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Article *in* Resources Policy · April 2024

DOI: 10.1016/j.resourpol.2024.105045

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Resources Policy 93 (2024) 105045

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A systematic framework for compilation of critical raw material lists and their importance for South Africa

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ARTICLE INFO

Keywords:
CRMs
South Africa
Ranking
Circular economy
Mineral resources
Policy
ESG

ABSTRACT

Mineral resources are important contributors to the global economy and societal wellbeing. Directly, they provide employment, revenue and taxes through the extraction, processing and sale of minerals. Indirectly, they are essential to all modern industries, including: energy, manufacturing, construction, biotic and abiotic resource extraction and agriculture. The principle that 'one cannot understand the value of what they have until they measure it' is particularly relevant with critical raw materials (CRMs). CRM is a concept that categorises select resources (mainly minerals and metals) as critical in the sense that, at a national level, they are essential and difficult to replace, and their supply is prone to disruption. It is becoming increasingly recognised that the continuity of civilisation and living standards as some have envisioned them in the future is constrained by the quality and quantity of various minerals. National-level strategic planning, including energy policy, foreign relations policy, geopolitical operations, national defence, education and infrastructure planning, among others, all require knowledge of the requirement and supply of raw materials towards a practical strategic implementation. Hence, a national CRM framework is essential for a prosperous, productive and stable future. To effectively manage the supply and use of CRMs, it is important to comprehend both their formal (e.g., economic) and informal (e.g., social and environmental) values, and to measure and monitor these values effectively over time. This study examines international practices and methodologies as components of a comprehensive CRM framework. We then propose a prototype CRM framework for South Africa as such a framework is currently missing.

All CRM frameworks feature one or more rating schemes to identify the degree of criticality of raw materials. The actual rating metrics are divided into dimensions (or factors), such as: socio-economic importance, technological importance, environmental, social and governance risks. Such dimensions are important due to the following reasons.

- Delineating criticality from non-criticality: by rank-ordering CRMs based on various factors, a country can identify which ones are the most important for its economy, industry and national security. This information can help policymakers prioritise the development of domestic production and secure a stable supply of CRMs.
- Assessing resource sustainability and supply stability: by rating CRMs based on environmental, social and ethical factors, a country can assess the sustainability of its resource use and identify

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https://doi.org/10.1016/j.resourpol.2024.105045
Received 3 April 2023; Received in revised form 13 November 2023; Accepted 27 April 2024
Available online 7 May 2024

areas for improvement. This information can help policymakers develop strategies to mitigate resource depletion, and supply chain disruption, minimise negative environmental and social impacts, and promote responsible resource management.

- Supporting informed decision-making: an ordered ranking of CRMs provides quantitative and qualitative information to governmental bodies, industry and other stakeholders to support informed decision-making, including strategic planning. This information can help stakeholders make informed choices about the sources and types of CRMs they use and the sustainability of their resource use.
- Promoting transparency and accountability: adopting suitable business ethical dimensions, such as through a corporate social responsibility framework, enables a country to promote transparency and accountability in its resource use and supply chains. This approach can help reduce illicit financial flows, corruption, and abuse of power, while increasing trust and confidence in the resource sector.
- Innovation and investment opportunities: a CRM framework enables a nation to establish policy conditions that foster innovation and investment in key activities such as measuring, monitoring, sustainability, extracting, responsible processing, and efficient use of CRMs.

Findings from this study underscores the necessity of a structured CRM framework in South Africa to effectively manage the complexities of resource management, economic ground, and sustainability. Integrating these frameworks into national policies can enable South Africa to secure a sustainable, economically viable, and environmentally responsible future. Such strategic initiatives are impor tant for national security, industrial policy, structural transformation, and economic stability, as well as aligning with global initiatives for responsible sourcing and climate change.

1. Introduction

Many raw materials are increasingly becoming critical to the continuity of modern societies. In Global North countries, the concept of critical raw materials (CRMs) is increasingly well developed and has already begun to shape national policy, economic growth, scientific inquiry and infrastructure planning (e.g., European Commission, 2020; Kelley et al., 2021; Government of Canada, 2022). For example, the European Union's 5th CRM list has a total of 34 CRMs (European Commission, 2023). CRMs are used in a variety of industries, including: 1) high-tech/technology (Bobba et al., 2020), 2) energy (Grandell et al., 2016; Martin et al., 2022), 3) defence (Powell-Turner and Antill, 2017), and 4) infrastructure (Eid et al., 2016), among others. In the context of modern societal issues, for instance, CRMs play a key role in the green energy transition, but their supply is at risk of disruption (Ghorbani et al., 2024b; Martin et al., 2022; Ghorbani et al., 2024a). Since the exact needs of various countries generally vary, the definition, value and importance of CRMs also vary by country or super-national groups (Hayes and McCullough, 2018). Some countries, such as Canada and the United States use the terminology 'critical minerals' and 'strategic minerals', respectively, to refer to materials of a similar definition. In this paper, we adopt the term CRMs to generalise the nomenclature of all such materials.

South Africa is a country undergoing a transition towards greater socio-economic equality by integrating customary indigenous practices, modern rule-of-law principles, while taking global trends towards sustainability into account.. In system terms, the global and South African socio-economic resources, as well as other related systems, are undergoing a period of rapid evolution in response to both internal and external drivers. Navigating these rapid and multi-level societal changes requires a clear view of the role of CRMs, in terms of their risks and impacts, to enable coordinated, well-informed and timely decisions on a national level. Presently, there is no established CRM list for South Africa or even a CRM list with an identifiably African focus. This means that other CRM lists have less meaning for Africa, mainly because of disparities in economic, infrastructure and societal development, as well as cultural differences. This unfortunately creates an unequal footing for the planning of the South African economy, infrastructure, national policy and international engagement, because other global interests interact with South Africa with an a-priori and informed goal, while South Africa does not yet have an equivalent vision. This potentially creates a situation that could enable 'mineral colonialism' – the targeting of under-informed but resource-rich countries, such as African countries, by mineral-poor countries to secure their future supplies. This study attempts to create a framework that generalises known methodology and rationale to permit the creation of a CRM list that benefits to South Africa. Consistent with existing methodologies, we define South African CRMs as materials that: 1) make a significant economic contribution to key sectors; 2) have a notable high supply risk(s) due to very-high import dependence; 3) exhibit a high level of concentration in other countries and/or regions; and 4) have generally limited, to no (viable) substitutes, because of their unique and reliable properties for current and future applications (Ferro and Bonollo, 2019).

South Africa is a major producer of many CRMs, as per non-South African definitions, including: vanadium, chromium, iron and manganese, and hosts the world's largest known reserves of platinum group metals (PGMs; Hofmann et al., 2018; Nwaila et al., 2022a). In absence of a South African CRM list, we here discuss the contribution of externally-defined CRMs to South Africa. The benefits of a South African CRM list would obviously extend these contributions in the future. The mining and processing of CRMs is a significant contributor to the South African economy, providing employment and revenue for the country (Van der Merwe, 2011; Marais et al., 2022). The value-adding stages after mineral processing are generally foreign to South Africa. However, the supply of CRMs in South Africa faces several challenges (Nwaila et al., 2022a). Notably, the increasing global demand for CRMs is adding pressure on existing supplies (Martin et al., 2022), and declining ore grades are making it increasingly difficult to extract these materials (Nwaila et al., 2022a). Additionally, the extraction and processing of CRMs can have significant environmental and social impacts, including air and water pollution (Nwaila et al., 2022a), land degradation and displacement of communities (Fayiga et al., 2018). These impacts can have long-term consequences on the wellbeing of affected communities, as well as the sustainability of the minerals industry (Olufemi et al., 2018).

To effectively manage its CRMs, South Africa needs to adopt a comprehensive and strategic approach that considers the country's long-term needs and goals. Key considerations for creating an effective CRMs policy framework in South Africa include.

- Identifying and prioritising needed CRMs and developing a strategy to secure a reliable supply of these materials. This may involve incentivising the development of a domestic production of CRMs, establishing partnerships and collaborations with other countries, and promoting the recycling and re-use of these materials.

- Ensuring that the extraction and processing of CRMs are congruent with societal customary and statutory standards (health and safety, environmental and sustainability). This may involve revising current legislation and establishing regulatory frameworks, promoting best practices, mineral chain-wide integration and innovation, and supporting the development of sustainable and responsible value chains.
- Investing in research and development to promote short- and long-term supply and substitution of CRMs, particularly through the use of modern technologies such as mineral exploration drones, geothermal energy and advanced recycling methods.
- Promoting transparency and accountability in the CRMs sector, through the publication of data, supply chain transparency and the implementation of reporting requirements.
- Encouraging collaboration and information sharing among different stakeholders in the CRMs sector, including industry, academia and civil society.

Considering these challenges and the importance of CRMs associated with their supply and use, it is important to have a comprehensive and strategic approach to managing the materials. In this study, we review the importance of CRMs for South Africa and identify key considerations for measuring the criticality and managing these materials in a sustainable and responsible manner.

2. A brief history of CRM lists

Awareness of the necessity and preciousness of various minerals and metals predate modernity. In history, various civilisations that have sought materials such as iron, copper, silver and gold, recognised their intrinsic preciousness and leveraged them to build economies that were highly characteristic of the materials that empowered them (e.g., the bronze and iron ages, in particular). The modern history of rating and ranking schemes for CRMs can be traced back to the mid-20th century, when the demand for strategic materials began to increase due to their use in industrial and military applications, in turn leading to increased awareness of their critical role (Burnett et al., 2022, Fig. 1). This led to the creation of schemes that variably designated materials as 'strategic', which promoted national strategies to secure, stockpile and examine the supply and usage sustainability of such materials. As time and therefore societies evolve, material requirements also change.

One of the earliest ranking schemes was developed by the United States Bureau of Mines in the 1970s, which listed 15 critical minerals based on their economic importance and vulnerability to supply disruption (Schulz, 2017, Fig. 1). This list was later updated in the 1980s and 1990s to include additional materials, such as rare earth elements (REEs), which were becoming increasingly important for a variety of emerging applications (Schulz, 2017). In the European Union, the first set of CRMs was first introduced in 2011, consisting of 14 CRMs based on their economic importance and supply risk (European Commission, 2011). In 2014, 2017, 2020 and 2023 the 2nd, 3rd, 4th and 5th sets were published, expanding to 20, 27, 30 and 34 materials, respectively, with the latter sets imposing additional criteria or dimensions such as societal importance (European Commission, 2014, 2017a, 2017c, 2020, 2023, 2017a). In February 2022, the U.S. Department of the Interior and the U. S. Geological Survey (USGS) also released a list of 50 CRMs deemed essential to economic and national security (Applegate, 2022). Presently, several countries and international organisations have developed ranking schemes for CRMs, which include.

- European Union (EU): The EU has identified a list of 34 CRMs based on criteria such as economic importance, supply risk and societal importance (European Commission, 2023).
- United States: The United States has several ranking schemes for CRMs, including the USGS's list of 'strategic and critical minerals' (Schulz, 2017) and the U.S. Department of the Interior's list of 50 'critical minerals' (Applegate, 2022).
- Japan: The Japanese government has identified 31 'strategic minerals' that are considered important for the country's economic and national security (Giese, 2022).
- Canada: The Canadian government published a list of 31 'critical minerals' considered important to spur economic growth and to mitigate supply chain issues (Government of Canada, 2022).
- Organisation for Economic Cooperation and Development (OECD): The OECD has identified a set of 17 CRMs based on their economic importance and supply risk (Koyamparambath et al., 2022; Mathieux et al., 2017; David et al., 2021; Girtan et al., 2021; Guzik et al., 2021).
- China: The Chinese government has identified a list of 24 'REEs and other strategic minerals' that are considered important for the country's economic development and national security (Hurst, 2010; Massari and Ruberti, 2013; Zepf and Zepf, 2013; Dutta et al., 2016; Andersson, 2020).

Several international organisations also provide ratings on CRMs or related topics. Here are a few examples (Ghamisi et al., 2021a,b; Hool et al., 2022; Murguía, 2022; Martin et al., 2022).

- European Commission: The European Commission publishes a list of CRMs for the EU, which is updated every three years. The list is based

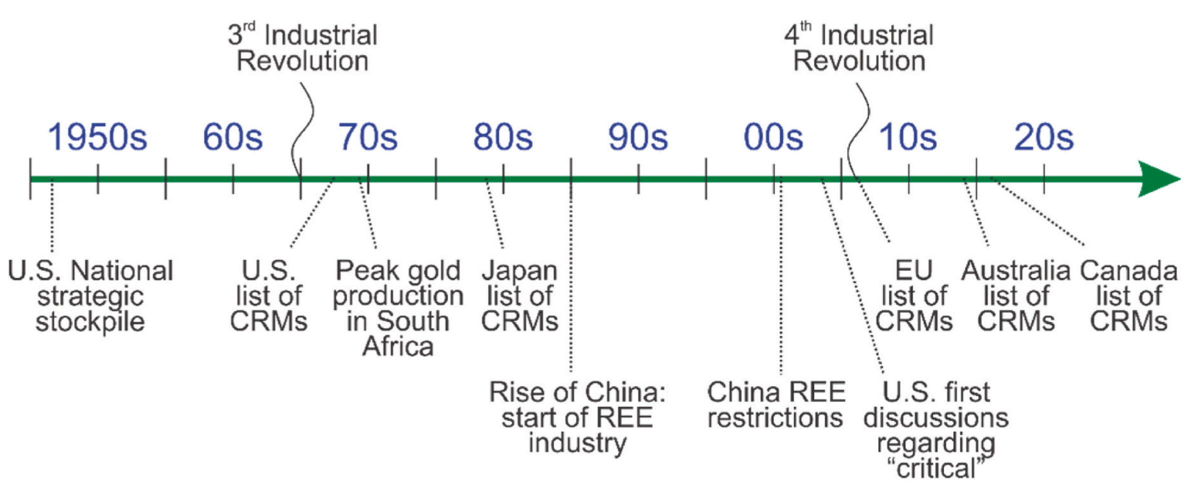

Fig. 1. Schematic timeline of the development of CRM lists (initial studies for the EU, Australia and Canada) and significance worldwide.

on an assessment of the economic importance, supply risk, environmental, geopolitical and social impacts of CRMs. The assessment is carried out by the Joint Research Centre (JRC) of the European Commission.
- World Bank: The World Bank's Commodity Markets Outlook analyses commodity markets. The report includes information on production, consumption, trade, prices and other economic indicators for a range of commodities, including CRMs.
- Global Risk Insights: Global Risk Insights is a consultancy that analyses and forecasts global risks. The company publishes research and reports on CRMs risks and trends, including supply chain disruptions, price volatility and geopolitical risks.
- Bloomberg: Bloomberg is a financial news and data provider that publishes information and analysis for a range of commodities. The company's commodities team provides insights and analyses CRMs markets, trends and forecasts.

Current methodologies to assess the criticality of materials differ by country (and presumably the data that were used to support the assessments), although many CRMs consistently overlap across assessments. For instance, the United States employs a two-stage process, whereby in the first stage, the geometric mean of indicators for supply risk, production growth and market dynamics is calculated. This is followed by the second stage, whereby a threshold analysis is performed to determine criticality and ranking (Nassar et al., 2020; Nassar and Fortier, 2021). The EU uses a single-stage process, whereby all materials are assessed for their economic importance and supply risk, while a hard threshold is also overlaid to delineate criticality (European Commission, 2017b). The differences between these methods are not substantial as the guiding principles are essentially identical. This is the key reason why many CRMs overlap across individual assessments. Critical analysis of CRM frameworks and lists is currently sparse and a single example exists that analysed the EU's evolving CRM lists with specific implications for South Africa (Zhang et al., 2023). The analysis revealed that the EU's methodology exhibits a few weaknesses that enable spontaneous criticality of materials ('emerging criticality') that include (Zhang et al., 2023): (1) a hidden nomination phase; (2) non-dynamic criticality baselines; (3) insufficiently pragmatic motivations; (4) a blurring of civilian and military needs; (5) a lack of foresight; and (6) no explicit consideration of system behaviours. Key observations for South Africa and similar countries include (Zhang et al., 2023): (1) just energy transition is important to transition away from energy poverty; (2) a locally relevant definition of criticality; (3) the possibility of an export-bound CRM list and a domestic-needs CRM list, due to relative economic development differences between the Global North and the Global South.

The current assessment methodologies in all published CRM frameworks employ a dimension-based, metric and threshold-delineated combination using a minimum of two (qualitatively) orthogonal dimensions along which metrics are calculated. Properties of CRMs and their mineral value chain that are not fully quantitative are nevertheless assigned numerical scores to facilitate calculation. Essentially, two key and semi-independent dimensions are always assessed, one along supply and the other demand. The supply dimension is intended to capture the temporal-spatial robustness of the supply chain of materials, such that the assessments along this dimension relate to the reliability of such supply chains. The substitutability of materials is also generally considered, which can modify the considerations of risk under the supply dimension, depending on the range and extent of substitutions possible for known material uses. Similarly, the demand dimension is intended to anticipate the level of demand given a certain forecasted or vision of the future state of the society. This is due to the supply and demand behaviour of market systems, in which the CRM value chain resides. Additional dimensions that gauge auxiliary or secondary concerns can provide supplementary constraints to refine primary assessments, such as climate change mitigation capacity and military significance (e.g., Bensch et al., 2015). Once the dimensions are defined, the remaining tasks are to engineer feasible measures and metrics. The remainder of the methodology revolves around the establishment of comparisons, which can occur in the form of empirical baselines or theoretical targets. This effectively sets quantitative thresholds of criticality and therefore a mechanism to rank-order CRMs. It is important to recognise that CRM assessment schemes assume societal progression and usually embeds a vision component (e.g., Government of Canada, 2022). Consequently, CRM assessments and the associated methodology are often revised and updated periodically. Furthermore, because CRM assessment schemes are driven by assumptions of societal progression and political vision, it is critical that a country willing to adopt the CRM concept must design its own CRM assessment methodology using its assumptions of the future.

3. The importance of rating CRMs for South African policy

The South African policy landscape is evolving rapidly, driven partly by its rapid pace of social and economic changes, and with it comes significant changes to the country's consumption of materials. As the Global North countries attempt to move towards a more sustainable future, Global South countries are facing a dichotomous set of realities that involves the staging of their own economies (e.g., many are primary or secondary and less involved in tertiary beneficiation industries). Global South countries face a delicate balance between international and domestic consumption needs, and need to secure primary energy generation resources as such nations seek to industrialise and increase their standards of living. South Africa is in a rapidly evolving state of juxtaposition of modernity, statutory and customary (or traditional) values, following the end of Apartheid in 1994. Consequently, South African material needs is exceptionally diverse, compared to Global North CRMs (e.g., of high-tech minerals like REEs), and compared to nations that are in the early stages of industrialisation (e.g., of base metals, coal and shale for brickmaking; Figs. 2–4). The importance of establishing a South African-specific set of CRMs to support national policy-making cannot be overstated, because without an awareness and strategic planning, global influence will inevitably exert control over domestic production and prosperity outcomes. The general trend of rating CRMs based on economic and technological importance, as well as resource availability, are valuable for an industrialising nation (Fessehaie and Rustomjee, 2018; Jannesar Niri et al., 2024). Foreseeable policy and societal outcomes of such an assessment and its associated CRM list include.

- Prioritising domestic production and stockpiling of CRMs: Rating CRMs based on economic and technological importance allows a country to determine which CRMs are most essential for its industry and economic growth (Fessehaie and Rustomjee, 2018). This information can assist policymakers in prioritising the development of domestic production and processing of CRMs, which can create jobs, promote economic growth and reduce import dependency (Government of Canada, 2022).
- Attracting investment in the resource sector: Rating CRMs based on resource availability enables a country to provide investors with pertinent information regarding potential resource development (Guzik et al., 2021). Policy mechanisms including the provision of financial and taxation incentives, priority exploration and focused education curriculum can all contribute to attracting investment. This can help attract investment in the resource sector, contributing to economic growth, employment creation and generating revenue for the government.
- Promoting sustainable resource use: Rating CRMs through business ethics frameworks allows a country to encourage the utilisation of CRMs with fewer negative impacts on the environment and communities, thus promoting sustainable resource usage (Government of Canada, 2022). This can help reduce resource depletion, minimise

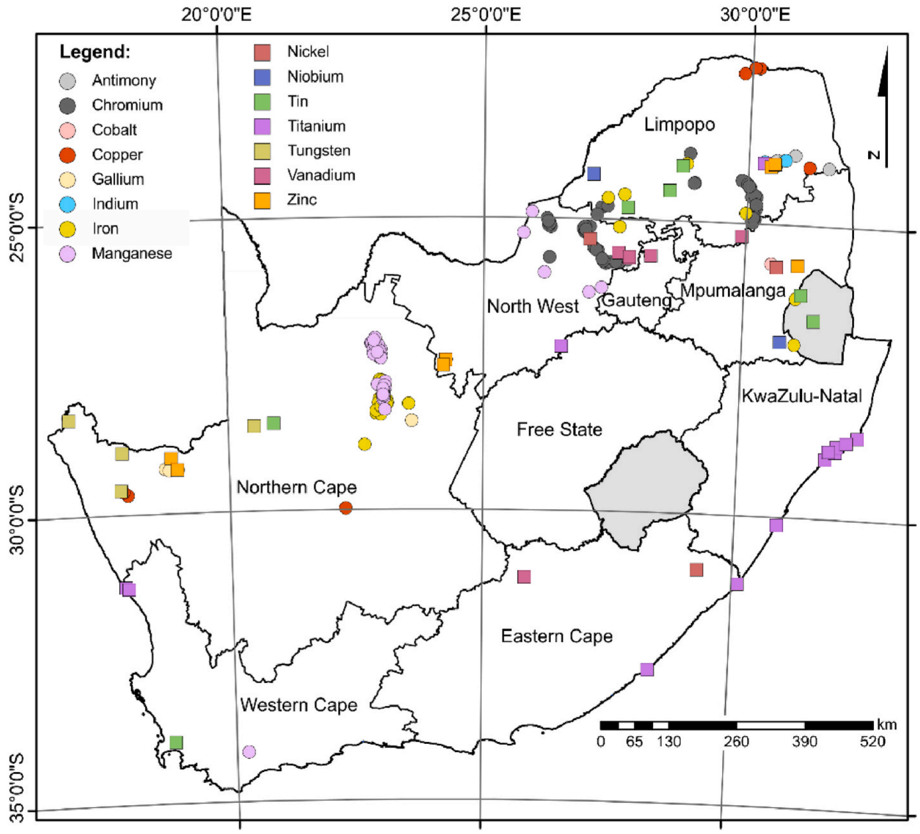

Fig. 2. Historically known and actively mined base metal deposits in South Africa. Data sourced from Padilla et al. (2021) and South Africa Department of Mineral Resources and Energy (DMRE; Operating mines 2022: https://www.dmr.gov.za/mineral-policy-promotion/operating-mines). Data included as supplementary material.

adverse environmental and community impacts, and support responsible resource management.

To initiate a CRM rating scheme, the following steps and factors need to be considered (Ghorbani et al., 2024a,b; Koyamparambath et al., 2022; Galos et al., 2021; Salim et al., 2022; Domaracka et al., 2022).

- Assume a realisable future societal state and identify the materials to be rated: The first step is to create a realistic vision of the future and identify materials that are currently or will be important for the country's industry, economy and national security.
- Define the rating dimensions: The next step is to establish the rating dimensions to be used, which may include economic importance, environmental risk, social risk, governance risk, technological importance, among others.
- Construct metrics and weights for each rating dimension: Metrics and weights should be assigned to each criterion to assess its relative importance. For example, if the objective is to emphasise CRMs that are crucial for the country's industry and economic growth, economic importance may be given a higher weight.
- Collect data on the CRMs: Data must be collected on the CRMs to be rated in accordance with rating criteria. This data may include information regarding location, economic importance, environmental, social and governance (ESG) risks, technological importance, among others. Data can be sourced from various locations, such as government statistics, industry reports, market dynamics and academic research.
- Calculate ratings: Using the collected data, metrics and weights, ratings can be calculated for each CRM. This will provide a score for each CRM based on the chosen rating criteria.
- Analyse and interpret ratings: Ratings can then be analysed and interpreted to understand the strengths and limitations of each CRMs and identify areas for improvement. Ratings can also be used to guide decision-making, prioritise domestic production development and ensure a stable supply of CRMs.
- Documentation: The final adopted ratings must be accurately documented and secured. Models that allow automatic rating updates based on the formulae and rating criteria used need to be created for easy analysis in case of a national change in priorities. Ultimately, the knowledge management model detailing the governance of the CRM list in terms of updates, sharing and use must equally be developed.

4. The role of the CRM list for corporate social responsibility (CSR) initiatives

A CRM list can facilitate CSR initiatives, such as the effective usage of ESG frameworks in several ways. The list can be used to optimise exploration and exploitation of materials, as well as to manage acceptable risks and impacts to the environment and society (Kemp and Owen, 2022; Jannesar Niri et al., 2024; Lèbre et al., 2020). Once a list is compiled, organisations and governments will be better positioned to prioritise their efforts to engage stakeholders, reduce risk(s) and minimise impact(s) (Ferro and Bonollo, 2019; Chipangamate et al., 2023), for example, by providing informed scenario planning and simulating various outcomes in advance of an activity. Furthermore, the list can help organisations and governments identify opportunities to source materials from more sustainable and/or responsible sources (e.g., locally recycled resources). A CRM list can promote research and development efforts to find alternative sources of materials or substitutes, especially for high-risk materials, thus reducing resource extraction-associated

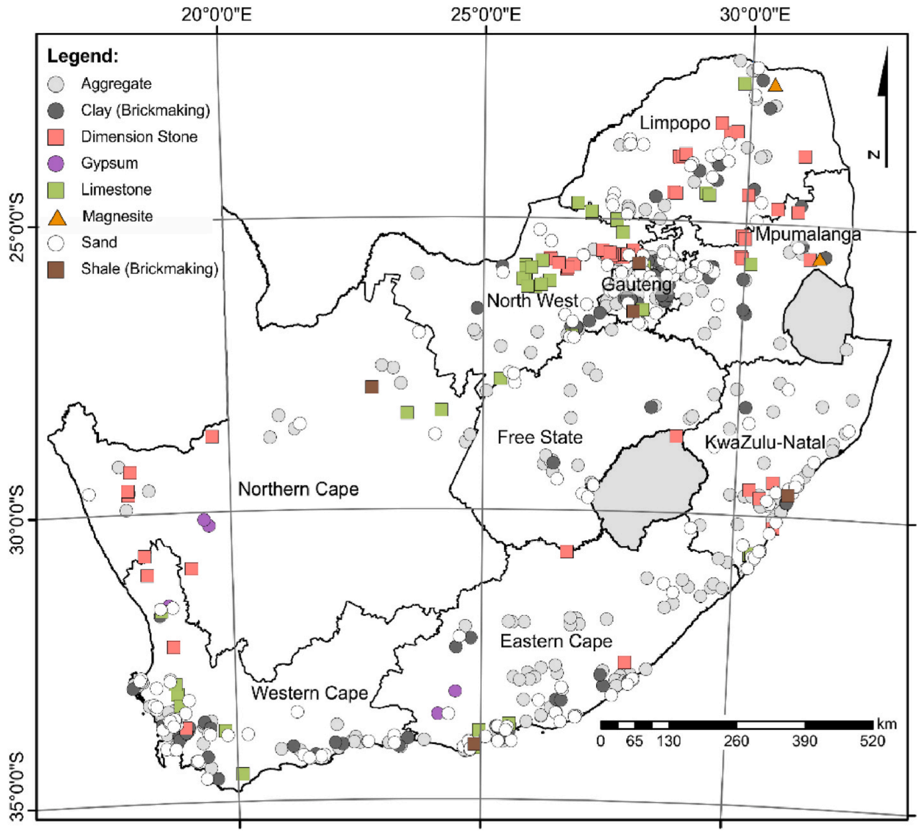

Fig. 3. Historically known and actively mined construction-related deposits for the continuing industrialisation of South Africa. Data sourced from Padilla et al. (2021) and South Africa Department of Mineral Resources and Energy (DMRE; Operating mines 2022). Data included as supplementary material.

environmental and social impacts, while bolstering supply chain resilience (Wall et al., 2017). In addition, data supporting the evaluation of CRMs can be used to perform socio-economic cost-benefit analyses to rank-order various ESG initiatives, and therefore, shape national policy.

Designating a CRM implies that more scrutiny around its supply chain must necessarily occur. Hence, a CRM list can help increase transparency around the supply of materials, which can, in turn, help improve the accountability of organisations and governments (Ghamisi et al., 2021a, b). This can help ensure that materials are sourced in a responsible and sustainable manner, and that the potential risks and impacts of their extraction and processing are adequately addressed (Christmann, 2021). More directly, a CRM list can help inform the development of regulatory frameworks and policies to govern the extraction, processing, and use of different materials for security and sustainability reasons (Talapin and Braun, 2020). This can help ensure that these activities are carried out in a responsible and sustainable manner and that the risks and impacts are effectively managed (Talapin and Braun, 2020; Government of Canada, 2022). A CRM list can improve international cooperation on resource management issues by providing common ground for different countries to work together to share knowledge, address challenges and create opportunities (Kelley et al., 2021). This can include initiatives to increase the sustainability and resilience of supply chains, promote the development of substitute materials, or support research and development efforts (Wall and Pell, 2017). In addition, tracking illicit trading of materials (Oloruntoba, 2017), as well as formalisation of artisanal and small-scale mining are facilitated by the existence of a CRM list. Transparent and total scrutiny of supply chains and usage is key in comprehending the trade-offs between overall benefits and negative impacts of CRMs at a time when there are intentions to reduce global carbon emissions (Dewit, 2021).

A CRM list can help facilitate stakeholder engagement on resource management challenges by providing a common set of materials and issues for different stakeholders to discuss and address (e.g., Chipangamate et al., 2023). This can include engaging with industry, academia, communities and other relevant groups to identify shared goals and priorities, and to develop strategies to address shared challenges and create opportunities. For example, the multi-stakeholder framework used by the Extractive Industry Transparency Initiative (EITI) would be greatly enhanced by a CRM list, as it would promote ownership disclosure and transparency around production and remittance between organisations, local authorities and governments (Sovacool et al., 2016; Wilson et al., 2021). In addition, a CRM list could inform investment decisions of organisations and governments by providing a common set of knowledge and risks to consider. This ensures that investments are made in an informed manner, and that they support the long-term resilience and sustainability of supply chains. A CRM list can help organisations and governments identify and manage the risks associated with the supply of different materials (Government of Canada, 2022). Measures adopted to manage risks can include: stockpiling, diversifying sources of supply and developing contingency plans to mitigate the impact of supply disruptions. Additionally, a list can help support the development of a circular economy, by identifying essential materials and promoting recycling and re-use of these materials (European Commission, 2014). In turn, this can help reduce the pressure on primary mineral extraction, minimise environmental and social impacts, and increase the resilience and sustainability of supply chains (Nwaila et al., 2022a). A CRM list may create a remarkable opportunity for mining waste, of which South Africa has plenty, thus capturing or creating additional value, and in some cases in collaboration with local communities (Morseletto, 2020).

Together, the ideas align well with various sustainability, ESG, CSR and national security considerations (Bontempi et al., 2021; Dewit, 2021). Much of the work on mitigating environmental impacts and enhancing social contribution hinges on responsible and sustainable

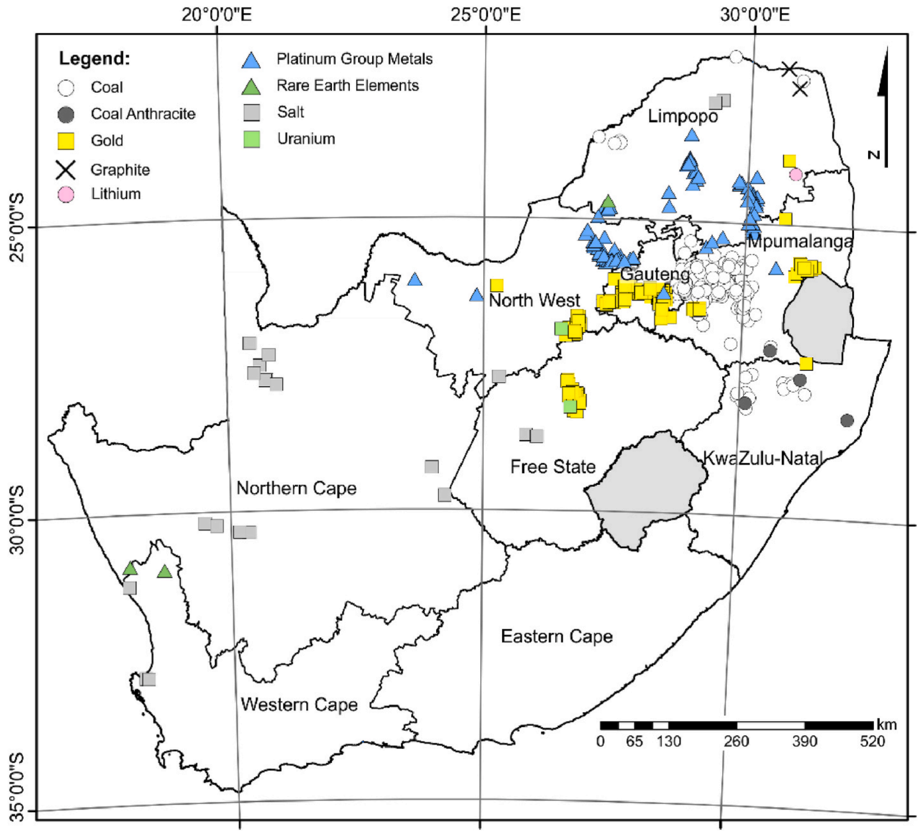

Fig. 4. Historically known and actively mined deposits for the economic and energy prosperity of South Africa. Data sourced from Padilla et al. (2021) and South Africa Department of Mineral Resources and Energy (DMRE; Operating mines 2022). Data included as supplementary material.

exploration, exploitation and use of CRMs.

5. The role of a CRM list for research, development and innovation

At the moment, South Africa's minerals sector is in a state of slumber, following decades of high output and global leadership (Neingo and Tholana, 2016; Frimmel, 2019). Numerous operations have been shut down and mining companies have expressed low interest in the continuation of mineral resource extraction. A future effect of the continuation of this reality is that South Africa will likely become more reliant on foreign supplies of materials. This exacerbates the criticality of non-local materials. Innovation is a significant component to solve issues encountered in the minerals sector, particularly if it can be integrated seamlessly (e.g., Ghorbani et al., 2022, 2023a, b; Nwaila et al., 2022a). At the moment, the challenges facing the South African minerals sector are many: (1) declining ore grades; (2) worker unrest and labour conditions; (3) low technological and innovation investment; (4) increasingly more complex geology/ore bodies; (5) increasing ESG scrutiny and investor sentiment; and (6) unstable national electrical grid (Neingo and Tholana, 2016). Although these challenges seem harsh, they are technically solvable. Indeed, innovation is critically needed in the South African minerals sector to modernise it towards: (1) faster and more targeted exploration; (2) increased operational agility; (3) more energy-efficient operations; (4) enhanced extraction capability; (5) better environmental monitoring; and (6) safer working environments (e.g., Neingo and Tholana, 2016; Nwaila et al., 2022a; Ghorbani et al., 2023a). In the last decade, the South African government has launched a number of initiatives aimed at addressing some of the above challenges in the minerals and extractive industry. These include the "Minerals Beneficiation Strategy," published in June 2011; "Operation Phakisa," a fast-track program launched in July 2014 to help accelerate the goals of the National Development Plan; and the South African Minerals Extraction Research, Development, and Innovation (SAMERDI) strategy.

The establishment of a South African CRM list has the potential to catalyse the growth of research, development and innovation (RDI) in the minerals industry, as well as other linked sectors. This is because ideas and innovation on the extraction, processing and use of CRMs altogether depend on their perceived value by stakeholders. Therefore, having clear ratings for South Africa's CRMs will help the country's policymakers prioritise funding of various RDI activities. Hence, designation of materials as 'critical' creates the necessary conditions for effective policy conditions to catalyse RDI through directing research and development funding and the re-focus of academies, institutions and private entities, which are critical to the rejuvenation of South Africa's minerals industry. The effect of RDI enabled by the existence of a CRM list is tripartite, because any RDI that assists with the exploration, extraction, processing and recycling of CRMs would necessarily alleviate the criticality of those CRMs. For example, funding for RDI could result in an increase in the use of modern transdisciplinary approaches such as using artificial intelligence towards mineral targeting. This is highly beneficial to alleviate the criticality of CRMs, because re-purposing of legacy exploration data, such as geochemical data and seismic data, and big data, such as satellite-borne remote sensing data are absolutely necessary to ensure, for example, the timely discovery of mineral deposits and/or valorisation of tailings (e.g., Nwaila et al., 2021a, b, 2022b, c; Mutshafa et al., 2022; Zhang et al., 2022).

6. The challenges associated with ranking CRMs in South Africa

Establishing a CRM list can be challenging for several reasons. The ideal of 'critical' exhibits geographical, economic and temporal characteristics, which implies that the definitions of criticality are subject to change, especially with rapidly evolving global economic and geopolitical conditions. South Africa is facing an unprecedented energy supply challenge with rolling blackouts (load shedding) that limit all forms of productivity (Ibrahim et al., 2021). This is probably the most rapidly developing social concern and could destabilise society at large. Minerals related to the energy infrastructure are needed to stabilise the energy grid until an energy transition can be reasonably achieved (e.g., Fig. 4).

To further complicate the creation of a South African CRM list, while the specific geographical and socio-economic context changes with time, the CRM designation methodology itself is also evolving, and no universal methodology of assessment exists, nor best practices because the outcomes of CRM lists have yet to be correlated to the inputs. However, there seems to be an excellent agreement at the meta-methodology level, which is to say that high level concerns around supply robustness and the degree of necessity of materials are common internationally and throughout time (Fortier et al., 2019; Lèbre et al., 2020; Kelley et al., 2021). However, the specifics of the methodology vary greatly. Different organisations and governments generally establish quantitatively dissimilar metrics and thresholds, such as for economic importance, supply risk and strategic importance, which themselves are fluid concepts. Furthermore, it is difficult, but not impossible (e.g., scaling criticality ratings by their range to obtain a relative comparison), to quantitatively compare results from different assessments across nations, simply because numerical results are not directly comparable. The impacts of these differences imply that the more marginal a CRM is, the more likely it will change with variations in assessment methodology and data sources, although a core group of CRMs is likely to remain robust across assessments. In this context, setting a threshold with a buffer margin is probably a good practice methodologically to accommodate for potential variability in the data, metric and weight choices, at the cost of a potentially enlarged number of CRMs. As a result, there may be disagreements about which materials should be listed, and thus, the lists will continue to evolve with time. In this context, a ranking of criticality in terms of assessment robustness may be a welcoming addition to existing methodologies.

Aside from quantitative methodological differences and deficiencies of existing approaches, perhaps a greater challenge is the exactitude of qualitative assumptions, supporting data and goals. For example, it is unclear if the data underpinning the assessments worldwide are themselves comparable and to what degree, despite the fact that producers of some materials (e.g., REEs and cobalt) are highly centralised. Other factors that may need to be taken into account include the softer considerations, including: geopolitical risks, social licence risks, resource depletion, technological change, among others. Geopolitics can change very rapidly on a global scale, and similarly for technological innovation (De Ridder, 2013; Johansen, 2019). For example, new technologies may emerge, requiring new materials. In order for the list to remain relevant, it must be continuously reviewed and revised. The revision rate must be fast enough to accommodate for changes in underlying factors but not too fast, so as to prevent the use of such lists for decision-making. This means that CRM lists must be created with an a-priori and pragmatic balance of the bias of such a list (e.g., a vision of future needs) and variance (e.g., of rapidly changing market conditions, geopolitics and supply chain configurations) (Zhang et al., 2023). Hence, it is important that the lists be updated under two conditions: (1) a set amount of time has elapsed since the last update, triggering a new update; and (2) sudden and lasting change has occurred in the underlying conditions well before an update interval that affects the value of the list itself. For (1), an example time interval, using the EU method, is every three years (European Commission, 2014, 2017a, 2020, 2023). This is generally a long enough time to match with the timescales of the policy cycle in the EU (from consideration and consultation to rollout). To ensure that some stability of CRM methodology and lists exists, and the core group of CRMs remain stable, it is important to have a consistent and unwavering set of guidance principles in the designation of criticality, which stabilises the design of an assessment methodology during policy implementation. This is likely where South African needs will diverge from those of the Global North, given its current state of socio-economic development and substantial intra-national contrast in living standards.

In addition, reliable data (e.g., objective, accurate and timely) and information are necessary to accurately assess the supply risks and economic importance of different materials. However, this information can be difficult to obtain, especially for materials that are not widely traded or for which there is limited data available, such as material derived from artisanal and small-scale mining or materials strongly related to military use. This includes certain materials that may have political implications, as it may affect the trade and production of these materials or where other political or social priorities compete with access to CRMs (e.g., resource assessment over protected land or habitat). Consequently, there may be pressure from special interest groups (domestic and international, grassroots and organised) to include or exclude certain materials from the list (e.g., Applegate, 2022).

Some of CRMs are produced as by-products of other industries and are often sourced from or partly processed material. For example, cobalt is a by-product of copper and nickel mining in the Democratic Republic of Congo, with further refining mostly conducted in China (Savinova et al., 2023 and references therein). This can make it difficult to accurately assess the risks to the supply of these materials, as disruptions in one part of the supply chain may have knock-on effects on the availability of the material. For these materials, the shape of the supply chain is topologically less of a linear stretch but more convoluted with potentially complex feedback and mesh-like topology. This complicates simple and linear assessments of supply chain risks and impacts (e.g., difficult to correlate inputs and outputs in a mesh topology). More advanced supply system modelling may be necessary to anticipate complex network dynamics. For some CRMs, there may be limited substitutes or alternatives available at different time periods. This can make mitigating supply disruption risks difficult, as there may be few easy or cost-effective material alternatives. The prices of CRMs can be affected by a wide range of market forces, including supply and demand, economic growth and currency exchange rates. These dynamics can make it challenging to accurately assess the economic importance of different materials and forecast them appropriately in anticipation of the coming-into-effect of any CRM list. The complex system nature of the market is also difficult to predict, and in extreme situations, designation of criticality may trigger those materials to be hoarded or stockpiled by private firms or competing international interests, in anticipation of increased market demand and government subsidies, which would be counterproductive. Some materials may be essential for certain industries or applications but may be limited to other sectors. This can make it difficult to accurately assess the overall importance of these materials, as they may need to be factored in the overall demand or supply calculations.

Some global and local disruptions, especially in the case of black swan events (events and their magnitudes that are statistically unobserved before and therefore unforeseeable), such as the recent COVID-19 pandemic and the Russia-Ukraine war, are difficult to predict but continue to create deleterious, rapid and fluid global impacts, and are perhaps the most recent reminders of the peril of national dependency on global supply chains for CRMs (Allam et al., 2022). Together, these factors position the global CRM context as volatile, uncertain, nonlinear, complex and ambiguous, and therefore, difficult to predict with exactitude. These factors highlight the timeliness of CRM designations and the need to dynamically assess the criticality of materials.

7. A link between CRMs and a ‘just’ energy transition

The ‘just’ energy transition is a vision that focuses on a fairer transition to a low-carbon energy system. For South Africa, the potential financing of R200 billion to R8.5 trillion depending on scale of implimentation to achieve the transition could lead towards substantial levels of growth and jobs; whereby the gross domestic product could increase at a yearly average of about 2.3% between 2022 and 2050 (World Bank, 2022). However, it is unclear how this projection interacts with the predicted losses in gross domestic product of an aggregate of 9% for developing countries due to climate change from 2022 to 2100 (IPCC, 2022). Some authors estimate that two in three jobs will be created by investing in climate mitigation and adaptation for each of the 300 000 jobs that may be lost in the high-emission sectors (O'Brien, and Leichenko, 2000; Fankhaeser et al., 2008; Paavola, 2008; Wahlgren et al., 2010; Frosch et al., 2018). CRMs are often used in the production of clean energy technologies, such as solar panels, energy storage facilities, wind turbines and electric vehicles (Dewit, 2021). This could also include nuclear power and biomass energy. Specifically, critical elements include: REEs, lithium, cobalt and copper (Pommeret et al., 2022; Ghorbani et al., 2024a). In addition to clean energy technologies, CRMs are used in other energy-adjacent sectors, such as transportation, construction and industry (Furszyfer Del Rio et al., 2022). For example, CRMs are used in the production of light-weight materials for the automotive and aerospace industries, which can help reduce fuel consumption and greenhouse gas emissions (Pommeret et al., 2022; Jannesar Niri et al., 2024). Therefore, the availability and sustainable use of CRMs are important for the transition to a low-carbon, energy-efficient and resource-efficient economy (Valero et al., 2021). Since required CRMs in the energy transition are invariant with respect to the country utilising them, it is imperative that South Africa establishes its own CRM list to balance between domestic needs versus exports, such that the energy transition remains just. Additionally, it is important to also consider current sources of energy supply, because the energy transition process itself requires energy and its implementation should be smooth and productive. By rating CRMs based on various factors, such as economic importance, ESG risks and technological importance, South Africa can identify which CRMs are most important for its energy transition strategies and develop strategies to secure stable supply and promote sustainable resource use (Bontempi et al., 2021; Christmann, 2021). CRMs are probably the most important ingredient in the quest to achieve the International Energy Agency (IEA) objective of net zero carbon emissions by 2050 (Dewit, 2021). Examples of CRMs used in the green energy sector include (Fig. 5).

- REEs: Neodymium, dysprosium and cerium are used in the production of permanent magnets, which are essential components of wind turbines and electric vehicles.
- Lithium: Used to produce lithium-ion batteries, which are in turn widely used in electric vehicles, portable electronics and energy storage systems.
- Cobalt: Used in the production of cathodes for lithium-ion batteries, in turn used in electric vehicles and portable electronics.
- Copper: Used in the production of electrical wiring, printed circuit boards, motors and transformers, all of which are needed in a range of energy-related applications, including electric vehicles, renewable energy systems, and energy transmission and distribution.
- Graphite: Used to produce lithium-ion batteries, fuel cells and nuclear reactor-core components.
- Gallium: Used in producing photovoltaic cells and producing high-temperature superconductors, which have potential applications in energy transmission and distribution.
- Silicon: Used to manufacture photovoltaic cells and semiconductor devices, which are in turn used in a range of energy-related applications, including renewable energy systems and energy-efficient electronics.

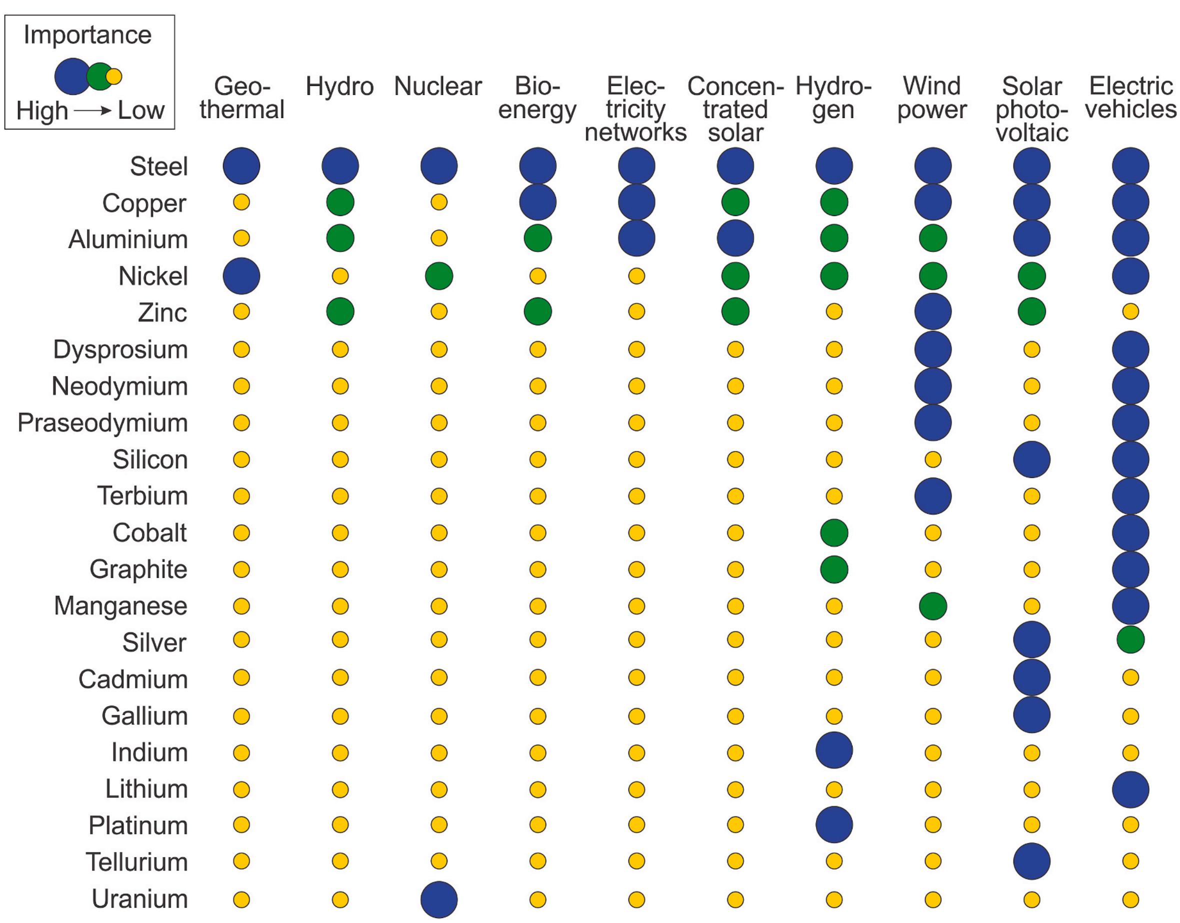

Fig. 5. Materials critical for the transition to a low-carbon economy by technology type (https://www.mining.com/sponsored-content/minings-energy-challenge/).

- Indium: Used in producing photovoltaic cells and in producing thin-film solar panels.
- Tin: Used in producing photovoltaic cells and in producing lead-free solders which is used in the electronics industry.
- Aluminium: Used in producing wind turbines and light-weight structural materials for the automotive and aerospace industries, which can in turn help reduce fuel consumption and greenhouse gas emissions.
- Molybdenum: Used in manufacturing steel alloys, which are used in the construction of wind turbines, as well as in producing catalysts for fuel cells.
- Tungsten: Used in producing light-weight materials for the automotive and aerospace industries and in producing X-ray tubes and high-speed cutting tools.
- Zinc: Used to produce galvanised steel, needed for constructing wind turbines and producing zinc-carbon batteries.
- Tellurium: Used in producing photovoltaic cells and in producing alloys for the aerospace industry.
- Nickel: Used in producing stainless steel, needed for constructing wind turbines and in producing nickel-metal hydride batteries.
- Platinum: Used in producing catalysts for fuel cells, internal combustion engines, jewellery and other luxury products.
- Palladium: Used in producing catalysts for fuel cells, jewellery and other luxury products.
- Bismuth: Used to produce lead-free solders, which are in turn used in the electronics industry and in the production of pharmaceuticals and cosmetics.
- Calcium: Used to produce steel alloys, which are in turn used in constructing wind turbines, create cement and other building materials.
- Iron: Used in the production of steel, which is needed for constructing wind turbines, and in the production of a range of other products including automobiles, machinery and appliances.

In South Africa, present knowledge of the aforementioned CRMs indicate that they are mainly concentrated in four provincial mining districts, namely: (1) the Northern Cape, (2) Limpopo, (3) North West, and (4) Mpumalanga provinces (Figs. 2 and 4). None of these provinces has downstream beneficiation facilities (and therefore no value-adding activities), and materials mined are often shipped to Europe, Asia and North America for further refining, including the production of industrial and technology materials and components, respectively. To reduce carbon emissions, there is therefore a need for South Africa to attentively observe how materials and energy are used in production, transportation, processing and use, to thus ensure a fair and equitable outcome (Dewit, 2021).

8. Role of stakeholders

Stakeholders play a vital role in ensuring the availability of CRMs. From governments to industry and academia, stakeholders can engage in a variety of activities to ensure the responsible and secure supply of CRMs. From the technical side of mineral resources, geological surveys can play an important role in updating lists of CRMs by providing data and information on the occurrence, distribution and availability of these materials, unless CRMs are designated for national security reasons (Lawley et al., 2021). Geological surveys can collect and analyse data on the geology, mineralogy and geochemistry of different materials, which can be used to evaluate their potential as CRMs. This information can help identify new sources of CRMs and assess the potential risks and opportunities associated with their extraction and processing (Deetman et al., 2018). Geological surveys can also provide data on the environmental and social impacts of CRM mining and processing, which can be used to inform policy decisions and support sustainable resource management. They can also collaborate with other government agencies and stakeholders to share knowledge, develop strategies and plans for the responsible and sustainable supply of CRMs (Ghorbani et al., 2024a,b; Kelley et al., 2021). In this way, geological surveys can contribute to the updating and revising of CRM list by providing data and information that can assess the criticality of different materials.

The private sector can have input on lists of CRMs through a variety of channels. For example, companies that are involved in the mining and processing of CRMs, or original equipment manufacturing (technology and innovation sector), play a crucial role in the identification and revision of CRMs (Cimprich et al., 2022; Applegate, 2022). They can provide information about the materials they use, the sources of these materials, and the challenges and opportunities associated with their supply and use. This information can help inform policy decisions and support the development of strategies for the responsible and sustainable supply of CRMs. Private sector organisations can also engage with policymakers and regulators through consultation and stakeholder engagement (Chipangamate et al., 2023). For example, they can provide input on draft CRM lists or policy proposals through written submissions, public hearings, or other consultation processes. Private sector organisations can also participate in industry associations or forums that address CRM-related issues and provide a platform for dialogue and collaboration with policymakers and other stakeholders. In addition, private sector organisations can support RDI efforts focused on improving the sustainability of CRM extraction, their processing and/or developing alternatives to these materials. This can help reduce environmental and social impacts of CRM use and mitigate supply disruption risks.

Civic organisations and the general public can also have input on lists of CRMs through a variety of channels. For example, non-foreign non-governmental organisations (NGOs) can engage with policymakers and regulators to provide information and perspectives on CRM-related issues. They can provide input on draft CRM lists or policy proposals through written submissions, public hearings and/or other consultation mechanisms (Gray et al., 2016; Applegate, 2022). Civic organisations can also engage with the private sector and other stakeholders to promote the responsible and sustainable use of CRMs (Arond et al., 2019). The general public can also have a voice in developing CRMs through participation in public consultation processes and their choices as consumers. For example, the public can support firms and products that use CRMs responsibly and sustainably, or advocate for the adoption of policies and practices that promote the responsible and sustainable use of these materials (Wilson et al., 2021). The general public can also raise awareness about CRM-related issues and mobilise support for action on these issues through social media, online petitions, or other forms of grassroots activism.

In addition to the public, local communities hosting CRM extraction and/or processing are important stakeholders as they have a significant role in informing any possible disruption of supply through social resistance (Wilson et al., 2021; Jannesar Niri et al., 2024). This includes formal or informal artisanal and small-scale mining communities. A few mining projects have been disrupted or prevented altogether by host communities. The communities have a significant interest as traditional custodians of the land where mining occurs and as the most directly affected by negative environmental and social impacts of mineral exploitation (Mabey et al., 2020). In addition, local communities are most likely to be benefitted by the extraction and value-adding activities associated with CRMs. As such, involving them early in identifying and disseminating any CRM list is of paramount importance. Host communities are sometimes displaced from their land to pave way for generally large-scale mining activities; therefore, engaging them meaningfully should be integral to the identification of CRM lists (Cha, 2020; Svobodova et al., 2021). Communities, especially when they collaborate with civil society organisations, are responsible for ensuring that organisations extract and use natural resources responsibly and sustainably (Cole and Broadhurst, 2022).

End users, such as retail store owners, can also have input on CRM lists through a variety of channels. Retail store owners can engage with policymakers and regulators to provide information about the materials and products they use and sell, and the challenges and opportunities associated with their supply and use. This information can help inform policy decisions and support the development of strategies for the responsible and sustainable supply of CRMs. Retail store owners can also engage with suppliers and manufacturers to ensure that the products they sell are sourced from responsible and sustainable sources. For example, they can obtain information about the materials used in the products they sell and choose to work with suppliers that use CRMs responsibly and sustainably. Retail store owners can also communicate with their customers about the importance of responsible and sustainable sourcing, and encourage them to support responsible and sustainable CRMs products. In addition, retail store owners can support research and development efforts focused on improving the sustainability of CRMs extraction and processing or developing alternatives to these materials. This can help reduce the environmental and social impacts of CRMs usage and mitigate supply disruption risks. Other downstream users could include recyclers, because as more primary material circulates through the market, there will be more material that would be recycled and this stream is likely to grow in significance with the rise of CRMs in circulation. Adequate early engagement around recycling would facilitate organised, productive and value-adding circular activities that include urban mining and encourage investment into energy- and labour-efficient solutions, because circular activities are generally very labour intensive and currently results in low-wage and manual labour jobs (Llorente-González and Vence, 2020).

Academia and educational institutions are important public stakeholders as they have the expertise to coordinate through education and research, and disseminate information through training for continuous or life-long learning as CRM lists are created and updated. Building a comprehensive CRM list is complex and requires collaborative efforts of primary and secondary research that are within the purview of interdisciplinary scholars, and into the social dimension, such as how stakeholders perceive the issue of CRMs. While general stakeholders, such as private companies may have their own agendas, scholars are probably more capable of using broader reliable data and research evidence to assist in creating a comprehensive and unbiased (in an agenda sense) list. For example, some environmental civil society organisations or non-governmental groups may be against extractive activities for various reasons. Therefore, uncompromised and unbiased scholars may provide evidence of why and how sustainable extraction, processing and usage are in fact, necessary for greater sustainability. Creation and maintenance of a CRM list requires a network of scholars who are dedicated to scientific research, data and policy gathering and analysis, and economic planning.

Availability of information about the production, processing and usage of CRMs can be very difficult to obtain as the mining industry is by nature secretive and conservative. For that reason, the government or some effective third party (e.g., a geological survey) can play a critical role in collecting and sharing of information, and in crafting policies and statutes that encourage the generation/update of CRM lists by making available useful data and information. The government is also an important stakeholder as the chief consumer of the list as well as informing the country's strategic direction (e.g., regarding energy infrastructure planning, national exploration and geopolitics), which is also central to defining which materials could be part of that ambition (e.g., Government of Canada, 2022).

9. Development of the methodology for ranking CRMs in South Africa

Several methods are already published to identify and select CRMs (Tkaczyk et al., 2018; Černý et al., 2021; Hackenhaar et al., 2022). These methods always consider multiple important dimensions (or characteristics), notably: material importance, supply risk and geopolitical impact. Thereafter, the crafting of performance indicators and metrics along dimensions depends on the definition of criticality in a socio-economic and technological context. The importance dimension captures the significance of a material to some current or envisioned future societal state. The risk dimension captures the probability that a significant (e.g., prolonged) discontinuation of supply would occur given a set of probable considerations. The impact dimension captures the repercussions of a discontinuation of material supply. The product of risk (probability of occurrence) and impact is an effective proxy of the net economic cost of inaction, whereas material importance proxies net economic gain of action. A dimensional framework would also work for South Africa, but material importance cannot be solely based on present needs, given its developing nation status, but also in a large proportion, driven by forecasts that are guided by a vision of the future state of the society. This was also a conclusion reached by Khan et al. (2022), which identified a potential vision of the society and linked it to technologies with known material requirements. Although dimensional frameworks are intended to feature dimensions that are as decorrelated as possible, correlation of indicators across dimensions can occur if the system being measured exhibits significant feedback (dynamically complex). For instance, indicators measuring material importance and impact could be interconnected in the context that a material deemed highly important due to its economic significance might also have substantial environmental and societal impacts in case of a supply disruption. For example, if a CRM such as lithium is crucial for the production of electric vehicle batteries (importance) and electric vehicles are already a major mode of transport (impact), then importance and impact dimensions are correlated. However, this is not always the case, because importance can be forecasted, and hence, at least partially pertains to the future, and impact is grounded to the present state. Thus, a CRM may be important for future uses, whose impacts are not realisable presently. Consequently, and particularly for South Africa, material importance and impact could be generally temporally decoupled to reduce feedback and correlation. Using a vision of the future to assess material importance was also determined to be a feasible approach by Khan et al. (2022).

The degree of criticality is a multi-dimensional composite or model of indicator scores (as assessed through the use of at least one metric and data). If there exists significant correlation across indicators, then outcomes maybe exaggerated (excessive model variance). In this case, a combination of knowledge-driven and statistical methods to decorrelate variables could be used to enhance assessment robustness. Some of the most common indicators along various dimensions include.

- Economic importance: selection based on economic considerations, including contribution to the gross domestic product (GDP), employment and trade. A material's economic significance can be influenced by its strategic importance. For instance, a CRM that is dual-use would be significantly affected by its consumption rate or stockpiling in the defence sector.
- Strategic importance: selection based on strategic national concern. Moreover, strategic importance can also exhibit significant system-level feedback with supply risk, as materials critical to national security may face supply chain vulnerabilities due to geopolitics.
- Supply risk: selection based on notions of probability of disruption. Supply risk must be examined in context of complex systems, such as geopolitical and market competitions, because the dynamics of either is difficult to predict and includes competitive and anti-competitive behaviours, and system behaviours such as panic hoarding.
- Environmental impact: selection based on notions of environmental costs and benefits, which include lifecycle assessments of CRMs. Materials with a lower environmental impact may be preferred to those with a higher impact. Additionally, materials with a high environmental impact may face regulatory scrutiny and pressure to adopt more sustainable practices, potentially influencing their supply and societal impacts.

- Agenda impact: selection based on democratic agendas, which could include poverty reduction, which is a part of the sustainable development goals. Agendas are essentially a type of societal principle, whose interpretation and implementation depends on pragmatic context. Favourable interpretation could be associated with reduction in supply risk (e.g., diversification of energy mixture), for example.
- Societal impact: selection based on potential societal impacts of a disruption in supply, e.g., employment, social stability, continuity of society, health and quality of life. Disruptions in the supply of materials crucial for essential services or industries can have cascading effects on society, affecting employment, social stability, and overall quality of life. Clearly there could be overlap of indicators along this dimension and economic importance, since societal activities contribute to economic activity.

A variety of actual rating methods exist to cater to different purposes. To ensure an objective assessment of criticality, it is essential to carefully consider interdependencies and potential biases when selecting and weighting indicators. This can be examined systematically using statistical methods, by treating the indicators as models that are driven by supporting data. Consequently, the extent of correlation between indicators could be anticipated via statistical analyses of supporting data (e.g., nonlinear correlation and causality analysis) and effects such as hidden weightings could be minimised in principle. This leads to more transparent methodologies and a more accurate evaluation of material criticality. It is important to carefully consider the strengths and limitations of each method when rating CRMs. Regardless of the method and data used to perform ratings, a key fundamental control on the identification of CRMs is the a-priori guiding vision, which imparts a bias towards some CRMs. For example, a pre-supposition of an increasing adoption of electrification essentially dictates that materials that are important in electrification (e.g., lithium, cobalt, copper and REEs) would become critical by any reasonable rating method. Designing a sound vision is important to crafting achievable, realistic and contextually relevant principles to guide CRM assessments. In general, it is important to adopt at least two key orthogonal criteria along supply and demand (one for significance and one for risk), such that the criticality can be defined as a function of supply and demand simultaneously. Additional criteria can be used to disambiguate closely ranked materials for better differentiation.

In subsections 9.1 to 9.12, we provide example formulae and calculations that demonstrate an implementation of our framework. Each subsection addresses a dimension of criticality, such as economic importance, supply risk, environmental, agenda and societal impacts. Each subsection provides an example of a quantitative assessment, which bridges the gap between the theoretical aspects of our framework and its practical application. More specifically, they permit us to implement a metric-based approach to assessing each dimension. Note that the indicators in the examples are intended to be strictly positive, and their exact values are not critical since they represent weighted scores based on various factors, normalised to a sum of 1.

9.1. Formula and example calculation for rating CRMs based on economic importance

Formula:

Relative economic importance score = Value of production of CRMs / Total value of production of all CRMs

Example Calculation:

Suppose we want to rate three CRMs (A, B and C) based on their economic importance. We have the following data on the value of production of each CRM.

- CRM A: $100 million; CRM B: $200 million; CRM C: $300 million.
- The total value of production of all CRMs = $600 million.

To calculate the relative economic importance score for each CRM, we can use the formula above.

- Relative economic importance score for CRM A = $100 million/$600 million = 0.17.
- Relative economic importance score for CRM B = $200 million/$600 million = 0.33.
- Relative economic importance score for CRM C = $300 million/$600 million = 0.50.

Based on this calculation, CRM C has the highest relative economic importance score, followed by CRMs B and A.

9.2. Formula and example calculation for rating CRMs based on supply risk

Formula:

Supply risk score = Weighted sum of factors affecting supply risk

Factors affecting supply risk may include.

- The concentration of production: The degree to which CRMs are produced in a small number of countries or regions.
- Diversity of sources: The degree to which a CRMs is sourced from a diverse range of countries or regions.
- Importance of CRMs to various industries: The extent to which CRMs are used in a variety of industries.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.

Example Calculation:

Suppose we want to rate three CRMs (A, B and C) based on their supply risk. We have the following data on the factors affecting supply risk for each CRM.

1. CRM A:
   - The concentration of production: Low (production is spread across multiple countries).
   - Diversity of sources: High (sourced from a diverse range of countries).
   - Importance of the CRMs to various industries: Moderate.
2. CRM B:
   - The concentration of production: High (production is concentrated in a single country).
   - Diversity of sources: Low (sourced from a few countries).
   - Importance of the CRMs to various industries: High.
3. CRM C:
   - The concentration of production: Moderate (production is concentrated in a few countries).
   - Diversity of sources: Moderate (sourced from a few countries).
   - Importance of the CRMs to various industries: Low.

We assign the following weights to each factor.

- The concentration of production = 0.3
- Diversity of sources = 0.4
- Importance of the CRMs to various industries = 0.3

These weights represent a maximum score, which may range from 0 to a maximum, e.g., a CRM can score 0.1 out of 0.3 for the possible concentration of production.

To calculate the supply risk score for each CRM, we can use the

Table 1
Supply risk scoring matrix.

CRMs	The concentration of production	Diversity of sources	Importance of the CRMs to various industries	Total
A	0.3	0.4	0.3	1
B	0.3	0.1	0.3	0.7
C	0.3	0.2	0.0	0.5

formula above and sum the weighted values for each factor. Thus, the general supply risk score = The concentration of production + Diversity of sources + Importance of the CRMs to various industries. Therefore, in our example: 0.3+0.4+0.3 = 1 (Table 1).

9.3. Formula and example calculation for rating CRMs based on environmental impact using life cycle assessment (LCA)

Formula:

Environmental impact score = Weighted sum of environmental impacts over the life cycle of the CRM

Environmental impacts may include.

- Greenhouse gas emissions.
- Air pollution.
- Water pollution.
- Land use.
- Waste generation.

The weight assigned to each impact can depend on the specific context and the relative importance of each impact.

Example Calculation:

Suppose we want to rate three CRMs (A, B and C) based on their environmental impact using LCA. We assign the following weights to each impact (Table 2).

- Greenhouse gas emissions: 0.3
- Air pollution: 0.2
- Water pollution: 0.2
- Land use: 0.2
- Waste generation: 0.1

Based on this calculation, CRM A has the highest environmental impact score, followed by CRMs B and C, which have the same score.

9.4. Formula and example calculation for rating CRMs based on social impact

Formula:

Social impact score = Weighted sum of social impacts of the CRM

Social impacts may include.

- Number of jobs related to the production and use of the CRM.
- Health impacts of the CRM.
- Impacts on quality of life.

Table 2
Environmental impact risk matrix.

CRMs	Greenhouse gas emissions	Air pollution	Water pollution	Land use	Waste generation	Total
A	0.3	0.2	0.2	0.2	0.1	1
B	0.2	0.2	0.2	0.2	0.0	0.8
C	0.3	0.2	0.1	0.1	0.1	0.8

Table 3
Social impact risk matrix.

CRMs	Number of jobs related to the production and use of the CRM	Health impacts of the CRM	Impacts on quality of life	Total
A	0.4	0.3	0.3	1
B	0.3	0.3	0.3	0.9
C	0.2	0.2	0.1	0.5

The weight assigned to each impact can depend on the specific context and the relative importance of each impact.

Example Calculation:

We assign the following weights to each impact (Table 3).

- Number of jobs related to the production and use of the CRM = 0.4
- Health impacts of the CRM = 0.3
- Impacts on quality of life = 0.3

Based on this calculation, CRM A has the highest social impact score, followed by CRMs B and C, respectively.

Below are a variety of other considerations when rating CRMs. Some examples include.

- Governance risk: CRMs can be rated based on the risk of governance problems, such as corruption, poor regulation, or lack of transparency, which can affect the supply and use of the material.
- Financial importance: CRMs can also be rated based on their financial importance, which may be influenced by factors such as the price of the material, the extent to which it is traded and the extent to which it is used as a financial asset.
- Technological importance: CRMs can be rated based on their technological importance, which refers to the extent to which the material is essential for the development and use of new technologies.
- Political importance: CRMs can be rated based on their political importance, which refers to the extent to which the material relates to political and strategic considerations, such as national security or foreign relations.
- Health and safety: CRMs can be rated based on their potential impacts on health and safety, including the potential for accidents, spills, or exposure to hazardous materials.
- Social and ethical considerations: CRMs can also be rated based on social and ethical considerations, such as the potential impacts on human rights, the environment, or local communities.

Different considerations may be more relevant depending on the specific context and the purpose of the rating.

9.5. Formula and example calculation for rating CRMs based on governance risk

Formula:

Governance risk score = Weighted sum of factors affecting governance risk

Factors affecting governance risk may include.

- Transparency: The extent to which information about the CRMs is available and accessible to stakeholders.
- Regulation: The extent to which the CRMs are regulated and the effectiveness of the regulatory system.
- Corruption: The extent to which corruption is present in the production, trade and use of CRMs.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.

Table 4
Governance impact risk matrix.

CRMs	Transparency	Regulation:	Corruption	Total
A	0.2	0.3	0.2	0.7
B	0.4	0.3	0.3	1.0
C	0.2	0.1	0.1	0.4

Example Calculation:
We assign the following weights to each factor (Table 4).

- Transparency = 0.4
- Regulation = 0.3
- Corruption = 0.3

Based on this calculation, CRM B has the highest governance impact score, followed by CRMs A and C, respectively.

9.6. Formula and example calculation for rating CRMs based on financial importance

Formula:

Financial importance score = Weighted sum of factors affecting financial importance

Factors affecting financial importance may include.

- Price: The current price of the CRMs and the extent to which it is expected to fluctuate.
- Trading volume: The volume of the CRMs traded and the extent to which it is traded in multiple markets.
- Use as a financial asset: The extent to which the CRMs is used as a financial asset, such as through the use of futures contracts or other financial instruments.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign the following weights to each factor (Table 5).

- Price = 0.4
- Trading volume = 0.3
- Use as a financial asset = 0.3

Based on this calculation, CRM C has the highest financial importance score, followed by CRMs B and A.

9.7. Formula and example calculation for rating CRMs based on technological importance

Formula:

Technological importance score = Weighted sum of factors affecting technological importance

Factors affecting technological importance may include.

- Use in new technologies: The extent to which the CRMs is essential for the development and use of new technologies.
- Use in existing technologies: The extent to which the CRMs is used in existing technologies and the importance of those technologies.
- Potential for substitute materials: The availability and feasibility of substitute materials that could potentially replace the CRM.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign the following weights to each factor (Table 6).

- Use in new technologies = 0.4
- Use in existing technologies = 0.3
- Potential for substitute materials = 0.3

Based on this calculation, CRM A has the highest technological importance score, followed by CRMs C and B.

9.8. Formula and example calculation for rating CRMs based on health and safety

Formula:

Health and safety score = Weighted sum of factors affecting health and safety

Factors affecting health and safety may include.

- Accident risk: The risk of accidents occurring during the production, transportation, or use of the CRM.
- Spill risk: The risk of spills or releases of the CRMs occurring during the production, transportation, or use of the CRM.
- Hazardous properties: The hazardous properties of the CRM, such as its toxicity or flammability.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign the following weights to each factor (Table 7).

- Accident risk = 0.4.
- Spill risk = 0.3.
- Hazardous properties = 0.3.

Based on this calculation, CRM A has the highest health and safety score, followed by CRMs B and C.

9.9. Formula and example calculation for rating CRMs based on resource availability

Formula:

Resource availability score = Weighted sum of factors affecting resource availability

Factors affecting resource availability may include.

- Annual global production: The annual global production of the CRM.
- Annual global demand: The annual global demand for the CRM.

Table 5
Financial importance risk matrix.

CRMs	Price	Trading volume	Use as a financial asset	Total
A	0.4	0.1	0.0	0.5
B	0.4	0.2	0.1	0.7
C	0.4	0.3	0.2	0.9

Table 6
Technological importance risk matrix.

CRMs	Use in new technologies	Use in existing technologies	Potential for substitute materials	Total
A	0.4	0.3	0.3	1.0
B	0.2	0.2	0.1	0.5
C	0.3	0.3	0.2	0.8

Table 7
Highest health and safety risk matrix.

CRMs	Accident risk	Spill risk	Hazardous properties	Total
A	0.4	0.3	0.3	1.0
B	0.4	0.2	0.2	0.8
C	0.3	0.1	0.2	0.6

- Reserve base: The estimated amount of the CRMs economically and technically recoverable.
- Recycling rate: The percentage of the CRMs recycled.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign the following weights to each factor (Table 8).

- Annual global production = 0.4.
- Annual global demand = 0.3.
- Reserve base = 0.2.
- Recycling rate = 0.1.

Based on this calculation, CRM A has the highest resource availability score, followed by CRMs C and B.

9.10. Formula and example calculation for rating CRMs based on ethical considerations

Formula:

Ethical considerations score = Weighted sum of factors affecting ethical considerations

Factors affecting ethical considerations may include.

- Working conditions: The working conditions at the production sites of the CRM.
- Child labour: The use of child labour in the production of the CRM.
- Human rights violations: The occurrence of human rights violations in the production, processing, transportation, or use of the CRM.
- Transparency: The level of transparency in the supply chain of the CRM.

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign the following weights to each factor (Table 9).

- Working conditions = 0.4
- Child labour = 0.3
- Human rights violations = 0.2
- Transparency = 0.1

Based on this calculation, CRM A has the highest ethical considerations score, followed by CRMs C and B.
Lastly, technical scores can also be incorporated such as geological and metallurgical scores.

Table 8
Resource availability and safety risk matrix.

CRMs	Annual global production	Annual global demand	Reserve base	Recycling rate	Total
A	0.4	0.3	0.2	0.0	0.9
B	0.2	0.1	0.1	0.1	0.6
C	0.3	0.2	0.2	0.0	0.7

Table 9
Ethical considerations and safety risk matrix.

CRMs	Working conditions	Child labour	Human rights violations	Transparency	Total
A	0.4	0.3	0.1	0.0	0.8
B	0.2	0.1	0.1	0.1	0.6
C	0.3	0.2	0.2	0.0	0.7

9.11. Formula and example calculation for rating CRMs based on geological importance

Formula:

Geological importance score = Weighted sum of geological factors

Geological factors may include.

- Probability of resource depletion.
- Geographical location of resource deposits.
- Quality and characteristics of the material (such as purity, rarity and versatility).
- Impact of extraction on the environment (including habitat destruction and pollution).

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.
Example Calculation:
We assign weights to each factor (Table 10).

- Probability of resource depletion = 0.2
- Geographical location of resource deposits = 0.2
- Quality and characteristics of the material = 0.3
- Impact of extraction on the environment = 0.3

Based on this calculation, CRM A has the highest geological importance score, followed by CRMs B and C, which have the same score.

9.12. Formula and example calculation for rating CRMs based on metallurgical importance

Formula:

Metallurgical importance score = Weighted sum of metallurgical factors

Metallurgical factors may include.

- Demand for the material in various industries (such as construction, automotive, electronics, etc.).
- Versatility of the material (its ability to be used in a wide range of applications).
- Recyclability of the material.
- Ease of processing (including factors such as melting point, reactivity and toxicity).

The weight assigned to each factor can depend on the specific context and the relative importance of each factor.

Table 10
Geological importance and safety risk matrix.

CRMs	Probability of resource depletion	Geographical location of resource deposits	Quality and characteristics of the material	Impact of extraction on the environment	Total
A	0.1	0.2	0.3	0.3	0.9
B	0.2	0.1	0.2	0.3	0.8
C	0.2	0.1	0.1	0.3	0.7

Table 11
Metallurgical importance and safety risk matrix.

CRMs	Demand for the material in various industries	Versatility of the material	Recyclability of the material	Ease of processing	Total
A	0.3	0.2	0.2	0.3	1.0
B	0.3	0.1	0.1	0.3	0.8
C	0.3	0.1	0.1	0.3	0.8

Example Calculation:
We assign the following weights to each factor (Table 11).

- Demand for the material in various industries = 0.3
- Versatility of the material = 0.2
- Recyclability of the material = 0.2
- Ease of processing = 0.3

Based on this calculation, CRM A has the highest metallurgical importance score, followed by CRMs B and C, which have the same score.

10. A potential CRM list for South Africa

Based on the metrics that were demonstrated in an example implementation of our framework (section 9), we perform an actual prototype assessment using available data. In this assessment, we use uniform weighting of all indicators across all dimensions. This is because the weights depend strongly on an overall supply and consumption chain analysis (e.g., to increase weighting on supply-bottleneck components), and political focus (e.g., focus on primary resource or infrastructure development versus decarbonisation), which are beyond the scope of this study. In addition, not all dimensions could be assessed using our data sources. There was only sufficient data to assess: supply risk, ESG risks and economic importance. Data was sourced from reliable databases, which are those of the S&P Global (https://www.spglobal.com/en/) and Minerals Council of South Africa (https://www.mineralscouncil.org.za/). They consisted of published datasets and reports. Each jurisdiction or producer was evaluated based on a set of plausible criteria specific to the non-technical or non-economic aspect in question, and the scores were then aggregated to give an overall score for each indicator. This method ensured that our assessment was not only grounded in measurable data but also incorporated realistic variability. However, the assessment of non-technical and non-economic aspects is intrinsically more qualitative than the other aspects, because there are no universally adopted accountability frameworks (e.g., ESG frameworks) that could be used in data poor and high poverty regions. We do not regard the confidence of social and governance risks at the same level as technical and economic data-informed aspects.

Based on the calculations and framework parameters discussed above, we here present a prototype CRM list for South Africa in Table 12, with the location of some of the proposed CRMs presented in Fig. 6. In Table 12, we observe a diverse range of CRMs ranked based on various criteria, including supply risk, ESG risks and economic importance. Notably, PGMs are listed with a supply risk-score of 0.34, which appears relatively low compared to other CRMs. While PGMs may be essential for many countries lacking local resources, their supply for domestic consumption is seemingly non-critical. It is also evident that the CRMs listed benefit from domestic production, as indicated by their economic importance. This leads to the outcome that criticality scores are higher for elements that are not domestically available. The results in Table 12 emphasise the significance of geographic diversity in CRM production. Elements such as cobalt and heavy rare earths, which are largely concentrated in specific regions such as the Democratic Republic of Congo (DRC), Zambia, Malawi and Namibia, demonstrate high supply risk indicators. Conversely, CRMs such as coal, natural gas and oil, which are available in multiple countries, exhibit comparatively lower supply risk indicators. These findings underscore the importance of diversifying sources and reducing dependence on a limited number of regions to enhance supply security and mitigate associated risks.

11. A CRM list as an opportunity for South Africa

South Africa has an opportunity to take advantage of the changing global economic landscape and reposition its economy to become a leader in the production, processing and further value-adding of CRMs. With a strategic focus on developing the country's resources and expanding its industrial base, South Africa can emerge as a major supplier of the essential materials needed to drive the world's modern economy. South Africa has several opportunities to position itself for success in the production of CRMs and clean energy. One key strategy is the development of a comprehensive CRM strategy that identifies the CRMs that are most important for the country's energy goals, and outlines strategies to secure stable supply and promote sustainable resource use. Investing in RDI can also be beneficial, as it can improve the efficiency and sustainability of CRM extraction, processing and recycling,

Table 12
Potential list of South Africa's CRM based on the proposed framework using commodity and economic data sourced from S&P Global (https://www.spglobal.com/en/) and Minerals Council of South Africa (https://www.mineralscouncil.org.za/). Note: DRC = Democratic Republic of Congo.

Ranking 2022	CRM	Supply Risk	Environmental Risk	Social Risk	Governance Risk	Economic Importance	Average score	Region in Africa
1	Cobalt	0.78	0.79	0.87	0.62	0.72	0.76	DRC, Zambia and South Africa
2	Heavy Rare Earths	0.92	0.68	0.75	0.59	0.64	0.72	Malawi, Namibia and South Africa
3	Niobium	0.97	0.72	0.51	0.55	0.61	0.68	Tanzania
4	Coal, Natural Gas and Oil	0.60	0.65	0.83	0.58	0.66	0.67	Botswana, Mozambique, Nigeria, South Africa and Zimbabwe
5	Light Rare Earths	0.88	0.61	0.57	0.54	0.61	0.65	Malawi, Namibia and South Africa
6	Aluminium	0.63	0.45	0.64	0.55	0.79	0.62	Guinea, Mozambique and Ghana.
7	Graphite	0.75	0.53	0.60	0.49	0.64	0.61	Mozambique and Tanzania
8	Chromium	0.62	0.47	0.57	0.48	0.79	0.60	South Africa
9	Antimony	0.71	0.55	0.65	0.43	0.41	0.57	South Africa
10	Vanadium	0.69	0.42	0.63	0.42	0.55	0.56	South Africa
11	Tungsten	0.67	0.41	0.54	0.38	0.68	0.56	Zimbabwe
12	Tantalum	0.55	0.54	0.76	0.32	0.54	0.55	Rwanda and Mozambique
13	Germanium	0.53	0.39	0.57	0.29	0.49	0.49	DRC and Namibia
14	Manganese and Iron	0.43	0.43	0.49	0.22	0.85	0.48	Morocco and South Africa
15	Copper	0.44	0.37	0.44	0.19	0.82	0.46	Botswana, South Africa, Namibia, DRC, Zambia
16	Platinum Group	0.34	0.45	0.44	0.18	0.57	0.46	South Africa and Zimbabwe

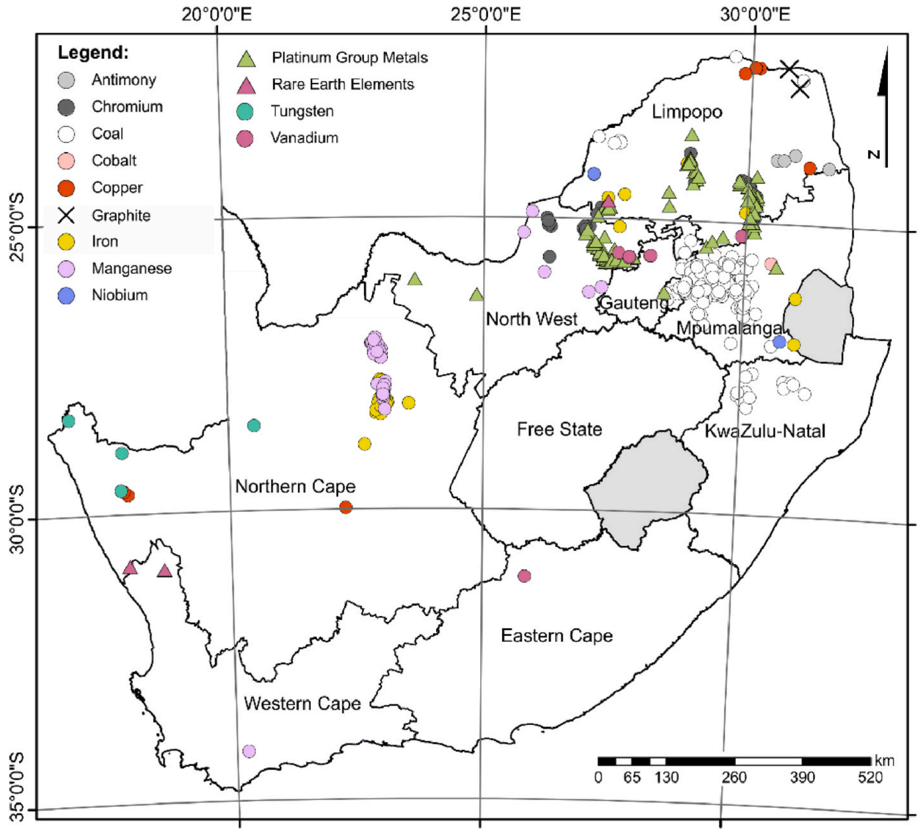

Fig. 6. Historically known and actively mined CRM deposits in South Africa using the proposed list presented in Table 12. Data sourced from Padilla et al. (2021) and South Africa Department of Mineral Resources and Energy (DMRE; Operating mines 2022). Data included as supplementary material.

and can lead to developing new technologies and applications for CRMs.

In addition, South Africa can promote material circularity activities such as recycling of CRMs to reduce reliance on primary production, reduce environmental impacts and create economic opportunities. In this case, mine waste (tailings) re-use through valorisation can lead to effective opportunities to simultaneously remove sources of environmental pollution and create a new source of employment. Encouraging domestic processing of CRMs can also create value-added products and reduce the country's reliance on importation of finished products (Robinson and Von Below, 1990; Fessehaie and Rustomjee, 2018). South Africa can promote domestic demand for clean energy technologies and products that utilise CRMs, such as electric vehicles, renewable energy systems and energy-efficient devices to create market opportunities for local companies. Finally, South Africa can also consider collaborating with other countries, particularly other African countries, to exchange knowledge, share expertise and resources to develop joint strategies for CRMs production, processing and recycling. Similarly, collaboration with countries that are heavily specialised in value-adding activities can promote skill and knowledge transfer and build a bridge towards a post-extractive industrial economy. South Africa could become a leader in the manufacturing and usage of CRMs and renewable energy by adopting these actions.

12. Policy positions to enable comprehensive management of CRMs

South Africa's approach to CRM management should be timely, strategic and proactive. One crucial step in this direction is identifying and prioritising CRMs that are critical to the country's present and foreseeable future needs, while also directly measuring any discrepancy between domestic production and use, as well as measuring international demand and consumption (Løvik et al., 2018). Establishing a national CRM strategy that considers the long-term needs and goals of the country, and that is reviewed and updated regularly can help to ensure that South Africa's approach to CRM management is sustainable and effective (Ferro and Bonollo, 2019). However, we emphasise that activities in the implementation of any CRM strategy can only occur after South Africa has a clear established and formalised vision of its own CRM interests, and formed its own CRM policy-ecosystem, including a foundational CRM framework and an initial list. Consequently, the role of state involvement in this process is important, as a vision for the future and an accompanying strategy require extensive democratic engagement. After a CRM framework and a list have become available, stakeholder engagement and collaboration can more effectively occur on a basis of mutual understanding of national CRM goals (Tomazinakis et al., 2022). A strategic and coordinated approach to CRM policy, guided by a national vision and strategy, across different sectors and levels of government will ensure that: (1) the needs of all stakeholders are considered (Barteková and Kemp, 2016); (2) informed international cooperation and dialogue on CRM issues can occur (Barteková and Kemp, 2016); and (3) a regulatory framework governing the extraction, processing and use of CRMs, including environmental and social responsibility standards becomes available (Cimprich et al., 2022).

Policies aimed to encourage the development of CRM supplies and downstream industries occur primarily as domestic and foreign. Domestic policies could, for example, be focused on the capacity building of the minerals industry, energy and transport infrastructures, knowledge and data acquisition, and talent development. Promoting the recycling and re-use of CRMs including the re-use of mine waste can reduce reliance on primary production and minimise environmental impacts. Developing contingency plans to mitigate the potential impact of supply disruptions, such as stockpiling and alternative sourcing strategies, are also important to stabilise society and ensure future prosperity (Løvik et al., 2018). Encouraging the use of substitute materials where possible can reduce the demand for CRMs and reduce reliance on a single source of supply (Novák et al., 2021). Encouraging the use of best practices and innovative technologies to minimise the environmental and social impacts of CRM extraction and processing can help to maximise material sustainability and responsibility (Ciliberto et al., 2021). Enhancing education to maximise innovation and integration can create desirable talents that would be suitable for a wide variety of industries. This would have a sustained future return. Supporting the development of pragmatic, sustainable and responsible value chains for CRMs through the use of certified products and the implementation of responsible sourcing practices can also be advantageous, e.g., blockchain for supply chain traceability (Hastig and Sodhi, 2020). Maximisation of the equality of opportunity and its associated benefits of a future CRM market in South Africa should be a prime constraint in designing the CRM policy-ecosystem. Finally, promoting public awareness and understanding of the importance of CRMs, the challenges and opportunities associated with their supply and use, can help to build support for South Africa's CRM strategy, and ensure that it is aligned with the needs and priorities of all stakeholders (Lane et al., 2015).

Foreign policies could, for example, be focused on establishing partnerships and collaborations with other countries and regions to secure accesses to CRMs, including through diplomacy, such as trade agreements, joint ventures and geopolitical collaboration. South Africa can also engage with international organisations and initiatives focused on the supply of CRMs, such as the European Union's CRMs Resilience Platform, the World Bank's Raw Materials Financing Facility (Fila et al., 2022) and China's Belt and Road Initiative. This is also inevitable given geopolitics and the use of game theory, which is already resulting in the formation of alliances and trade blocs, being countered by rival organisations (Zhang et al., 2023; Ghorbani et al., 2024b). However, it is only after the establishment of a South African CRM list and its associated national policies that South Africa can engage on an equal footing with other international organisations that have their own CRM lists. This is because geopolitical competition and foreign policy requires a practical goal and understanding other entities' moves. For example, South Africa would not be able to effectively counter vertical integration or national sufficiency moves in other countries (e.g., of nickel in Indonesia, Widiatedja, 2021), because it is unclear whether nickel is critical to current or future South African needs and how much of it is currently imported versus domestically produced. Participation without goals implies that South African needs would become subsumed by the needs of others. This is particularly important for South Africa, because it is not as developed compared to other nations and is currently affected by energy shortages (Ibrahim et al., 2021). Consequently, South Africa is not immediately ready as compared with many nations with already established CRM frameworks, who are relying on the import of CRMs to realise their visions, for example, the energy transition. This factor was recognised by Zhang et al. (2023), which also suggests that South Africa (and other comparable nations) would be faced with at least two types of CRMs – one for domestic consumption and one for export, and additionally would consider reserves in planning for the ratio of export versus domestic consumption to meet future requirements. Through adopting a comprehensive, clear and strategic approach, South Africa not only safeguards its own future but also ensures its active, fair and equal participation in the global CRM landscape.

13. Benefits for regional collaborations between South Africa and other African countries

Regional trade is a significant enabler of a South African CRM market (Table 13). This is because nearby countries are likely to share a substantial amount of ethnography and cultural heritage, as well as challenges (e.g., climate, supply of energy and level of industrialisation). Fostering local trade and regional collaborations strengthens South Africa's image and leadership role and enables an overall more prosperous Africa. This aligns closely with the Africa Mining Vision, which promotes transparent, equitable, and optimal exploitation of mineral resources to support broad-based sustainable growth and socio-economic development. The Africa Mining Vision was endorsed by Heads of State at the February 2009 African Union summit, following the October 2008 meeting of African Ministers responsible for Mineral Resources Development. It represents Africa's own strategy to address the paradox of immense mineral wealth existing alongside widespread poverty. In addition, due to South Africa's geographical location, trades with distant nations incur higher environmental costs (e.g., transportation), which are increasingly unbeneficial to the resource sector due to heightened ESG awareness and global energy prices. Overall, there are several ways in which South Africa can benefit from trading CRMs with other African countries.

- Diversification of supply: Trading CRMs with other African countries enables South Africa to diversify its sources of supply and reduce its reliance on any single country or region. This can help to reduce the risk of supply disruptions and increase the overall security of supply for South Africa.
- Economic benefits: South Africa can derive economic benefits from trading CRMs with other African countries by generating new markets and opportunities for local producers. This can boost economic growth and development in the nation, spurring greater development in the southern African region, and leading to the creation of

Table 13
Some globally recognised CRMs and countries of recorded presence in Africa based on field studies by the authors. Note: DRC = Democratic Republic of Congo. Metals such as gold, copper, nickel and others are also recorded in many other African countries and not limited to those tabled here.

CRM	Use	Country of recorded CRMs presence
Cobalt	A metallic element used in the production of batteries and other electronic products.	DRC Zambia Morocco
Copper	A metallic element used in the production of wire and cable, and in a variety of other applications.	DRC Zambia Morocco
Iron Ore	Used in the production of steel.	Liberia Gabon Mauritania
Manganese	A metallic element used in the production of steel and other alloys.	Ghana Gabon South Africa
Nickel	A metallic element used in the production of stainless steel and other alloys, and in the production of batteries.	Madagascar Zambia South Africa
Uranium	A radioactive element used as fuel in nuclear power plants.	Niger Namibia Zambia
Zircon	Used in the production of ceramics and refractories, and in the production of abrasives.	South Africa Sierra Leone Senegal
Limestone	A sedimentary rock used in the construction industry as a raw material for cement and other building materials.	Egypt Morocco Tunisia
Gypsum	Used in the production of cement and plaster.	Morocco Tunisia Algeria
Phosphate	Used in the production of fertilisers.	Morocco Tunisia Algeria
Platinum	A metallic element used in a variety of applications, including catalytic converters for vehicles, electronics, and jewellery.	South Africa Zimbabwe Tanzania
Gold	A metallic element used in a variety of applications, including jewellery, electronics, and as a store of value.	South Africa Ghana Mali
Palladium	A metallic element used in producing catalytic converters for vehicles and in other industrial applications.	South Africa Zimbabwe Tanzania

dependent markets, such as beneficiation, battery manufacturing and recycling industries.
- Strengthening regional ties: Trading CRMs with other African countries can help to strengthen regional ties and promote collaboration and cooperation within the continent. This can help foster a sense of shared interests and goals among African countries, leading to greater political stability and economic development in the region.
- Environmental benefits: South Africa can reduce its reliance on long-distance shipping by increasing regional trades. This would also help to improve the social acceptance factor for South African companies in the regional context.

14. Opportunity to collaborate with the Global North countries

There are several ways South Africa can use its CRM-derived policies to collaborate with the Global North countries.

- Identify areas of mutual interest: South Africa can leverage its policies to identify areas of mutual interest with the Global North, particularly regarding the common CRMs of importance to both regions. This can help to create opportunities for cooperation and collaboration in terms of CRM production, processing and recycling.
- Promote South African expertise: South Africa can use its policies to highlight its expertise and capabilities in the CRM sector, and to showcase its potential as a partner for CRM projects in the Global North. This can help attract investment, talent exchange and collaboration from the Global North and create opportunities for South African companies to participate in CRM projects in other countries.
- Share information and best practices: South Africa can use its CRM policies to share information and best practices with the Global North, particularly regarding sustainable resource management and recycling of CRMs. This can help to promote the adoption of more sustainable practices in the global CRM sector, and can help to reduce the environmental impacts of CRM extraction and processing.
- Participate in international engagements: South Africa can use its CRM policies to participate in international engagements and initiatives that focus on CRMs. This can help raise South Africa's profile as a participant in the global CRM sector, providing opportunities for South Africa to engage with other countries and regions on CRM-related issues.

Overall, well-crafted CRM policies can provide a range of opportunities for South Africa to collaborate with Global North countries on CRM-related challenges, promoting the country's expertise and capabilities in this sector.

15. Conclusions

CRMs play an important role in the economy and society, but are at risk of supply disruption due to a variety of factors, including: resource depletion, geopolitical conflicts, environmental and social impacts. Many countries and supernational entities have established their own CRM frameworks, which are followed by the establishment of a CRM ecosystem through legislation and policies. South Africa is in a period of rapid societal evolution and exhibits unique characteristics, for example, in terms of its staging of economy, social wellbeing and energy supply stability. The development of a South African CRM framework can help formalise the importance of materials and provide the necessary context for a national strategic approach to CRM management and governance. In this study, we have reviewed the history of CRMs and their assessment methods, and identified key areas of positive contribution of a comprehensive and timely CRM framework to South Africa, as well as discussed the role of different stakeholders, including the private sector, civil society and the general public. Based on our review and analysis, we recommend that a national CRM framework be established, followed by CRM policies to create a CRM ecosystem. This can involve a range of actions, including developing/updating CRM lists based on robust and transparent indicators and data, promoting research and development efforts focused on improving the sustainability of CRM extraction and processing, and engaging different stakeholders in the policy-making process.

Domestic and foreign policies in pursuit of CRMs must be driven by a combination of present and future needs, altogether shaped by a local context. A CRM ecosystem for South Africa, starting with a prototype CRM framework and list, not only serves South Africa, but also other aspiring nations to consider their interests, assess their developmental state and geopolitical position, and develop a convincing and achievable vision. Lastly, we recommend that policymakers and regulators consider the broader implications of CRM use and supply, including system behaviours (e.g., formation of trade blocs), as well as environmental and social impacts.

Competing financial interests

The authors declare no competing financial interests.

Funding

Funding for this research was provided by the Minerals Council of South Africa and the Department of Science and Innovation (DSI) through Mandela Mining Precinct's SAMERDI research centres hosted at the Wits Mining Institute, University of the Witwatersrand. Additional funding is from the DSI-National Research Foundation (NRF) Thuthuka Grant (Grant UID: 121973) and DSI-NRF CIMERA.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is provided as supplementary material

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2024.105045.

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