓		✓	✓		
Zirconium	✓		✓	✓	✓	
Copper	✓	✓		✓	✓	
Platinum Group Metals[2]		✓	✓	✓	✓	
Manganese		✓	✓	✓	✓	

Mineral	China	EU	Russia	USA	South Africa	Common Across All*
Titanium	✓	✓	✓		✓	
Vanadium	✓	✓		✓	✓	
Scandium	✓	✓	✓	✓		
Gallium	✓	✓		✓		
Germanium	✓	✓		✓		
Niobium		✓	✓	✓		
Tantalum		✓	✓	✓		
Beryllium		✓	✓	✓		
Gold					✓	
Diamonds			✓			
Iron Ore					✓	
Coal					✓	
Ferroalloys			✓			
Uranium			✓		✓	
Phosphate					✓	

*Notes: [1] EU lists rare earths as "light" and "heavy" groups; USA lists these individually. [2] Platinum group includes platinum, palladium, rhodium, ruthenium, iridium, and osmium. Minerals in the "Common Across All" column are listed as critical by China, EU, Russia, and the USA, signifying consensus on their global strategic relevance (SIPRI, 2024: Table 2.2). *The "Common Across All" column indicates minerals designated as critical by all 5 jurisdictions included in the comparison: China, the EU, Russia, the USA, and South Africa.*

As seen on the table, there is a core group of minerals that includes aluminium/bauxite, antimony, cobalt, fluorspar, graphite, lithium, nickel, rare earth elements, and tungsten. These minerals are recognised across China, the EU, Russia, the USA, and South Africa, reflecting their central role in global supply chains related to energy transition, advanced manufacturing, and strategic technologies. Beyond this shared core, variations emerge, with

some minerals appearing across most but not all jurisdictions, while others reflect region-specific priorities shaped by resource endowments, industrial structures, and geopolitical considerations. For example, South Africa's inclusion of bulk commodities such as gold, iron ore, coal, and phosphate highlights a resource-based perspective, whereas the EU and USA place emphasis on technology-critical minerals such as gallium and germanium due to their dependence on imported inputs for high-technology industries. Overall, the table reiterated what is noted above, that critical mineral classifications are not universal but instead are guided by country needs.

2.3.1 Strategic Importance of Critical Minerals

The strategic importance of critical minerals lies in their applications across green technologies, digital transformation, advanced manufacturing, and defence applications. These are sectors that are vital to national security, industrial competitiveness, and sustainable development (Government of South Africa, 2025). These minerals underpin the production of batteries, solar panels, wind turbines, semiconductors, and other components essential for achieving the United Nations Sustainable Development Goals (SDGs), particularly Clean Energy (SDG 7), Industry, Innovation and Infrastructure (SDG 9), and Climate Action (SDG 13) (Government of South Africa, 2025).

Figure 1 illustrates the connection between mining and the SDGs - a relationship that has become even more pronounced within the global discourse on green and critical minerals. Mining activities contribute directly or indirectly to most of the Sustainable Development Goals, with particularly strong linkages to clean energy, industry, innovation, decent work, and infrastructure. However, their influence also extends to goals on water, land, and communities, thus emphasising the need for balanced, responsible mineral development that advances social and environmental wellbeing alongside economic growth.

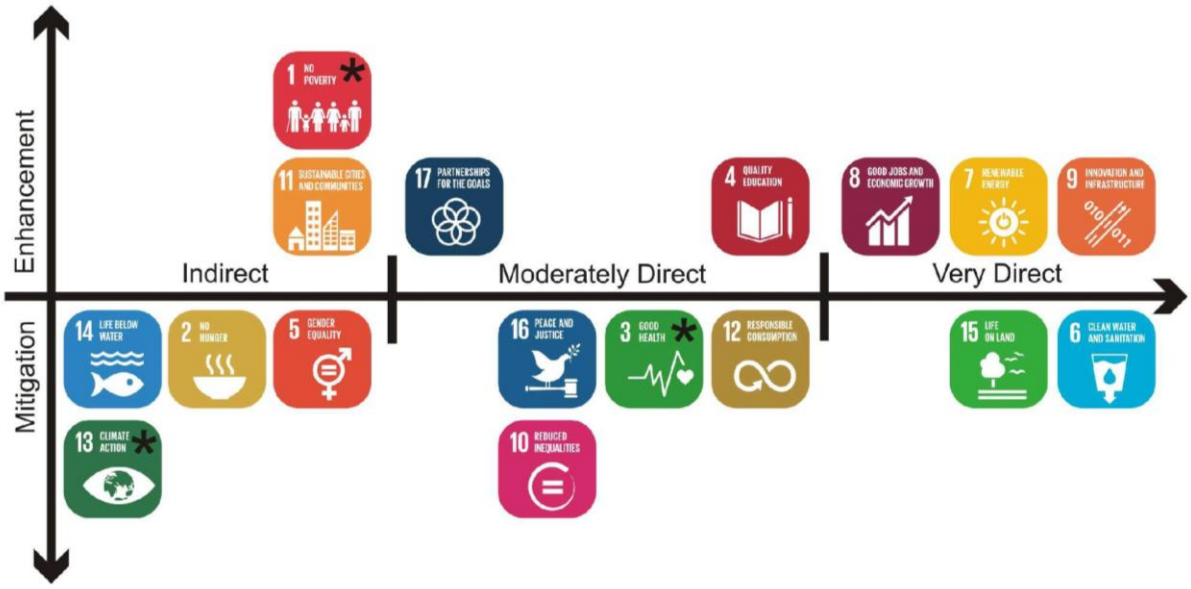


Figure 1: Mining and its relative contribution to the 17 Sustainable Development Goals

(Image source: World Economic Forum, 2015)

What sets critical minerals apart is not only their technological value but also their potential to drive economic diversification and job creation in resource-rich regions (IISD, 2023). However, their geographic concentration in a limited number of countries heightens supply vulnerabilities, intensifies geopolitical competition, and has prompted national efforts to secure resources through policy frameworks, trade restrictions, and strategic alliances (UN DESA, 2025; IGF, 2023).

Major economies have responded with dedicated critical minerals strategies, including the U.S. Inflation Reduction Act (2022), the EU Critical Raw Materials Act (2023), and South Africa's own national strategy (Government of South Africa, 2025; OECD, 2023). There have also been international alliances such as those between Japan, Canada, and Australia which have focused on joint exploration, refining, and stockpiling to establish security of supply (IISD, 2023; OECD, 2023). As a result, critical minerals are now as important to today's global economy as oil was in the past, with both importing and exporting countries focusing on supply security and sustainable development (Parliament of South Africa, 2025; Edinburgh University Press, 2023; IISD, 2023).

The growing strategic importance of critical minerals has therefore intensified attention on production and supply dynamics worldwide. As nations compete to secure access to these resources, questions of ownership, beneficiation, and sustainability have moved to the forefront of global policy debates. Understanding where and how these minerals are produced, and the extent of associated risks and dependencies, is essential for shaping South Africa's participation in the evolving global value chain.

2.3.2 Role of Critical Minerals in Emerging Industries

Critical minerals form the foundation of almost all green and digital technologies forming the foundation of modern economies (SFA Oxford, 2025; World Economic Forum, 2025). Their applications span clean energy, mobility, digital infrastructure, and defence, and are notably important for:

- **Clean energy systems:** Rare earth elements provide high-performance magnets for wind turbines and electric motors, while copper, aluminium, and nickel are vital to grid expansion and energy storage (Parliament of South Africa, 2025; RBA, 2025; IGF, 2025).
- **Battery and e-mobility sectors:** Lithium, cobalt, manganese, and graphite are integral to battery cathodes and anodes, with demand projected to rise steeply over the next two decades as electric vehicles and grid storage scale up (World Economic Forum, 2025; Parliament of South Africa, 2025; SFA Oxford, 2025).
- **Hydrogen economy:** Platinum-group metals (PGMs), particularly platinum and iridium, are essential for electrolysers and fuel-cell catalysts (SFA Oxford, 2025; Parliament of South Africa, 2025).
- **Digital and defence applications:** Gallium, germanium, and titanium are fundamental to semiconductors, aerospace alloys, and advanced electronics manufacturing (World Economic Forum, 2025; IGF, 2025).

In 2022, the global critical minerals market was valued in the hundreds of billions of US dollars and is projected to expand substantially by 2040, with some estimates anticipating a 500 percent increase in demand for key minerals by 2050 (Government of South Africa, 2025; World Bank, 2018). This rapid growth will test the resilience of global supply chains and

further elevate the strategic importance of responsible resource governance and international cooperation (OECD, 2023; Parliament of South Africa, 2025; ICMM, 2023). These global trends present both an opportunity and challenges that may mount up if national policies, industrial strategies, and skills development initiatives (i.e., *amongst key enablers*) are not aligned to respond to growing demand, manage risks, and maximise the benefits of participation in the critical minerals value chain.

Against this global backdrop, understanding South Africa's unique resource endowment, strategic positioning, and policy approach becomes essential for determining how the country can leverage its critical minerals to secure long-term, sustainable advantage. The next section turns to South Africa's critical minerals landscape, outlining its strategic priorities, resource base, and evolving value chains that shape the demand for such skills.

2.4 South Africa's Landscape of Critical Minerals

2.4.1 Strategic Prioritisation of South Africa's Critical Minerals

South Africa's Critical Minerals and Metals Strategy (2025) document provides a structured framework for ranking minerals and metals according to their economic, strategic, and developmental significance. The classification aims to support evidence-based decision-making in investment, beneficiation, and skills development, ensuring that policy attention aligns with both immediate and long-term national priorities. The prioritisation is guided by several key criteria:

- Economic importance and contribution to GDP and exports;
- Supply risk, including dependency on imports or concentrated suppliers;
- Potential impact of disruption on domestic and global value chains;
- Scope for industrialisation, job creation, and export diversification; and
- Technological significance and integration within strategic trade partnerships.

Based on these criteria, minerals are grouped into three criticality tiers, reflecting their current and emerging roles in South Africa's economy. This is summarised in Table 2.

(Source: DMPR, 2025)

Minerals in the high-criticality tier are foundational to South Africa's industrial base, energy systems, and export competitiveness. They anchor established sectors such as manufacturing, infrastructure, and energy production, led by platinum, manganese, iron ore, coal, and chrome.

Those classified as moderate to high criticality form the basis of advanced manufacturing and technological innovation, particularly in hydrogen, battery, and renewable energy technologies. Vanadium, PGMs (especially palladium and rhodium), and the rare earth elements which are in this category are key enablers of catalytic converters, fuel cells, and high-performance electronics.

The moderate-criticality group includes minerals currently playing supporting roles in industrial diversification and technology development but expected to rise sharply in importance as the global energy transition accelerates. These include lithium, cobalt, graphite, nickel, and titanium (which are essential for batteries and alloys), alongside industrial inputs such as phosphate, fluorspar, zirconium, and aluminium.

Importantly, the strategy emphasises that this classification is dynamic, subject to periodic review as global markets, technologies, recycling rates, and geopolitical conditions evolve (Government of South Africa, 2025). This adaptive framework ensures South Africa remains responsive to the shifting contours of global demand while advancing its domestic goals of beneficiation, industrialisation, and inclusive growth.

2.4.2 Resource Base and Distribution of Critical Minerals

South Africa is widely recognised as the most richly endowed African nation in terms of critical minerals, positioning it at a strategic advantage within the global critical minerals' economy (Clearkin et al., 2025). Figure 2 illustrates the relative abundance of critical minerals across Africa, emphasising South Africa's diversity and volume of resources compared with other countries (Clearkin et al., 2025). The country's endowment in platinum-group metals (PGMs), manganese, vanadium, and chromium is unmatched globally. Historically, the mining sector was dominated by gold and coal exports, but contemporary policy increasingly prioritises future-facing commodities that underpin the green transition and knowledge-intensive industries. PGMs are now key inputs for hydrogen fuel-cell technologies and catalytic

converters; manganese remains vital for both steel alloying and next-generation battery chemistries; while vanadium's role in redox-flow batteries positions South Africa as a global leader in stationary energy storage solutions (DMPR, 2025; SFA Oxford, 2025).

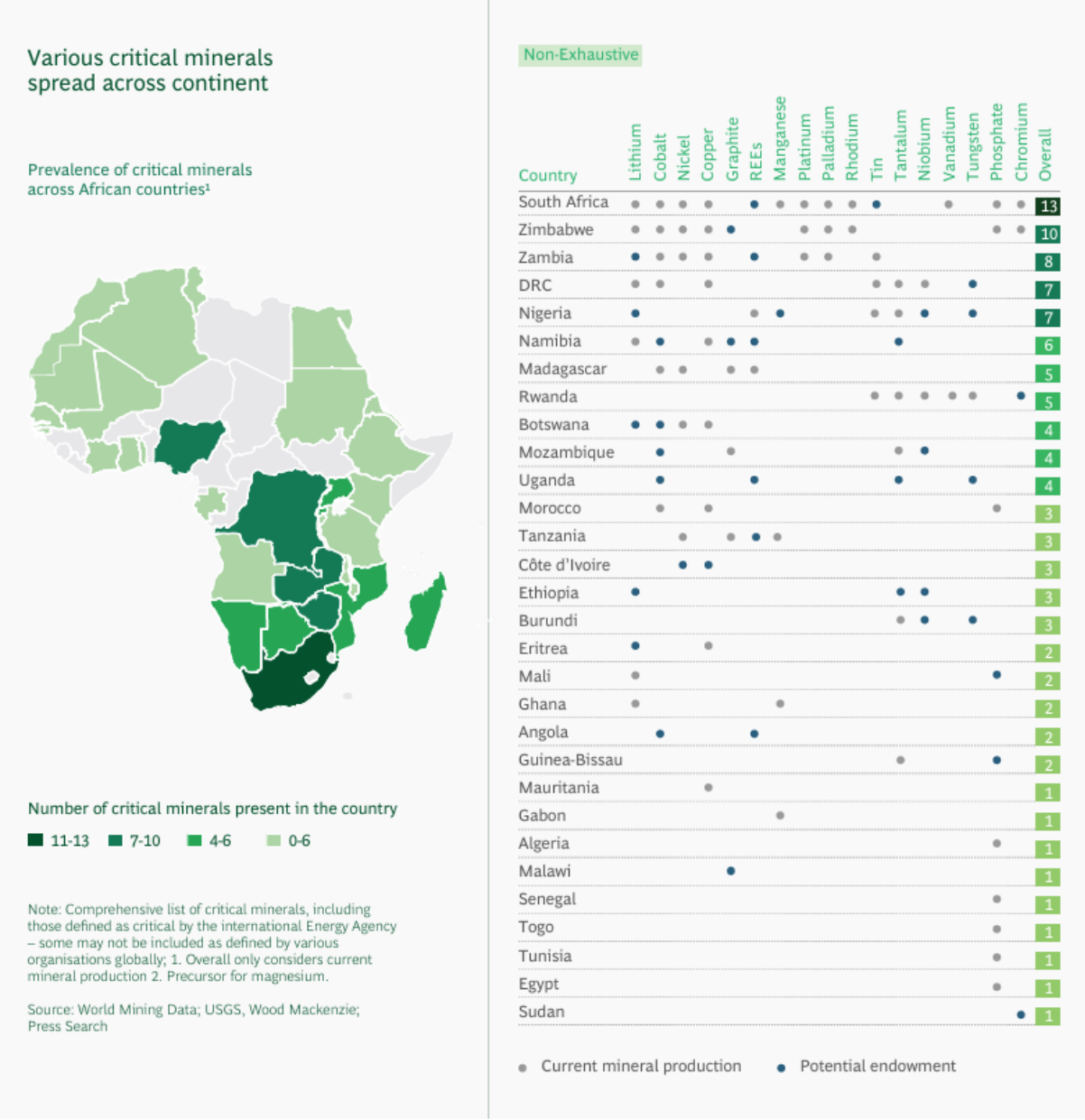


Figure 2: Critical minerals endowment and production across countries in Africa

(Image source: Clearkin et al., 2025, p.8)

The geographical distribution of these and other key minerals is summarised in Table 5, illustrating the breadth of South Africa's mineral portfolio and its strategic relevance for the critical minerals sector. South Africa's critical minerals occur within geologically diverse and

resource-rich formations, providing the country with a strong comparative advantage across multiple value chains (Government of South Africa, 2025). The distribution of these minerals follows distinct geological provinces, each supporting different industrial applications and export markets.

Table 5: Geographical distribution of South Africa's critical minerals and metals

Mineral/Metal	Key Locations/Fields	Province(s)
Platinum	Bushveld Igneous Complex (Rustenburg, Polokwane, Steelpoort)	Limpopo, North West, Mpumalanga
Palladium	Bushveld Igneous Complex (with platinum)	Limpopo, North West, Mpumalanga
Rhodium	Bushveld Igneous Complex (with platinum)	Limpopo, North West, Mpumalanga
Manganese	Kalahari Manganese Field (Hotazel, Kuruman)	Northern Cape
Iron Ore	Sishen, Kolomela, Postmasburg	Northern Cape
Gold	Witwatersrand Basin (Johannesburg, Carletonville, Welkom)	Gauteng, Free State, Mpumalanga
Coal	Witbank, Highveld, Waterberg, Ermelo, Secunda	Mpumalanga, Limpopo, Free State
Chrome Ore	Bushveld Igneous Complex (Rustenburg, Steelpoort, Thabazimbi)	Limpopo, North West, Mpumalanga
Vanadium	Bushveld Igneous Complex (Brits, Steelpoort, Mokopane)	Limpopo, North West, Mpumalanga
Rare Earth Elements	Phalaborwa, Steenkampskraal, Glenover	Limpopo, Western Cape
Copper	Phalaborwa, Okiep, Prieska	Limpopo, Northern Cape
Cobalt	Phalaborwa (as byproduct), Namaqualand	Limpopo, Northern Cape
Lithium	Springbok Flats, Northern Cape pegmatites	Limpopo, Northern Cape
Graphite	Limpopo (Giyani), North West	Limpopo, North West
Nickel	Bushveld Igneous Complex, Barberton	Limpopo, Mpumalanga
Titanium	Richards Bay, Xolobeni, Namakwa Sands	KwaZulu-Natal, Eastern, Western Cape

Mineral/Metal	Key Locations/Fields	Province(s)
Phosphate	Phalaborwa, Langebaan	Limpopo, Western Cape
Fluorspar	Vergenoeg, Outjo, Witkop	Gauteng, Limpopo, North West
Zirconium	Richards Bay, Namakwa Sands, Western Cape minerals sands	KwaZulu-Natal, Western Cape
Uranium	Karoo, Witwatersrand Basin, Phalaborwa	Northern Cape, Free State, Limpopo
Aluminium	Richards Bay (imported bauxite, smelting)	KwaZulu-Natal

The Bushveld Igneous Complex (BIC), spanning Limpopo, North West, and Mpumalanga, remains the cornerstone of South Africa's mineral wealth. It hosts the world's largest deposits of platinum-group metals (PGMs), alongside extensive chrome and vanadium reserves. The Bushveld Igneous Complex alone accounts for over 74 percent of global PGM reserves (DMRE, 2025; USGS, 2024).The BIC supports vertically integrated mining, smelting, and refining activities, and is increasingly vital for the hydrogen economy, advanced materials manufacturing, and traditional industries such as catalytic converters and specialty alloys (Government of South Africa, 2025; USGS, 2024).

The Kalahari Manganese Field in the Northern Cape represents more than 80 percent of the world's high-grade manganese ore, consolidating South Africa's position as a global manganese supplier. This region underpins the manganese alloys industry, which is critical for steel decarbonisation, battery-precursor manufacture, and the chemical sector. The same province hosts major iron-ore operations at Sishen, Kolomela, and Postmasburg, collectively reinforcing the Northern Cape as a strategic mining and logistics hub (Government of South Africa, 2025). New exploration frontiers are rapidly emerging and include the following:

- Springbok Flats Basin (Limpopo) shows strong potential for lithium-bearing pegmatites.
- Rare earth element (REE) prospects in Phalaborwa (Limpopo), Steenkampskraal (Western Cape), and Glenover (Limpopo) are attracting renewed attention amid rising

global demand for renewable-energy technologies, electronics, and permanent-magnet components.

- Copper and cobalt resources, often as polymetallic by-products, are present in Okiep and Springbok (Northern Cape) and Limpopo, offering opportunities to integrate with regional supply chains and expand domestic beneficiation capacity (Government of South Africa, 2025; USGS, 2024; Parliament of South Africa, 2025).

Spatial analysis of these mineral systems reveals clustering along established mining corridors, particularly the Bushveld-Limpopo axis and the Northern Cape belt. These clusters align closely with existing logistics, energy, and export infrastructure, presenting strong opportunities for industrial-corridor development, regional integration, and balanced economic growth (Government of South Africa, 2025). South Africa's resource base therefore offers both depth and diversification, anchoring traditional strengths in PGMs, chrome, manganese, and iron ore, while opening new frontiers in battery and technology minerals critical for the energy transition. However, unlocking this potential will depend on increased exploration funding, streamlined permitting processes, and sustained investment in geoscience data, innovation, and technical skills, but also on building sufficient capacity for value addition and beneficiation.

2.4.3 South Africa's Position in the Value Chain

South Africa's Critical Minerals and Metals Strategy (2025) places value chain development and integration at the centre of its green industrialisation agenda. This is because, despite its mineral endowment, mineral production and processing in South Africa is yet to be fully realised. Figure 3 illustrates an overview of the continent's current mining and processing activity.

While the country possesses globally significant upstream capabilities, anchored in world-class mining and extraction of PGMs, manganese, chrome, and iron ore, its midstream and downstream capacities remain uneven. Refining and advanced processing are well established for some commodities, notably PGMs and manganese, but limited for emerging minerals such as lithium, cobalt, and rare-earth elements (Government of South Africa, 2025).

As a result, South Africa's mineral economy remains largely upstream, dominated by extraction and primary exports. The country exports PGMs, manganese, and chrome mainly as concentrates or semi-processed materials, forfeiting substantial downstream value in manufacturing and technology-intensive sectors. Most downstream value is still realised outside the country, and this has limited participation in global value chains for clean-energy technologies such as lithium batteries, hydrogen fuel systems, and renewable-energy infrastructure (UNCTAD, 2025; IGF, 2025).

Barriers to full beneficiation include high energy costs, infrastructure bottlenecks, limited R&D funding, and the slow adoption of advanced processing technologies. In addition, tightening environmental, social, and governance (ESG) standards are introducing new compliance requirements that demand a digitally skilled, sustainability-oriented workforce (Parliament of South Africa, 2025; UNCTAD, 2025).

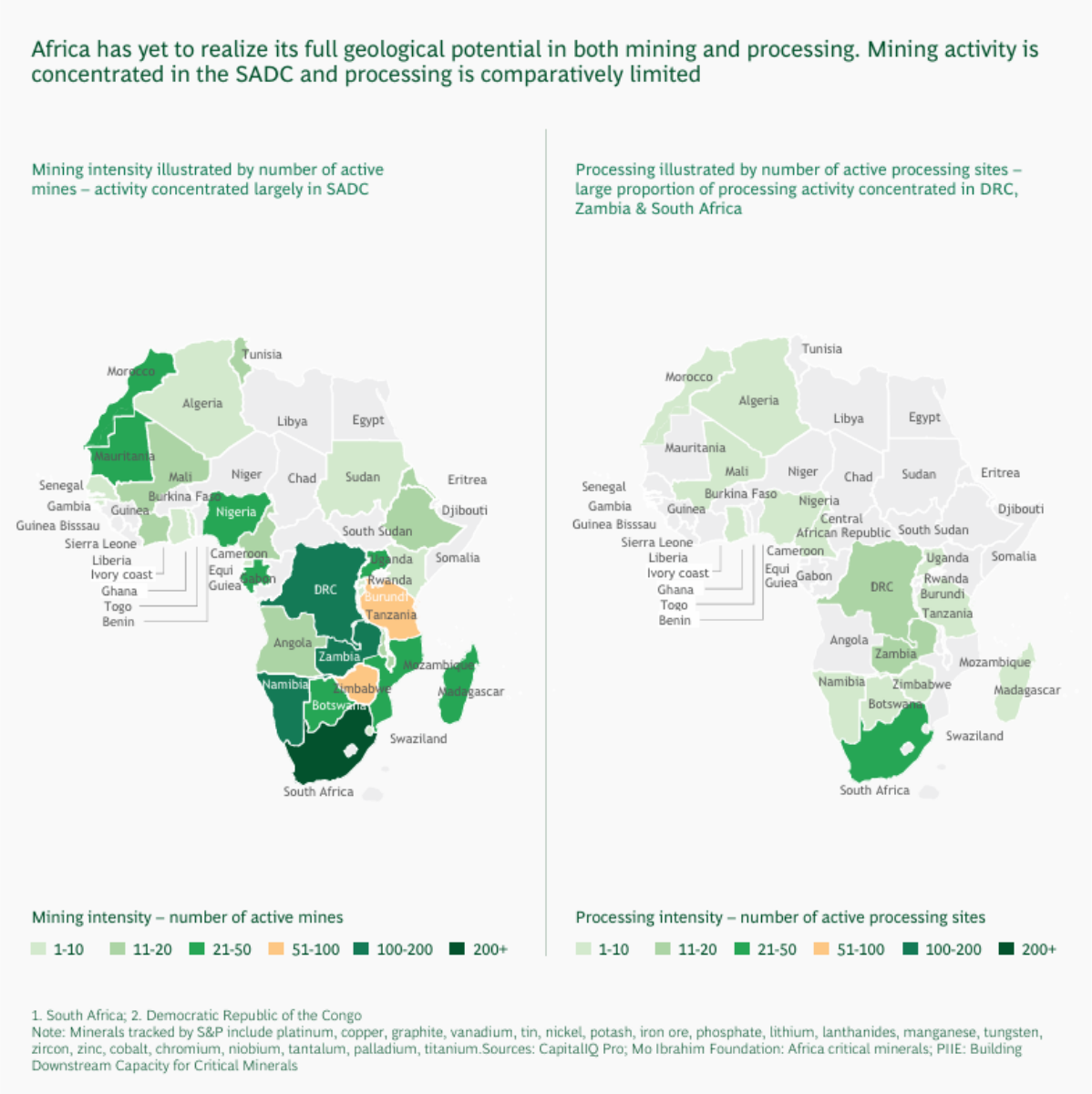


Figure 3: Mining and processing activity in the African continent

(Image source: Clearkin et al., 2025, p.9)

Emerging opportunities, however, point toward diversification and localisation through initiatives that link mining to domestic manufacturing and technology development. Strategic alignment between government, industry, and research institutions are essential to converting these opportunities into inclusive, innovation-driven growth. To strengthen competitiveness across the value chain, the national strategy identifies three core levers:

- Local beneficiation and processing capacity: expanding refineries and advanced-materials facilities for batteries, hydrogen, and next-generation technologies (Government of South Africa, 2025).
- Industrial partnerships and technology transfer: collaborating with global markets such as Japan, the European Union, and Canada to localise manufacturing inputs and co-develop innovation ecosystems (Government of South Africa, 2025).
- Skills and research alignment: linking vocational and tertiary education, as well as targeted R&D, with the needs of emerging sectors such as green hydrogen, advanced materials, and circular manufacturing (Government of South Africa, 2025).

Complementary investment in infrastructure, stable energy supply, and trade facilitation is also essential. When combined, these measures are expected to enable South Africa to evolve from a mineral exporter into a strategic global supplier within the low-carbon economy (Government of South Africa, 2025; T20 South Africa, 2025; Hofmeyer, 2025).

2.4.4 Overview of South Africa's Critical Minerals Projects and Industrial Initiatives

South Africa's critical minerals development landscape is characterised by a mix of mature operations, large-scale expansion projects, and emerging exploration ventures. Table 6 summarises current and emerging projects across key commodities, highlighting their geographic focus, development stage, and strategic contribution to South Africa's industrial-growth objectives. The table shows that South Africa is developing a diverse pipeline of critical minerals projects across different stages of the value chain, with a strong focus on energy transition minerals and technologies. While many projects are still in early phases such as exploration and feasibility, there is clear progress toward value addition through initiatives like battery manufacturing, hydrogen development, and titanium beneficiation. The involvement of public institutions and private partners highlights the importance of collaboration in building technical capacity, advancing innovation, and supporting skills development.

Table 6: Overview of Key Critical Minerals Projects and Industrial Initiatives

Project / Cluster	Primary Mineral(s)	Location / Province	Stage of Development	Strategic Focus / Description	Lead Partners / Institutions
Vaal SEZ Battery Hub	Lithium, Cobalt, Nickel, Manganese (battery precursors)	Gauteng / Free State corridor	Pilot / Early production (2024)	Battery precursor manufacturing, cell assembly, recycling; regional EV supply chains	Mintek, CSIR, MQA, Provincial Government
Green Hydrogen Valley	PGMs (Platinum, Iridium)	Limpopo-Gauteng-KwaZulu-Natal (Hydrogen Corridor)	Demonstration / Scale-up (2023)	Hydrogen fuel-cell manufacturing, hydrogen mobility, R&D integration	DST / NRF, HySA, Anglo American
Vanadium Redox Flow Battery (VRFB)	Vanadium	East London SEZ / Eastern Cape	Construction / Pilot (2024)	Vanadium-electrolyte processing, flow-battery manufacturing, grid storage	Bushveld Energy, OEMs, SADC partners
Steenkampskraal REE Project	Rare Earth Elements	Western Cape	Pre-production / Feasibility (recommissioned 2023)	High-grade REE supply for technology and defence industries	Steenkampskraal Holdings, Private Investors
Phalaborwa REE & Phosphate Recovery	REEs, Phosphate	Limpopo	Feasibility / Early implementation (2022)	Tailings re-processing and co-product extraction	Private Investors, Mintek
Springbok Flats Lithium Exploration	Lithium (Pegmatites)	Limpopo	Exploration (active 2023-2025)	Battery supply-chain integration potential	Junior Explorers, DMRE
Graphite Exploration (Limpopo / Mpumalanga)	Graphite	Limpopo, Mpumalanga	Exploration (ongoing 2023-2025)	Scalable battery-grade graphite projects	Junior Explorers
Copper & Cobalt Clusters	Copper, Cobalt	Northern Cape, Limpopo	Feasibility / Early production (2023)	Regional supply into continental battery chains	Orion Minerals, Okiep Copper, Private Investors

Project / Cluster	Primary Mineral(s)	Location / Province	Stage of Development	Strategic Focus / Description	Lead Partners / Institutions
Karoo Uranium Projects	Uranium	Northern Cape	Exploration (renewed 2024)	Nuclear minerals for energy security	Various Exploration Firms
Titanium Beneficiation Complex	Titanium (TiO_2 Pigment)	Richards Bay IDZ, KZN	Construction / Scale-up (2023-2025)	Local manufacture of titanium-dioxide pigment for export and domestic markets	Nyanza Light Metals, IDC, RBIDZ
Phosphate & Zirconium Projects	Phosphate, Zirconium	Phalaborwa, Richards Bay	Construction / Operational (2023)	Industrial processing for fertilisers and advanced materials	Mintek, Private Sector
PGM Expansions (Bengwenyama, Waterberg, Thaba JV)	PGMs (Platinum, Chrome)	Limpopo, North West	Feasibility / Construction (2023-2025)	Large-scale PGM and chrome expansions with export impact	Ivanplats, Sibanye-Stillwater, Joint Ventures
Sishen Ultra-Dense Media Separation	Iron Ore	Northern Cape	Construction (commissioned 2024)	Premium-grade iron-ore expansion, mine-life extension	Kumba Iron Ore / Anglo American
Regional Beneficiation & Skills Hubs	Multi-commodity	National (Various SEZs)	Long-term / Implementation (2022-)	Processing facilities, skills and R&D ecosystems for batteries, hydrogen, renewables	Mintek, CSIR, MQA, TVET Colleges

Taken together, these initiatives indicate that South Africa's emerging critical minerals project pipeline is concentrated strongly around energy transition value chains, particularly battery minerals, hydrogen and fuel-cell technologies, energy storage and rare earth elements. While several projects remain at exploration, feasibility or pilot stage, the presence of initiatives extending into precursor production, mineral processing, recycling, fuel-cell manufacturing and battery technologies suggests an emerging shift beyond extraction towards greater downstream participation. The prevalence of partnerships between government institutions, research organisations and private-sector actors further indicates that development of these value chains will depend not only on mining capacity, but also on specialised technical, processing, manufacturing, research and innovation capabilities. From a skills perspective, the project landscape therefore points to growing demand for competencies spanning mineral

processing and beneficiation, battery and hydrogen technologies, advanced manufacturing, recycling and circular-economy processes, alongside the conventional exploration and mining skills required upstream.

The projects include Vaal Special Economic Zone (SEZ), which is positioning South Africa as a regional leader in battery precursor manufacture and e-mobility supply chains (Government of South Africa, 2025; UNCTAD, 2025). Similarly, the Green Hydrogen Valley is integrating mineral extraction with hydrogen fuel-cell deployment, localising manufacturing, job creation, and STEM talent pipelines along a strategic Limpopo-Gauteng-KwaZulu-Natal corridor (Government of South Africa, 2025; Parliament of South Africa, 2025). Advances in vanadium redox flow batteries, anchored in the Bushveld Igneous Complex, are enabling the country to scale grid storage facilities, while pilot beneficiation plants in the East London SEZ aim to localise vanadium electrolyte production for both regional and export markets (Bushveld Minerals, 2025; Hofmeyer, 2025).

Emerging resource frontiers, including Steenkampskraal and Phalaborwa, demonstrate the strategic role of rare earth elements (REEs) in powering the shift to renewables, electronics, and electric vehicles (Steenkampskraal Holdings, 2024; Government of South Africa, 2025). South Africa's exploration hotspots in lithium (Springbok Flats), graphite (Limpopo and Mpumalanga), copper and cobalt (Okiep, Springbok, and Limpopo), and uranium (Karoo) reflect both geographic diversification and an anticipation of global supply-demand trends for energy-transition minerals (Government of South Africa, 2025; Hofmeyer, 2025; UNCTAD, 2025).

Major expansion projects in PGMs, such as Bengwenyama, Waterberg, and the Thaba Joint Venture, illustrate the sector's capacity to scale, innovate, and contribute to global decarbonisation (Government of South Africa, 2025; Hofmeyer, 2025). Multi-commodity hubs, such as the Richards Bay Titanium Beneficiation Complex and regional beneficiation and skills hubs, emphasise the importance of cross-sector integration, skills pipelines, and policy support for inclusive, sustainable growth (Government of South Africa, 2025; Nyanza Light Metals, 2024).

What distinguishes South Africa's current landscape, both from its traditional extractive model and from many other resource-dependent economies, is the explicit integration of skills development (through Mintek, CSIR, MQA, and TVET colleges), public-private partnerships, and cross-border collaboration, especially with the DRC and Zambia, into both the design and deployment of critical-mineral projects (Government of South Africa, 2025; Hofmeyer, 2025). This approach is designed to maximise local value addition, facilitate innovation ecosystems, and establish South Africa as a strategic node within global green-technology value chains (Government of South Africa, 2025).

At the strategic level, the Critical Minerals and Metals Strategy aligns with the National Development Plan (NDP 2030), prioritising inclusive growth, job creation, poverty alleviation, and sustainable development through minerals-driven industrialisation (Government of South Africa, 2025; National Planning Commission, 2012; Parliament of South Africa, 2025). The six pillars of the strategy, namely geoscience mapping, value addition, research and skills, infrastructure and energy, financial instruments, and streamlined regulation, together with social justice, circular-economy, and environmental, social, and governance (ESG) commitments, shape both the composition and the objectives of the project pipeline (Government of South Africa, 2025; UNCTAD, 2025). These principles ensure that the utilisation of mineral resources advances broader developmental goals and strengthens South Africa's competitive position in global value chains (Government of South Africa, 2025; OECD, 2023). The next section unpacks the value chains of priority critical minerals to provide an understanding of activities and processes involved which have bearing on skills needs and training requirements.

2.4.5 Critical Minerals Value Chains

Building on the flagship projects and industrial initiatives outlined above, this section examines how South Africa's critical minerals are positioned within the broader value chain, from exploration to advanced manufacturing. Understanding this value chain structure is essential to identifying where the greatest opportunities for value addition, skills development, and industrial upgrading lie.

A critical minerals value chain encompasses the full sequence through which mineral resources are transformed from geological deposits into end-use products for modern

economies. It is typically divided into upstream, midstream, and downstream segments, each requiring specific skills, infrastructure, investment, and policy support (Government of South Africa, 2025; UNCTAD, 2025).

The upstream stage includes exploration, geological surveying, extraction, and primary processing, such as crushing, milling, and concentration. These activities determine the extent, quality, and reliability of South Africa's mineral supply.

Midstream activities involve refining, smelting, and chemical processing to produce metals, oxides, or intermediate products. This stage offers increased potential for value addition and technological innovation but remains underdeveloped for many of South Africa's minerals (Government of South Africa, 2025).

The downstream segment covers fabrication, assembly, and advanced manufacturing, transforming processed materials into products such as batteries, fuel cells, wind-turbine components, and catalytic converters for global supply chains (UNCTAD, 2025).

An increasingly important circularity stage, encompassing recycling, material recovery, and reuse. This stage is critical for improving resource efficiency, reducing waste, and strengthening supply security in alignment with sustainability objectives (OECD, 2023). The typical critical minerals value chain is illustrated in Figure 4 below.

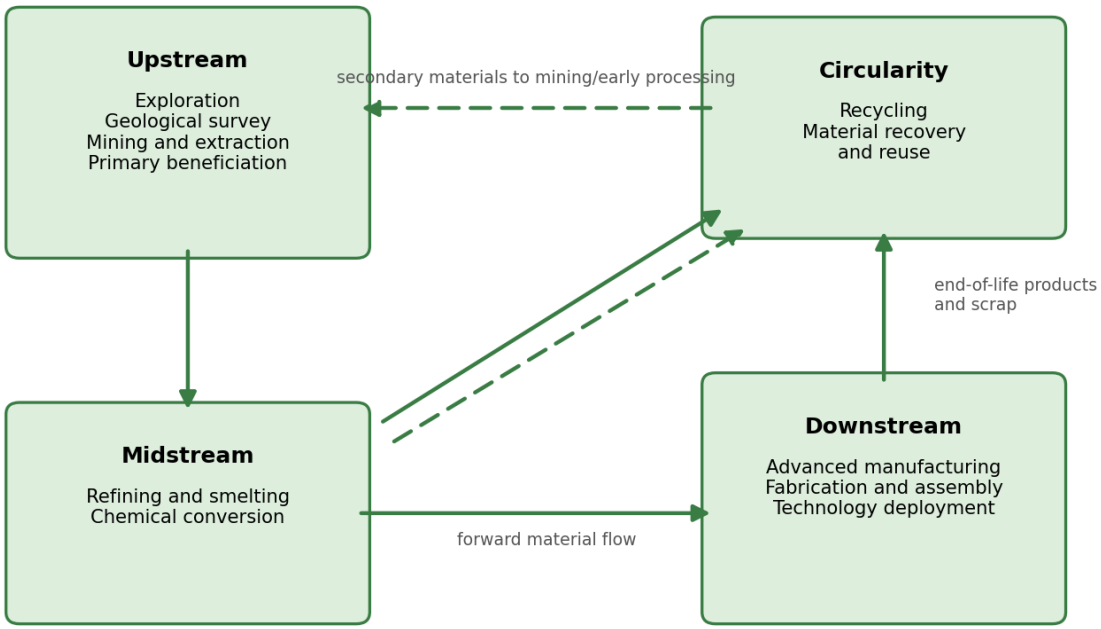


Figure 4: Stages of the critical minerals value chain

Figure 4 illustrates the structure and interconnections of the critical minerals value chain, spanning from upstream activities (exploration, geological survey, mining, and primary beneficiation) through midstream processing (refining, smelting, chemical conversion), to downstream applications (advanced manufacturing, assembly, and technology deployment). The bold, unidirectional arrows show the “forward” linear flow of mined material - moving sequentially through each stage as ore is converted to market-ready technology components.

Circularity processes, that is, recycling, recovery, and reuse, are depicted in a dedicated node, connected to the value chain through key feedback loops. Solid arrows from downstream to circularity represent the flow of end-of-life products and manufacturing scrap, which are essential inputs for recycling systems. The dashed lines from midstream to circularity signify the recovery of industrial process scrap and secondary materials generated during refining or smelting, which are often routed back into circular economy processes for further valorisation. The dashed arrow from circularity to upstream highlights that, in some instances, secondary materials or recovered metals are blended with primary ores during early processing or even in mining operations, thereby closing material loops and reducing reliance on virgin extraction.

Together, these linkages demonstrate that a circular economy for critical minerals is not a simple linear extension of the value chain, but a dynamic and multi-directional system where materials and value can “loop back” to any stage, supporting sustainability, supply security, and resource efficiency across the entire sector.

2.4.6 Value Chains and Associated Activities Within Targeted Industries

Building on the preceding value-chain framework, this section illustrates how South Africa’s critical minerals support its priority industries. Each example outlines the main stages, products, and applications, accompanied by simplified process diagrams. Together, these value chains demonstrate how raw materials are transformed into industrial and consumer products, revealing opportunities for value addition, skills development, and circularity (Government of South Africa, 2025; UNCTAD, 2025).

Across these value chains, progression from extraction to downstream production is enabled by cross-cutting infrastructure, logistics and market linkages. These include reliable energy, water and processing infrastructure; road, rail and port networks connecting extraction and processing activities to domestic and export markets; and access to downstream manufacturing and end-use markets. The strength of these linkages influences the feasibility of moving beyond mineral extraction towards beneficiation, manufacturing and other higher-value activities. The simplified value chain diagrams that follow should therefore be read alongside these enabling conditions, which connect the individual stages and shape opportunities for domestic value addition. These linkages also connect mineral production to demand in domestic, regional and international markets, with downstream market opportunities influencing where value addition and associated skills requirements emerge along the value chain.

Platinum Group Metals (PGMs) - Hydrogen and Catalytic Technologies

South Africa’s PGMs, principally platinum and iridium from the Bushveld Igneous Complex, are central to hydrogen fuel cell and catalytic converter technologies that enable low-carbon mobility and industrial decarbonisation

Purpose: PGMs form the foundation of hydrogen fuel cells, catalytic converters, and electrolysers (Government of South Africa, 2025).

Flow Diagram: Exploration - Mining - Refining - Component Manufacture - Application (Fuel Cells, Catalytic Systems) - Recycling.

Applications: Automotive catalysts, green-hydrogen production, electrochemical systems.

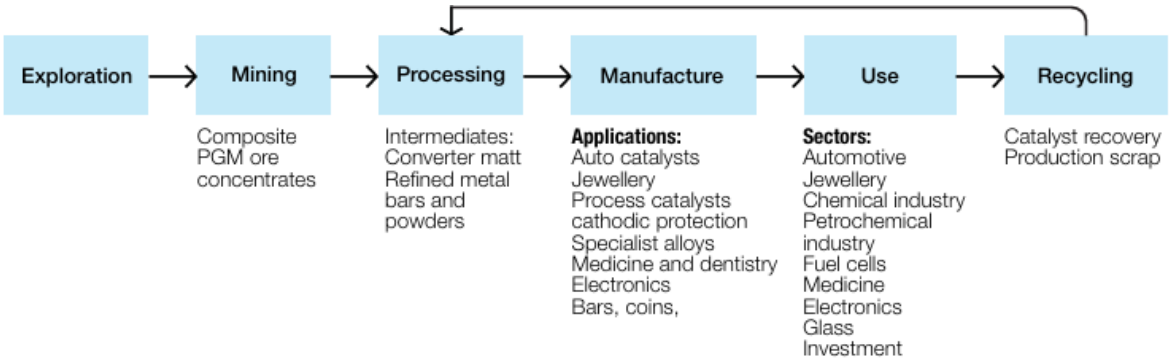


Figure 5: Simplified value chain of platinum group metals

(Image source: AGMS, 2024, p.53)

Manganese and Vanadium - Energy Storage and Alloys

Manganese from the Kalahari Field and vanadium from the Bushveld Igneous Complex strengthen South Africa's role in both alloy production and emerging battery markets. These elements support decarbonised steelmaking and grid-scale energy storage.

Purpose: Manganese and vanadium are critical for steel alloys, batteries, and grid storage (Government of South Africa, 2025; OECD, 2023).

Flow Diagram: Exploration - Mining - Beneficiation - Refining - Alloy / Battery-Material Manufacture - Industrial Use - Recycling / Reuse.

Applications: Steelmaking, vanadium redox-flow batteries, electric-vehicle batteries.

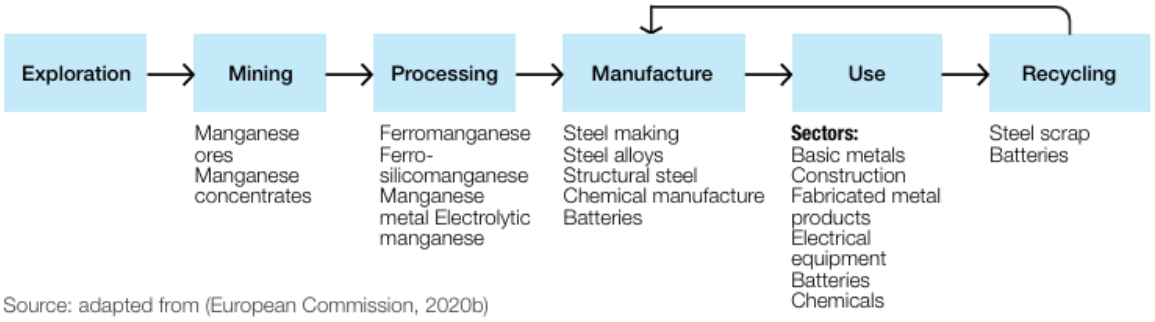


Figure 6: Simplified value chain of Manganese - Image source: AGMS, 2024, p.49

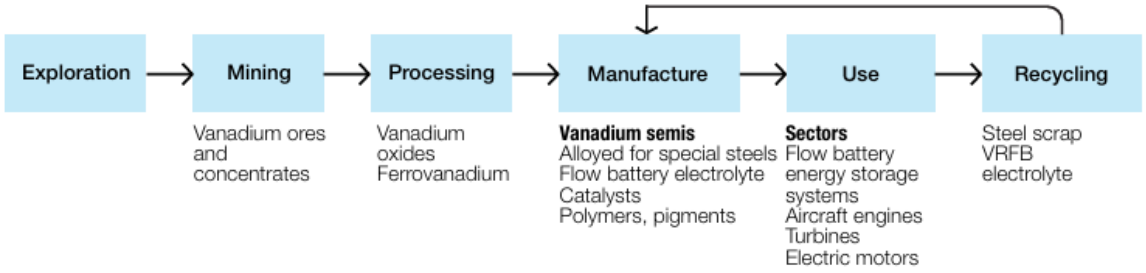


Figure 7: Simplified value chain of Vanadium - Image source: AGMS, 2024, p.55

Coal - Transitional Energy and Industrial Feedstock

Despite its declining role in global energy systems, coal remains classified as a critical mineral within South Africa's national framework due to its importance for energy generation, industrial stability, metallurgical processes, and export revenue (Government of South Africa, 2025). The strategy recognises coal's transitional role in maintaining energy security and supporting downstream industries such as steel, cement, and chemical production while renewable capacity scales up.

Purpose: Coal continues to underpin domestic power generation and energy-intensive industries, though policy now emphasises just-transition pathways and cleaner technologies (DMRE, 2025; Parliament of South Africa, 2025).

Flow Diagram: Exploration - Mining - Processing (Washing, Carbon Products) - Industrial Application (Energy, Steel, Chemicals) - Transition (Carbon Capture, Repurposing).

Applications: Electricity generation, metallurgical coke, synthetic fuels, industrial carbon feedstocks.

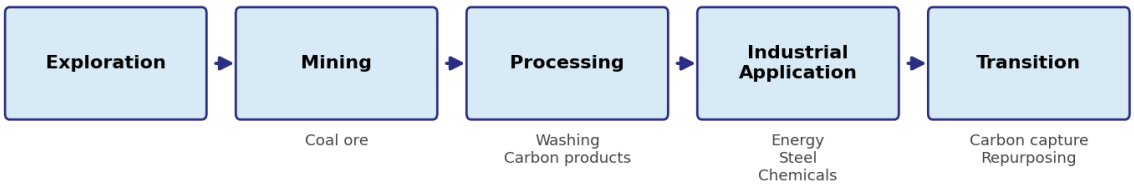


Figure 8: Simplified Coal Value Chain - Transitional Energy and Industrial Use

South Africa's inclusion of coal among its high-criticality minerals reflects a pragmatic approach to the energy transition: recognising current dependence while accelerating decarbonisation and job diversification in coal-mining regions such as Mpumalanga and Limpopo. Integrating retraining, re-employment, and local-enterprise development within these regions is central to achieving a just transition rather than a disruptive phase out (Government of South Africa, 2025).

Lithium, Cobalt, Graphite and Nickel - Battery and E-Mobility Chain

Battery minerals anchor South Africa's participation in regional e-mobility and renewable-energy value chains. They enable cell manufacturing, storage systems, and future recycling industries.

Purpose: These minerals power electric vehicles (EV) and renewable energy storage systems (UNCTAD, 2025; Government of South Africa, 2025).

Flow Diagram: Exploration - Extraction - Chemical Processing - Cathode / Anode Production - Battery Assembly - Use (EVs, Storage) - Recycling.

Applications: EV batteries, portable electronics, grid-storage systems (Government of South Africa, 2025).

Figures 9 to 12 illustrate the simplified individual value chains of lithium, cobalt, graphite and nickel.

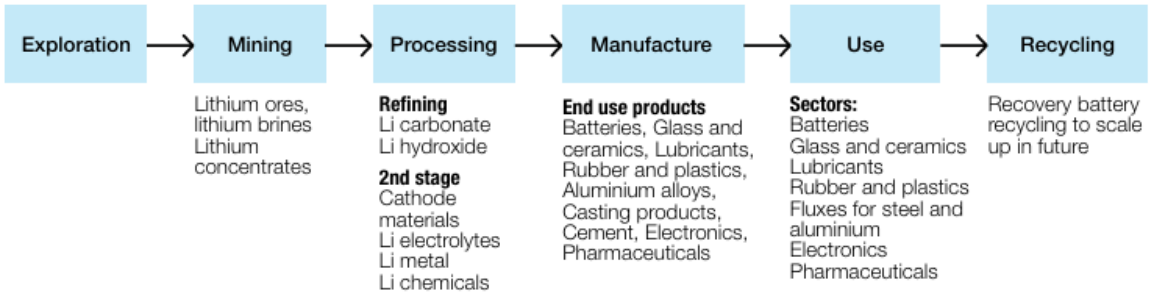


Figure 9: Simplified Lithium value chain

(Image source: AGMS, 2024, p.49)

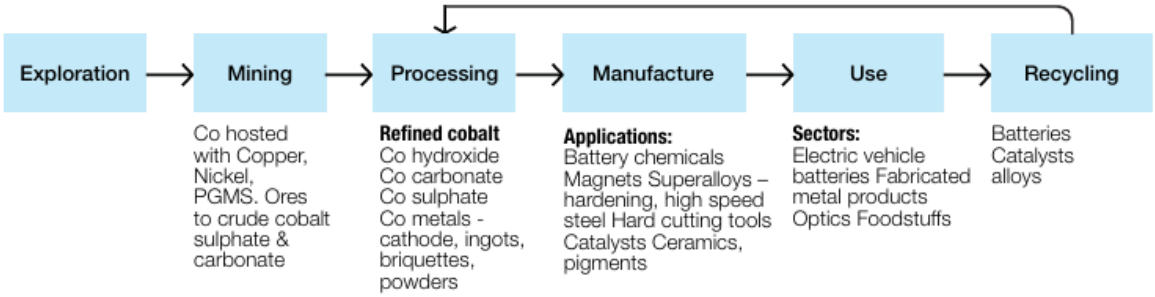


Figure 10: Simplified Cobalt value chain

(Image source: AGMS, 2024, p.43)

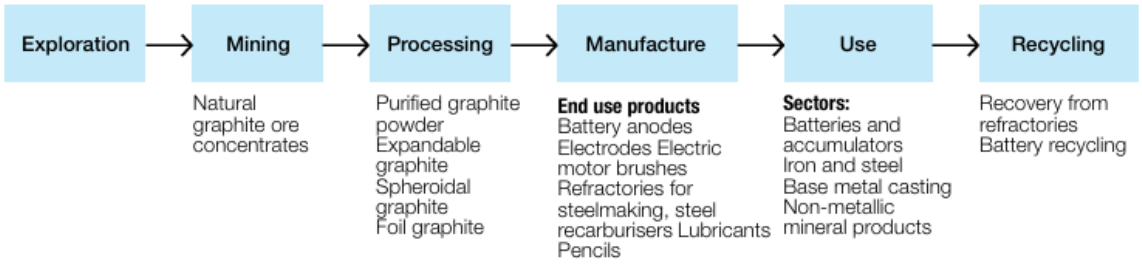


Figure 11: Simplified Graphite value chain

(Image source: AGMS, 2024, p.45)

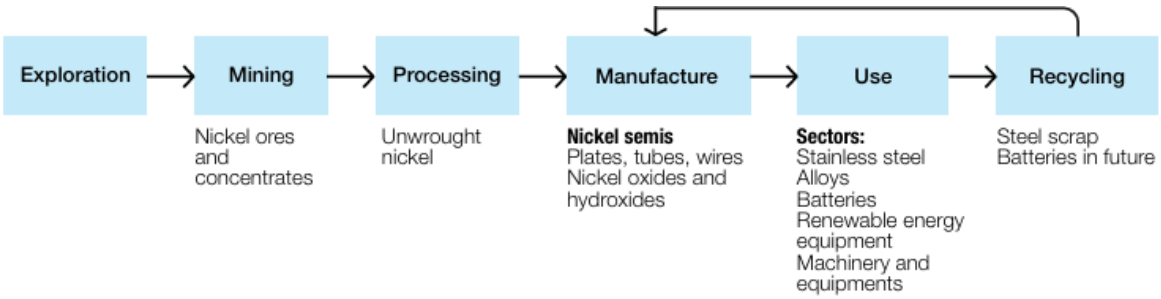


Figure 12: Simplified Nickel value chain

(Image source: AGMS, 2024, p.50)

Titanium, Zirconium and Industrial Minerals - Advanced Manufacturing

Titanium and zirconium processed at coastal Industrial Development Zones (IDZs) feed advanced manufacturing for aerospace, pigments, and ceramics. Beneficiation converts mineral sands into high-value materials for industrial and export markets.

Purpose: Used in pigments, aerospace components, and additive manufacturing (DMRE, 2025; Nyanza Light Metals, 2024).

Flow Diagram: Exploration - Mining - Processing - Metal / Compound Production - Manufacturing - Product Use - Recycling / Reprocessing.

Applications: Pigments, ceramics, aerospace materials, high-tech engineering.

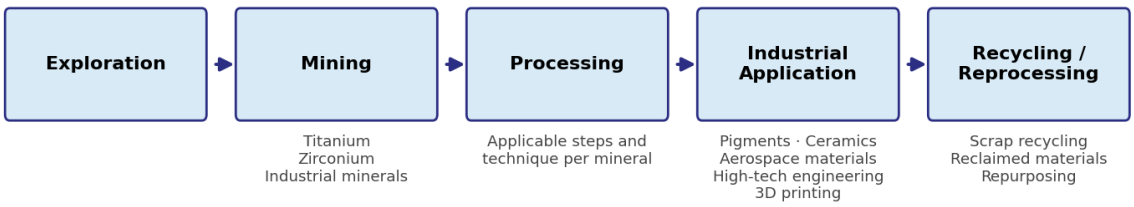


Figure 13: Simplified Titanium, Zirconium and Industrial Minerals value chain

Rare Earth Elements (REEs) - High-Tech and Renewable Applications

Rare-earth projects such as Steenkampskraal and Phalaborwa supply key inputs for magnets used in turbines, electric motors, and electronics. They are pivotal to South Africa's integration into global high-technology and renewable-energy industries.

Purpose: REEs are essential for magnets, wind turbines, and electronics (Steenkampskraal Holdings, 2024; UNCTAD, 2025).

Flow Diagram: Exploration - Mining - Separation / Refining - Magnet / Component Manufacture - Use (Electronics, Turbines) - Recycling.

Applications: Renewable energy, defence systems, information technology (Government of South Africa, 2025).

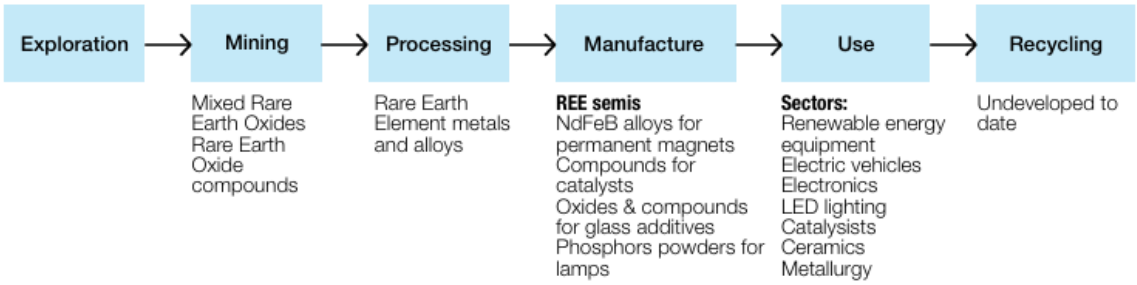


Figure 14: Simplified Rare Earth Elements value chain

(Image source: AGMS, 2024, p.54)

Cross-Cutting Circular Economy - Urban Mining and Recycling

Recycling and secondary-recovery initiatives close the loop in South Africa's critical-minerals economy, recovering metals from industrial and consumer waste to reduce environmental impact and import dependence.

Purpose: Secondary recovery of metals reduces waste and resource dependency (DMRE, 2025; UNCTAD, 2025).

Flow Diagram: Collection - Sorting - Processing - Material Recovery - Reuse - Circular Reintegration.

Applications: E-waste recycling, secondary smelting, ESG-driven manufacturing (OECD, 2023).

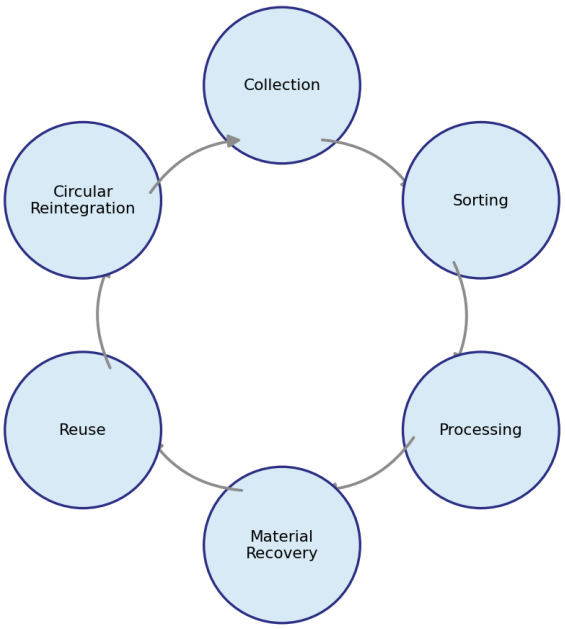


Figure 15: Simplified circular economy value chain

Together, these simplified value chains demonstrate how South Africa's critical minerals potentially enable the country's most strategic industrial sectors while enhancing opportunities for value capture, research, innovation, and green employment at every stage from mining to market (European Commission, 2020a; Government of South Africa, 2025; UNCTAD, 2025).

2.5 Skills, Research, Development and Inclusion

The successful positioning of South Africa as a strategic partner in the global green minerals economy requires substantial investment in developing people and technological capabilities, a priority reflected in Pillar III of the country's Critical Minerals and Metals Strategy (CMMS). This pillar emphasises the development of future-ready skills, strengthening research and innovation systems, and building technical and institutional capacity to support the full critical minerals value chain.

2.5.1 Skills for a Just and Sustainable Minerals Transition

While technical competencies remain essential, the future of critical minerals development depends on how effectively South Africa integrate human and environmental intelligence into their skills ecosystems. While traditional mining models have prioritised extraction efficiency;

the new minerals economy demands a more holistic capacity; one anchored in ecological resilience, ethical governance, social partnership, and digital transformation.

Critical minerals extraction increasingly occurs in ecologically and culturally sensitive regions, from arid zones and highlands to coastal and forested ecosystems, biodiversity hotspots and culturally important sites, placing unprecedented responsibility on professionals to balance extraction with conservation and community wellbeing (Franks et al., 2025; Savige et al., 2025). Additionally, critical minerals value chain operations both contribute to and are affected by climate change, as flooding, heat stress, and drought which are expected to increasingly disrupt production across Africa and Latin America (Franks et al., 2025; Savige et al. 2025). Simultaneously, the rapid rise of informal and artisanal mining of critical minerals in some countries, has expanded the sector's social and governance challenges, heightening the need for regulation, and inclusion skills (McKay, 2025).

To meet these demands, skills development must evolve from a narrow focus on mining efficiency and productivity to an integrated system that values environmental literacy, ethical leadership, and systems thinking alongside engineering excellence. Table 7 depicts the evolution of mining skills required to shift from traditional mining competencies to being strategically positioned for the critical minerals value chains.

Table 7: Evolution of Mining Skills - Comparison Between Traditional and Critical Minerals Mining and Value Chain Competencies

Skill Category	Traditional Mining Skills	Critical Minerals Mining Skills (Green / Modern Sector)
Geology & Exploration	Basic geological mapping, mineral identification, drill-core logging	Geospatial modelling, critical mineral deposit mapping, remote sensing
Engineering	Mine engineering, rock mechanics, traditional mineral processing	Battery chemistry, hydrometallurgy, recycling-process engineering, PGM / REE expertise
Environmental	Environmental impact assessment, environmental monitoring, remediation	Advanced ESG due diligence, climate risk assessment, water stewardship, biodiversity management, integration of indigenous and traditional ecological knowledge

Skill Category	Traditional Mining Skills	Critical Minerals Mining Skills (Green / Modern Sector)
Workforce & Safety	Health and safety compliance, underground rescue, first aid	Safety for automation and extreme heat; climate change adaptation; advanced ergonomics; human-factor understanding and integration
Digital & Automation	Computer-Aided Design (CAD) use, mine planning software	Data analytics, artificial intelligence (AI) / Internet of Things (IoT) integration, robotics, industrial automation, traceability systems, real-time information systems management
Regulatory / Compliance	Compliance with national mining law, permitting processes	ESG reporting, supply chain traceability, international regulatory engagement (OECD, EITI)
Policy & Social	Community relations, conflict resolution, stakeholder consultation	Critical thinking, climate / ESG policy analysis, inclusive stakeholder consultation
Artisanal / Informal Mining	Not typically addressed in formal sector	ASM formalisation, governance, anti-criminality frameworks, social protection
Climate & Carbon	Mine closure plans, air / water quality monitoring	CO_2 accounting, scenario planning, climate adaptation, just-transition design
Sustainability & Circularity	Waste management, mine closure procedures	Circular economy skills, urban mining / recycling, life cycle analysis
Research & Innovation	Laboratory assays, mineral characterisation	Advanced materials research and development (R&D), process innovation, technology transfer, Centre-of-Excellence roles

(Adapted from AGMS Pillar II, African Union, 2024; Government of South Africa, 2025)

Figure 16 shows skills relevance across critical minerals value chain stages. The heatmap (Figure 16) illustrates how key skill domains vary in importance across the upstream, midstream, and downstream stages of South Africa's critical minerals value chain. Shades of green indicate increasing relevance and sustainability intensity. The figure shows that sustainability and inclusion are now integral to upstream activities, where ESG diligence, community engagement, and climate-risk planning must inform exploration and mining. In the midstream, technical, digital, and process-engineering skills dominate due to the

complexity of beneficiation and environmental management. Downstream stages rely heavily on automation, traceability, and circular economy design to meet low-carbon and ethical manufacturing standards. Overall, the pattern demonstrates that the critical minerals workforce must combine technical proficiency, digital capability, and sustainability literacy to ensure industrial growth aligns with environmental stewardship and social equity.

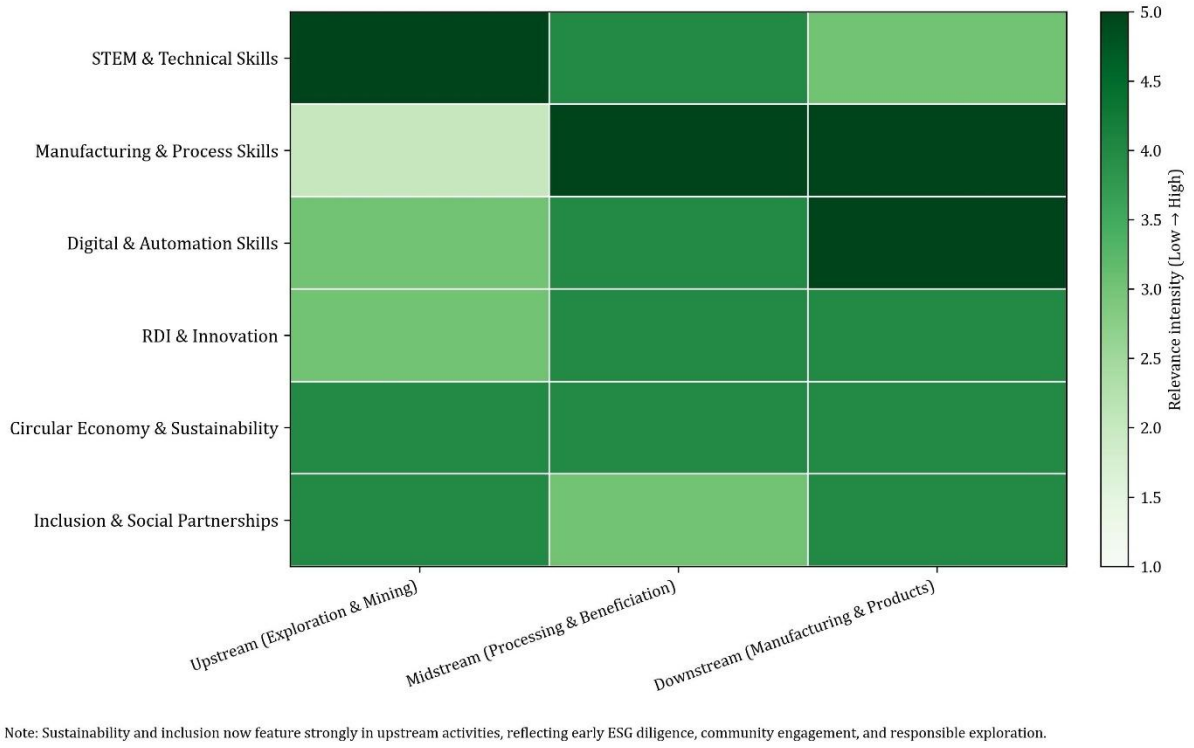


Figure 16: Skills relevance across critical minerals value chain stages

Essentially, the next generation of mining professionals must combine engineering competence with ethical intelligence and climate literacy. The challenge for South Africa is not merely producing more geologists or metallurgists, but cultivating environmental scientists, social practitioners, and policy innovators who can guide extraction within ecological limits and social legitimacy. The transition from “digging deeper” to “thinking wider” defines the future of critical-minerals leadership.

Historically, sustainability and social inclusion have been treated as downstream concerns, addressed after extraction or at project closure. In the critical minerals era, these competencies must instead be embedded from the outset of the mining cycle. For instance, engineers, geoscientists, and planners working in exploration, design, and operations require fluency in ecological sensitivity, cultural heritage protection, and community engagement.

By prioritising sustainability skills in upstream operations, South Africa can prevent the replication of past ecological degradation and social exclusion typical of legacy mining. A future-ready mining workforce must be able to restore landscapes, respect cultural values, and build social trust, not merely extract ore. To this effect, skills development must be broad, anticipatory, and rooted in a holistic understanding of environmental, social, and governance imperatives. Critical minerals mining must not replicate older social and environmental failures but instead equip the workforce with the tools for resilient, transparent, and justice-driven green industrialisation.

2.5.2 National Skills Application Framework

To operationalise these ambitions, there is a need to align education and labour-market systems with the demands of the green minerals economy. Key areas to consider include:

- **Core Science, Technology, Engineering and Mathematics (STEM) and Technical Skills:** Chemistry, metallurgy, and mechanical and electrical engineering remain foundational. Electrochemists, materials scientists, and hydrogen engineers are increasingly sought after. Because of the increasing awareness that the critical minerals economy is more than technical, there is also growing impetus for a STEAM approach; that is, the integration of Arts into the traditional STEM concept.
- **Manufacturing and Value Chain Skills:** Beneficiation and advanced manufacturing require technicians in process control, quality assurance, and automation; battery and electric vehicle assembly depend on hybrid engineering-ICT competencies.
- **Digital and Automation Capabilities:** Fourth-Industrial-Revolution (4IR) technologies underpin both productivity and ESG traceability; robotics, AI, and IoT monitoring are becoming standard practice. Coding, remote sensing, and geographic information systems (GIS) are also increasing in demand.
- **Circular Economy and Sustainability Skills:** Expertise in waste valorisation, recycling, and resource recovery ensures that mining contributes to long-term environmental resilience.
- **Inclusion and Social Partnerships:** Expanding bursaries, apprenticeships, and TVET-university collaboration for women and youth and other previously disadvantaged

groups remains vital for equitable participation in the critical minerals value chain. This must also include deliberate action towards inter-, multi-, and trans-disciplinary research and work.

Sustaining and scaling these capabilities will require deliberate and sustained investment in workforce development. This includes expanding reskilling and upskilling initiatives in STE(A)M, ESG, and research, development, and innovation (RDI), ensuring that investment in people keeps pace with advances in extraction and processing technologies. Regional Centres of Excellence and new certification and testing laboratories focussing on climate risk, inclusion, and ethical technologies are needed. The inclusion of women, youth, and local communities in STEM and ESG skills pipelines remains essential. Expanding partnerships among universities, technical and vocational education and training (TVET) colleges, and industry will be key to developing a resilient, multidisciplinary workforce capable of meeting the demands of a rapidly changing minerals economy.

More so, R&D remains a critical enabler of competitiveness within the critical minerals sector. The AGMS (2024) recommends that mineral investors allocate defined shares of payroll to science, technology, engineering and mathematics (STEM) and ESG training, and a portion of sales to research, development and innovation (RDI) (African Union, 2024). Establishing regional Centres of Excellence and testing facilities will accelerate technology transfer and quality assurance. The African Centre of Excellence for Advanced Battery Research (CAEB) in the DRC exemplifies this model and is exploring partnerships with South African universities such as Wits and Pretoria to expand electrochemistry and materials-science expertise (Kanda et al., 2023).

Within South Africa, the Critical Minerals and Metals Strategy (2025) calls for targeted R&D in battery precursors, hydrogen technologies, titanium beneficiation, and AI-enabled mining (Government of South Africa, 2025). The national RDI ecosystem, spanning Mintek, the Council for Scientific and Industrial Research (CSIR), and universities and other training institutions, is central to achieving this goal. However, under-investment in exploration and human capital renewal continues to constrain industrial competitiveness.

2.6 South Africa's Policy Environment and Stakeholder Efforts

South Africa's critical minerals development occurs within a complex policy and institutional landscape that seeks to balance economic competitiveness, sustainability, and social inclusion. The country's policy architecture has evolved to align mineral development with national industrialisation, energy transition, and skills priorities, while responding to emerging continental and global frameworks. This section reviews the policy instruments and institutional efforts shaping South Africa's participation in the critical minerals value chain, from national initiatives to continental and global partnerships (Government of South Africa, 2025; Hofmeyer, 2025; Hidayat, 2025).

2.6.1 Review of Relevant Policy Frameworks

South Africa's critical minerals policy is situated within an evolving, multi-layered policy architecture designed to integrate mineral resource management with industrialisation, skills development, the energy transition, and sustainable development objectives. Collectively, these frameworks provide the legislative, strategic, and operational foundation for aligning exploration, beneficiation, and green-skills development with both national and regional priorities (Government of South Africa, 2025; National Planning Commission, 2012; Department of Science and Innovation [DSI], 2023).

Critical Minerals and Metals Strategy (Government of South Africa, 2025120251.11)

The Department of Mineral and Petroleum Resources (DMPR) Critical Minerals and Metals Strategy (CMMS) (2025) establishes a clear roadmap for maximising South Africa's mineral endowment. It identifies 21 priority commodities and proposes six strategic pillars: geoscience and exploration; value addition and localisation; research, innovation, and skills; infrastructure and energy security; financial instruments; and regulatory harmonisation. The strategy strongly embeds circular-economy and ESG integration across these pillars, representing a deliberate shift from an export-oriented approach to one centred on beneficiation, industrial development, and green-technology innovation, with strong emphasis on skills, inclusion, and competitiveness (Government of South Africa, 2025; Hofmeyer, 2025).

As an overarching policy instrument, the CMMS provides a strength in its integrated treatment of exploration, beneficiation, research and skills, infrastructure, financing and regulatory harmonisation across the critical minerals value chain. It also creates opportunities to link South Africa's mineral endowment more deliberately to domestic value addition, green technology development and skills formation. However, the strategy's effectiveness depends on coordinated implementation across the institutions and policy instruments responsible for industrial development, skills, innovation, infrastructure and the energy transition. The alignment between these instruments is therefore critical to translating the CMMS's strategic priorities into implementable outcomes.

National Development Plan (NDP) 2030 (National Planning Commission, 2012)

The National Development Plan (NDP) 2030 positions South Africa's mineral wealth as a lever for inclusive and sustainable growth. It calls for strengthening value addition, innovation, and human capital, while identifying beneficiation and workforce transformation as essential for repositioning mining as an engine for industrial diversification and socio-economic development. The NDP identifies the need for collaborating with industry and post-school institutions to address skills mismatches and ensure that South Africa's intermediate and advanced skills base can support new technologies, green beneficiation, and a more inclusive mining sector (National Planning Commission, 2012).

Just Energy Transition Investment Plan (JET-IP) (Government of South Africa, 2023)

The Just Energy Transition Investment Plan (JET-IP) forms a cornerstone of South Africa's climate and industrial policy, mobilising public and private investment for low-carbon infrastructure, renewable energy, and reskilling initiatives. Critical minerals occupy a central role in this plan, underpinning technologies such as battery storage, hydrogen fuel systems, and electric vehicles. The JET-IP promotes social protection and just transition mechanisms for workers in coal-dependent regions while fostering innovation, local value addition, and employment creation (Government of South Africa, 2023; Parliament of South Africa, 2025).

National Skills Development Plan (NSDP, 2024) and Industrial Policy Action Plan (IPAP, DTIC, 2024)

The National Skills Development Plan (NSDP) (2024) and Industrial Policy Action Plan (IPAP) (2024) jointly address South Africa's dual challenge of skills shortages and limited industrial capacity. The NSDP prioritises technical and digital skills development aligned with future industrial demand, while the IPAP provides a framework for stimulating beneficiation, Special Economic Zone (SEZ)-based manufacturing, and localisation through targeted industrial incentives. Together, they promote stronger linkages between industry and research institutions and align domestic industrial priorities with green-economy objectives and global value-chain participation (DTIC, 2024).

Taken together, these frameworks perform complementary functions within South Africa's critical minerals policy environment. The NDP provides the overarching development rationale for mineral based industrialisation and human capital development, while the CMMS translates these priorities into a mineral-specific strategic framework. The JET-IP connects critical minerals development to the country's energy transition and reskilling agenda, while the NSDP and IPAP provide supporting skills development and industrial policy mechanisms. Their alignment is particularly evident around beneficiation, localisation, innovation, skills development and the transition towards higher value and lower carbon economic activity. The principal challenge is therefore not an absence of policy direction, but the need to coordinate these overlapping mandates and translate them into coherent implementation across the critical minerals value chain.

2.6.2 National Initiatives

While these policy frameworks establish the strategic and regulatory foundation for critical-minerals development, their success ultimately depends on coordinated implementation. The following initiatives illustrate how national departments, research institutions, and public-private partnerships are operationalising this agenda across exploration, beneficiation, infrastructure, and skills ecosystems. Together, these efforts represent South Africa's transition from a policy-based vision to an action-oriented, innovation-driven approach to mineral-led growth (Government of South Africa, 2025; Hofmeyer, 2025).

South Africa's policy ambitions are being translated into tangible programmes, institutional partnerships, and investment mechanisms designed to build capacity across the critical-minerals value chain. National initiatives now extend beyond traditional mining regulation to

include research, innovation, logistics, and workforce development, reflecting an integrated approach to mineral industrialisation and sustainability (Government of South Africa, 2025; Hofmeyer, 2025).

Department of Mineral and Petroleum Resources (DMPR)

The DMPR leads implementation of the Critical Minerals and Metals Strategy (2025) through coordinated mineral mapping, licensing reform, and beneficiation initiatives. Priority programmes include the expansion of geoscience data through the Council for Geoscience, the modernisation of the Mineral and Petroleum Rights Administration System (SAMRAD), and incentives for local processing and green-technology deployment. The DMPR also plays a central role in advancing regional collaboration under the SADC and AfCFTA frameworks, aiming to harmonise mineral governance and promote cross-border value chains (Government of South Africa, 2025).

Department of Science and Innovation (DSI) and the Hydrogen Society Roadmap

The DSI spearheads science, technology, and innovation (STI) initiatives that link mineral development to industrial and environmental outcomes. The Hydrogen Society Roadmap (2021 to 2030) connects platinum-based hydrogen technologies with decarbonisation efforts in transport, manufacturing, and energy. It supports pilot plants, industry clusters, and R&D facilities to promote localisation of hydrogen fuel-cell manufacturing, storage systems, and electrolysers (DSI, 2023). The DSI also funds technology transfer through the Technology Innovation Agency (TIA) and collaborative projects between universities, research councils, and industry (DSI, 2023; Government of South Africa, 2025).

Council for Scientific and Industrial Research (CSIR) and Mintek

Both institutions reinforce South Africa's minerals research infrastructure. CSIR drives applied research in advanced materials, automation, circular-economy modelling, and ESG analytics for mining. Mintek focuses on mineral processing, beneficiation technologies, and pilot-scale metallurgical innovation. Jointly, they support industry modernisation through partnerships with the DMRE and DTIC, targeting clean processing, resource efficiency, and recycling technologies (CSIR, 2024; Mintek, 2025).

Mining Qualifications Authority (MQA)

The MQA coordinates the mining sector's human-capital development under the National Skills Development Plan (2024). It identifies occupational shortages and develops curricula for 4IR-aligned mining, geoscience, and environmental management. The MQA is a key implementing partner in initiatives such as the Hydrogen Valley skills pipeline, the Battery Manufacturing SEZ programme, and Women in Mining and Innovation training schemes, ensuring that workforce readiness aligns with new industry demands (MQA, 2024).

Department of Trade, Industry and Competition (DTIC) and Special Economic Zones (SEZs)

The DTIC promotes localisation, industrial clustering, and export competitiveness through its Industrial Policy Action Plan (IPAP, 2024) and Special Economic Zones (SEZ) network. Flagship examples include the Vaal SEZ, dedicated to battery manufacturing and recycling; the East London SEZ, which anchors vanadium electrolyte and flow-battery production; and the Richards Bay IDZ, which supports titanium beneficiation and pigment manufacturing (DTIC, 2024). These zones act as testing grounds for industrial partnerships and technology transfer, strengthening the integration between mining, processing, and manufacturing.

Infrastructure and Logistics Reforms (Operation Vulindlela)

Through Operation Vulindlela, government addresses systemic bottlenecks in transport, energy, and water infrastructure, which areas are essential for investment in critical minerals projects. Reforms include modernising Transnet's freight corridors, enabling private-sector energy generation, and expediting regulatory approvals for industrial projects. These measures directly enhance South Africa's competitiveness in the global critical-minerals market (Operation Vulindlela, 2024).

Public-Private Partnerships and Innovation Ecosystems

Public-private collaboration remains central to scaling investment and technology adoption. Partnerships such as Anglo American's Hydrogen Valley Consortium, Bushveld Energy's Vanadium Flow Battery Initiative, and Nyanza Light Metals' Titanium Beneficiation Project

illustrate how industry aligns with national policy objectives. Collaboration with universities and R&D agencies further reinforces innovation ecosystems, particularly in hydrogen, battery, and renewable-energy technologies (Government of South Africa, 2025).

Collectively, these initiatives demonstrate the institutional relationships through which South Africa's critical minerals policy objectives are operationalised. The DMPR provides mineral policy leadership and regulatory coordination; the DSI, CSIR and Mintek support research, technological development and innovation; the MQA links emerging value chain requirements to workforce development; and the DTIC and SEZs provide mechanisms for localisation and industrial expansion. Infrastructure reforms and public-private partnerships provide further enabling conditions for investment and technology deployment. These roles are therefore complementary rather than discrete: effective implementation of the CMMS depends on coordination across the mineral, industrial, innovation, skills and infrastructure systems represented by these institutions. Together, they provide the practical mechanisms through which South Africa seeks to shift from resource extraction towards a diversified, technology-driven and inclusive critical minerals economy.

2.6.3 Continental Initiatives

South Africa's critical-minerals strategy aligns closely with continental efforts to reposition Africa as an integrated and competitive player in global green-industrial value chains. These initiatives emphasise beneficiation, regional cooperation, and harmonised governance to advance shared goals of sustainable development and industrialisation (African Union, 2025; UNECA, 2023; SADC, 2015).

At continental level, the African Green Minerals Strategy (AGMS, 2025) and the African Continental Free Trade Area (AfCFTA) provide overarching frameworks for regional value chain integration, harmonised standards, and joint beneficiation. South Africa plays a leading role in operationalising these frameworks through the African Union's critical minerals platforms and in implementing pilot initiatives that connect resource endowments with continental industrial and skills-development priorities (African Union, 2025).

African Mining Vision (AMV, 2009; reviewed 2023)

The African Mining Vision (AMV) remains Africa's guiding blueprint for mineral governance, transparency, and equitable development. It emphasises linkages between the minerals sector and other areas, including manufacturing, services, and research, to drive industrial transformation, value-chain integration, and inclusive growth. South Africa's national priorities of regional cooperation, skills development, and beneficiation closely reflect the AMV's aims (UNECA, 2023; African Union, 2024).

African Green Minerals Strategy (AGMS, 2025)

The African Green Minerals Strategy, adopted by the African Union in February 2025, represents a transformative shift in Africa's engagement with its mineral endowment. The AGMS seeks to move the continent beyond raw-mineral exports by promoting responsible mining, value addition, regional industrialisation, and robust skills development. Its four key pillars are: (1) advancing mineral development; (2) building human and technological capabilities; (3) developing strategic continental value chains (leveraging the AfCFTA for integrated trade and investment); and (4) promoting prudent mineral stewardship, including environmental, social, and governance (ESG) and circular-economy practices. South Africa's approach, with its focus on beneficiation, technology transfer, and skills harmonisation, mirrors these AGMS priorities (African Union, 2025).

African Continental Free Trade Area (AfCFTA, 2019)

The AfCFTA establishes a single continental market for goods and services, creating opportunities for cross-border mineral trade, standards harmonisation, and joint infrastructure development. For the minerals sector, it provides a framework to link upstream mining in the DRC and Zambia with downstream projects such as South Africa's battery-precursor and recycling industries, supported by shared trade and investment mechanisms (African Union, 2024).

SADC Industrialisation Strategy and Roadmap (2015-2063)

The SADC Industrialisation Strategy and Roadmap promotes regional cooperation in value addition, research, skills corridors, and infrastructure. It prioritises resource-led

industrialisation through integrated value chains, innovation partnerships, and centres of excellence. South Africa's leadership in platinum group metals (PGMs), manganese, vanadium, and battery manufacturing aligns with SADC's drive for industrial modernisation and regional R&D collaboration (SADC, 2015; African Union, 2024).

Continental Integration and Pilot Projects

South Africa actively shapes and pilots the priorities around continental integration, taking the lead in initiatives such as the DRC-Zambia-South Africa Battery Corridor, SADC Skills Corridors, and AfCFTA skills-mobility pilots. Regional special economic zones (SEZ), including the Vaal-Gauteng hub, Kolwezi in the DRC, and emerging hubs in Zambia, facilitate skills transfer and joint ventures in battery, renewable energy, and recycling technologies, demonstrating strong cross-border and institutional linkages (African Union, 2024; AfDB, 2025).

Other Key Continental Initiatives and Platforms

In addition to the flagship frameworks discussed above, several complementary continental initiatives strengthen Africa's collective capacity to manage, industrialise, and govern its critical minerals resources. These platforms reinforce the African Union's drive for policy coherence, circular-economy integration, and shared value chain participation, and are outlined below.

a) African Minerals Development Centre (AMDC). The African Minerals Development Centre (AMDC) serves as the technical agency of the African Union (AU) responsible for coordinating implementation of the African Mining Vision (AMV) and its Action Plan.

The AMDC guides mineral policy harmonisation, supports beneficiation initiatives, and assists member states in upgrading mineral inventories and attracting responsible investment. Increasingly, the Centre's work focuses on critical minerals, promoting policy reform, capacity building, infrastructure integration, and cross-border value-chain linkages aligned with the African Green Minerals Strategy (AGMS) and Agenda 2063.

b) Continental Battery Minerals Value-Chain Initiatives. Africa is advancing a network of battery-minerals platforms. These are pan-African partnerships for research, pilot projects, gigafactory investment, and shared standards for cobalt, lithium, manganese, graphite, and related battery metals. High-level forums such as the DRC-Africa Battery Metals Forum and multi-state pilot corridors promote beneficiation, regional integration, and new investment models for battery-mineral industrialisation. These initiatives are central to Africa's ambition to become a global hub for sustainable battery manufacturing and energy-storage innovation.

c) AU Circular Economy Action Plan (2024-2034). The African Union Circular Economy Action Plan (CEAP) provides a continent-wide framework for embedding circular economy principles in mining, waste management, and urban-mining practices. It aims to strengthen environmental, social, and governance (ESG) performance, build regional recycling and recovery capacity, and position Africa as a leader in responsible mineral value chains and sustainable resource management.

d) Africa-Europe Critical Raw Materials Platform and Partnerships. Strategic dialogue mechanisms such as the Africa-Europe Foundation, the Sustainable Energy for All (SEforALL) Transition Minerals Partnership, and the Africa-Europe Critical Raw Materials Platform are deepening cooperation on critical and transition minerals. These joint initiatives promote policy alignment, knowledge exchange, and capacity building, thus anchoring African priorities within European Union (EU) regulatory frameworks and enhancing Africa's participation in global green supply partnerships.

e) Africa Mining Policy Harmonisation Forums. Periodic policy and regulatory harmonisation forums, convened by the AMDC, provide member states and Regional Economic Communities (RECs) with platforms to exchange legal and technical best practices. These summits aim to develop joint negotiating frameworks for supply agreements, improve contract transparency, and increase Africa's collective bargaining power within international markets. Table 8 gives a summary of these additional continental initiatives and their associated key references.

Table 8: Summary of Additional Continental Initiatives

Initiative / Platform	Focus / Function	Key Reference
African Minerals Development Centre (AMDC)	Policy harmonisation; AMV & AGMS implementation; regional mapping; capacity building	African Union (2024)
Battery Minerals Value-Chain Platforms (Corridors, Forums)	Battery minerals research, integration, and manufacturing; pan-African coordination network	African Union (2024); AfDB (2025)
AU Circular Economy Action Plan (2024-2034)	ESG integration, recycling, urban mining, circular supply chains in minerals	African Union (2024)
Africa-Europe Critical Raw Materials Platform and Partnerships	AU-EU joint projects, technical exchange on green minerals and gigafactories	SEforALL (2024); European Commission (2025)
Continental Policy Harmonisation Forums	Legal and institutional reform; coordinated supply-negotiation frameworks	African Union (2024); AMDC (2025)

2.6.4 Global Initiatives

Globally, South Africa engages through multilateral partnerships and strategic alliances that seek to secure critical minerals supply chains, foster innovation, and strengthen responsible governance. Participation in these frameworks opens opportunities for investment, technology transfer, and collaborative research and development (R&D) while reinforcing environmental accountability, transparency, and alignment with international standards (Government of South Africa, 2025).

G20 and Minerals Security Partnership (MSP)

As 2025 G20 President and an active participant in the Minerals Security Partnership (MSP), South Africa supports global efforts to diversify supply chains and ensure sustainable resource governance. The MSP, led by major economies including the United States, Japan, and the European Union, aims to reduce supply vulnerabilities and promote ethical mineral sourcing, essential for clean-energy and digital transitions. South Africa's participation aligns with its ambition to attract investment into refining and beneficiation while promoting

environmental, social, and governance (ESG) compliance and regional value chain integration (G20 Secretariat, 2025; OECD, 2023; Hund et al., 2020).

EU-Africa Cooperation and Global Gateway

Under the EU-Africa Global Gateway Initiative, South Africa participates in dialogue and co-investment programmes focused on renewable energy, digital infrastructure, and mineral beneficiation. The partnership prioritises responsible sourcing, traceability, and green value-chain development, leveraging South Africa's established governance frameworks and technical capacity. Joint projects, such as European Union support for geodata transparency and ESG monitoring through the Council for Geoscience and the Council for Scientific and Industrial Research (CSIR), exemplify the collaboration (European Commission, 2024; Government of South Africa, 2025; Cloete et al.,2025).

BRICS Cooperation

As a founding member of BRICS (Brazil, Russia, India, China, South Africa), the country participates in joint programmes on industrialisation, mining innovation, and sustainable energy transitions. The BRICS Partnership for a New Industrial Revolution (PartNIR) advances cooperation in advanced manufacturing, clean energy, and digital transformation. Through partnerships with China, India, and Brazil (and other nations in the growing BRICS group), South Africa has expanded collaboration in mineral-processing technology, battery manufacturing, and research, directly supporting national localisation and beneficiation objectives (BRICS Secretariat, 2024; Government of South Africa, 2025).

United Nations and OECD Frameworks

At a normative level, South Africa's critical minerals policy aligns with global standards for responsible mining, transparency, and sustainability. These include adherence to the Organisation for Economic Co-operation and Development (OECD) Due Diligence Guidance for Responsible Mineral Supply Chains, the United Nations Global Compact, and the Sustainable Development Goals (SDGs). Together, these frameworks emphasise human rights, fair labour practices, community engagement, and environmental stewardship;

principles embedded within South Africa's Critical Minerals and Metals Strategy (CMMS) and its ESG commitments (United Nations, 2015; OECD, 2023).

World Bank and IMF Platforms

Through interaction with the World Bank's Climate-Smart Mining Initiative and the International Monetary Fund (IMF) Resilience and Sustainability Trust, South Africa stands to benefit from technical assistance and policy dialogue on integrating critical minerals development with decarbonisation, climate finance, and environmental resilience. These partnerships provide analytical tools and investment frameworks to help balance mineral extraction with sustainability imperatives (World Bank, 2024; IMF, 2024).

Other Relevant Global Initiatives

Beyond participation in major multilateral frameworks, South Africa contributes to a broader network of global initiatives and alliances that shape responsible critical-minerals governance, market accountability, and innovation.

- **Extractive Industries Transparency Initiative (EITI) -** Although not yet an implementing country, South Africa supports EITI principles and aligns with its requirements on disclosure, contract transparency, and beneficial ownership through multi-stakeholder engagement. Dialogue among government, industry, and civil society continues to advance adoption, with major corporates voluntarily disclosing according to EITI principles (EITI, 2025; Corruption Watch, 2022).
- **International Council on Mining and Metals (ICMM) -** South African industry leaders participate actively in this forum, which sets global standards for ESG, health and safety, environmental stewardship, and ethical conduct. Engagement helps align domestic policy guidelines with evolving global expectations, enabling access to green finance and responsible supply chains (ICMM, 2025).
- **International Energy Agency (IEA) Critical Minerals Data Collaboration -** South Africa provides data and technical input for global monitoring, forecasting, and scenario planning, particularly for energy-transition minerals such as platinum group metals

(PGMs), vanadium, and manganese. Collaboration under the IEA strengthens transparency and enhances the reliability of supply forecasts (IEA, 2024).

- **World Economic Forum (WEF) Initiatives -** South Africa participates in multi-stakeholder forums such as the Securing Minerals for the Energy Transition initiative, addressing critical minerals financing, traceability, and digital supply chain innovation. These forums enhance access to investment and risk assessment tools while aligning national responses with global market trends (World Economic Forum, 2025).
- **United Nations Principles on Critical Energy Transition Minerals -** South Africa contributes to developing emerging UN frameworks for responsible investment and supply chain management in an era of decarbonisation and digitalisation (SAIIA, 2025).
- **Bilateral Partnerships -** South Africa has concluded memoranda of understanding and technical-cooperation agreements with several mineral-importing economies, including the United States, Germany, and others, focusing on joint innovation, responsible trade, and resilient supply infrastructure (SAIIA, 2025).

Collectively, these initiatives reinforce South Africa's efforts towards transparent, accountable, and future-oriented mineral resource management. They strengthen domestic policy coherence, facilitate access to international investment and technology, and ensure that the national critical-minerals sector remains aligned with evolving global expectations for sustainable and inclusive growth (Government of South Africa, 2025; EITI, 2025; IEA, 2024). In all, the national, global and continental engagements and initiatives discussed in this section provide a strong foundation for developing the skilled workforce, research capacity, and technological innovation that bolsters South Africa's future readiness in the critical-minerals economy.

2.7 Conclusion

Critical minerals represent a strategic opportunity for South Africa to strengthen its position within global value chains and drive economic growth. The country's resource endowment places it in a favourable position; however, realising this potential depends significantly on the availability of relevant and future-oriented skills. The analysis highlights that participation in critical mineral value chains extends beyond extraction to include processing, manufacturing, and innovation-driven activities, all of which require a diverse and highly

skilled workforce. Addressing existing skills gaps, aligning education and training systems with industry needs, and fostering collaboration among government, industry, and academic institutions are essential steps toward building this capability. Ultimately, developing a responsive and agile skills ecosystem will be critical for enabling South Africa to leverage opportunities in the evolving global critical minerals landscape and to support inclusive and sustainable economic development. Building on this review, the primary research will examine how these identified skills needs and gaps manifest across the critical minerals value chain, assess the capacity of education, training and industry institutions to respond, and provide evidence to inform targeted future-ready skills development interventions.

3. RESEARCH METHODOLOGY

This section outlines the methodological approach employed in the study. It presents the conceptual framework that guided the study, the research design, the methods used to collect and analyse data, the measures taken to ensure the reliability and validity of the research, the ethical considerations observed, and the challenges encountered during the study.

3.1 Conceptual Framework

Figure 17 illustrates the conceptual framework for the study. The basis of this framework is that critical minerals are not newly discovered minerals; they are minerals that have been and are currently being mined in various countries including South Africa. What distinguishes them as "critical" is not their novelty, but their strategic importance in enabling key technologies and advancing national economic, environmental, and security objectives. In the South African context, critical minerals are those that hold the potential to support the country's economic development, job creation, and industrial advancement.

As noted, the World Bank Group (2018) projects that global demand for critical minerals may rise by as much as 500 per cent over the next 25 years. Given the nature of mining and its role in economies, this projected surge in demand presents a dual-edged scenario for mineral-rich countries like South Africa.

On the one hand, it offers economic opportunities across the critical minerals value chain, particularly in the end-use segment, where there is potential to establish industries such as renewable energy, battery storage, green hydrogen, fuel cell technologies, and advanced manufacturing. These sectors not only offer avenues for economic diversification but also play a pivotal role in supporting South Africa's transition to a low-carbon, innovation-driven economy.

On the other hand, this growth trajectory brings with it complex challenges. These include risks of environmental degradation, social disruption, health and safety concerns, and governance issues, all of which will need to be addressed if South Africa is to fully benefit from the rising demand for critical minerals. In this context, the identification of skills is grounded in understanding both the opportunities and risks associated with the critical minerals sector.

Mapping these provides a foundation for defining the core and emerging skills required to support South Africa's participation in the sector.

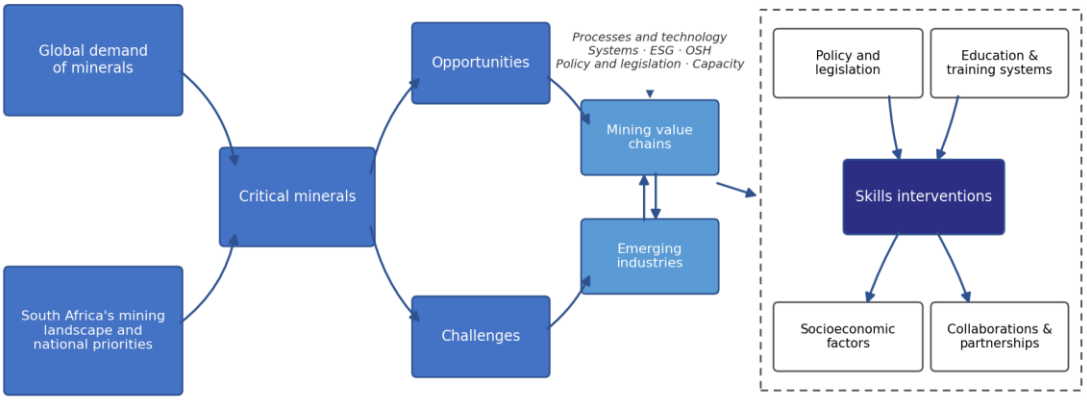


Figure 17: Conceptual framework for the study

Once the skills are identified, recommendations towards skills interventions need to consider overarching aspects such as existing policy and legislative frameworks that govern skills development, capacity of the education and training system, socioeconomic considerations and opportunities for collaboration and partnerships across different stakeholders. This conceptual framework guided both the data collection and the analysis of findings.

3.2 Research Design

The study employed a mixed method research approach. This encompasses the use of both qualitative and quantitative research methods to respond to research questions (Kemper et al. 2003). This method was selected because it takes advantage of the strengths of various methods, ensuring a well-rounded understanding of the issues being investigated. Its main benefit is that it can study a phenomenon from different perspectives, leading to a comprehensive understanding of the subject matter.

Qualitative methods, as used in the study, are designed to gather non-numeric data which is critical in understanding the nuanced aspects of the research topic (Sardana et al. 2023). Quantitative methods, on the other hand, involve the collection of data (i.e., both numeric and categorical) that can be analysed statistically, providing insights that are measurable

(Sardana et al. 2023). Practically, this method was deemed suitable to provide understanding of skills development, which is a multifaceted issue affecting different stakeholders.

3.3 Data Collection Methods

The study incorporated both primary and secondary data sources. Secondary data was gathered through a systematic review of existing literature, policy documents, and strategic frameworks. This process involved identifying, evaluating, and synthesising relevant materials to inform various components of the study (Carrera-Rivera et al., 2022). The outcome of this process is presented in section 2 of this report.

Primary data was collected through a combination of online surveys, key informant interviews, and a webinar. Because this study is exploratory in nature, the overall population size was unknown, and therefore a precise sample size could not be predetermined. While this is the case, the survey was widely distributed to a range of stakeholders in the mining and minerals sector. Several platforms were used to disseminate the survey and these include the research team's *own* industry networks, stakeholder database developed for the study composed of professionals who have done work on critical minerals, social media platforms (i.e., the survey was posted on LinkedIn). The survey was also distributed to the MQA's WSP-ATR database. Despite efforts to distribute the survey widely, several potential respondents indicated that they had limited knowledge of critical minerals and related value chains, which affected their ability to participate in the survey. The survey can be accessed on this link: xxxx.

A total of 36 survey responses were received from stakeholders across the critical minerals' ecosystem. While the sample size is relatively small, the results provide a foundation for understanding emerging skills needs and dynamics within the critical minerals value chain in South Africa - highlighting aspects that need attention. The surveys were complemented by eighteen (18) in-depth interviews, which provided deeper qualitative insights. The distribution of interviews across stakeholder groups is presented below (i.e., see table 9). Insights were obtained from a wide range of stakeholder groups including government, academia, mining companies and industry bodies, research institutions, and community representatives.

Purposive and snowball sampling were used to gather research participants. Purposive sampling was necessary as nuanced experience and information relating to South Africa's mines and minerals sector was crucial to the research. Snowball sampling was achieved through participant referrals. Amongst the advantages of this method is that it ensures access to participants that may be unknown and/or difficult to reach (Naderifar et al., 2017). Key informant interviews were conducted between November 2025 and May 2026.

Table 9: Distribution of key informant interviews across stakeholder groups

Stakeholder group	No. of interviews
Government	1
Academia	7
Mining companies and industry bodies	6
Research institutions	2
Community	2

Following the key informant interviews, the research was subjected to a stakeholder validation webinar in the form of an online Critical Minerals Webinar, hosted by the Wits Mining Institute and the Mining Qualifications Authority in May 2026. The webinar was attended by 35 individuals, with 54 having registered interest in attending the event. Participants included executive management from mining houses, technical leads from science councils, leaders from industry organisations, community representatives, stakeholders from ASM, and academic heads and researchers from leading universities. The webinar served as a research validation and additional data collection platform.

The use of three complementary data collection methods ensured triangulation of findings, thereby enhancing the reliability and depth of the analysis, and enabling a more comprehensive understanding of skills requirements within South Africa's critical minerals value chains.

3.4 Data Analysis Methods

Data collected through the survey was analysed quantitatively to identify trends and patterns across stakeholder responses. Descriptive statistical techniques, including frequency and percentage distributions and mean ratings, were applied to the closed-ended questions, while

multiple-response questions were analysed by tallying the number of respondents selecting each option. Open-ended survey responses and data obtained from key informant interviews were analysed using thematic analysis, which is a method for identifying, analysing, and reporting patterns (themes) within data (Clarke and Braun, 2014).

3.5 Research Reliability and Validity

Research reliability and validity are important measures in research that ensure the quality and trustworthiness of the research and findings being presented (Kaman and Othman, 2016). There are various methods that can be used to establish validity and reliability of quantitative and qualitative research. In this study, reliability and validity were established through the use of the triangulation method. There are different triangulation methods - data triangulation (i.e., the use of multiple data), investigator triangulation (i.e., involving multiple researchers collecting and analysing the data), theory triangulation (i.e., application of multiple theories to test the findings) and methodological triangulation (i.e., the use of different approaches to collect and analyse data) (Arias, 2022). This research study used multiple sources of data (i.e., secondary and primary data) as well as different investigators to collect, analyse and cross-check the data.

3.6 Ethical Considerations

The study was conducted in accordance with the University's ethical requirements, and the ethics application was submitted to the University's Human Research Ethics Committee. The key aspects of ethics adhered to are:

- **Risk level** - The risk associated with the study is minimal. As defined by the University, minimal risk encompasses research where questions are posed to solicit the perspectives of the participants on aspects relevant to the study. The participants were not asked to provide personal information.
- **Anonymity** - This could not be guaranteed during data collection because of the sampling techniques and data collection methods used in the study. Anonymity is maintained in this report: the study findings are presented in a generalised and aggregated format to protect participant identities.

- **Confidentiality** - This could not be guaranteed because the data collected from the study is compiled into a report and submitted to MQA.
- **Consent** - Informed consent was obtained from all participants prior to their participation in the study. Participants were provided with information about the study and the nature of their participation and were given an opportunity to ask questions and seek clarity on aspects that were not clear. Consent to participate was recorded at the start of the survey instrument.

3.7 Limitations and Delimitations of the Study

3.7.1 Limitations of the study

The study faced several challenges, primarily related to stakeholder availability and participation. Engagement with key stakeholders was constrained by factors beyond the researchers' control, including limited availability. To ensure representation across the different stakeholder groups, the research team made concerted efforts to reach a broad range of participants and leveraged existing professional networks to enhance participation. As a result, an adequate number of interviews were conducted, which helped to complement the relatively low number of completed surveys. More insights were also gathered through the stakeholder validation webinar, which added more information and helped strengthen the findings.

The final survey sample was limited, partly due to feedback from potential participants who indicated that they did not feel sufficiently knowledgeable or confident in their understanding of critical minerals to complete the survey. While this affected the survey completion rate, it also highlights a broader issue of limited awareness and understanding of critical minerals across certain stakeholder groups. In response, it was highlighted to government (i.e., Department of Minerals and Petroleum Resources) that there is a need for knowledge-sharing sessions to improve awareness and understanding of the country's critical minerals and metals strategy.

3.7.2 Delimitations of the study

The main delimitation of the study is that the findings are primarily based on the views and experiences of stakeholders who participated in the surveys, interviews, and validation webinar. As a result, the insights may not fully represent the perspectives of all stakeholders within South Africa's critical minerals ecosystem. While efforts were made to engage a diverse range of participants from across the sector, the study findings should be interpreted within the context of the stakeholder groups that contributed to the research.

4. STUDY RESULTS: STAKEHOLDER SURVEYS

4.1 Introduction

This section presents the results of the stakeholder survey. The survey was designed to gather stakeholders' perspectives on a range of issues related to critical minerals, including levels of awareness and understanding, the importance of critical minerals to South Africa, the availability of current skills, existing and emerging skills gaps, training and institutional requirements, and interventions required to build a skilled workforce for the MMS.

4.2 Respondent Profile

Figure 18 presents the distribution of respondents by organisation type. Mining companies (12 respondents; 33%) and academia/training providers (11; 31%) together accounted for almost two thirds of the sample. The remainder comprised civil society organisations (3; 8%), industry associations (2; 6%), and one respondent each from a professional body, government, and an exploration company. Five respondents (14%) selected “other”, specifying consulting and engineering firms, a research organisation, a mining labour organisation, and one respondent with a combined mining, academic, manufacturing and regulatory background. The sample captured perspectives from across the value chain.

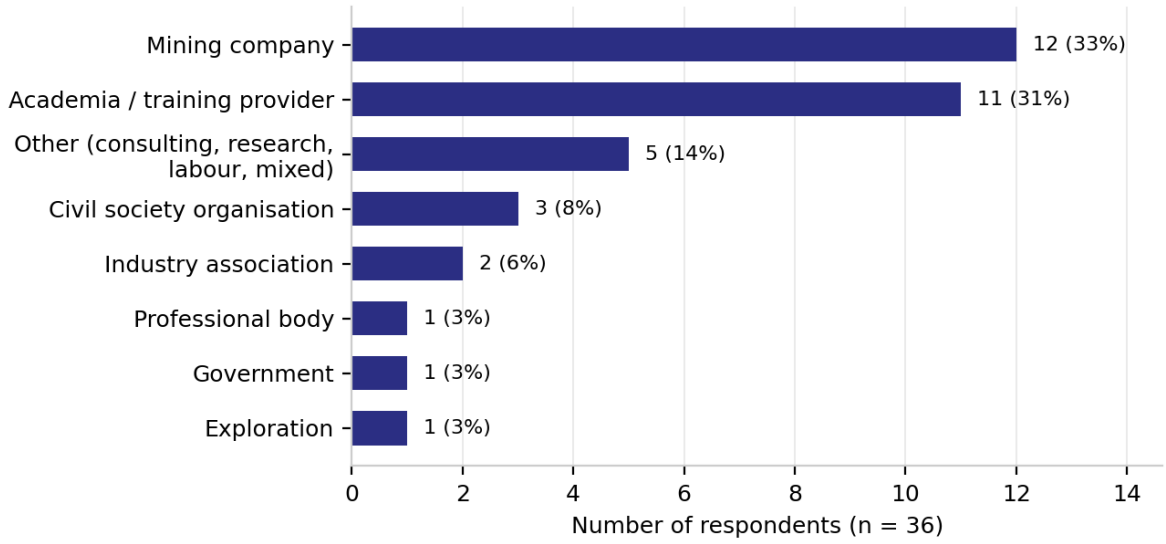


Figure 18: Distribution of respondents by organisation type (n = 36)

In terms of roles, eleven identified as executives or senior managers and eleven as researchers, with a further four technical specialists and three educators/trainers. Respondents selecting "other" included a director, a programmes officer, a community advocacy practitioner, an explosives technician, and a student. Figure 19a shows the working experience of the respondents. Of the total respondents, 24 respondents (67%) reported more than ten years of experience in the mining and minerals sector, of whom 13 (36%) reported more than twenty years. Only four respondents (11%) had less than five years of experience. Overall, the sample comprises experienced respondents.

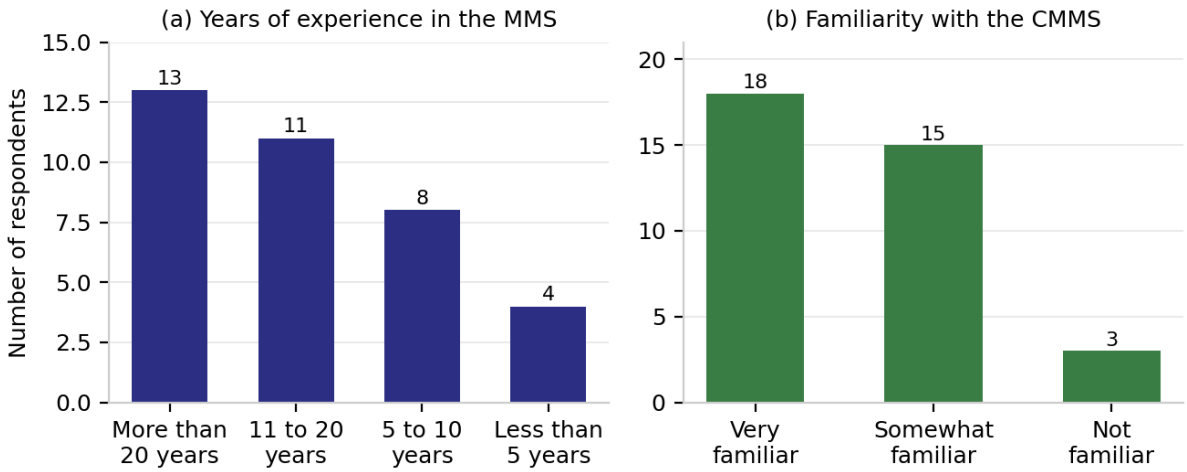


Figure 19: Respondents' (a) years of experience in the mining and minerals sector and (b) familiarity with South Africa's Critical Minerals and Metals Strategy (n = 36)

4.3 Awareness and Perceived Strategic Importance of Critical Minerals

Figure 19b shows the level of familiarity with South Africa's Critical Minerals and Metals Strategy (CMMS). As seen on the figure, familiarity with the strategy is relatively high. Half of the respondents (18; 50%) indicated that they were very familiar with the strategy and a further 15 (42%) were somewhat familiar; only three respondents (8%) were not familiar with it. Given that the CMMS was published in 2025, this level of awareness amongst sector stakeholders is encouraging, though the presence of respondents unfamiliar with the strategy suggests that more dissemination is necessary, particularly beyond the policy and research community.

In terms of the perceptions of the importance of critical minerals for South Africa's economic growth, the responses were near-unanimous. Of the 34 respondents who answered this

question, 25 rated critical minerals as extremely important and 8 as important; only one respondent was neutral, and none considered them unimportant. This strong consensus across mining, academia, civil society, and industry associations mirrors the positioning of critical minerals in the national strategy as instruments for economic development, job creation and industrial advancement (DMPR, 2025), and confirms that the strategic framing of the sector resonates with stakeholders on the ground.

4.4 Mineral and Industry Priorities

4.4.1 Minerals Expected to Be in Highest Demand

Respondents were asked which critical minerals they believe will have the highest demand over the next ten years (Figure 20). Rare earth elements were selected most frequently (28; 78%), followed by platinum (25; 69%) and manganese (23; 64%). Iron ore (18; 50%), coal and chrome (17 each; 47%), gold (16; 44%), vanadium (15; 42%) and palladium (12; 33%) were also commonly selected. These selections align closely with the minerals identified in the high and moderate-to-high criticality tiers of the CMMS (see Table 2) and with the global demand outlook for energy-transition minerals discussed in Section 2.3.

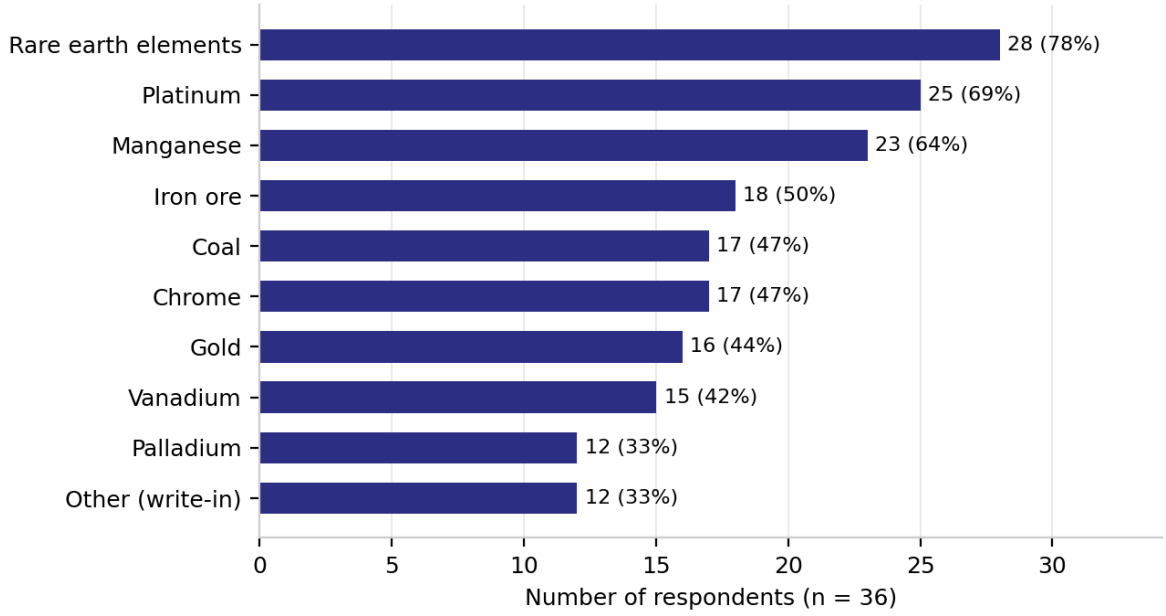


Figure 20: Minerals expected to be in highest demand over the next ten years (multiple responses; n = 36)

Notably, a third of respondents (12; 33%) used the “other” option to write in additional minerals, most frequently copper and cobalt (eight mentions each), lithium (seven) and nickel (five). The prominence of copper in the write-in responses is striking given that copper was not offered as a pre-coded option in this question and is classified only as a moderate-criticality mineral in the national strategy. The write-in pattern suggests stakeholders perceive battery and conductor minerals as rising faster in strategic importance than their current classification implies, supporting the CMMS’s own provision that the criticality classification is dynamic and subject to periodic review (Government of South Africa, 2025).

4.4.2 Minerals South Africa Should Prioritise

When asked which minerals South Africa should prioritise given global demand trends, local resource availability, and industrial development potential (Figure 21), respondents most frequently selected platinum group metals (27; 75%), manganese (25; 69%), rare earth elements and lithium (22 each; 61%), and chrome (18; 50%). Iron ore (13), vanadium, coal and cobalt (12 each), titanium (10) and nickel (7) followed. Copper was again written in by several respondents. One qualitative comment warrants attention: a respondent cautioned that prioritisation should distinguish between “current” minerals and “future-facing” minerals with large future potential.

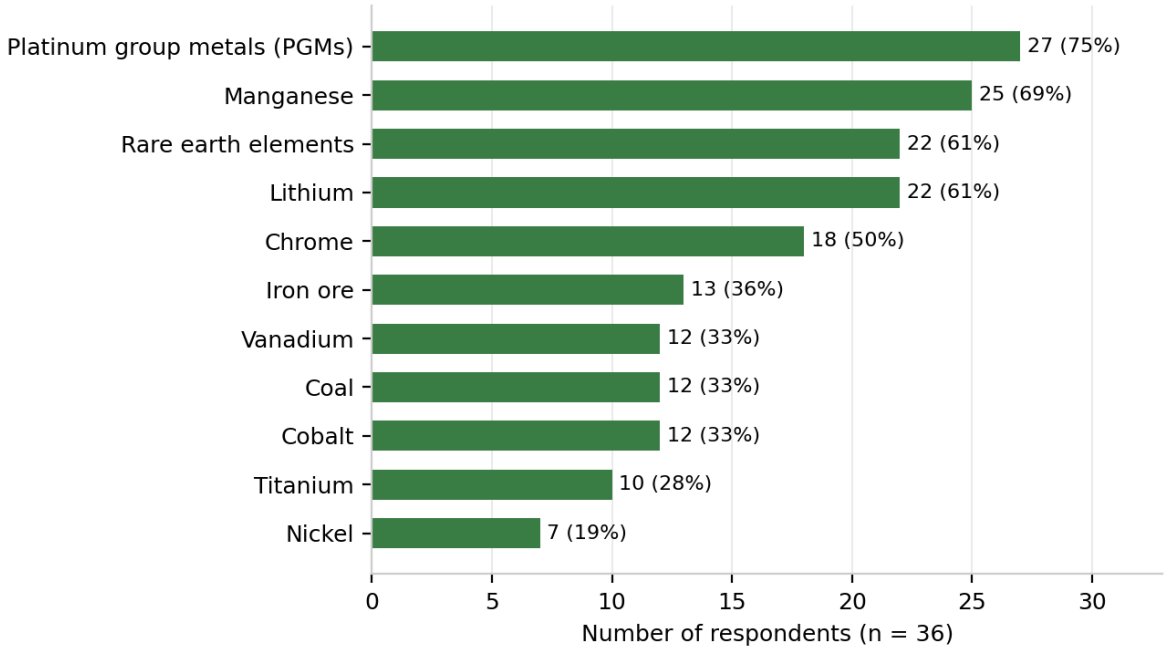


Figure 21: Minerals respondents believe South Africa should prioritise (multiple responses; n = 36)

The combination of established strengths (PGMs, manganese, chrome) and emerging battery minerals (lithium, REEs, cobalt) in the stakeholder priority set reflects the dual structure of South Africa's comparative advantage described in Section 2.4: world-class endowments in the Bushveld Igneous Complex and Kalahari Manganese Field on the one hand, and new exploration frontiers in the Springbok Flats, Steenkampskraal and Phalaborwa on the other.

4.4.3 Priority Industries for Investment

Respondents identified renewable energy systems (28; 78%), hydrogen and fuel cells (23; 64%), digital and information technologies (22; 61%) and battery manufacturing (21; 58%) as the key industries toward which South Africa should direct investment, with advanced manufacturing selected by a third of respondents (12; 33%) (Figure 22). Write-in responses added the revival of steel production focused on supplying African markets. These priorities correspond directly to the end-use industries that anchor the critical minerals value chains reviewed in literature (hydrogen and catalytic technologies for PGMs; energy storage for manganese and vanadium; the battery and e-mobility chain for lithium, cobalt, graphite and nickel), indicating stakeholder alignment with the industrial logic of the national strategy.

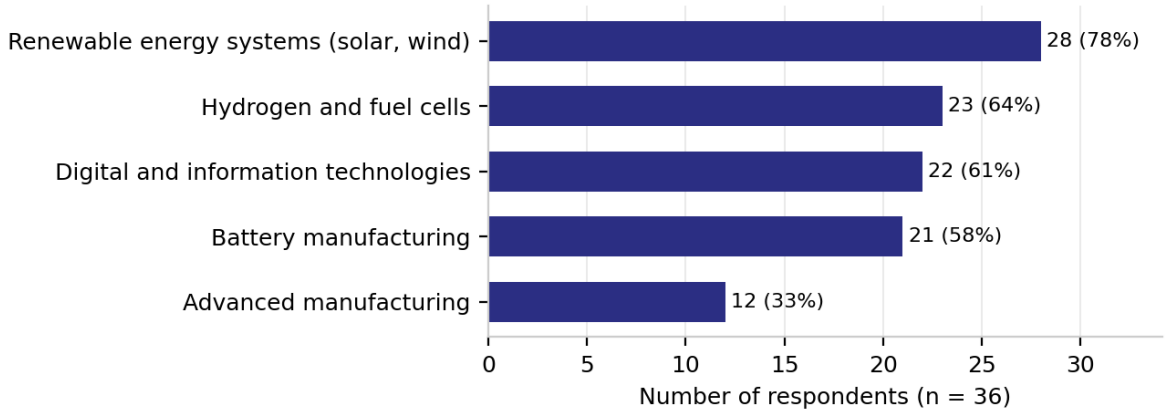


Figure 22: Key industries toward which South Africa should direct investment (multiple responses; n = 36)

4.5 Skills Requirements for the Critical Minerals Value Chain

Respondents were asked which technical and non-technical skills are most needed to support the critical minerals value chains (Figure 23). Amongst technical skills, processing and beneficiation and manufacturing and downstream applications were each selected by 28 respondents (78%), clearly ahead of mining itself (24; 67%). Automation and robotics and geoscience mapping and exploration were each selected by 21 respondents (58%), followed by recycling and circular economy and data analytics and AI (20 each; 56%) and ESG and sustainability (19; 53%). Occupational health and safety, while fundamental to the sector, was selected by 13 respondents (36%), likely reflecting a perception that this is an area of existing strength rather than emerging need.

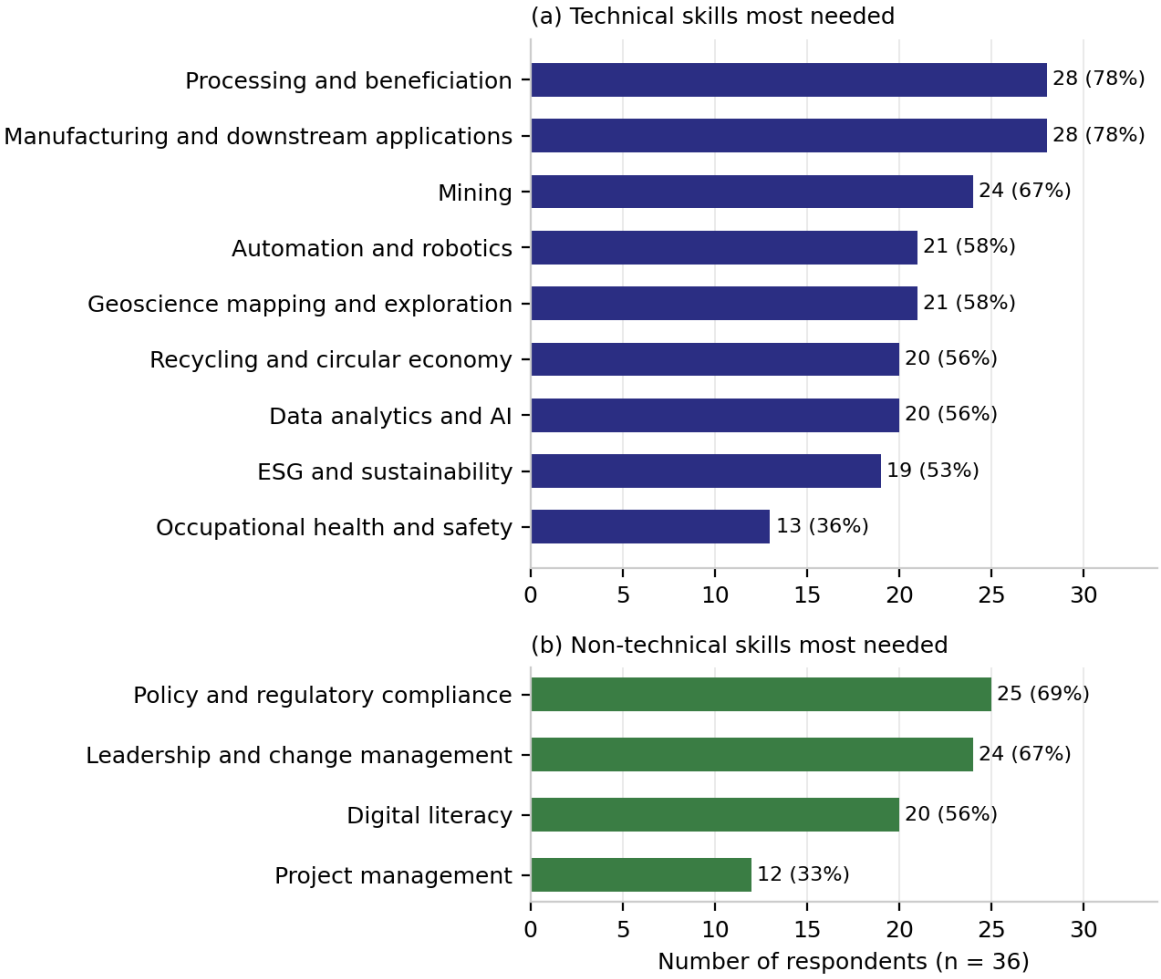


Figure 23: (a) Technical and (b) non-technical skills most needed to support the critical minerals value chains (multiple responses; n = 36)

Overall, stakeholders see the greatest skills needs in the midstream and downstream segments of the value chain (i.e., processing, beneficiation, manufacturing) and in the 4IR-related domains of automation, robotics, data analytics and AI. This corresponds closely with the evolution of mining skills described in the literature, in which competencies such as hydrometallurgy, battery chemistry, recycling-process engineering, data analytics and industrial automation distinguish the critical minerals era from traditional mining (African Union, 2024; Government of South Africa, 2025).

Amongst non-technical skills, policy and regulatory compliance (25; 69%) and leadership and change management (24; 67%) led, followed by digital literacy (20; 56%) and project management (12; 33%). The prominence of policy and regulatory compliance is consistent with the tightening ESG, traceability and reporting requirements discussed in literature, while

the emphasis on leadership and change management speaks to the scale of organisational transformation the sector faces. One respondent observed that all the listed skills are relevant; however, identification of specialised skills will depend on the targeted mineral, its value chain and end-use products. Essentially, skills planning will need to be anchored within interested value chains.

4.6 Workforce Competency Assessment

Respondents rated the competency levels of the current mining and minerals sector workforce across ten domains on a five-point scale from “poor” to “very good”. Figure 24 presents the full distribution of ratings, ordered by mean score (where poor = 1 and very good = 5), and Table 10 summarises the mean ratings.

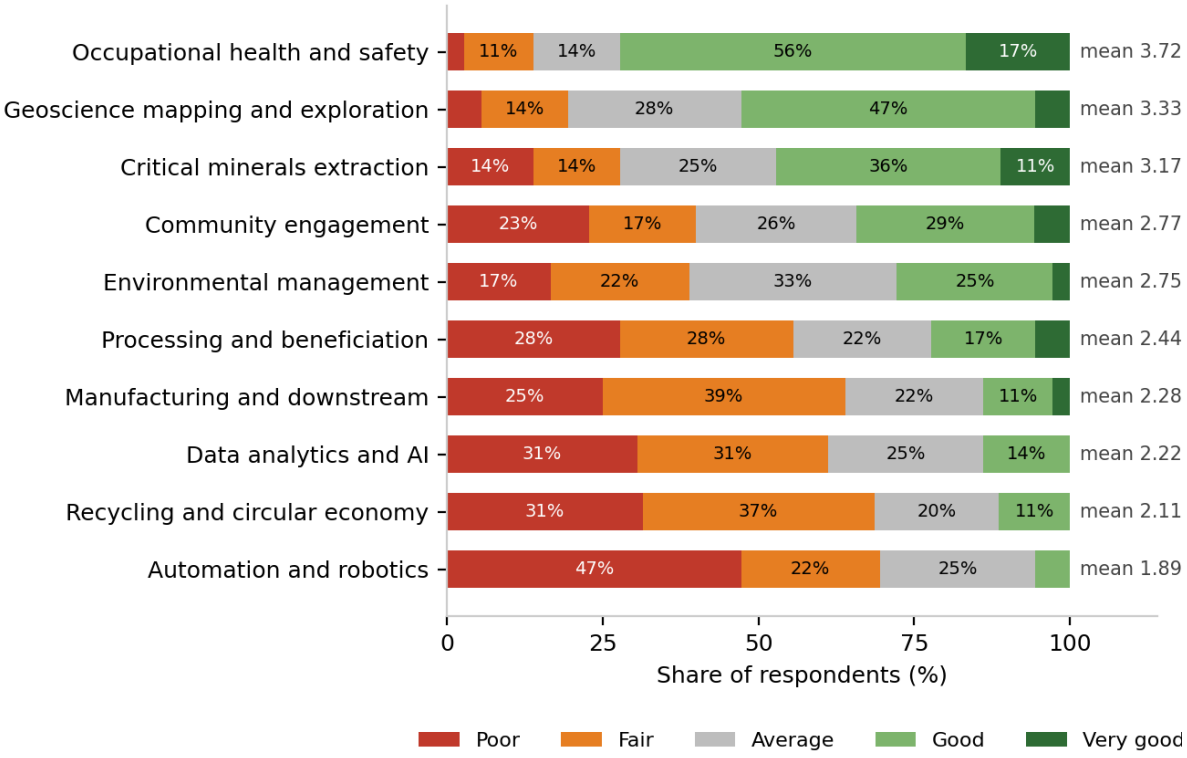


Figure 24: Ratings of current workforce competency by domain, ordered by mean score (n = 35 - 36 per item)

Table 10: Mean workforce competency ratings by domain (poor = 1; very good = 5)

Competency domain	Mean rating	Share rating "poor" or "fair"
Occupational health and safety	3.72	14%
Geoscience mapping and exploration	3.33	19%
Technical skills in critical minerals extraction	3.17	28%
Community engagement	2.77	40%
Environmental management	2.75	39%
Processing and beneficiation expertise	2.44	56%
Manufacturing and downstream applications	2.28	64%
Data analytics and AI	2.22	61%
Recycling and circular economy	2.11	69%
Automation and robotics	1.89	69%

The results reveal a consistent competency gradient along the value chain. The workforce is rated strongest in the traditional, upstream and compliance-driven domains: occupational health and safety (mean 3.72, with 72% of respondents rating it good or very good), geoscience mapping and exploration (3.33) and extraction (3.17). Ratings decline through the social and environmental domains, in particular, community engagement (2.77) and environmental management (2.75) and fall sharply in the midstream, downstream and digital domains: processing and beneficiation (2.44), manufacturing and downstream applications (2.28), data analytics and AI (2.22), recycling and circular economy (2.11), and automation and robotics, the weakest-rated domain at 1.89, with 47% of respondents rating the workforce "poor" in this area and not a single "very good" rating.

The results indicate that South Africa is characterised by strong upstream capabilities, alongside uneven and underdeveloped midstream and downstream capacity. The competency assessment suggests that the country's value-chain position and its skills base are mutually reinforcing; the workforce is strong where the industry has historically operated, and weak where the national strategy seeks to expand. The relatively weak ratings for community engagement and environmental management are also noteworthy given the

centrality of social licence, ESG diligence and just-transition considerations to the critical minerals era (Franks et al., 2025; ILO, 2015).

4.7 Skills Gaps and Priority Intervention Areas

Consistent with the competency ratings, respondents located the biggest skills gaps in the current workforce in processing and beneficiation (22; 61%), automation and robotics (21; 58%), data analytics and AI (20; 56%), manufacturing and downstream applications (18; 50%) and community engagement (17; 47%) (Figure 25(a)). Gaps in extraction (14), recycling and circular economy (13), geoscience (8) and environmental management (8) were cited less frequently, and only one respondent identified occupational health and safety as a major gap. Write-in responses highlighted ESG considerations, including responsible "cradle-to-cradle" mining, which fall within the domain of ESG-related skills focused on long-term development and environmental sustainability in the context of climate change.

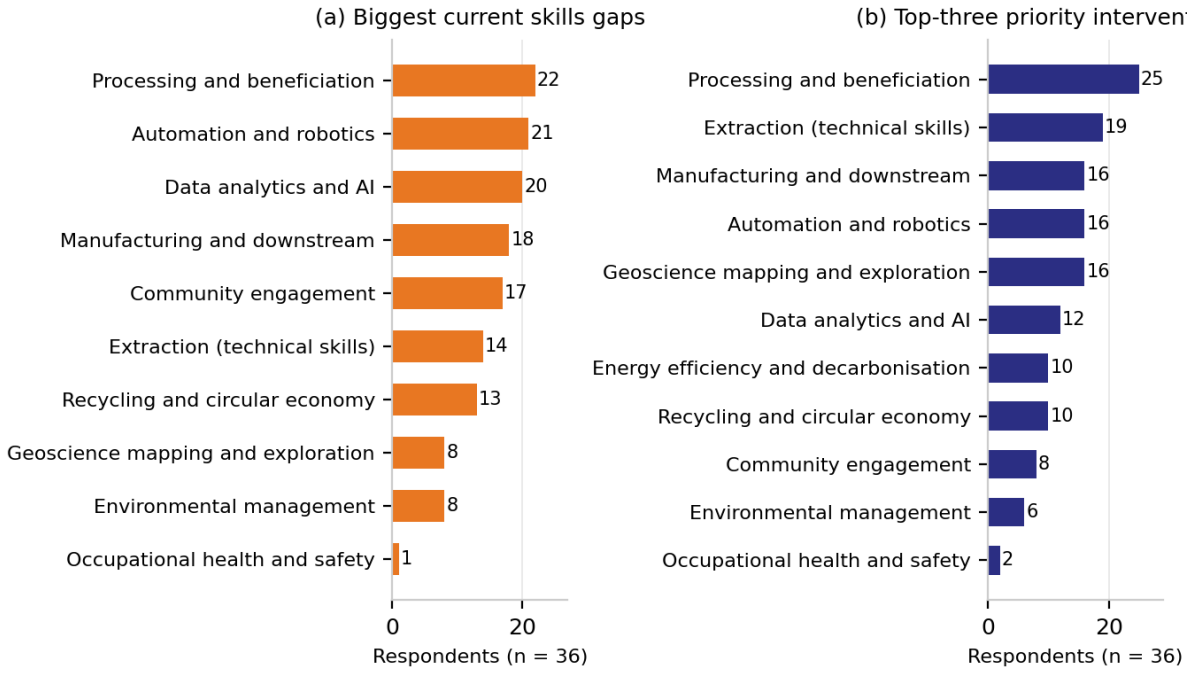


Figure 25: (a) Biggest skills gaps in the current workforce and (b) areas to prioritise for skills development interventions (top three; multiple responses; n = 36)

When asked to select the top three areas that should be prioritised for skills development interventions (Figure 26(b)), respondents again placed processing and beneficiation first (25; 69%), followed by technical skills in critical minerals extraction (19; 53%), and then

manufacturing and downstream applications, automation and robotics, and geoscience mapping and exploration (16 each; 44%). Data analytics and AI (12), energy efficiency and decarbonisation (10), recycling and circular economy (10), community engagement (8) and environmental management (6) completed the list.

Two main points come out when comparing the gaps and priorities. First, processing and beneficiation are the focus of the sector. They are seen as the most important technical skill, one of the weakest areas currently, the most common gap, and the top priority for improvement. Second, although extraction skills were not among the most identified gaps, they are ranked as the second priority for intervention. This suggests that stakeholders see the need to maintain and strengthen core mining skills as a foundation, even while developing new midstream, downstream, and digital capabilities. This shows a dual need: to maintain strong upstream capabilities while also building skills in beneficiation and 4IR technologies. This reflects what the literature describes as a layered skills approach, where new skills are added to existing ones rather than replacing them (AGMS, 2024).

4.8 Responsiveness of the Current Training Curriculum

Respondents were asked to rate their agreement with six statements about the responsiveness of the current training curriculum to the needs of the critical minerals value chain (Figure 26).

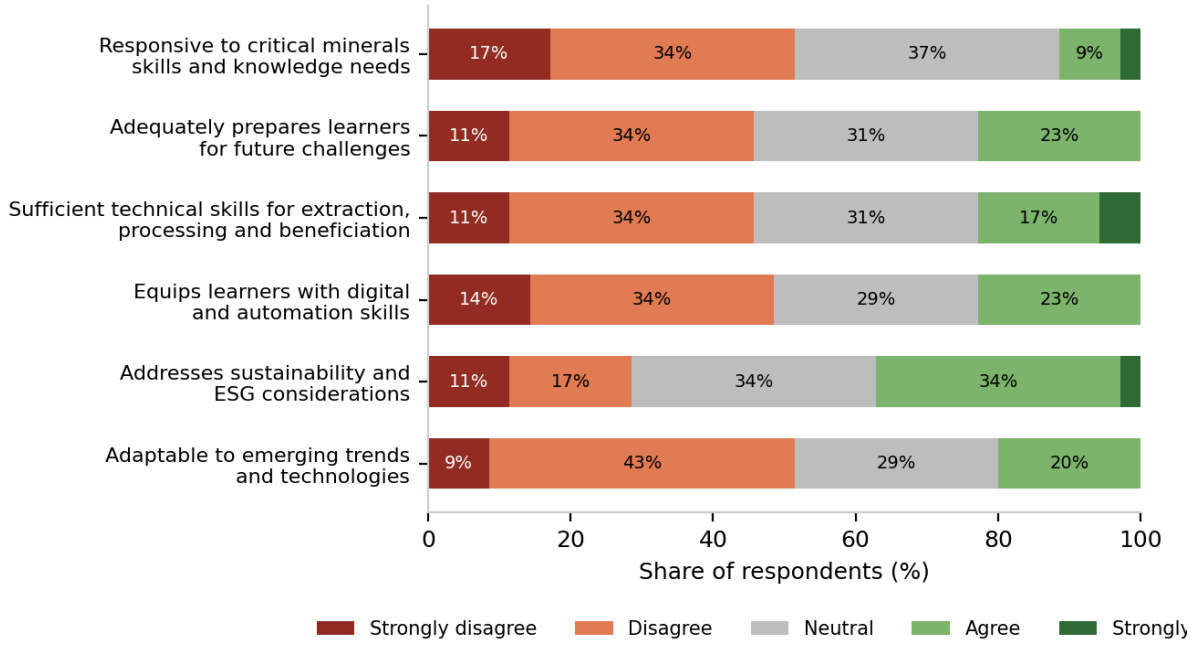


Figure 26: Stakeholder perceptions of the current training curriculum (n = 35 per item)

The overall picture indicates mixed views. In response to the statement that the current training curriculum meets the skills and knowledge needs of the critical minerals value chain, just over half of respondents (51%) disagreed or strongly disagreed, 37% were neutral, and only 11% agreed. Similar patterns emerged on whether the curriculum adequately prepares learners for future challenges (46% disagreement vs 23% agreement), provides sufficient technical skills for extraction, processing and beneficiation (46% vs 23%), and equips learners with digital and automation skills (49% vs 23%). Adaptability received the lowest rating, with 52% of respondents disagreeing (i.e., this includes those that "strongly disagree" and "disagree") that the curriculum is responsive to emerging trends and technologies, compared to 20% who agreed.

Sustainability was the only area with more positive feedback: 37% of respondents agreed that the curriculum covers sustainability and ESG, compared to 28% who disagreed. This suggests that recent efforts to include environmental and ESG topics are starting to be noticed. However, the curriculum is still seen as weak in technical, digital, and beneficiation areas. The high number of neutral responses (29-37%) may also mean that not all stakeholders are familiar with the curriculum.

These findings directly support the need for curriculum modernisation highlighted in the literature. They align with the MQA Sector Skills Plan's identification of ongoing gaps in technical, digital, and managerial skills (MQA, 2024), as well as recommendations to update occupational standards and qualifications to reflect automation, ESG reporting, circular economy principles, and climate-resilient practices.

4.9 Causes of Skills Gaps and Barriers to Skills Development

Respondents attributed the skills gaps in the MMS to three interrelated causes (Figure 27(a)): a lack of industry-specific training (26; 72%), technological changes in the mining sector (25; 69%), and outdated curricula at academic institutions (23; 64%). As seen on the figure, two respondents (6%) attributed gaps to an insufficient supply of graduates. The problem, in stakeholders' assessment, is one of relevance and quality rather than quantity: the system produces graduates, but not with the industry-specific, technologically current capabilities the critical minerals economy requires. Write-in responses supported this view. They pointed to low investment in research, development, and innovation; limited opportunities for practical experience; gaps in basic education affecting the quality of graduates; and a negative image of the sector that discourages top graduates from choosing mining careers.

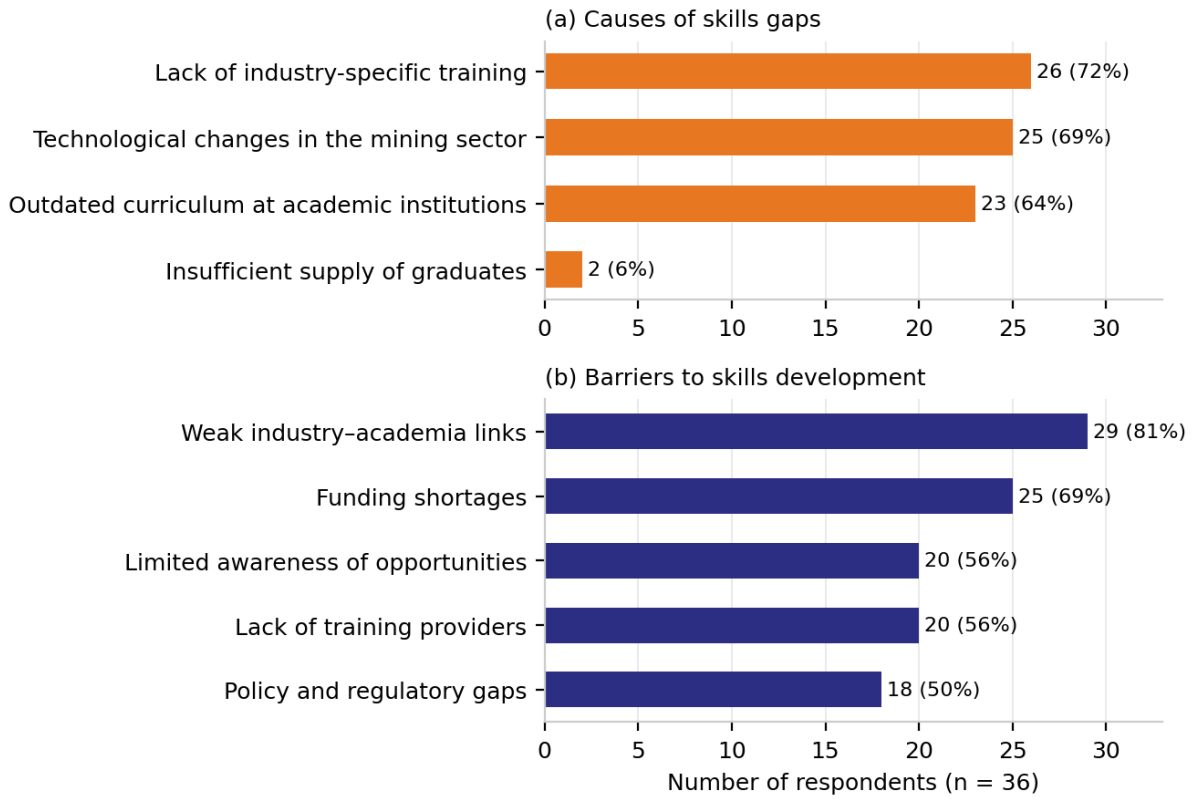


Figure 27: (a) Causes of skills gaps and (b) barriers to skills development in the mining and minerals sector (multiple responses; n = 36)

The respondents were also asked about the main barriers affecting skills development in the MMS (i.e., see Figure 27b). The most frequently cited barrier was weak industry-academia links, selected by 29 respondents (81%). Funding shortages followed (25; 69%), then limited awareness of opportunities and a lack of training providers (20 each; 56%), and policy and regulatory gaps (18; 50%).

4.10 Training Interventions and Institutional Changes

In terms of the training interventions that should be considered to close the skills gaps, the top-rated options were industry-led programmes (27; 75%), short courses (25; 69%) and TVET programmes (24; 67%) ahead of university courses (17; 47%) (i.e., see Figure 28a). This ranking matches the findings in Section 4.9. The shortage of industry-specific remains a concern and so industry-led training programmes, particularly those that are shorter, flexible and aligned to on-the-job requirements are needed. Write-in suggestions included immersive learning, an annual conference on developments in mining technology, and more investment towards targeted skills development.

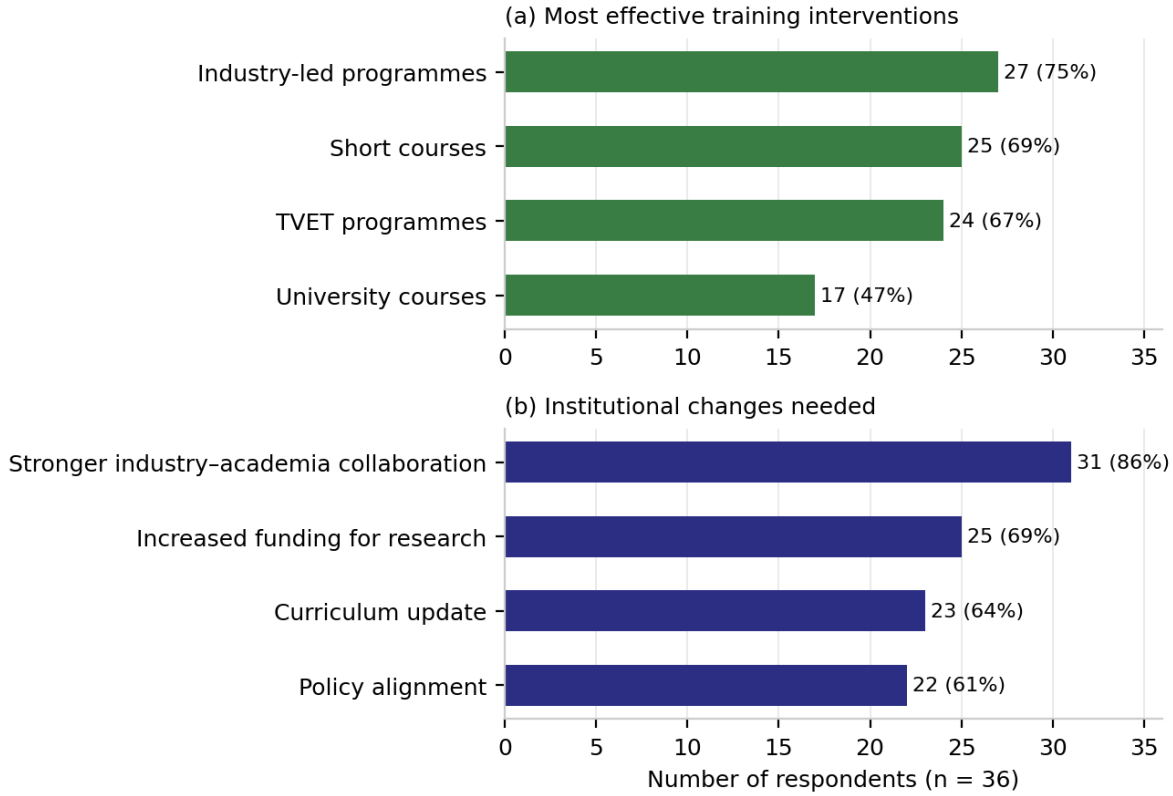


Figure 28: (a) Most effective training interventions and (b) institutional changes needed to support skills development for critical minerals (multiple responses; n = 36)

Amongst the last questions, respondents were asked "*what institutional changes are needed to support skills development for critical minerals"* (i.e., see Figure 28b). The following results emerged: stronger industry-academia collaboration was selected by 31 respondents (86%), followed by increased funding for research (25; 69%), curriculum updates (23; 64%) and policy alignment (22; 61%). Open-ended responses added the need for a local research centre (noting that regulation increasingly mandates technology that is not produced locally, forcing reliance on imports), more training centres focused specifically on critical minerals, more commitment and participation by industry in supporting capacity building and knowledge development.

Taken together, Sections 4.9 and 4.10 show a pattern that needs attention. Stakeholders link skills gaps to a lack of industry-based training, identify weak links between industry and academia as a key barrier, and support industry-led programmes and stronger collaboration as the solution. All of this points to one main issue: the gap between the workplace and the education and training system remains a challenge for the MMS.

4.11 Perceptions of the MQA and Stakeholder Recommendations

Respondents were asked whether they believe the current MQA programmes are adequate to develop a skilled workforce for the critical minerals sector (Figure 29). Only seven respondents (19%) answered “yes”, while 13 (36%) answered “no”, nine (25%) answered “maybe”, and seven (19%) did not know. These results points to both a gap between current programmes and the needs of the critical minerals sector, and some uncertainty about what the MQA currently offers. This also suggests that there is a need to improve how MQA programmes are communicated and made visible.

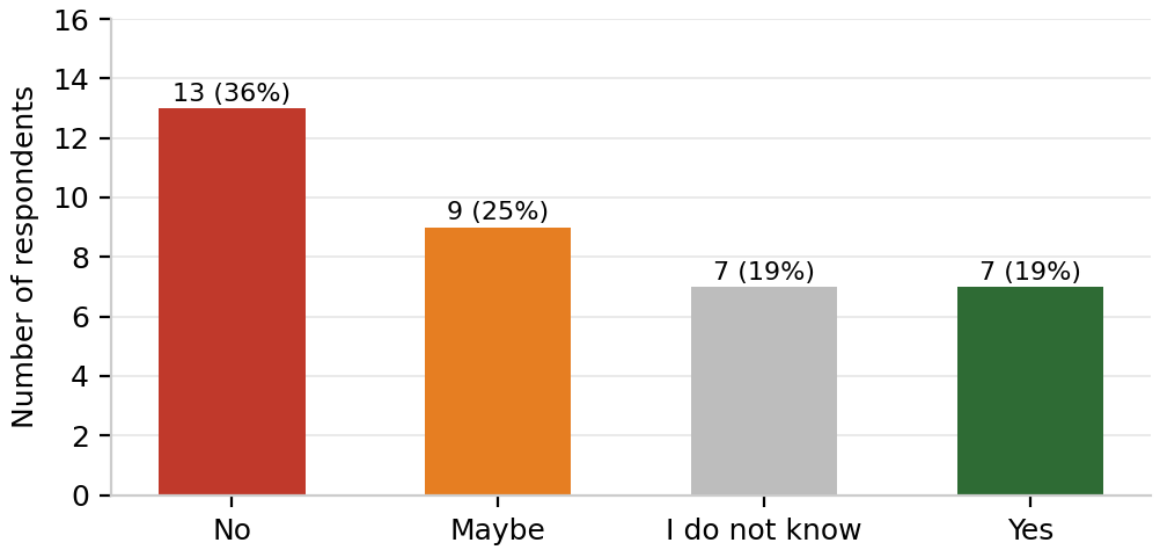


Figure 29: Perceived adequacy of current MQA programmes for developing a skilled workforce for the critical minerals sector (n = 36)

Twenty respondents provided open-ended recommendations for the MQA. Thematic analysis of these responses identified six recurring themes, summarised in Table 11.

Table 11: Themes emerging from stakeholder recommendations to the MQA

Theme	Illustrative content from responses
Deeper, broader stakeholder collaboration	Convene multi-stakeholder consultations to test the outputs of sector skills diagnostics; collaborate closely with all players in the value chains; consolidate engagements between industry, the regulator and the MQA; include original equipment manufacturers (OEMs) and other service providers, who house a large contingent of the sector’s

Theme	Illustrative content from responses
	technical skills; involve mining-affected communities and their leadership in skills development.
Curriculum and framework reform	Pursue curriculum reforms and strengthened collaboration with universities, FET/TVET colleges, associated SETAs and strategic stakeholders; update sector skills plans and development frameworks; orient skills development to current issues, the future of mining and the long-term impact and composition of mining companies.
Beneficiation and value-chain skills	Implement training of skills for beneficiation and manufacturing; collaborate with Mintek and the Department of Science, Technology and Innovation to develop a complete value chain for at least one product - such as a Vanadium Redox Flow Battery (VRFB) - for domestic and regional markets.
Work-integrated learning and exposure	Expose all students to mines from first year in their respective fields; create platforms (modelled on bodies such as the SAIMM or the Colorado School of Mines) for industry professionals to publish, present and exchange knowledge; provide immersive learning opportunities.
Accountability and quality of funded training	The MQA should hold itself and its industry partners accountable to ensure that training offered at mines funded by the MQA is not merely for compliance and subsidy purposes, but for the genuine benefit of the industry and its stakeholders.
Research, development and innovation	Prioritise research, development and innovation across the critical materials value chain holistically; reckon with the long-term risks associated with the industry and reposition it as a positive contributor to development, thereby improving the quality of candidates attracted to mining careers.

These recommendations align closely with the MQA-specific actions proposed in the literature review (Section 2.7), in particular the modernisation of occupational standards, the establishment of funding windows for ESG-linked internships, and research on the social and ecological dimensions of the minerals transition (Redflank, 2024). The proposal to anchor skills development around a complete domestic value chain for a flagship product such as a VRFB must be noted, as it would connect skills interventions directly to the East London SEZ vanadium initiatives described in the literature.

5. STUDY RESULTS: KEY INFORMANT INTERVIEWS

5.1 Introduction

This section presents a thematic analysis of the key informant interviews (KIIs) conducted as part of this study. Respondents were drawn from varied stakeholder groups including academia, research institutions, industry, professional bodies, community representatives, and government. As noted in the methodology (i.e., see section 3.6), no personal names will used to protect the respondents. Instead, direct quotations are attributed using generic stakeholder labels (e.g. industry respondent, academic respondent, government respondent, or ASM respondent). The insights emanating from the interview are organised into themes, which are presented below.

5.2 Theme 1: Defining Criticality - Global Pressures Versus Local Needs

5.2.1 The National Paradox: Balancing Domestic Stability and Global Green Transition

A foundational insight emerging from the research is that "criticality" is neither a static nor a globally uniform designation. Stakeholders emphasise that what is deemed critical by international bodies, such as the European Union or the United States, does not automatically align with South Africa's localised developmental, social, and industrial requirements. This creates a national paradox, and it is important for the country to balance global green energy demands with its own needs for inclusive economic development. In this regard, respondents echoed the need for South Africa to define criticality on its own terms rather than to adopt external definitions. It was advanced that government must develop a framework that prioritises minerals based on what the country's industries and communities need. The following aspects surrounded the discussion on definition of critical minerals.

The Coal Paradox

This is in direct contradiction to global green energy mandates, as well as South Africa's own decarbonisation goals as contemplated in the Just Energy Transition Investment Plan (JET-IP). Several respondents warn that domestic infrastructure and manufacturing stability must take precedence to global drives, noting that over-indexing on global green demands could leave local industries vulnerable. As one industry respondent put it:

"If we were to shut off coal tomorrow, the South African economy will collapse." (Industry respondent, energy sector)

This view was reinforced by other respondents who noted a fundamental gap between the rhetoric around coal and the practical reality of the national energy grid. One industry association respondent pointed out that South Africa's strategy deliberately classifies coal as high criticality because no replacement energy source is yet available at scale.

Survival Minerals for Local Development

Several respondents argued for a redefinition of "criticality" that encompasses survival minerals essential for local development and poverty alleviation. Minerals such as phosphate (for fertilisers and food security) and limestone (for cement and housing) were cited as examples. An academic respondent observed:

"We need to decide what is critical for our own people - iron and steel for infrastructure, coal for power, phosphate and limestone for agriculture and food security - rather than just following Western trends." (Academic respondent)

Respondents noted that while South Africa does have a national Critical Minerals Strategy with a tiered list of minerals, several questioned whether the list truly reflects what is critical for the country's specific needs, versus simply cataloguing its full mineral endowment.

The Waste-as-Critical Mindset

Several respondents highlighted the need for the country to stop treating mine waste as worthless. A research respondent working in applied sciences argued that "everything you throw away is critical," pointing to the strategic value of minerals like pyrite currently sitting in coal and gold waste streams. This waste-as-resource mindset connects to a broader call for circularity and systems thinking across the sector.

5.2.2 Resource Sovereignty: Avoiding the Export Trap

South Africa is in a vulnerable but potentially powerful position in the global minerals market. The international rush for critical minerals offers real economic opportunity, but respondents

warned strongly against repeating historical patterns of extraction without local benefit. A research respondent described the pattern bluntly:

“We are essentially squandering our legacy - exporting raw materials and not beneficiating them in any way. It is Africa in particular that is exporting its raw minerals.” (Research respondent)

Respondents identified what they called the “export trap”: raw ores are exported to dominant economies, processed abroad, and then returned to South Africa as expensive finished products. Exporting raw ores only to re-import finished products, such as battery cells, is identified as a significant economic failure and a perpetuation of the "resource curse". In the same vein, respondents call for interrogation of the space that South Africa wishes to occupy in the global critical minerals value chain. While there is a consensus to move away from the export trap, respondents also expressed concern over South Africa’s capability to process minerals before export or trade. The respondents reiterated the need to clearly define what beneficiation is possible and will be economically viable for South Africa, and who must be mandated to oversee and facilitate beneficiation processes. A respondent from a leading mining house said.

“Don't put the onus [of beneficiation] on a miner, because we are miners." Similarly, other respondents expressed that “beneficiation must be conducted by those who will benefit from it” (Industry respondent)

The same respondent used a real example to show the scale of the problem: in one coal-to-liquids project in China, the mine cost $1 billion but the beneficiation plant cost $5 billion. Forcing miners to also fund and run processing plants without addressing this capital gap is commercially unrealistic. A research respondent from a mining institute reinforced this from an infrastructure angle: “without cost-effective power, beneficiation remains unviable.”

An ASM respondent offered a very different perspective, arguing that beneficiation is not just a technical or commercial issue but a matter of development justice:

"Beneficiation is the most important thing here, because it brings life into the minerals. These minerals should be beneficiated here in the country so that they develop our industries." (ASM respondent)

The evidence from the interviews suggests a sequenced approach. Enabling conditions such as reliable energy, logistics infrastructure, and mineral characterisation capability need to be in place before beneficiation policies can be effectively implemented. In addition, investment should be a shared responsibility among industry, government, and strategic partners, rather than resting solely with primary mining companies.

Friend-Shoring and Geopolitical Shifts

The global economic landscape is shifting as major powers move supply chains closer to trusted partners to reduce geopolitical risk; a trend known as "friend-shoring." This creates an opening for South Africa to position itself as a preferred supplier. However, respondents cautioned that this opportunity could backfire if the country remains locked into low-value extraction roles. The only way to convert friend-shoring into real benefit is to build processing and manufacturing capability rather than just exporting more raw ore.

Governance and Reactive Policy

A major concern raised by several respondents was the reactive nature of South African governance. By the time policy responds to global trends, the country is often far behind. One industry respondent noted that South Africa tends to be "10 steps behind" the rest of the world when it comes to turning policy into action. This was paired with calls for intentional investment in research and development, with one respondent noting that "knowing leads to doing."

5.3 Theme 2: Beneficiation - The Most Important Priority and the Hardest Challenge

There is broad agreement that South Africa should actively pursue a manufacturing-led approach to beneficiation. This would require policy measures that incentivise local value addition, with the aim of retaining more downstream manufacturing value within the country. At the same time, key enablers of beneficiation including infrastructure, reliable water supply, and consistent electricity need to be in place to support and sustain this agenda.

5.3.1 The Onus of Beneficiation Debate

While there is general agreement on the importance of beneficiation for South Africa's critical minerals sector, there is a key difference in views on who should drive it. Academic and government stakeholders tend to support mandatory local processing, while industry representatives argue that beneficiation should be guided by commercial viability and global competitiveness. They caution that requiring mining companies to take on manufacturing roles could be risky if they cannot compete with well-established global centres such as China. As a result, South Africa's beneficiation strategy should be informed by complete analysis of its specific capabilities and the economic viability of different opportunities.

5.3.2 Why Beneficiation Matters

The strongest area of agreement across all respondents was the need to move beyond simply extracting and exporting raw minerals. All stakeholders agreed that South Africa must add more value to its minerals before they leave the country. However, disagreements emerged about how to do this, in what sequence, and who should be responsible.

A research respondent with expertise in geosciences argued that the most important first step is not building processing plants, but building the human capability to run them:

"Priority must be given to refining capability, developing the skills to beneficiate commodities rather than just the physical refining of metals. We must also track value loss across the entire chain to avoid massive revenue leaks." (Research respondent, geosciences)

5.3.3 The Technical and Geological Reality of Critical Minerals

The KII analysis reveals a fundamental shift in what beneficiation actually means for critical minerals, compared to traditional commodities. Unlike gold or coal, many critical minerals, particularly rare earth elements (REEs) occur in very low concentrations as trace elements within rock. This completely changes the technical requirements for extraction and processing, and so there are aspects that must be considered (i.e., these are elaborated below).

The 'Pinprick' Challenge

Respondents described what they called the ‘pinprick’ challenge: the need to extract a tiny ‘hair-sized’ amount of mineral from a massive block of rock without processing the entire volume. Current large-scale bulk mining methods are not suited to this kind of precision extraction. If the country cannot develop smarter extraction methods, it will continue to waste enormous amounts of energy and water to recover very small amounts of material. These technical needs to be taken into account and these are:

Characterisation and Chemical Complexity

Even highly qualified scientists struggle to characterise many critical minerals because of their similar yet complex chemical properties. A research respondent working in hydrometallurgy described the challenge:

“Scientists, qualified scientists are struggling with this - just to characterise [minerals]. The chemistry of rare earth elements is so similar that they are difficult to separate and identify. It requires an experienced and very patient person.” (Research respondent, hydrometallurgy)

These minerals are often locked inside complex chemical matrices and isolating them requires advanced chemical processing and separation techniques that are not yet widely established or scalable in South Africa. In addition, there is a shortage of industry experience among professionals in the country’s MMS.

Value Lost to Waste Streams

Current processing infrastructure is built for primary commodities and routinely loses valuable trace minerals to waste streams. Retrofitting existing plants to capture these secondary minerals requires specialised solutions that have not yet been widely adopted. This creates an urgent need for tailored investment in advanced metallurgical research and development and upskilling of professionals leading this work.

5.3.4 Mine Tailings as a Strategic Opportunity

In addition to the technical challenges of primary extraction, respondents also identified South Africa's historical mining waste, specifically tailings dams, slag heaps, and rock dumps as immediate and practical opportunity for the MMS. These were described as ‘low-hanging fruit’ because the minerals are already above ground, require less capital to access than new

underground mines, and offer the added benefit of environmental rehabilitation. It was noted that large volumes of critical minerals remain in historical tailings that were not recovered during original processing.

However, a debate exists about who should process these assets. Some respondents submitted that these should earmarked for artisanal and small-scale miners due to lower barriers to entry. Others cautioned that even processing waste streams still requires advanced technology and economies of scale that only larger industrial operations can achieve. This points to the need for a tiered approach that creates space for both types of levels of mining (i.e., ASM and LSM).

5.3.5 Infrastructure as the Foundational Requirement

A cross-cutting message from all respondent groups was that no amount of skills development or policy will succeed without stable, affordable energy; functional water supply; and reliable logistics. Beneficiation processes for minerals such as ferrochrome and platinum group metals are energy intensive. The recent closure of South African smelters was driven not by a lack of skills but by uncompetitive electricity costs and grid instability. Respondents argued that infrastructure must be treated as the foundational enabler of the entire value chain, from exploration through to the final manufactured product.

5.4 Theme 3: What Skills Does the Sector Actually Need?

A key finding of this research is that the transition to a critical minerals economy is currently constrained by weaknesses in the human capital pipeline. Respondents described this not as a simple labour shortage, but as a deeper structural mismatch, where academic qualifications do not translate into practical, operational skills. The evidence suggests that, without a significant shift in how skills are developed and applied, South Africa risks missing the limited global opportunity to benefit from the growing demand for energy transition minerals. To this effect, respondents highlighted the need for a multi-layered skills architecture for South Africa to participate meaningfully in critical minerals value chains. This architecture spans technical skills at multiple levels, digital and 4IR capabilities, and foundational STEM competencies.

5.4.1 The Shift from Bulk Commodity to Precision and Trace Element Skills

The transition to critical minerals requires different kind of technical skills compared to traditional bulk commodity mining. South Africa's century of mining experience was built on extracting large volumes of gold, coal, and platinum. Critical minerals especially rare earth elements occur in very small concentrations and cannot be extracted using the same methods. As a result, the focus of human capital shifts from basic labour and toward advanced metallurgy, specialised chemical engineering, and precision mineralogy. In addition to this, respondents also highlighted the importance of by-product recovery stating that some critical minerals occur only as by-products of primary mining operations. If processing plants are not set up to capture these secondary streams, these minerals will be lost to tailings. As such, value-chain understanding would need to become a core competency amongst professionals in the MMS.

5.4.2 Technical Skills Across the Value Chain

At the exploration and geoscience end, a research respondent described a shift from traditional field mapping to "analytics and geodata science". Geologists must be able to work with AI-assisted geological modelling and remote sensing tools and must understand how minerals behave during processing, not just how to find them in the ground. The traditional role of the geologist must expand from "finding the ore" to "stewarding the entire value chain".

In the midstream and downstream segments, one research respondent highlighted a near-total gap in chemical engineering and separation science, particularly in processes such as distillation, ion exchange, and solvent extraction required for rare earth elements. This points not only to a training gap, but to a broader research and capability deficit that will require targeted national investment to address.

At the foundational level, respondents highlighted the danger of neglecting basic artisan and craft skills including metalwork, carpentry, electrical work which support many industrial systems, even as the country aspires to build advanced downstream manufacturing. This was noted by the respondent:

"There is a need to move away from a purely academic focus and revitalise artisan training. The low number of matric students taking mathematics is a serious concern - it is essential for technical, manufacturing, and engineering work." (Academic respondent)

5.4.3 Digital Engineering and 4IR Skills

The findings pointed to a significant shift from traditional mining methods toward a more digital, engineering-driven approach. This transition is changing the skills needed in the workforce and requires new competencies to remain globally competitive. One of the respondents characterised the current period as the "digital engineering era" where digital skills are now required at every level of the value chain, not just in data and IT roles. The research identified three specific emerging competencies:

Mechatronics and Automated Systems

Traditional technical roles are being redesigned. Future workers will not only operate machinery but will supervise robotic platforms and self-driving vehicles. This requires skills in mechatronics which involves the integration of mechanical, electrical, and computer engineering. Industry association respondents confirmed that this shift is already happening in modern mining operations.

Prompt Engineering and AI Literacy

A critical emerging skill identified by respondents is "prompt engineering," defined as the ability to effectively query and manage Artificial Intelligence to interpret large volumes of data. This capability is viewed as essential for transforming vast amounts of raw information into actionable insights that improve both operational efficiency and site safety. Without this capability, the sector risks being data rich but insight poor, unable to leverage the technological investments necessary for complex mineral extraction. This finding also aligns with the growing importance of data analytics skills in South Africa's critical minerals sector.

Hybrid Communication and Systems Thinking

Modern mines require workers who understand the full flow of data between underground operations and surface control rooms. This requires hybrid communication skills integrating

wireless, Bluetooth, and database systems. Alongside this, systems thinking which is the ability to see how different parts of the value chain connect was identified as one of the key skills which are missing in the sector. As one respondent observed: “We kind of think the same, but we don’t think together.” (Research respondent). While benefits of AI are recognised, there are concerns about the overreliance on these technologies without the necessary underlying skills and critical understanding. One respondent raised an important caution about over-reliance on AI:

“There is a growing concern that dependency on AI tools is preventing the younger workforce from thinking for themselves or developing deep expertise. Critical thinking is taking a back seat.” (Research respondent)

Multidisciplinary Skills

Respondents said that workers in the critical minerals sector need skills from different fields and must be able to work across industries. This is because people now need to understand how technical work links to economic and social issues. In smaller mining operations, workers often need to do many roles, including technical work, legal tasks, and working with communities. Respondents also noted that many organisations in South Africa work in the same space but do not collaborate. Building multidisciplinary skills is important given the complexity of critical mineral value chains.

5.5 Theme 4: A Broken Pipeline - From School to the Workplace

Another key finding affecting the transition to a digital era of mining is weaknesses in the education and training pipeline. This is often described as a “broken pipeline” that fails to produce graduates who are ready for industry.

5.5.1 The STEM Foundation Crisis

Almost every respondent pointed to the state of mathematics and science education in South African schools as a serious problem. An industry respondent challenged the credibility of reported pass rates:

"Why are we expecting kids to only get one out of every three questions correct? Schools are claiming 100% pass rates in mathematics when the average grade is 20% or 30%." (Industry respondent)

Another respondent described a related "reading for meaning" crisis. It has been reported that more than half of Grade 4 learners in South Africa cannot read for meaning, making it very difficult to train workers for technology-intensive roles. The concern on pass rate was highlighted by another respondent stating that the 35% Matric pass mark in Mathematics and Science 'is a disaster' that leaves students unprepared for technical training. This culture of low pass marks, coupled with replacing Pure Mathematics with Maths Literacy, is viewed as creating a false sense of achievement among learners who are ultimately ill-equipped for the requirements of university or TVET environments.

5.5.2 The Knowledge Versus Competency Gap

Stakeholders highlighted a growing gap between academic training and industry needs. While universities produce graduates with strong theoretical knowledge, it was noted that many lack the practical skills required to contribute effectively from the outset. This gap slows the transition from education to employment and remains a key structural barrier for young people entering the sector. One respondent captured the problem:

"The pipeline is broken because it lacks coordination. Individual entities are doing good work in isolation, but there is no overarching systems perspective." (Professional body respondent)

5.5.3 The 'Nursing College' Model: Learning by Doing

To bridge the gap between knowing and doing, respondents proposed what they called the "nursing college" model: a training approach where graduates are ready to perform specific tasks from their first day of work, just as a newly qualified nurse can take blood pressure immediately. This model shifts the emphasis from purely theoretical learning to practical, job-ready skills.

Respondents identified TVET colleges as the most immediate opportunity to build this kind of task-ready competency in technical and artisan trades. However, a significant problem is that TVET lecturers themselves often lack hands-on industry experience, which limits the quality

of practical training they can deliver. This contributes to an unintended outcome where communities located closest to mining operations remain among the least able to benefit from employment opportunities in the sector because of limited access to relevant skills and quality training.

5.5.4 Addressing Outdated Curriculum

Current mining curricula are seen as outdated and still focused on traditional, manual methods. Respondents suggested that the MQA should update training standards to include technical processes and digital mining skills, not just basic safety. Without these changes, the system will continue to produce graduates for an industry that has already changed. They also highlighted the importance of learning from countries and institutions with more advanced expertise, through exchange programmes and practical learning opportunities.

5.5.5 TVETs Versus Universities: Complementary Roles, Not Competition

A major point of discussion was the relationship between university education and TVET colleges. Respondents were clear: both are needed, but the system has over-invested in university degrees and under-invested in vocational training. One respondent from a major mining company argued that the most urgent opportunity for improving the skills pipeline lies not in universities but in the TVET sector. She called for universities to actively support TVET colleges and ensure their programmes are tailored to the specific industries operating in each region. Building on this, another respondent highlighted the social perception problem that worsens the TVET underinvestment:

"Society needs to stop viewing a vocational technical skill as lesser than an academic degree. Most of the time we cannot function at a university without the technicians running and fixing the instruments." (Academic respondent)

Current mining and minerals curricula were also criticised as being tied to traditional, manual 'pick and shovel' methods. Respondents urged the MQA to modernise unit standards to go beyond basic safety training and include the technical processes and digital literacy required for modern mining.

5.5.6 Work-Integrated Learning: The Experience Catch-22

The respondents identified the gap between graduation and being industry-ready as the most critical break in the pipeline. The problem is self-reinforcing: industry wants experienced workers, but is not set up to give graduates the experience they need. One respondent described this as a "catch-22" and called for apprenticeships that combine training and practical hours so that experience is no longer a barrier to entry.

5.5.7 Too Many Graduates, Too Few Jobs

An industry respondent from a major mining company raised a sharper concern: even where graduates exist, the industry is not growing fast enough to absorb them. She warned against using further education as a "holding cage" for youth unemployment:

"We are fixing the problem of youth unemployment by putting people into a holding cage of further education when there is no market available to absorb them." (Industry respondent)

Another respondent framed this as a "supply side trap". Skills development must be anchored in economic growth and real investment ; producing graduates for a sector that is not expanding does not solve unemployment.

5.6 Theme 5: Institutional Fragmentation and the Governance Gap

5.6.1 Thinking the Same but Not Together

A recurring problem described by respondents was that many institutions including universities, science councils, government departments, industry bodies, and SETAs are all working on similar issues without coordinating their efforts. One respondent captured this clearly:

"We kind of think the same, but we don't think together. That is my main barrier to creating impact" (Research respondent)

This fragmentation means that organisations compete for the same limited funding rather than building complementary capabilities. The same respondent proposed the "Quadruple Helix" as the structural solution. This comprises of a formal coordination model that brings together government, industry, academia, and society to work toward shared goals. One

respondent highlighted the need for cross-functional teams within mining companies that combine technical experts with social scientists and development economists to ensure that solutions are holistic.

5.6.2 Policy Without Activation

Several respondents criticised the pattern of reactive policy-making in South Africa. An industry respondent was direct:

"South Africa doesn't need more research. The MQA must not jump on the bandwagon just because critical minerals have become a new buzzword. What is needed is activation." (Industry respondent)

Another respondent added: "Policy doesn't change stuff. People change stuff." Red tape, excessive paperwork, and slow bureaucratic processes are actively blocking the flow of skills and affecting progress. The goal of policy should be to create "flow" needed to move think, for example, an enabling environment that supported moving a student from first year through to productive employment.

The concern raised by most of the respondents was on the implementation capacity to release this vision. Their position is that the country has strong policy frameworks; what is missing is the will and the structure to execute them.

5.6.3 Community Voices Left Out

Community representatives spoke about the governance failures that play out at the grassroots level. It was noted that mining companies hire consultants who file reports about community needs without engaging those communities. This has created issues, where training programmes brought to communities do not align with their needs, interests and local economies. The respondents called for a "bottom-up" approach where communities are included in the decision-making and planning processes.

5.7 Theme 6: Artisanal and Small-Scale Mining

5.7.1 A Contested Role

The role of artisanal and small-scale mining (ASM) in the critical minerals sector was one of the most debated topics across the interviews. Views ranged from strong support to technical scepticism. Technical specialists expressed doubts about the role of artisanal and small-scale mining (ASM) in minerals such as rare earth elements (REEs), noting that these minerals occur in very small amounts and require complex processing. One respondent noted, even qualified scientists struggle at this level. She suggested ASM participation might be better suited to higher-concentration minerals like lithium rather than trace elements.

However, respondents emphasised that suitability depends on the type of mineral. Some minerals, such as lithium, can be more suitable for small-scale operations. One participant noted that certain deposits can support small groups of miners over several years, helping to sustain local livelihoods. This reflects the reality of rising unemployment and the growing number of people involved in informal and small-scale mining in South Africa. It also highlights the need for a more strategic approach, where the type of mining operation is matched to the specific characteristics of each mineral.

5.7.2 What ASM Can Contribute

Several respondents agreed that an avenue for ASM to benefit in the critical minerals sector is in reprocessing mine tailings and surface waste. These require less capital than underground mining and carry lower operational risks. A research respondent noted that smaller, specialised operators are often better suited to extracting certain minerals that are not profitable for large companies with high costs. The key is to match the size of the operation to the specific mineral and its conditions.

5.7.3 The ‘Big Umbrella’ Model and Regulatory Reform

The discussions on ASM expanded to the challenges facing the ASM sector and the need for formalisation. An industry respondent emphasised the need to formally separate legitimate artisanal operators from criminal syndicates - the two must not be treated as the same. A

research respondent warned against applying different environmental and safety standards to ASM:

“ASM can’t be conducted under different rules. They must be held to the same environmental and safety standards as large mines. The cobalt slides in the DRC are a warning of what happens when small-scale mining is not done responsibly.” (Research respondent)

To address safety, environmental and legal operation concerns, the research respondents suggest a "Big Umbrella" model where ASM players are encouraged to operate under the technical and safety guidance of large-scale mining companies or within regional cooperatives, while making the legal requirements applicable to the operating scale of ASM and junior miners. This requires a clear delineation between organised criminal syndicates and legitimate, economically motivated artisanal miners to protect responsible local participants. Respondents advocate for the decriminalisation and formal regulation of the sector, including the formation of trade organisations to secure better commodity prices and regional technical councils to share skills and operational best practices. These are critical in ensuring that small-scale miners benefit from the demand of critical minerals which they can efficiently mine and process.

6. STUDY RESULTS: STAKEHOLDER VALIDATION WEBINAR

6.1 Introduction

As noted in the methodology, the research team hosted a stakeholder validation webinar titled *"Critical Minerals, Critical Skills: Is South Africa Ready to Leverage Emerging Global Value Chains?"* The webinar served two purposes: it gave stakeholders the chance to validate, challenge, and add to the preliminary findings; and it generated new data through live discussion. The insights that emerged from the discussions were thematised and the key findings are presented below. For each theme, the discussion indicates whether the webinar confirmed, refined, challenged or extended the preliminary survey and interview findings.

6.2 Theme 1: Validating the Skills Priorities

6.2.1 Broad Agreement, But a Call for Deeper Detail

The preliminary survey findings showing processing and beneficiation, automation and robotics, and data analytics and AI as the three most needed technical skills were broadly accepted by webinar participants. However, several participants highlighted the need for granular details on the specific skills that are needed. This was the comment of one of the attendees during the webinar:

"Do you know, when you talk about processing, what exactly are the skills that are defined under processing? When you talk about AI, do you know exactly what types of tasks are needed? There seems to be a mismatch between industry and what academia and authorities are coming out with." (Industry participant, webinar)

Another webinar participant extended the point, calling for skills maps that show what specific AI tasks a geologist needs compared to a metallurgist:

"Prompt engineering will cut across different value chains - exploration, mining, processing and so on. But we need use cases for the different sections of the value chain, to say: for this cross-cutting technology, these are the skills needed for someone working in exploration versus someone in metallurgy." (Industry participant, webinar)

Adding to the skills needed, the importance of business and financial skills were highlighted as these were absent from the survey's skills categories. In summary, the skills needed in the sector span across not only the technical skills but also business, legal, and social capabilities that are important in leveraging the opportunities across critical mineral value chains.

6.3 Theme 2: Universities and TVETs - Synergy, Not Competition

The other point of discussion during the webinar centred on the relationship between universities and TVET colleges. The key message that emerged was clear: both are needed, and they must work together rather than compete. This was a comment made by one of the participants:

"In the ecosystem of education and skills, there's a place for vocational and trades, which sits largely within TVETs, and there's a space for universities. Many artisan trades go through the TVETs and I don't think that's going to change much. You need to think about it from a skills mix." (Industry participant, webinar)

Concerns were raised about the quality of graduates produced by PSET institutions. In particular, participants noted that the discontinuation of certain practical programmes has led to a noticeable decline in the readiness and quality of new entrants to the industry. Linked to this, governance concerns were also raised. One opined that South Africa often reacts to changes rather than planning ahead, adding that "the space in which we can operate determines the skills we need."

The webinar confirmed the "Nursing College" model proposed in the key informant interviews. Participants agreed that the sector must "train people to get dirty again". This is important to addressing the growing trend where qualified geologists and engineers prefer office-based roles over essential field work. Overall, the webinar confirmed the preliminary finding that universities and TVET colleges have complementary rather than competing roles, while reinforcing the need for more practical, industry-aligned training. It also validated the "Nursing College" model identified through the key informant interviews, with no substantive challenge to this finding.

6.4 Theme 3: The Knowledge Gap - Who Actually Understands Critical Minerals?

Another finding from the webinar was how limited the knowledge of critical minerals is, even among people actively working in the sector. This discussion stemmed from a question, which critical minerals should be prioritised by South Africa. One industry participant answered this question by saying:

"From where I'm standing, we've got more questions than answers. We are not quite knowledgeable enough about some of the minerals that are being earmarked." (Industry participant, webinar)

Understanding specific minerals and their value chains is important, as this should guide skills development and training needs. One participant suggested that, rather than trying to cover all critical minerals, South Africa should start with those it already knows and mines well - such as PGMs, manganese, and copper - before expanding to less familiar minerals. This discussion extended the preliminary findings by highlighting that skills planning is constrained not only by skills shortages, but also by uneven knowledge of specific critical minerals and their value chains. The webinar therefore added a stronger case for prioritising mineral-specific capability development rather than treating all critical minerals uniformly.

6.5 Theme 4: Skills as a Competitive Strategy

Several participants emphasised that skills development must be seen as a strategic tool for competitive advantage, not just a training obligation. A senior industry participant argued that skills planning must start with a clear "pathway to sale" for each mineral on the critical list - what does the value chain actually look like for PGMs versus lithium versus REEs, and what specific skills are needed at each step?

"South Africa has been known to be a mining country. We have lost some of that skill set over the last couple of decades. I would start with enhancing what we have before we go off on a tangent and do something completely new." (Industry participant, webinar)

Several participants converged on the view that skills development in this rapidly changing environment requires not just fixed qualifications, but platforms for continuous learning and

re-skilling as technology and markets evolve. The focus should be on building people with the aptitude to keep adapting, not just training them for a fixed set of tasks.

The webinar therefore largely confirmed the preliminary finding that future skills development must extend beyond traditional mining competencies, while refining it in two respects: skills planning should be anchored to specific mineral value chains and should strengthen existing capabilities alongside the development of emerging skills. Participants also reinforced the need for continuous learning and reskilling as technologies and markets evolve.

6.6 Theme 5: What Stakeholders Expect from the MQA

The webinar highlighted that stakeholders expect the MQA to focus less on research and administration, and more on active facilitation, coordination, and delivering real outcomes. An industry participant also emphasised the need for ongoing engagement, noting a gap between academic research and practical application: "*There seems to be a disconnect between what academia is finding and what's actually practical..[].. so that we can close that gap"* (industry participant, webinar). These views broadly confirmed the preliminary findings that stakeholders expect the MQA to strengthen coordination, industry engagement and practical skills development. The webinar further sharpened this finding by emphasising implementation and sustained facilitation: participants expected the MQA not only to support research and training, but to help translate identified skills needs into coordinated, practical outcomes.

7. INTEGRATED DISCUSSION: WHAT THE EVIDENCE TELLS US

7.1 Introduction

This section brings together findings from all three data sources, namely the stakeholder survey (Part I), the key informant interviews (Part II), and the stakeholder validation webinar (Part III) to draw out key findings and their implications for skills planning and the MQA's strategic role. The discussion is organised around nine main findings, each cross-referenced with the literature and policy frameworks reviewed in Chapter 2.

7.2 Finding 1: Emerging Skills for South Africa's Critical Minerals Sector

The three data sources revealed that the skills requirements associated with South Africa's critical minerals sector extend far beyond traditional mining occupations. Stakeholders consistently highlighted a shift towards data intensive exploration, advanced mineral processing, automation enabled operations, and sustainability driven resource management. Rather than representing isolated occupational shortages, these findings point to four interconnected skills pillars that are expected to underpin the future competitiveness of South Africa's critical minerals value chain. These pillars span the continuum from mineral characterisation and beneficiation to digital operations and environmental stewardship, while being supported by a set of cross-cutting enablers related to foundational education, adaptability, application-driven learning, and industry collaboration. at the back of key weaknesses that were identified affecting the current skills pipeline, including shortages in specialised technical expertise, inadequate foundational STEM competencies, and a persistent gap between educational outputs and industry requirements.

It is important to note that while the need for digital skills were highlighted, concerns were also raised about over-reliance on AI, where workers may depend on tools to generate answers without fully understanding them. This could limit the development of deep expertise needed to solve complex problems. The solution is not to choose between foundations and digital skills. The sector needs both, built in layers. One respondent described this as a "capability endowment": treating human capital the same way the industry treats physical assets, investing at every level. Figure 30 synthesises stakeholder insights on

emerging skills, and captures the most significant current skills shortages and emerging future workforce requirements identified across the critical minerals ecosystem.

7.3 Finding 2: The Skills Gap Is Deep and Structural

All three data sources converge on the same conclusion: South Africa's current skills base is not aligned with the requirements of the emerging critical minerals economy. This is not simply a question of a shortage of engineers, but a deeper structural mismatch. The education and training system has historically been designed to support an extractive, upstream-focused economy, rather than the beneficiation- and manufacturing-driven economy that the country now seeks to build.

The survey results illustrate this clearly. The workforce was rated strongest in occupational health and safety and geoscience - both traditional upstream capabilities. In contrast, it was rated weakest in areas such as automation and robotics, recycling and the circular economy, data analytics and AI, and manufacturing and downstream applications. These are precisely the capabilities required to maximise value from critical mineral value chains. The interview findings reinforce this picture. Participants in the research pointed out several skills deficits covering not only technical skills, but also digital, environmental, social, legal, multidisciplinary skills. A specific example from the interviews was the limited analytical capacity to characterise rare earth elements (REEs) to international standards, which is a foundational step in REE processing.

These findings align with international evidence showing that South Africa remains concentrated in upstream activities, exporting semi-processed materials while higher-value activities take place elsewhere (UNCTAD, 2025; Government of South Africa, 2025). In effect, the country's workforce remains strong in areas aligned with its historical economic structure, and weak in those required for its future trajectory.

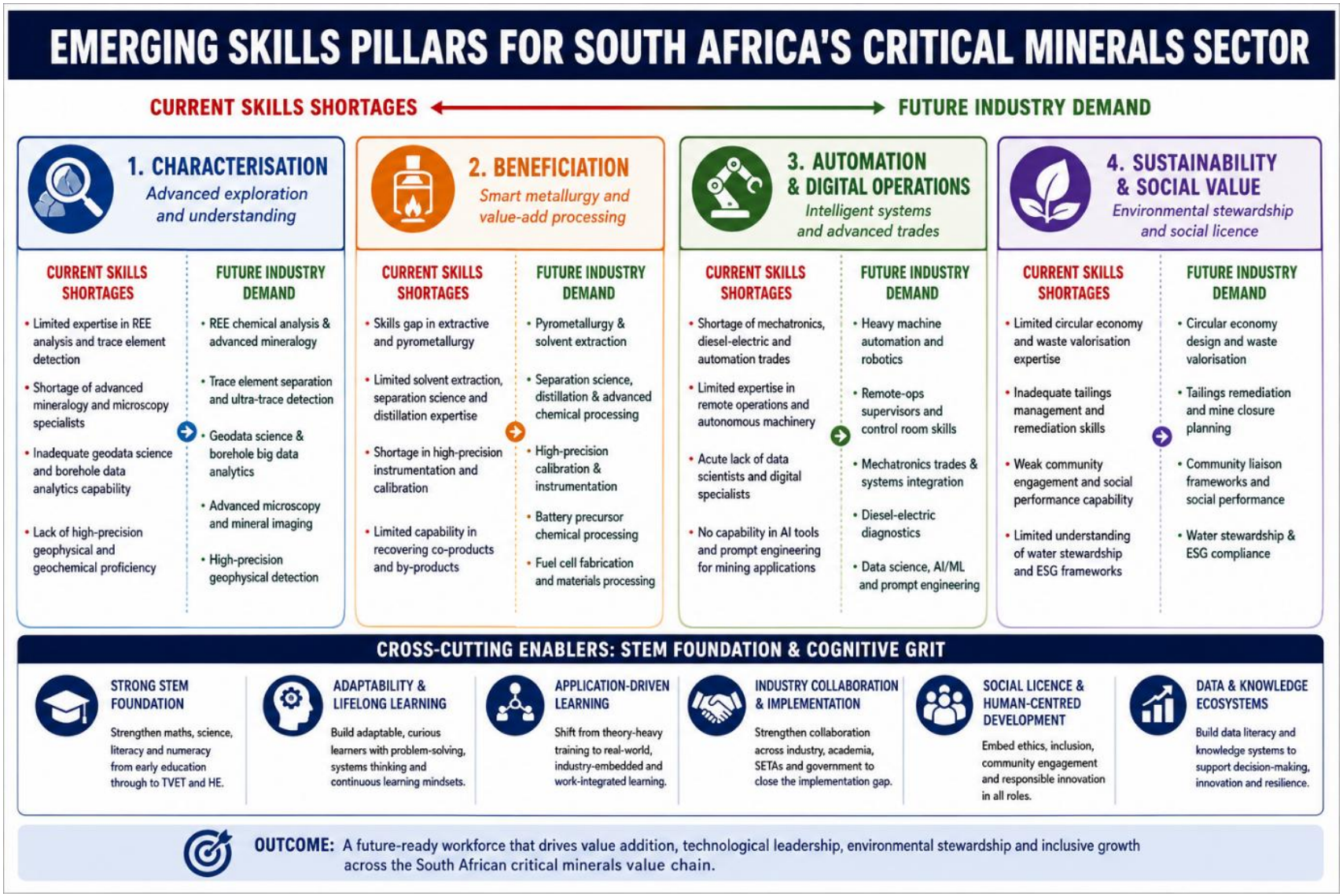


Figure 30: Emerging Skills Pillars for South Africa's Critical Minerals Sector

7.4 Finding 3: The Gap Between Industry and Education Is the Most Critical Fault Line

All three data sources converge on a common conclusion: the most significant structural barrier is the weak alignment between the industry and the education and training system. The survey findings were clear on this point in that weak industry-academia linkages were identified as the leading barrier to skills development. Similarly, stronger collaboration between industry and academia emerged as the most strongly supported institutional reform, while industry-led programmes were identified as the preferred training approach.

The interviews validated these findings, with respondents describing the transition from education to employment as a “broken” pipeline. Several concerns were raised around the lack of practical experience among graduates, limited opportunities for workplace exposure, and weak engagement between industry and training institutions. Respondents also pointed to a situation where industry expects experienced workers but does not always provide opportunities for individuals to gain that experience. In addition, there were concerns about training people for a job market that is not expanding fast enough to absorb them. These views were reinforced during the webinar, where an industry participant called for ongoing engagement to bridge the gap between academic outputs and practical industry needs.

This disconnect has been linked to three anchors. First, work-integrated learning is ineffective in that many graduates enter the labour market without practical experience, while employers face administrative and regulatory constraints that limit their ability to provide it. Second, curricula are often developed without industry input; respondents suggested practical measures such as regular industry seminars, active advisory boards, and co-designed short courses. Third, the labour market itself is not expanding sufficiently to absorb graduates, meaning that increasing the supply of graduates without parallel growth in the productive economy risks worsening youth unemployment.

7.5 Finding 4: Future Skills Requirements for the Critical Minerals Sector

Research participants expressed both converging and diverging views on South Africa’s future skills requirements for the critical minerals sector. One perspective emphasised the need for a comprehensive national skills inventory to identify existing capabilities, including underutilised skills and areas requiring reskilling. A contrasting perspective argued for a more

forward-looking approach, prioritising targeted reskilling, research and development, and the deliberate cultivation of future-ready competencies aligned with the evolving demands of the critical minerals value chain. Table 12 summarises this tension between existing capabilities and emerging requirements, highlighting the transition from legacy systems to a future-oriented skills and capability framework.

Table 12: Critical Minerals Skills Transformation (Existing vs. Future Requirements)

Strategic Pillar	Legacy Capability (Existing)	Future Mandate (Required)
Operational Focus	Conventional bulk extraction (gold, PGMs)	Complex beneficiation and rare earth element (REE) separation
Education Model	Theoretical mining and minerals knowledge base	Vocational, practice-led "nursing college" model producing work-ready practitioners
Technical Literacy	Manual and siloed processes	Mechatronics and AI-enabled systems literacy
Digital Integration	Discrete data management systems	AI-enabled data ecosystem and advanced analytics
Professional Role	Specialist geologist or engineer	Transdisciplinary value-chain steward
Value Recovery	Primary commodity extraction	Advanced mineral recovery and circular resource utilisation

7.6 Finding 5: Strategic Roadmap for Activation: A Unified Sectoral Mandate

Building on the identified shifts in sectoral capability requirements, stakeholders highlighted a set of cross-cutting priority or "power" skills that form the basis of the future critical minerals workforce. These competencies extend beyond technical expertise and reflect an increasing need for integrated, adaptive, and system-aware capability across the value chain. Table 13 summarises these strategic enablers and their implications for sector performance.

Table 13: Strategic Enabler Roadmap - Critical Skills Priorities

Strategic Enabler	Capability Focus	Sector Impact
Systems thinking & value-chain stewardship	Integrated understanding of the full minerals value chain	Strengthens coordination across the Quadruple Helix and reduces siloed decision-making
Transdisciplinary collaboration	Technical, commercial, and social skill integration	Enables flexible roles in complex and lean mining operations

Change management & resilience	Proactive adaptation to technological and market shifts	Builds organisational agility in volatile commodity and technology environments
Digital literacy & AI engagement	Effective use of AI tools and data systems	Maintains human oversight in increasingly automated environments
Commercial & financial literacy	Understanding beneficiation economics and value addition	Supports viable local processing and reduces export dependency
Implementation-oriented thinking	Converting strategy into operational execution	Bridges the gap between policy frameworks and industry delivery
Lifelong learning & adaptability	Continuous skills upgrading post-qualification	Aligns workforce capability with rapidly evolving technologies
Innovative problem-solving	New approaches to low-grade and waste resource recovery	Unlocks value from previously uneconomic mineral streams

Importantly, the need for continuous skills development also responds to the recruitment challenges identified in the survey and was reinforced during the validation webinar, where participants emphasised continuous learning and reskilling as technologies and markets evolve. Regional technical councils, supported by regular workshops, mentorship, peer learning and digital knowledge-sharing mechanisms, provide a practical mechanism for sustaining this exchange beyond initial qualifications.

7.7 Finding 6: Community and Environmental Skills Are Being Left Behind

One of the most concerning patterns across all three data sources is that community engagement and environmental management which are essential for the sector's long-term licence to operate are not being treated as priorities.

The survey showed this directly. Community engagement received a mean competency score of only 2.77 out of 5, and environmental management 2.75; both considered weak. Yet when respondents chose intervention priorities, both fell near the bottom of the list. The sector's attention is captured by technical and digital gaps, and the social and environmental dimensions remain overlooked.

The interviews showed the human cost of this gap. A community respondent described communities consulted by name only with reports filed without meaningful engagement. Another community respondent raised that communities find themselves mining in

dangerous abandoned shafts for basic survival because large companies left without rehabilitating sites. A research respondent cited the cobalt slide disaster in the DRC as a global warning of what unregulated small-scale mining without environmental competency looks like.

International research confirms that social licence is a precondition for viable mining (Franks et al., 2025). South Africa's history of mining-related community conflict makes this risk acute. ESG skills, community engagement, environmental management, and responsible mining practices must be built into every skills programme for the sector.

7.8 Finding 7: One Plan Cannot Fit All Minerals or All Contexts

A key insight that emanated from all three data sources is that there is no single skills plan that will work for all minerals, all stages of the value chain, and all types of operators. As noted during the webinar, *"there is no single solution, the value chain for coal is not the same as that for vanadium or PGMs."*

The interviews provided more detail. For example, extracting rare earth elements (REEs) from coal ash requires very different skills compared to processing PGMs. Similarly, an academic working on a phosphate project explained that each new mining project creates its own specific skills needs, from exploration to final processing. Different groups including large companies, junior miners, TVETs, universities, artisanal miners, and local communities all have different skills requirements. The main implication for the MQA is clear: skills planning must be tailored to each mineral and each stage of the value chain, rather than using a single, uniform approach. The government respondent confirmed that training must be "intentionally tailored" to specific value chains and cannot use a one-size-fits-all approach.

7.9 Finding 8: The Country Needs Action, Not More Analysis

Another key insight from the interviews and webinar was concern about the gap between research and implementation. South Africa has done a lot of research on skills challenges, but what is missing is the ability and willingness to act on it. An industry respondent from a major mining company made this point most directly:

"South Africa doesn't need more research or more study tours. It needs a policy environment that allows for activation." (Industry respondent)

Similar frustrations were expressed by several stakeholders, who questioned what tangible outcome the research would produce. It was also noted that training only creates value when it is "linked to a economic opportunities". Respondents also explained what action could look like in practice. This includes working with industry to design short courses; building a complete domestic value chain capability for a flagship product such as vanadium flow batteries; using the MQA's convening authority to bring fragmented players into a shared structure. One such initiative would simultaneously develop specific technical skills, generate a demonstrable industrial product, build industry-academia linkages, and create a template replicable across other minerals.

For the MQA, this would mean moving beyond skills planning documents and grant disbursements into active programme co-design, sustained stakeholder coordination, and real accountability for outcomes.

7.10 Finding 9: The Quadruple Helix Model: The MQA as Strategic Coordinator

The findings suggest that the MQA should take on a stronger role as a central coordinator within the Quadruple Helix model. This model brings together industry, academia, government, and society to work in a more coordinated way to develop skills. This will ensure that skills planning is targeted, data-driven, and aligned with the requirements of specific minerals and value chain stages. Figure 31 illustrates an envisioned role of the MQA as coordinating the quadruple helix, bridging the legacy base of traditional mining and the future mandate of the critical mineral sector's strategic evolution. The specific recommendations linking to the model are noted below Figure 31.

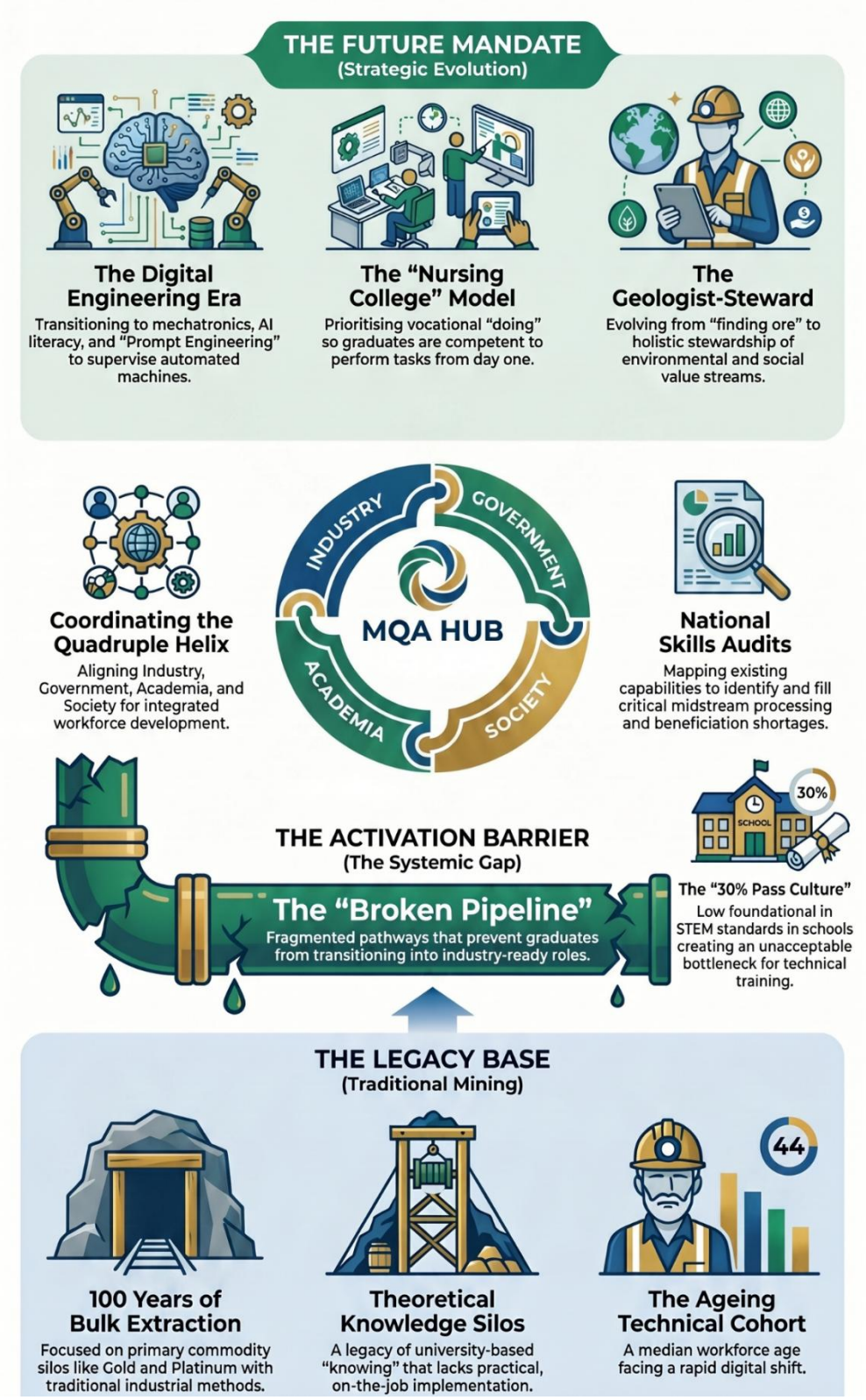


Figure 31: Envisioned role of the MQA as coordinating the quadruple helix

Bridging Institutional Fragmentation: Stakeholders characterised the MQA as the essential puzzle-solver needed to bridge current fragmentation within the sector. A recurring sentiment among respondents is that while many entities are currently "thinking the same,"

they are "not thinking together". This lack of coordination leads to a situation where organisations compete for limited funding rather than collaborating on integrated outcomes. By acting as a sectoral bridge, the MQA can link high-level policy roadmaps from the Department of Mineral and Petroleum Resources (DMPR), Higher Education and Training (DHET), and Trade and Industry (DTI) with the practical realities of the mining value chain. This role is essential to ensure that national strategies are successfully activated on the ground rather than remaining theoretical.

Leading National Capability Mapping: Participants advocated for the MQA to lead a comprehensive national skills audit. This mapping exercise must move beyond identifying generic "shortages of engineers" to accurately cataloguing workforce capabilities against the specific technical requirements of all the priority minerals identified in the national critical minerals strategy. By pinpointing the exact specialised roles that are missing, such as chemical processors or auto electricians for mechanised fleets, the MQA can ensure that training interventions are data driven and strategically aligned with resource sovereignty goals.

Curriculum Reform and Specialised Accreditation: There is a strong mandate for the MQA to drive a comprehensive modernisation of sectoral curricula to address the complexities of the digital engineering transition, through the following suggested mechanisms:

- **Dismantling Pick and Shovel Mindsets:** The research suggests that the MQA should lead industry wide consultative workshops to dismantle outdated training mindsets. Research informants noted that academic and vocational frameworks must pivot away from traditional bulk commodity extraction methodologies toward future oriented, high-tech competencies. This includes moving beyond a singular focus on safety to incorporate the technical process itself. Future curricula must formally integrate digital mining literacy and automated systems interaction to ensure the workforce can navigate modern, trackless mining environments. That said, it is important to note that the interventions must also consider, to quote a key informant of the research, “It’s just a mineral, right? ... You still have to mine the mineral. It’s not going to just appear for you.” This is to say that the traditional and foundational methods of mining and mineral processing should not be shunned but bolstered for applicability to the critical minerals sector.

- **Developing Future-Ready Skills:** The Mining Qualifications Authority is urged to develop new curricula for specialised competencies, specifically mechatronics, AI literacy, and prompt engineering. These skills are necessary to equip workers with the adaptive digital capabilities required to manage data-driven operations. Furthermore, in light of the complexities of trace elements, the MQA must upgrade its registered qualifications to include specialised chemical and metallurgical engineering competencies required for advanced midstream processing.

Fast-Tracked Safety Accreditation for ASM: To successfully integrate artisanal and small-scale miners into the formal value chain, informants recommended that the MQA develop streamlined, context specific accreditation pathways. These pathways should focus strictly on the core requirements of the Mine Health and Safety Act while utilising innovative, behavioural training methods. This approach embeds compliance without placing an unfeasible administrative burden on small-scale operations, allowing them to operate legally and safely.

Funding Activation and Practical Implementation: The research highlights a critical activation gap and recommends that the MQA overhaul its funding and delivery models to prioritise practical workforce outcomes over theoretical research. The following proposals were contemplated:

- **Shifting from Knowing to Doing:** Consistent with the proposed nursing college model, the MQA is encouraged to shift its focus from merely funding "knowing" through academic bursaries to supporting "doing" through vocational training. This ensures that graduates possess the practical capability to perform technical tasks from their first day of employment. To support this transition, respondents recommended that the MQA must aggressively expand its structured funding for Work-Integrated Learning (WIL) and apprenticeships, specifically targeting graduates **for roles within exploration juniors and secondary extraction operations.**
- **Strategically Targeted Bursaries and Transition Funds:** Stakeholders suggested that bursary allocations should be ringfenced for specific, high priority research topics, such as battery chemistry or rare earth extraction, rather than broad mining degrees. Additionally, the MQA is viewed as the ideal administrative partner for a dedicated

community skills transition fund. This fund, capitalised by large mining houses, would finance vocational and entrepreneurial programmes to equip local populations with the skills required to participate in the emerging critical minerals and green energy economy.

Global Knowledge Exchange and Regional Technical Councils*:* Recognising that South Africa lags behind in certain beneficiation technologies, research participants proposed that the MQA fund global exchange programmes. These would allow professionals to spend time at advanced facilities in countries like Finland, Germany, or the USA to learn midstream processing and bring those skills back to the domestic sector. Funding for attendance and presentation of bursary holders at international conferences could also form part of the MQA bursary award. Locally, the MQA should support regional technical councils to serve as institutional mechanisms for continuous skill sharing, mentorship, and peer-to-peer learning between large industry players and small-scale miners. This includes funding research chairs at local universities and facilitating critical minerals sector-based research across South Africa's different provinces.

Reducing Administrative Complexity: Finally, to re-engage universities and research institutions, respondents recommended that the MQA must reduce the noted cumbersome bureaucracy and paperwork associated with its funding. Streamlining these processes is viewed as an essential prerequisite for facilitating the high-level research and development needed to master the technical challenges of the critical minerals era.

MQA Intervention at Pre-Tertiary Education Stages: Respondents of the research identify the 30% Pass Culture; that is, the acceptance of 30% to 35% pass marks in foundational Mathematics and Science subjects; as an unacceptable bottleneck that severely threatens the long-term success of the critical minerals sector. This standard is described by multiple stakeholders as horrifying because it creates a false sense of achievement and forces universities to spend years on non-subsidised bridging programmes. To address this systemic crisis, the Mining Qualifications Authority (MQA) can implement the following strategic interventions:

Shift to Early-Year Interventions: It was proposed that the MQA should encourage mining companies to pivot their Social and Labour Plan (SLP) focus away from end-of-Matric bursaries

toward supporting STEM education as early as primary school. This proactive approach aims to build a sustainable talent pool rather than attempting to fix deficiencies only after students reach the tertiary level.

Utilise Mentorship from Retired Professionals: To bridge the foundational gap, the MQA can facilitate programmes that use the country's "endowment" of retired scientists and engineers to mentor students in Mathematics and Science at both primary and secondary school levels. Similarly, career guidance programmes could form a bridging tool to help students select study subjects for future careers wisely.

7.11 Conclusion

This chapter has presented an integrated overview of South Africa's critical minerals skills landscape, drawing on data from digital surveys, key informant interviews, and a stakeholder validation webinar. It has identified key themes emerging from the research, with a particular focus on implications for skills development within the critical minerals sector. Overall, the analysis provides a thematic synthesis of the findings and highlights strategic areas for intervention relevant to the Mining Qualifications Authority. Specific recommendations are presented in Chapter 8 of this report.

8. CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

This study assessed skills development needs and workforce readiness within South Africa's critical minerals sector, with a focus on the alignment between current skills development interventions, operational requirements, and longer-term sectoral transformation objectives. A mixed methods approach was used, drawing on literature review, online surveys, key informant interviews, and stakeholder validation webinar. This enabled a combined assessment of quantitative skills development patterns and qualitative insights into skills gaps, institutional constraints, and emerging workforce requirements within the critical minerals value chain.

South Africa possesses exceptional geological wealth in critical minerals. The national strategy is well-designed and broadly supported by stakeholders. Yet the country risks repeating its historical pattern of extractive, low-value participation in global commodity chains if it does not urgently address the structural skills misalignment that is visible at every level of the system; from school mathematics classrooms through to the absence of midstream processing chemists and beneficiation engineers.

The main findings all point to one issue: the workforce is still geared towards an old mining economy. There are strengths in areas like health and safety and early-stage geology, but there are serious gaps in processing, beneficiation, automation, and digital skills. The education and training system is producing graduates, but not with the skills that are actually needed. There is also limited collaboration between industry and universities, poor planning for future skills, and not enough focus on community and environmental skills.

The MQA is at an important turning point. Only 19% of stakeholders believe its current programmes are suitable for the critical minerals era. This should not be seen as failure, but as an opportunity. Stakeholders across different sectors see the MQA as the key organisation to bring everyone together and drive action. It has the mandate, funding, credibility, and research evidence needed to lead the response. The next section outlines the key recommendations from stakeholders.

8.2 Recommendations

A set of stakeholder-informed recommendations have been proposed, and these are structured in accordance with the SMART framework to ensure they are specific, measurable, achievable, relevant, and time-bound.

Recommendation 1: Strategic Coordination via the "Quadruple Helix" Model

The study identifies a clear “activation gap”, with stakeholders aligned in their thinking but not working in a coordinated way. To address this fragmentation, the MQA needs to reposition itself as a central coordinating body that connects government, industry, academia, and society, ensuring that policy priorities are translated into action. A critical starting point for this role is the development of a joint implementation roadmap for critical minerals skills, agreed upon by all key stakeholders. This roadmap should define shared priorities, roles, timelines, and accountability mechanisms to ensure coordinated and effective execution.

Activity	**Reposition the MQA as a strategic "puzzle-solver" and sectoral bridge between the DMPR, DHET, and the mining value chain to activate critical minerals strategies.**
Timeline	This project can be earmarked for the **2026/27 financial year**, with engagements scheduled on a periodic basis thereafter. This is an action item for the Stakeholder Relations Unit working with the Skills Development and Research Unit.

Recommendation 2: Develop Commodity- and Value-Chain-Specific Skills Profiles

As a follow up to this study, the MQA should initiate dedicated research that will develop detailed skills profiles for each of the 21 priority minerals, specifying the exact competencies required at each stage of the value chain (exploration, extraction, midstream processing, manufacturing, and circular economy/recycling). Each profile will distinguish between short-term (existing technology) and long-term (emerging technology) requirements.

Activity	**Develop Commodity- and Value-Chain-Specific Skills Profiles**
Timeline	Four profiles per quarter beginning Q2 of 2026/27, completing all 21 within 18 months. High-criticality minerals (PGMs, manganese, chrome, coal, platinum) to be completed first within 6 months. This is an action item for the Skills Development and Research Unit.

Recommendation 3: Launch a Flagship Value-Chain Skills Initiative

The MQA should partner with key stakeholders to co-design and fund a flagship, end-to-end skills development initiative centred on a fully integrated domestic critical minerals value chain. Building on ongoing developments in vanadium redox flow battery (VRFB) manufacturing, the initiative should be implemented in collaboration with organisations such as Mintek, the Department of Science and Innovation (DSI), and the East London Special Economic Zone (SEZ). The programme should combine skills development with industrial innovation by equipping learners with specialised competencies in areas such as electrolyte chemistry, battery engineering, cell assembly, materials science, and advanced manufacturing. In addition to producing a tangible industrial product, the initiative would serve as a demonstration project and provide a scalable model that can be replicated across other priority critical mineral value chains in South Africa.

Activity	**Launch a Flagship Value-Chain Skills Initiative**
Timeline	2026/27: sign MOUs with Mintek, DSI, and East London SEZ; begin curriculum design. 2027/28: pilot training cohort of 50 learners. 2028/29: full programme operational with 200 learners per year. 2029/30: replicate for second mineral value chain. This could be a special project implemented within the office of the CEO. =

Recommendation 4: Modernise Unit Standards and Qualifications

The MQA should work closely with universities, TVET colleges, and industry partners to review and update existing curricula and qualifications. This should include supporting the development and accreditation of short courses and micro-credentials in emerging areas such as artificial intelligence (AI), automation, digital technologies, and advanced mineral processing.

Activity	**The MQA should lead an industry-wide modernisation of curricula and qualifications by working with education and training institutions to integrate key future skills, including mechatronics, AI literacy, prompt engineering, and advanced mineral recognition, into the national PSET framework**
Timeline	Year 1 (2026/27): complete curriculum gap analysis and identify 15 priority unit standards for revision. Year 2 (2027/28): submit revised standards to QCTO and begin pilot delivery with at least 3 TVET colleges and 2 universities. This project should sit within the Learning Programmes unit.

Recommendation 5: Revitalise TVET Colleges Through the 'Nursing College' Competency Model

To address the "broken pipeline" where graduates lack practical capability, stakeholders recommend a shift toward competency-based training. This model ensures graduates possess the hands-on ability to perform technical tasks from day one. It is recommended that MQA design and fund structured Work-Integrated Learning (WIL) pathways that guarantee every learner in an MQA-registered qualification gains documented, assessed practical experience in a real mining or minerals processing environment before graduating. This includes apprenticeships, learnerships, and graduate placement programmes.

Activity	**Shift funding focus from purely academic bursaries toward vocational, hands-on training pathways where "doing" precedes "knowing".**
Timeline	2026/27: conduct TVET landscape assessment across mining corridors and identify 10 pilot colleges. 2027/28: pilot the corridor alignment model in 5 colleges. 2028/29: scale to all 10 colleges and register first competency-based qualifications. This project should be implemented by the Learning Programmes and Monitoring and Evaluation units.

Recommendation 6: Expand Workplace-Integrated Learning (WIL) and Apprenticeships

The transition from graduation to industry readiness is a major bottleneck. The MQA should build on and improve the visibility and use of its existing Learner-Employer Interactive System (LEIS) to connect graduates with workplace learning, internship, and apprenticeship opportunities. The system should also support better tracking of learner placements and outcomes. Special focus should be given to opportunities in emerging areas such as tailings reprocessing, secondary mineral extraction, and other critical minerals value chain activities.

Activity	**MQA should raise awareness and promote the utilisation of its Learner-Employer Interactive System (LEIS) among learners, graduates, training providers, and employers to close the gap between graduates and practical experience.**
Timeline	This initiative can be implemented during the 2026/27 financial year, with MQA hosting awareness campaigns, stakeholder engagement sessions, and information workshops to promote the LEIS platform and encourage use by both learners and employers. This is an action item for the Stakeholder Relations and Learning Programme units.

Recommendation 7: Administer an Industry-Funded Community Skills Transition Fund

To help communities benefit from the energy transition, the MQA should promote the establishment of an industry-supported Community Skills Transition Fund. The fund would support skills development and training programmes that prepare local communities for

employment and business opportunities in the green economy, particularly in areas affected by changes in the mining and energy sectors.

Activity	**MQA should establish and coordinate a Community Skills Transition Fund to support training, reskilling, entrepreneurship development, and green economy employment opportunities for communities affected by the energy transition.**
Timeline	This project can be considered for establishment in the **2026/27 financial year**.

Recommendation 8: Institutional Regional Technical Councils

Stakeholders noted that continuous knowledge sharing is required to respond to rapid technological change. These councils should host regular workshops, mentorship programmes, and peer-learning sessions. A supporting digital platform should also be developed to capture, share, and update technical knowledge and best practices.

Activity	**Co-establish regular regional technical councils to facilitate continuous skill sharing, mentorship, and the dissemination of operational best practices.**
Timeline	This project can begin in the **2026/27 financial year**, with database and database updates scheduled periodically thereafter.

Recommendation 9: Global Knowledge Transfer and Exchange Programmes

South Africa lags behind in certain complex beneficiation technologies. Funding international exchanges would allow professionals to learn midstream processing techniques and "bring the skills home". The MQA should develop partnerships with leading international institutions and mining hubs in countries such as Finland, Germany, and the United States. It should fund scholarships and professional exchange programmes in priority skills areas. Participants should be required to transfer their knowledge locally through structured training, mentorship, or curriculum development initiatives upon their return.

Activity	**Fund exchange programmes where students and professionals spend time at advanced facilities in countries like Finland, Germany, or the USA.**
Timeline	This project can begin in the 2026/27 financial year, where the exchange programme framework is developed and MQA work towards signing one international MOU partnership.

REFERENCES

AfCFTA Secretariat. 2024. Trading under the African Continental Free Trade Area (AfCFTA). African Union, Addis Ababa. Available at: https://au.int/en/african-continental-free-trade-area.

African Minerals Development Centre (AMDC). 2025. African Green Minerals Strategy. African Union, Addis Ababa.

African Union Commission. 2009; 2023. Africa Mining Vision (AMV). African Union, Addis Ababa. Available at: https://au.int/en/ti/amv/about.

African Union Commission. 2015. SADC Industrialisation Strategy and Roadmap 2015-2063. African Union Commission, Addis Ababa.

Ahiakwo, N.I., Egwuonwu, A.C., and Okeke, O.C. 2018. A Review of the Geology and Mineral Resources of South Africa. International Journal of Advanced Academic Research (IJAAR), Nigeria.

Albatts. 2021. Sectoral Skills Intelligence and Strategy for the European Battery Sector. Albatts EU, Brussels.

Arias, V.M.M. (2022). Principles, Scope, and Limitations of the Methodological Triangulation. Invest Educ Enferm. 2022 Jun;40(2):e03. doi: 10.17533/udea.iee.v40n2e03.

Bulbulia, T. 2025. BLSA welcomes Operation Vulindlela progress, but calls for increased implementation momentum. Creamer Media, Johannesburg.

Carrera-Rivera, A., Ochoa, W., Larrinaga, F., and Lasa, G. (2022). How-to conduct a systematic literature review: A quick guide for computer science research. MethodsX, Vol. 29 (2024). https://doi.org/10.1016/j.mex.2022.101895.

Clarke, V. and Braun, V. (2014). Thematic analysis. In Encyclopedia of Critical Psychology, Springer, New York, pp. 1947-1952.

Clearkin, P., Moencks, T., Shongwe, L., and Chibabhai, M. 2025. Harnessing Africa's Critical Mineral Opportunity. Boston Consulting Group, Johannesburg.

Cloete, D., Jentel, L., Mzinyati, L., Wolf, N., Benkenstein, A., and Joseph, A. 2025. Anticipatory Governance of Critical Minerals in SADC: Strategic Policy Pathways for 2035. South African Institute for International Affairs, Johannesburg.

CSIR. 2024. Advancing Circular Economy South Africa. Council for Scientific and Industrial Research, Pretoria.

Department of Mineral and Petroleum Resources (DMPR) (2025). South Africa's Critical Minerals and Metals Strategy. Pretoria: Government Printers. Available at: https://www.gov.za/sites/default/files/gcis_document/202505/critical-minerals-and-metals-strategy-south-africa-2025.pdf.

Department of National Treasury. 2023. Operation Vulindlela: Supporting the Implementation of Priority Structural Reforms. Government Communication and Information System, Pretoria.

Department of Science and Innovation (DSI). 2022. Securing a clean, affordable and sustainable energy future for South Africa. Department of Science and Innovation, Pretoria.

European Commission (2023). Critical Raw Materials Act and CRM List. Brussels: European Union.

European Commission (2024). Critical Raw Materials Act: List of Critical Minerals. Brussels: European Union.

Franks, D. M., Gardner, N., Aska, B., Linus, J. H., Varshney, S., Rogers, P., Weldegiorgis, F., Lawson, L., Gallagher, L. 2025. How the rush for critical minerals is neglecting human needs. Nature, 647, 33-36. Nature Publishing Group, London.

Hale, T.N., Ali, S.H., Christman, P., Bleischwitz, R., Svobodova, K., Primmer, E., Moutinho, V. L. P., and Kulczycka, J. 2024. Critical minerals policies need clearer interface with scientifically credible targets. Cambridge University Press, Cambridge, UK.

Hidayat, M. 2025. G7 Critical Minerals Alliance: Game-Changer for Global Supply Chains. Discovery Alert, Sydney, Australia.

Hofmeyer, J. 2025. South Africa's new critical minerals strategy: promises and challenges. Afripoli Policy Institute, Cape Town.

Hund, K., La Porta, D., Fabregas, T. P., Laing, T., and Drexhage, J. 2018. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group, Washington, DC.

International Council on Mining and Metals (ICMM). 2023. Critical Minerals. ICMM, London.

International Energy Agency. 2023. Critical Minerals Market Review 2023. International Energy Agency.

Kaman, Z. and Othman, Z., 2016, April. Validity, Reliability and Triangulation in Case Study Method: An Experience. In Qualitative Research Conference (QRC) (Vol. 2016, pp. 24-26).

Kemper, E.A., Stringfield, S. and Teddlie, C. (2003). Mixed methods sampling strategies in social science research. In Handbook of Mixed Methods in Social and Behavioral Research, Sage, Thousand Oaks.

Khan, S., Godfrey, L., Maphalala, B., Magweregwede, F. & Nontso, Z. (2022). Mining and the Circular Economy: South Africa's resource availability as a driver for transitioning to a Circular Economy. CSIR/MIN/MMR/IR/2022/0001/A. Council for Scientific and Industrial Research, South Africa.

Khanna, R., Malinga, N. & Nwaila, G. (2024). 'Future-Ready Skills for a Low-Carbon Economy: Insights from South Africa's Mining Sector.' Journal of Sustainable Mining, 10(2), 51-67.

Li, S. and Wang, K. 2025. Critical Minerals, Explained. World Resources Institute, Washington, DC.

McKay, S. 2025. Critical minerals or criminal miners? The (in)formalization of artisanal and small-scale copper mining in Peru. The Extractive Industries and Society, 25, 101811. Elsevier, Amsterdam.

Minerals Council South Africa. (2025). Comprehensive Facts and Figures 2024. 05 August 2025.

Mining Qualifications Authority, 2023. Sector Skills Plan Update 2024/25 for the Mining and Minerals Sector. Final Submission. 31 August 2023.

Mintek (2022). Critical and Strategic Minerals in South Africa: Report for Policymakers. Randburg: Mintek.

Mintek. 2025. Annual Integrated Report. Mintek, Johannesburg.

Moshikaro, L. and Pheto, L. 2023. Localising Vanadium Battery Production For South Africa's Energy Security. Bushveld Energy, Johannesburg.

Naderifar, M., Goli, H., & Ghaljaie, F. (2017). Snowball sampling: A purposeful method of sampling in qualitative research. Strides in Development of Medical Education, 14(3), 1-6.

National Planning Commission (2012). National Development Plan 2030. Our future - make it work. Department: The Presidency. Republic of South Africa.

Nwaila, G., Malinga, N. & Thorpe, R. (2023). 'Mapping South Africa's Critical Minerals Landscape.' Resources Policy, 43(1), 89-104.

OECD (2015). Critical Minerals Today and in 2030. Paris: Organisation for Economic Co-operation and Development.

Open Access Government. 2025. Rare earth, critical minerals, and bio-molecules: Centering African IPLCs in the new resource economy. Open Access Government, London.

Parliament of South Africa. 2025. Harnessing Critical Minerals for Inclusive Growth and Sustainable Development. Research Unit, Parliament of South Africa, Cape Town.

Pervin, N. and Mokhtar, M. (2022). The Interpretivist Research Paradigm: A Subjective Notion of a Social Context. International Journal of Academic Research in Progressive Education and Development, 11(2).

Ramdoo, I., Bellois, G., and Hendriwardani, M. 2023. What Makes Minerals and Metals 'Critical'? Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development Secretariat, Ottawa, Canada.

Redflank. 2024. Framework For Future Skills Needs Identification for the MMS. Mining Qualifications Authority, Johannesburg.

Robinson, R.S. (2023). Purposive Sampling. In: Maggino, F. (eds) Encyclopedia of Quality of Life and Well-Being Research. Springer, Cham.

SADC. 2015. SADC Industrialization Strategy and Roadmap. SADC Secretariat, Harare, Zimbabwe.

Sardana, N., Shekoohi, S., Cornett, E.M., and Kaye, A.D. (2023). Qualitative and quantitative research methods. In Substance Use and Addiction Research, Academic Press, pp. 65-69.

Savige, T., Quigley, M., and Werner, T. T. 2025. Climate change is devastating mining of minerals needed to fight it. Nature, 647, 36. Nature Publishing Group, London.

SFA Oxford. 2025. Critical Minerals and the Energy Transition. SFA Oxford Ltd., Oxford, UK.

Simon, M.K., and Goes, J. (2011). Scope, Limitations and Delimitations.

Sonesson, C. 2015. How can mining contribute to the Sustainable Development Goals? World Economic Forum, Geneva.

United Nations Conference on Trade and Development (UNCTAD). 2025. Trade in critical minerals shapes energy transition, digital transformation and industrial development worldwide. UNCTAD, Geneva.

United Nations Department of Economic and Social Affairs (UN DESA). 2025. Harnessing the Potential of Critical Minerals for Sustainable Development. UN DESA, New York.

United Nations. 2015. The 17 Sustainable Development Goals. United Nations, New York. Available at: https://sdgs.un.org/goals.

USGS (2025). Methodology and Technical Input for the 2025 U.S. List of Critical Minerals. Washington, D.C.: U.S. Department of the Interior.

USGS (2025). What are Critical Minerals? U.S. Department of the Interior.

Vandome, C. 2025. Critical Minerals and South Africa's G20 Strategy. Georgetown University, Washington, DC.

Vishnevsky T, Beanlands H. (2004). Qualitative research. Nephrology Nursing Journal. 2004 Mar-Apr;31(2):234-8.

Willige, A. 2025. What are the critical minerals for the energy transition - and where can they be found? World Economic Forum, Geneva.

World Bank Group (2018). The Growing Role of Minerals and Metals for a Low Carbon Future. Washington, D.C.: World Bank.

Zhou, J., and Månberger, A. 2024. Critical Minerals and Great Power Competition. Stockholm International Peace Research Institute, Stockholm.