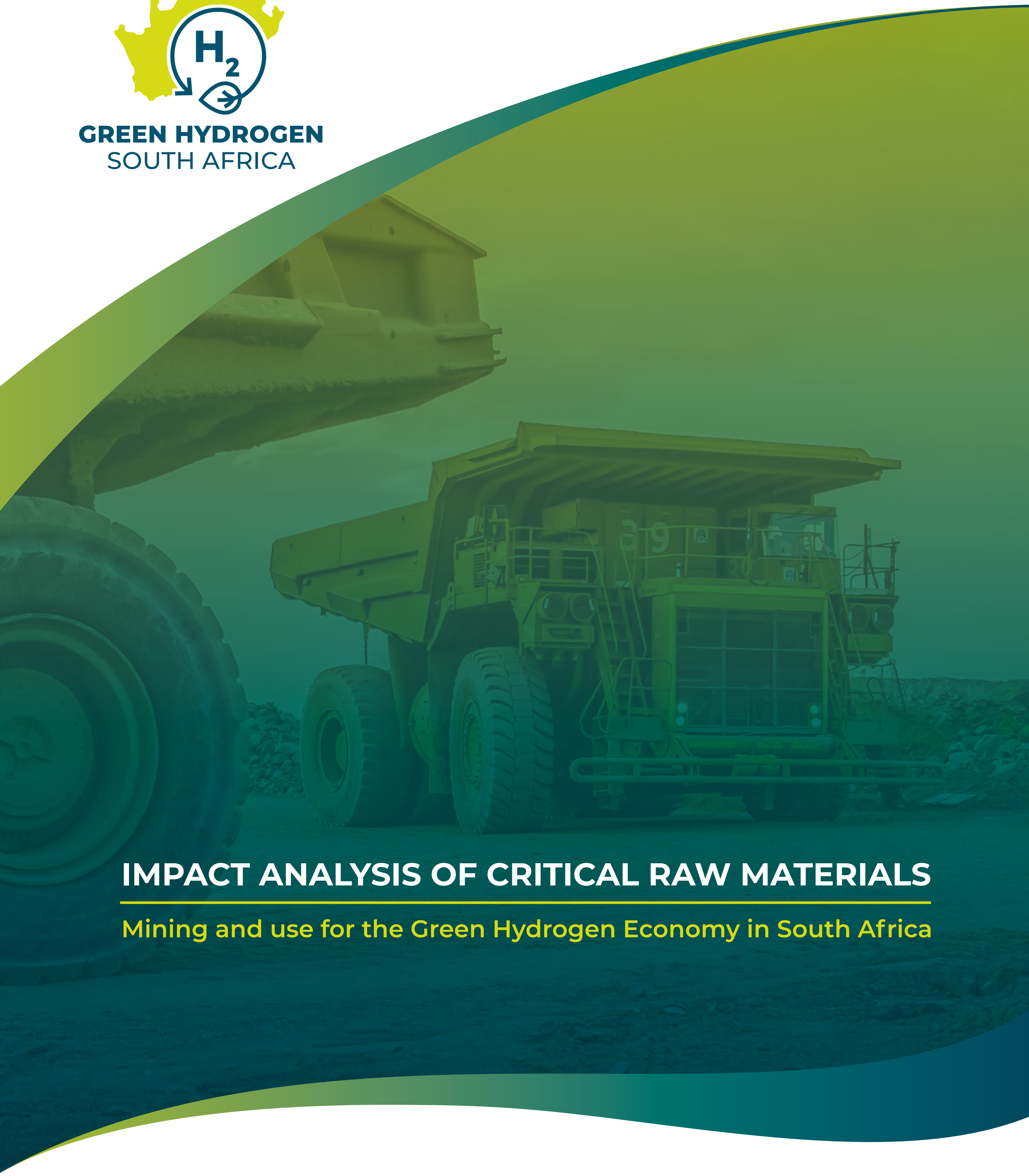
GREEN HYDROGEN
SOUTH AFRICA



IMPACT ANALYSIS OF CRITICAL RAW MATERIALS

Mining and use for the Green Hydrogen Economy in South Africa

german
cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by:
giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

IMPACT ANALYSIS OF CRITICAL RAW MATERIALS MINING AND USE FOR THE GREEN HYDROGEN ECONOMY IN SOUTH AFRICA

PUBLICATION: Impact Analysis of Critical Raw Materials Mining and use for the Green Hydrogen Economy in South Africa

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LAYOUT AND DESIGN: Studio112

PUBLICATION DATE: 15 December 2024

FUNDED BY: Promoting a Green Hydrogen Economy Program (H2.SA), funded by the German Federal Ministry of Economic Cooperation and Development, BMZ)

RESPONSIBLE INSTITUTIONS

Green Hydrogen South Africa (GHSA): GHSA is a multi-stakeholder initiative that promotes South Africa as a leading green hydrogen producer and investment destination of choice. It is led by The Presidency of South Africa and home of the South African Green Hydrogen Summit (SAGHS).

H2.SA: H2.SA is a project of the German Development Cooperation with South Africa. It is commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in close cooperation with the South African Government (I've added this instead of the Presidency to avoid the risk of not having the Presidency's logo on the document- everything else remains the same) . H2.SA's main objective is to promote a South African green and sustainable hydrogen economy. Working closely with its partners from Government, private sector, and civil society, H2.SA provides expertise, resources, and builds capacity for a secure and sustainable energy future that holds opportunities for all South Africans

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Acknowledgement

The findings of this Study are the result of extensive desktop research and valuable insights gathered from key stakeholders in the sector. We extend our sincere gratitude to all industry experts, partners, and stakeholders who contributed their time and knowledge to enrich this study. Your input has been instrumental in shaping a comprehensive understanding of the sector.

We also extend our appreciation to the dedicated Project Team listed below whose efforts and commitment made this study possible. Their expertise and hard work have been invaluable in compiling and analyzing the information presented.

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Contents

List of figures

List of tables

Acronym / Abbreviation

	Definition
ACGIH	American Conference of Governmental Industrial Hygienists
AI	Artificial Intelligence
AET	Education and Training
AE	Alkaline Electrolysers
AMD	Acid Mine Drainage
AU	African Union
Amplats	Anglo American Platinum
B-BBEE	Broad-Based Black Economic Empowerment
BESS	Battery Energy Storage System
BRPM	Bafokeng Rasimone Platinum Mine
CHP	Combined Heat and Power
CRMs	Critical Raw Materials
CSI	Corporate Social Investment
CSP	Concentrated Solar Power
CSR	Corporate Social Responsibility
DFFE	Department of Forestry, Fisheries, and Environment
DMRE	Department of Mineral Resources and Energy
DPSA	Department of Public Services and Administration
DWS	Department of Water and Sanitation
Eastplats	Eastern Platinum Limited
ELV	End-of-Life Vehicle
EPR	Extended Producer Responsibility
ESS	Energy Storage Systems
EU	European Union
E-waste	Electronic Waste
FPIC	Free, Prior, and Informed Consent
GHG	Greenhouse Gas
GIS	Geographic Information Systems

Acronym / Abbreviation

	Definition
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HMs	Heavy Metals
HIA	Heritage Impact Assessment
HRES	Hybrid Renewable Energy Systems
IC	Internal Combustion
IDPs	Integrated Development Plans
EIA	Environmental Impact Assessments
IEA	International Energy Agency
IIED	International Institute for Environment and Development
IPILRA	Interim Protection of Informal Land Rights Act
IRENA	International Renewable Energy Agency
ISA	Infrastructure South Africa
JET-IP	Just Energy Transition Implementation Plan
KMF	Kalahari Manganese Field
LEIP	Limpopo Eco-Industrial Park
MCDA	Multi-Criteria Decision Analysis
MFC	Microbial Fuel Cells
MPRDA	Mineral and Petroleum Resources Development Act
MW	MegaWatt
NIHL	Noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
PEM	Proton Exchange Membrane
PGMs	Platinum Group Metals
PPM	Pilanesberg Platinum Mine
RBPlat	Royal Bafokeng Platinum
RE	Renewable Energy
REEs	Rare Earth Elements
REIPPP	Renewable Energy Independent Power Producer Procurement

Acronym / Abbreviation

	Definition
SADC	South Africa Development Community
SAF	Sustainable Aviation Fuel
SEI	Stockholm Environmental Institute
SEZ	Special Economic Zone
SIP	Strategic Integrated Projects
SLP	Social and Labour Plan
SDGs	Sustainable Development Goals
TB	Tuberculosis
TDS	Total Dissolved Solids
TFR	Transnet Freight Rail
TSS	Total Suspended Solids
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
WEEE	Waste Electrical and Electronic Equipment

Executive Summary

Critical raw materials (CRMs) are central to the Just Energy Transition, enabling the global shift to cleaner energy sources and supporting technological advancements across industries. South Africa, endowed with significant reserves of platinum group metals (PGMs) could play a pivotal role in the global transition towards renewable energy and decarbonisation. Through frameworks such as the Just Energy Transition Implementation Plan (JET-IP), South Africa aims to integrate socio-economic development with sustainable energy transformation, ensuring equitable benefits for local communities while addressing the challenges of climate change.

Green hydrogen, a promising energy carrier, forms the cornerstone of renewable energy strategies and is deeply reliant on CRMs for the production of electrolysers and fuel cells. Technologies such as proton exchange membrane (PEM) electrolysers and hydrogen fuel cells utilise PGMs, particularly platinum and iridium, as critical catalysts. Green hydrogen, produced through water electrolysis powered by renewable energy, is poised to decarbonise energy-intensive sectors such as steel manufacturing, chemical production, shipping, and aviation. Projections indicate that renewable energy consumption for hydrogen electrolysis will rise substantially, from 295 TWh in 2019 to over 700 TWh by 2050, driven by global net-zero ambitions.

The extraction of CRMs in South Africa contributes significantly to the economy, generating R494 billion in GDP in 2022, alongside R74 billion in tax revenue and R14 billion in royalties. Mining supports employment, infrastructure development, and local economic upliftment. However, these benefits are accompanied by considerable socio-environmental challenges. CRMs mining is associated with greenhouse gas emissions, high energy and water consumption, and land disruption. Communities near mining operations often experience water contamination, land degradation, and air pollution, leading to health issues such as respiratory diseases and waterborne illnesses. Vulnerable groups, particularly women and indigenous communities, are disproportionately affected, facing displacement, cultural erosion, and limited economic gains.

To mitigate these impacts, a shift towards sustainable practices is critical. Recycling CRMs from end-of-life products and industrial waste offers a significant opportunity to reduce reliance on virgin materials while minimising environmental harm. Investments in recycling infrastructure, coupled with advancements in processing technologies, can align CRMs use with circular economy principles. Policy-driven projections suggest a 10–15-year ramp-up in CRM demand, followed by plateauing or declining trends as recycling and technological advancements reduce reliance on primary mining.

Technological innovation remains a key enabler in balancing CRMs extraction with sustainability goals. Artificial intelligence (AI) and advanced resource extraction methods can improve mining efficiency, reduce waste, and minimise environmental impacts. In parallel, advancements in electrolysers, such as reducing PGM loading and increasing energy efficiency, have the potential to lower the demand for critical materials over time. The integration of hybrid renewable energy systems (HRES) in mining operations further supports sustainability by reducing fossil fuel dependency and lowering operational costs.

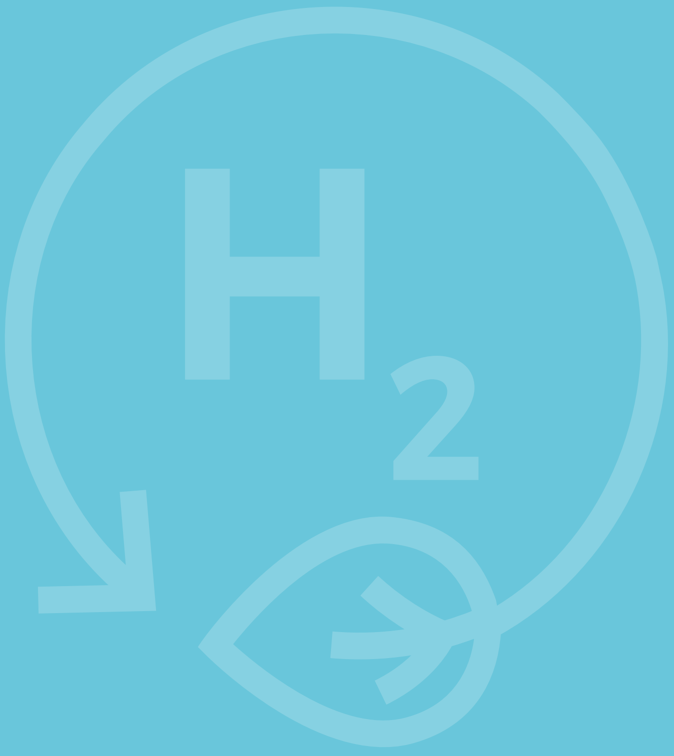
Infrastructure development for green hydrogen production and distribution also requires focused attention. Electrolysers, pipelines, and storage facilities tailored to hydrogen's unique properties will demand substantial investment and planning. Challenges such as high capital costs, long lead times for equipment, and insufficient local energy transmission infrastructure must be addressed to support the scale-up of renewable hydrogen production. Additionally, the high fixed and operating costs associated with CRMs processing and hydrogen technologies present barriers to economic viability, requiring sustained policy and financial support.

Economic considerations extend to ensuring that the benefits of CRMs extraction and hydrogen-related developments are equitably distributed. Community participation in decision-making, the adoption of social and labour plans (SLPs), and the incorporation of free, prior, and informed consent (FPIC) principles are essential to addressing power imbalances and promoting inclusive socio-economic outcomes.

In conclusion, the role of CRMs in the green hydrogen economy highlights the complex intersection of economic opportunity, environmental sustainability, and social equity. Addressing the challenges of CRMs mining through a combination of recycling, innovation, and infrastructure development is essential to meeting the demands of the Just Energy Transition.

Chapter 1

Introduction



1. Introduction

Critical raw materials (CRMs) are essential to the Just Energy Transition, which seeks to transform global energy systems towards cleaner sources while bolstering technological competitiveness. In South Africa, this transition is closely linked to the country's substantial reserves of CRMs, including platinum group metals (PGMs), rare earth elements (REEs), and other key minerals. This resource endowment places South Africa in a unique position within the global decarbonisation agenda, aligning its local energy goals with broader socio-economic development priorities under frameworks like the Just Energy Transition Implementation Plan (JET-IP). This framework emphasises that sustainable energy transformation must go hand-in-hand with socio-economic progress, ensuring benefits that are both sustainable and inclusive for local communities.

Green hydrogen, a promising energy carrier, is a cornerstone of this transition due to its high energy potential for powering industries and economies. However, the technology underpinning green hydrogen is capital-intensive and highly reliant on CRMs for its efficiency and operational capacity. PGMs, in particular, serve as crucial catalysts in both electrolysers, where they help separate water into hydrogen and oxygen, and fuel cells, which generate clean energy by enabling reactions between hydrogen and oxygen. The success of the green hydrogen sector is thus tied to the responsible and sustainable extraction of CRMs, which are vital to the production of fuel cells and electrolysers. As such, the future of green hydrogen—and the security of its supply chains—depends significantly on ensuring a stable and sustainable CRMs supply.

In a world that is increasingly focused on shifting away from coal and fossil fuels, in line with the Sustainable Development Goals (SDG, 2030) and global climate commitments, South Africa faces both opportunities and challenges. As one of the world's largest producers of PGMs, particularly platinum and rhodium, South Africa occupies a dominant position in these markets. However, with the global phase-out of internal combustion (IC) engines, the demand for PGMs may decrease, potentially impacting an industry that is essential for South Africa's foreign exchange earnings and employment. To mitigate this risk, the development of PGM beneficiation strategies—such as producing hydrogen fuel and ammonia from PGM feedstock and exporting these products—presents a potential pathway. Additionally, fostering fuel cell technology industries that use PGMs more efficiently than traditional IC engines could create longer-term economic opportunities.

Despite these possibilities, South Africa may not be the main future consumer of the green hydrogen produced within its borders. The country's government strategy is geared towards developing an export-oriented industry, with the aim of using green hydrogen to decarbonise external energy requirements and serve as a feedstock for greenhouse gas (GHG) intensive industries, such as ammonium production. With strong trade ties to Europe, South Africa is well-positioned to tap into emerging hydrogen markets and develop export industries that can offset anticipated declines in its coal and platinum sectors. Its abundant, low-cost renewable electricity resources, particularly wind and solar, also provide a competitive advantage by enabling cost-effective alkaline electrolysis, the most established method of hydrogen production.

This report delves into the intersection of CRMs mining with critical environmental, socio-economic, and technological factors. Through spatial analyses, it maps CRMs mining operations and their interactions with key natural and human systems, including communities, energy and infrastructure networks, water resources, and protected areas. These maps provide a comprehensive view of the impacts of CRMs mining and highlight the projected demand for critical minerals as South Africa advances its green hydrogen ambitions. This analysis examines the interaction of CRMs mining with GHG emissions, water and land use, and energy requirements, revealing the resource demands associated with the green hydrogen transition.

While CRMs mining brings substantial socio-economic benefits—such as job creation, infrastructure development, and local economic upliftment—it also poses considerable challenges. The environmental impacts of mining are significant, often leading to deforestation, soil erosion, water contamination, and biodiversity loss. These environmental consequences, in turn, have severe health implications for nearby communities, exposing them to increased risks of respiratory illnesses, waterborne diseases, and other health issues. Socially, CRMs mining frequently disrupts indigenous and rural communities, causing displacement, loss of cultural heritage, and limited economic gains that may not offset these disruptions. Women in mining-affected areas also face unique challenges, including restricted job opportunities, greater health risks, and heightened exposure to violence. Although efforts are underway to address these socio-economic impacts, significant gaps remain in ensuring meaningful community engagement and equitable distribution of benefits from CRMs mining.

This study underscores the importance of adopting innovative strategies to reduce reliance on primary CRMs extraction. By incorporating circular economy principles, recycling CRMs from end-of-life products, and diversifying supply chains, South Africa can alleviate pressure on mineral resources while promoting environmental sustainability. As a leading producer of PGMs, the country is well-positioned to lead CRMs recycling initiatives in line with its broader circular economy goals. However, the potential economic impacts on the mining sector must be carefully weighed to balance sustainability with economic resilience.

In this context, the report lays the foundation for a comprehensive analysis of the green hydrogen value chain in South Africa, exploring its resilience, security of supply, and the sustainable pathways needed to support a just and equitable energy transition

1.1 South Africa’s CRMs in Advancing the Green Hydrogen Economy

The CRMs produced in South Africa that are essential for advancing the green hydrogen economy include PGMs, REEs, nickel, cobalt, manganese, vanadium, lithium, and graphite (European Commission, 2020). These elements play key roles in hydrogen production, storage, and utilisation technologies, forming the backbone of the infrastructure needed for a sustainable hydrogen economy.

Platinum and iridium, both PGMs, are vital catalysts in PEM electrolysers, where they facilitate the production of hydrogen from water. Platinum is also crucial in hydrogen fuel cells, used in vehicles and power generation systems, as it enables the reaction between hydrogen and oxygen to produce electricity (Seck *et al*., 2023; Eikeng *et al*., 2024). Iridium’s role in electrolysers, particularly for oxygen evolution reactions, is equally critical. REEs, such as neodymium and dysprosium, are used in permanent magnets for wind turbines and hydrogen fuel cell vehicles (FCEVs). These magnets are vital for renewable energy generation and the electric motors that power fuel cells. Other REEs, like yttrium and lanthanum, are important in solid oxide fuel cells (SOFCs), which are used for efficient power generation (Eikeng *et al*., 2024).

Nickel plays a major role in alkaline electrolysers due to its effectiveness as an electrode material, while cobalt is a key component in lithium-ion batteries, crucial for storing renewable energy used in hydrogen production (Kamran *et al*., 2023; Eikeng *et al*., 2024). Manganese is also a significant element in lithium-ion batteries, particularly in lithium manganese oxide (LMO) batteries, where it enhances stability and reduces reliance on cobalt. Vanadium is used in vanadium redox flow batteries (VRFBs), large-scale energy storage systems that help integrate renewable energy into the grid. These systems are crucial for storing electricity generated by renewable sources and ensuring a consistent supply for hydrogen production through electrolysers (Eikeng *et al*., 2024).

Lithium is vitally important for lithium-ion batteries, which store renewable energy from solar and wind sources, facilitating the production of green hydrogen (Kamran *et al*., 2023). Finally, graphite is used in bipolar plates of fuel cells, managing the flow of electricity generated from hydrogen, and is also found in high-pressure hydrogen storage systems, including tanks and pipelines (Eikeng *et al*., 2024).

Chapter 2

Research Objectives

2. Research Objectives

The study objective was to analyse the environmental and socio-economic impacts of extracting CRMs essential for green hydrogen production in South Africa. The study focused on mapping the spatial distribution of CRMs mining activities, assessing their environmental and community implications, and evaluating the sustainability of these operations within the green hydrogen value chain.

This study employed a multi-faceted approach to address these objectives. Spatial clustering of CRM mining operations was conducted to visualise their distribution across South Africa and their intersections with environmental and socio-economic factors. These maps incorporated data on energy, water, infrastructure, biodiversity, and community demographics to provide a holistic understanding of CRM mining zones and their broader impacts. The selected CRMs—PGMs, REEs, nickel, cobalt, manganese, vanadium, lithium, and graphite—were prioritised due to their critical roles in green hydrogen technologies such as electrolysers and fuel cells as seen in the previous section.

Environmental and socio-economic impact assessments were carried out to evaluate the consequences of mining on air, water, land, biodiversity, and communities. These analyses relied on verified datasets, supplemented by stakeholder engagements and an extensive literature review. The assessment of socio-economic impacts focused on the benefits and challenges of CRMs mining for local communities, particularly in terms of employment, revenue generation, and infrastructure development.

The study also integrated a demand curve analysis for the selected metals, which was central to projecting the future dynamics of CRMs use in the green hydrogen economy. By defining baseline, low-demand, and high-demand scenarios, the study modelled potential growth trajectories for CRM consumption based on key demand drivers, including policy developments, technological advancements, and market trends. These scenarios enabled a forecast of environmental and socio-economic impacts under varying demand conditions, providing a strategic lens for evaluating the implications of different growth pathways.

Additionally, a technological assessment was conducted to explore advancements in mining practices and green hydrogen technologies that influence CRMs requirements. This included examining innovations aimed at improving resource efficiency, reducing environmental footprints, and promoting circular economy principles. The assessment highlighted opportunities to mitigate reliance on CRMs through emerging technologies and alternative materials, underscoring the need for continued investment in research and development.

Validation of findings was achieved through workshops and stakeholder engagements, ensuring that the research reflected the perspectives of key actors in the CRMs and green hydrogen industries. These sessions also provided an opportunity to refine data interpretations and incorporate feedback into the final analyses. The approach combined quantitative mapping and impact assessments with qualitative insights from stakeholder interactions, creating a robust framework for understanding the multi-faceted implications of CRMs mining for South Africa's green hydrogen economy.

Chapter 3

Scope and Limitations

3. Scope and Limitations

The tasks described in this study were reliant on data available at a desktop level and reflect the best information currently accessible in the public domain. However, the predictions made remain theoretical due to the limitations inherent in data processing and desktop-based research.

This study was intentionally designed as a high-level, desktop-only analysis. Outcomes may be influenced by factors such as market dynamics (e.g., competitive rivalry, supplier power, buyer power, threat of substitution, and threat of new entry) and socio-economic forces.

Stakeholder engagement was limited to respondents who agreed to participate in meetings. While several interviews were successfully conducted, responses from the mining industry were less robust than expected. This could result in insufficient representation of industry perspectives. Planned future stakeholder workshops will address these gaps, however, broader participation from the mining sector is critical to ensure a balanced and inclusive analysis. Furthermore, the impacts examined in this study are based on the assumption that existing and established mining methods remain unchanged.

Chapter 4

Literature review

4. Literature review

In South Africa, mining inputs into the green hydrogen value chain are central to enabling the transition to a low-carbon, just, and inclusive society, and may leverage the demonstrated strengths of the country's carbon capture and storage; solar, offshore wind, and wind resources; local electrolyser assembly; fuel cell and micro-grids; hydrogen storage, water electrolysis, and water reticulation; and storage and distribution industries. However, the development of the various minerals that are used in hydrogen technologies will add to water security and availability, climate, biodiversity, pollution, and socio-economic trade-offs (Hamukoshi *et al*., 2022; Masip *et al*., 2021; Khan *et al*., 2024; Boccas, 2022; Smith *et al*., 2022).

Green hydrogen is likely to become the energy carrier of choice due to its high energy conversion efficiencies, energy storage capabilities, versatility, modularity, scale, high energy density, universal applicability, dispatchability, and beneficial environmental and employment creation impacts (Oliveira *et al*., 2021; Jovan & Dolanc, 2020; Panchenko *et al*., 2023).

The EU has identified CRMs, constituting the foundational materials necessary to deliver the hydrogen economy. Hydrogen is critical because it can replace coal in the manufacture of electricity. Of these nineteen CRMs, eleven are metals: cobalt, iron, lead, lithium, indium, magnesium, PGMs (osmium, iridium, palladium, and platinum), silver, and titanium. There are an additional 42 materials on the "naughty list", as dubbed by the South African government, that South Africa has either a deficit of, does not have, or cannot be developed internally due to technical, environmental, or social issues. The "naughty list" is a subset of the wider list of materials important for the development of the hydrogen economy. Many of these materials are hydroxide salts or lithium used in batteries. A classic criticism of hydrogen fuel cells is that they are an indirect method of using electricity to produce work that nevertheless requires remediating the environment after the extraction of 28 materials: the 20 named in the two lists and the eight necessary to maintain the fuel and cells (Zhang *et al*., 2023; Černý *et al*., 2021; Domaracka *et al*., 2022; Girtan *et al*., 2021; Righetti & Rizos, 2024).

The EU's Hydrogen Strategy has identified the need to use locally available renewable energy sources and raw materials to minimise the environmental footprint of hydrogen and help boost local value chains. The EU's Hydrogen Strategy prioritises investments that help bolster Europe's industrial leadership. These policies are particularly advantageous for SA, as it would be one of the largest local stakeholders with a wealth of by-products and waste resource opportunities which can be used as feedstock for alkaline, proton exchange membrane (PEM), and solid oxide electrolysers. This would stimulate labour-intensive beneficiation activities, lead to a reduction in the cost of the electrolyser through waste minerals (such as graphite) that are currently shipped for further processing, and therefore avoid the shipping costs associated with them. The approach is therefore to analyse the capabilities, strengths, and weaknesses of the CRM inputs used in the value chain of a hybrid green hydrogen platform (Nunez & Quitzow, 2023; Phillips & Fischer, 2021; Weko, 2023; Pepe, 2023).

A green hydrogen value chain consists of three main segments: upstream, midstream, and downstream. The upstream segment consists of the extraction or production of raw materials and inputs required in the feedstock used during the production process. The midstream segment consists of processing the raw materials and inputs so that they can be utilized in the final product, and the downstream segment consists of the extraction or production of the final product, which in this case is green hydrogen synthesized by an electrolyser (Pettersen *et al*., 2022; Toscano & Saza, 2023; Li & Taghizadeh-Hesary, 2022).

This study indicates that logistics, high production risk and volatility, cash-flow, long pay-back times, safety and security risks, environmental concerns, responsible sourcing, and value chain risk are the top risks and challenges that need to be managed by the policymakers, regulators, and decision-makers (Gurtu & Johny, 2021; Um & Han, 2021; Odulaja *et al*., 2023; Pellegrino *et al*., 2021; Wang-Mlynek & Foerstl, 2020; Alicke & Strigel, 2020; Odimarha *et al*., 2024).

Hydrogen is regarded as the cleanest form of energy, but to produce green hydrogen, renewable sources must be used, and the green hydrogen must be produced using an environmentally friendly process. South Africa has renewable sources—sun and wind—and is blessed with large reserves of various mining resources that are critical to clean energy technology. With its well-established financial and industrial expertise, South Africa is determined, through its 2030 and 2050 visions, to harness its potential of becoming a significant player in green hydrogen development (Adeleke *et al*., 2021; Omole *et al*., 2024; Akinbami *et al*., 2021; Mutezo & Mulopo, 2021; Gielen, 2021; Church & Crawford, 2020).

Among various competing technologies, the green hydrogen produced by solar and wind energy is the most competitive. South Africa can produce the cheapest green hydrogen as it is in an area with abundant good quality wind and high irradiation, making it an ideal location for green hydrogen produced from renewable sources (Patonia & Poudineh, 2022; Trollip *et al*., 2022; Hassan *et al*., 2023; Van Wijk & Wouters, 2021; Ayodele *et al*., 2021).

Chapter 5

Maps of CRMs Production in South Africa

5. Maps of CRMs Production in South Africa

Mining represents a significant industrial sector characterised by its profound impact on landscapes, encompassing diverse geographical, environmental, and social dimensions. The ramifications of mining activities extend far beyond the immediate vicinity of extraction sites.

Geographically, mining operations are dispersed worldwide, albeit with notable clustering in specific areas. This spatial distribution results in disproportionate impacts on nearby communities and ecosystems. Consequently, understanding and mitigating these impacts necessitates a comprehensive assessment of the interplay between mining activities and their surrounding environments.

Critical to mining operations is the reliance on essential infrastructure, including transportation networks and power supply grids. The construction and maintenance of such infrastructure not only facilitate mineral extraction and transportation but also significantly influence the environmental and social landscapes of the areas in which they are situated.

Geographic information systems (GIS) are indispensable tools for analysing and visualising the spatial relationships between mining operations and receiving environments. By integrating geospatial data, GIS enables a thorough examination of terrain characteristics, land-use patterns, and proximity to sensitive ecological features. GIS facilitates the identification and assessment of environmental risks associated with mining activities, such as habitat disruption, water contamination, and air pollution. Through advanced spatial analysis techniques, GIS enables the visualisation of demographic trends, socioeconomic dynamics, and cultural heritage sites affected by mining operations. GIS also facilitates the evaluation of infrastructure networks supporting mining activities, providing insights into transportation routes, power distribution systems, and access to essential resources. Such analyses are paramount for ensuring sustainable resource management and guiding informed decision-making processes.

Spatial analysis techniques such as mapping and remote sensing offer opportunities to discern spatial relationships between mining sites, infrastructure networks, and protected ecological zones. This enables policymakers and stakeholders to identify areas of convergence or adjacency, informing strategic planning and policy formulation initiatives.

GIS and spatial analysis techniques provide a formal framework for understanding the complex interrelationships between mining activities, environmental considerations, and infrastructure dependencies. Through such analyses, it becomes possible to devise sustainable strategies that balance the imperatives of resource extraction with the preservation of environmental integrity and social well-being.

5.1 Methodology – CRMs Map Generation

To produce these maps, publicly available spatial datasets relevant to the themes were consulted. Data sources included renewable energy applications and protected area data from the Department of Forestry, Fisheries, and Environment (DFFE). Additionally, a 2023 spatial dataset featuring operational mines and related facilities was obtained from the United States Geological Survey (USGS) website, and DMRE and AmaranthCX open data portals. A full list of sources consulted to produce the maps is available in the annexures. Our data set covers a total of 459 mines and mineral processing facilities producing CRMs within the scope of this study.

All data collected was entered into the ArcGIS™ software package. Thematic layers were visualised alongside the CRMs mines to effectively convey spatial relationships. Appropriate styling techniques were applied to enhance map readability and clarity. The results are presented and discussed in the sub-chapters that follow:

5.2 CRMs Mines and Facilities

The distribution of CRMs mines and mining facilities depicted in Figure 1 shows that certain mineral mining sites are clustered. This is expected as areas with similar geological settings and mineralisation processes host similar mineral deposits. Figure 1 shows that the Northern Cape Province hosts significant manganese deposits within the Kalahari Basin, where mines are clustered due to favourable sedimentary conditions. PGM mines dominate the North-West Province, particularly in the Bushveld Igneous Complex, where extensive layered intrusions yield abundant platinum, palladium, rhodium, and other metals. Vanadium deposits, often associated with titaniferous magnetite ores, are prevalent in the same Bushveld Complex. Cobalt resources, though limited, are typically sourced as a by-product of nickel mining, particularly in the Eastern Limb of the Bushveld Complex.

5.2.1 Platinum Group of Metals (PGM) Mines

The South African PGMs mines are world leaders in terms of production. A significant proportion of the world's platinum is produced from mines in the Bushveld Complex, South Africa. These mines are on high-grade geological formations which are rich in the various PGMs.

Among the leading producers is Anglo American Platinum (Amplats), boasting several key operations. The Mogalakwena Mine, located near Mokopane in Limpopo Province, stands out as one of the largest open-pit PGMs mines globally, specialising in platinum alongside notable by-products like palladium and rhodium. The Amandelbult Complex, comprising the Tumela and Dishaba mines in the Thabazimbi area of Limpopo, also contributes significantly to the country's PGMs output. Additionally, the Rustenburg Operations, encompassing Khomanani, Thembelani, and Siphumelele mines in the North West Province, are pivotal in the production of PGMs.

Implats, another major player, operates key mines like the Impala Mine near Rustenburg, known for its deep-seated platinum reserves and substantial by-products of palladium and rhodium. Marula Mine, situated in Limpopo near Burgersfort, and Two Rivers Mine in Mpumalanga Province, a joint venture between African Rainbow Minerals and Impala Platinum, also bolster South Africa's PGMs production. Formerly Lonmin, now part of Sibanye-Stillwater, has notable assets such as Marikana Mine near Rustenburg and the Pandora Joint Venture (PJV) Mines in the Brits area, both significant contributors to the nation's PGMs sector.

Northam Platinum's Zondereinde Mine, located in Limpopo's Thabazimbi district, is a key underground operation focusing on platinum, palladium, rhodium, and gold extraction. Royal Bafokeng Platinum (RBPlat) operates the Bafokeng Rasimone Platinum Mine (BRPM) near Rustenburg as a joint venture with Anglo American Platinum. Eastern Platinum Limited (Eastplats) adds to the mix with its Crocodile River Mine in the western limb of the Bushveld Complex, while Tharisa Minerals' Tharisa Mine in the south western limb near Rustenburg is a significant producer of chrome and PGMs. While smaller in scale, mines like Northam Platinum's Zondereinde Mine in Limpopo's Thabazimbi district, along with Lonmin's (now part of Sibanye-Stillwater) Marikana Mine near Rustenburg and the Pandora Joint Venture (PJV) Mines in the Brits area, each make significant contributions to the nation's PGMs output.

5.2.2 Nickel Mines

The only nickel ore mine in South Africa is located at Nkomati. The mine is situated 300 kilometres east of Johannesburg. The ore is associated with mafic-ultramafic rocks of the Insizwa Layered Complex. The Nkomati Deposit is situated in the centre of the complex which is of great interest to explorationists and mining engineers. This is due to the grade, size, and processing of such large deposits and their relative geographical simplicity. This deposit presents itself as a primary nickel accumulation which has recently been modified by laterite to form a nickel bearing cap approximately 7–10 m thick. This saprolitic overburden is currently being stripped, resulting in an expensive mining process due to the nature of the ore body. The Nkomati Project has significant mine and process plant installed on location, making it the ideal research platform for studying the environmental impacts of mining.

5.2.3 Cobalt Mines

Cobalt mining in South Africa, though not as extensive as other minerals, contributes significantly to the country's mineral wealth. One of the primary sources of cobalt is the Mopani Copper Mine, located in Gauteng Province and operated by Glencore. While predominantly a copper mine, Mopani also yields cobalt as a by-product. Additionally, Nkomati Mine, situated in Mpumalanga Province and operated by African Rainbow Minerals and Norilsk Nickel, primarily focuses on nickel but also produces cobalt as a by-product. These operations play a crucial role in supplying cobalt, a critical component in lithium-ion batteries for electric vehicles and renewable energy storage systems. While South Africa's cobalt production may not match that of other countries, the presence of cobalt as a by-product in existing mining operations adds to the country's mineral diversity and economic output, contributing to global supply chains for key technologies.

5.2.4 Manganese

Manganese mining in South Africa is centred primarily in the vast expanse of the Kalahari Manganese Field (KMF) located in the Northern Cape Province. This field is globally renowned for its extensive manganese deposits, covering an area of around 33,000 square kilometres. Within the KMF, several major mines operate, contributing significantly to South Africa's manganese production. Tshipi Borwa Mine, owned by Tshipi é Ntle Manganese Mining, stands out as one of the newest and largest operations in the region, commencing operations in 2012 with substantial reserves. South32 operates several key mines in the KMF, including Mamatwan and Wessels mines in the Hotazel area. Nchwaning Mine, an underground operation known for its high-grade manganese ore, has been a stalwart producer since the 1970s. Gloria Mine, also part of the Hotazel complex, adds to the output from this prolific region. Additionally, smaller manganese mines such as Umkomaas and Sishen further contribute to the country's manganese output. Beyond the KMF, Nkomati Mine in Mpumalanga Province, primarily a nickel mine, also produces significant quantities of manganese as a by-product. Overall, South Africa's manganese mining sector plays a pivotal role in its economy and in meeting global demand for this essential mineral.

5.2.5 Vanadium Mines

Vanadium mining in South Africa is characterised by its significant reserves concentrated primarily in the Bushveld Complex, a vast geological formation spanning several provinces. This metal, crucial for steel production, energy storage, and various industrial applications, is extracted from several key mines across the region. Among these is Vametco Mine, operated by Bushveld Minerals, situated in the North West Province. Vametco is one of South Africa's leading vanadium mines, producing vanadium oxide and ferrovanadium, essential materials for various industries. High-grade vanadium ore deposits within the Bushveld Complex contribute significantly to the mine's output. Another notable operation is the Uitvalgrond 431 Mine. Evraz Highveld Steel and Vanadium, formerly significant in the industry, faced financial challenges and suspended operations in 2015. Despite this setback, its assets, including substantial vanadium resources, indicate the region's potential for vanadium mining. Ongoing exploration projects across the Bushveld Complex, including Uitvalgrond 431, hold promise for further vanadium extraction, supporting both domestic needs and global markets.

5.2.6 Lithium

South Africa, although possessing some lithium reserves, which are primarily situated in pegmatite deposits within the Bushveld Complex and the Northern Cape Province, has seen relatively minor lithium production compared to leading countries like Australia, Chile, and China.

One significant site contributing to South Africa's lithium potential is the Blesberg Project Mine in the Northern Cape Province. This mine stands out as one of the largest known economically mineralised pegmatite deposits in the region. With a rich history of over 250,000 tonnes of high-grade spodumene stockpiles, the company managing the Blesberg Project embarked on a re-processing initiative in the first quarter of 2023. Throughout 2023, the high-grade spodumene material underwent rigorous independent testing by various parties to validate its quality and economic viability. Marula Mining, the proprietors of Blesberg Mine, initiated the first shipment of high-grade 'run-of-mine' lithium ore as part of a $5-million lithium prepayment agreement that commenced in January 2023.

5.2.7 Rare Earth Elements (REE)

South Africa holds substantial reserves of REEs, though its mining activity in this sector has historically been limited compared to major producers like China, Australia, and the United States. The country's REE deposits are mainly concentrated in alkaline igneous complexes, particularly the Phalaborwa Complex. However, extracting these resources has faced challenges such as prohibitive costs, environmental concerns, and competition from global suppliers.

To address the growing global demand for REEs, South Africa has seen the emergence of projects aimed at tapping into its REE reserves. One such project is the Zandkopsdrift Rare Earth Project, located in the Namaqualand region of the Northern Cape Province. Spectrum Rare Earths obtained an exclusive 75-year prospecting license for this project in 2002.

Another significant initiative is the Steenkampskraal deposit, known for its abundance of neodymium and praseodymium REE. The Steenkampskraal Mine, located in the Western Cape Province and owned by Frontier Rare Earths, underscores the country's commitment to unlocking its mineral wealth. Discovered in 1982 on the St. Davids farm, this mine has changed ownership over the years, reflecting the dynamic nature of South Africa's mining sector. Additionally, the Rietveld farm, situated in the Witwatersrand Basin, represents a significant development for South Africa's rare earth industry.

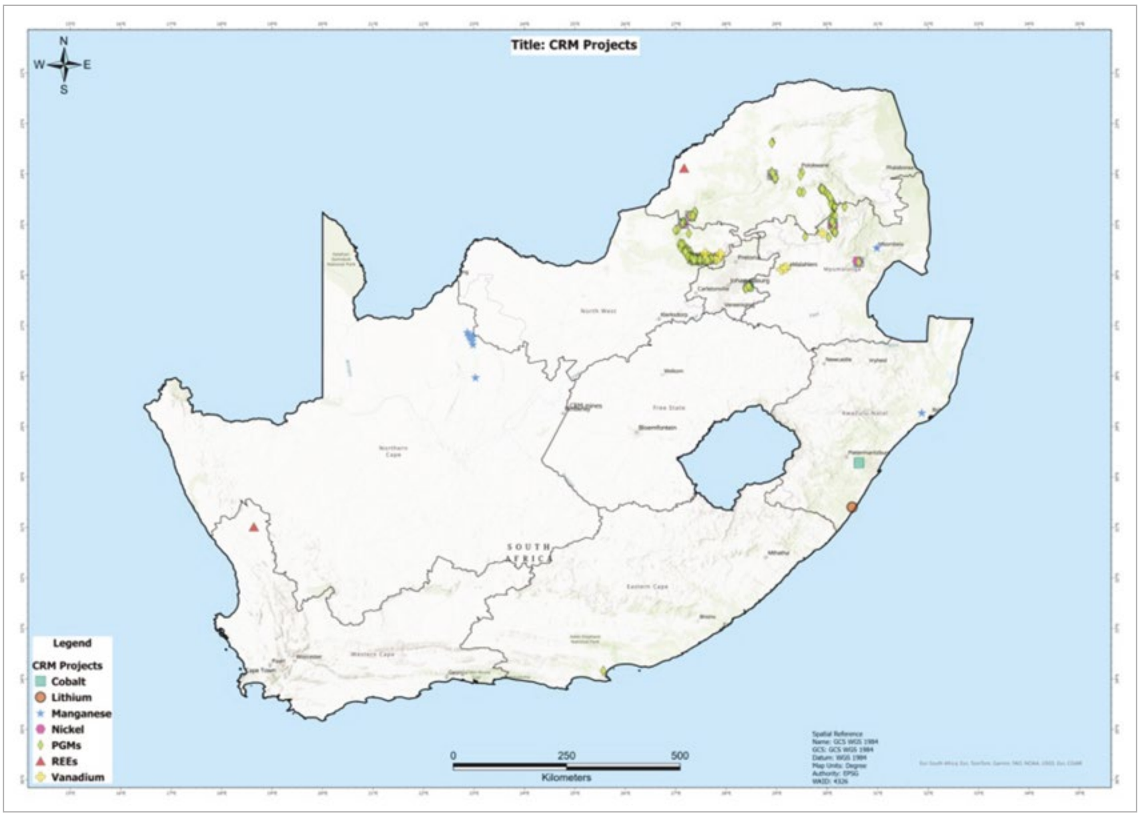


Figure 1: Critical Raw Materials (CRMs) mines and mining facilities in South Africa

5.3 Environmental Impacts of CRMs Mining

5.3.1 Biome and biodiversity impacts

Figure 2 shows major overlaps with vulnerable and endangered regions of the grassland biome in the western limb of the BIC and overlaps with vulnerable regions of the Savannah Biome in the eastern limb. Unfortunately, the effects of mining are often underestimated in planning and regulation processes. Standard environmental impact assessments (EIAs) typically focus on the immediate, localised impacts of mining on biodiversity, such as vegetation loss and soil disturbance, while largely neglecting the broader, long-term consequences, such as increased poaching and the spread of invasive species.

Although mining is prevalent in South Africa's grasslands, there is limited large-scale research on the risks it poses to agriculture and ecosystems (Olivier, 2020). The grassland biome accounts for roughly 30% of the country's land area and provides essential ecosystem services, including contributions to the global water supply, carbon sequestration, and pollination (South African National Biodiversity Institute, 2018). Yet, less than 3% of this biome is formally protected (Olivier, 2020). Due to ongoing habitat loss and fragmentation, as well as anticipated future threats, South African grasslands have been classified as critically endangered (Olivier, 2020).

Climate change compounds these challenges, with rising temperatures and mining disturbances driving the encroachment of the Savanna Biome into grassland regions (Fick, 2011). Increased CO_2 levels, coupled with higher minimum temperatures, are accelerating bush encroachment, transforming grasslands into woodlands and savannas. This shift threatens the survival of grassland species, many of which are uniquely adapted to this ecosystem.

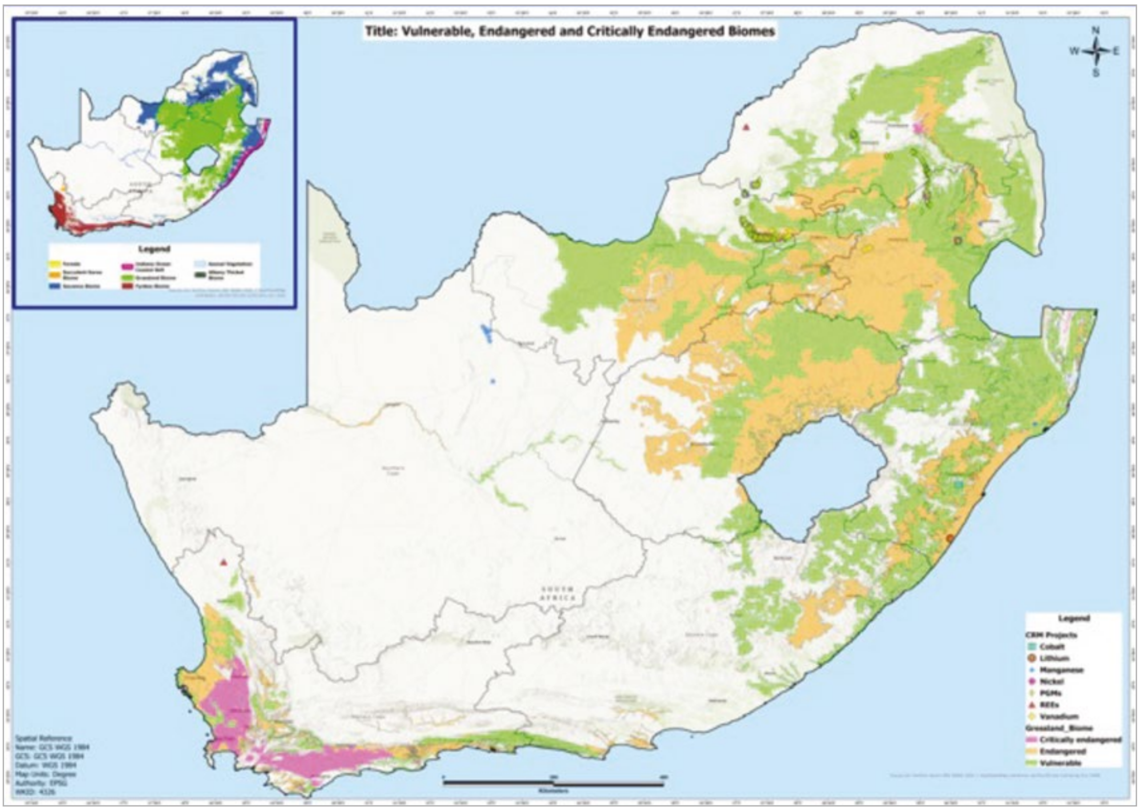


Figure 2: Map of CRMs mining facilities and threatened biomes.

5.3.2 Hydrology

Figure 3 shows CRMs mining operations in relation to South Africa's primary catchment with rivers and catchments affected by CRMs mining being highlighted. The primary impacts on hydrology can be seen in the PGMs, nickel, and vanadium clusters in the North West, Gauteng, Mpumalanga, and Limpopo provinces. Major impacts on these rivers are typified by numerous mining operations and mine settlements in the vicinity of the rivers, either directly affecting water quality and increasing pollution risk, or through the increased withdrawals of water that the operations and settlements result in. It must be noted that smaller impacts from more spatially diffuse operations have not been included in this section although we acknowledge that there are likely impacts occurring in these catchments too. Additionally, the clustered manganese mining operations of the KMF do not feature in this section due to the area's overall aridity and lack of major perennial rivers. The sub-chapters below provide a breakdown of the various rivers impacted by CRMs mining operations.

Limpopo River

Mining operations along the course of the Limpopo River in South Africa, particularly in areas rich with PGMs, manganese, nickel, and vanadium deposits, have impacted the river's ecosystem and the communities reliant on it. The ramifications of these activities extend far beyond the mines themselves, permeating the water quality, aquatic habitats, and the livelihoods of downstream populations.

One of the most pervasive issues stemming from mining in this region is the potential for pollution and acid drainage, a legacy left behind by decades of mineral extraction. The prevalence of old mines, particularly in Mpumalanga, acts as a potent source of contamination, leaching harmful substances into river systems. With approximately 1,900 mines scattered across the basin, the cumulative effect presents a challenge to the health of the Limpopo River.

Mining activity, already a significant consumer of water resources, is projected to escalate dramatically and, by 2025, it is anticipated that mining operations will demand 30% more water in this catchment system, exacerbating the strain on an already overburdened system. This surge in demand, coupled with the parallel rise in energy projects, requires judicious control of the delicate balance of water allocation in the basin. This exponential growth in demand not only threatens the availability of water for local communities but also places undue pressure on the river's ability to sustain its diverse aquatic

Olifants River

The Olifants River, which intersects regions heavily invested in mining activities, particularly in PGMs and manganese extraction, supports significant industrialisation within its boundaries. This manifests as polluted effluents, compromising both water quality and ecosystems. Urban expansion and ongoing mining operations exacerbate the strain on the river, as water is diverted to sustain mining activities and surrounding settlements, leading to reduced water levels and ecological risks.

The Steelpoort Valley, named after the Steelpoort (Tubatse) River, reflects the relationship between geography and human exploitation. Originating in the Highveld, this river, a significant tributary of the Olifants, faces the impact of industrial activities before joining the Olifants. The valley harbours economically valuable deposits of PGMs, nickel, copper, chrome, iron, and asbestos (though asbestos mines have ceased operation and have been rehabilitated). Existing mining operations and associated urban infrastructure strain the river's resources through water consumption and pollutant discharge. The prospect of new mines further threatens the river's health by increasing effluent volumes (WRC, 2011).

Analysis reveals a concerning trend of acidic mine drainage (AMD) affecting tributaries such as the Spookspruit and Klein Olifants, with degradation noted since at least 1990. Despite limited intervention, such as partial treatment of acidic seepage in the Klipspruit, water quality continues to decline.

Proposed mining expansion, exemplified by the Two Rivers Platinum mine within the B41G quaternary catchment of the Olifants Water Management Area, underscores the environmental toll of industrial ventures. The Olifants River, originating in Mpumalanga and flowing towards Mozambique, faces threats from industrial activities before joining the Limpopo River. Amidst plans for further industrialisation, including the Musina Special Economic Zone (SEZ) and Limpopo Eco-Industrial Park (LEIP), the spectre of pollution looms, with pollutants such as copper, mercury, nickel, TSS, TDS, and zinc posing risks to the catchment's ecological balance (DWS, 2016).

Crocodile River

Flowing through the platinum-rich Bushveld Igneous Complex, the Crocodile River is a vital water source for both local communities and the prevalent PGMs mining operations. As one of the most developed rivers in the country, it bears significant human influence, particularly evident in its stretch through northern Johannesburg and Pretoria. Downstream of Hartbeespoort Dam, extensive irrigation occurs, while north of the Magaliesberg, large mining developments occur. However, this human activity has sparked concern among local citrus farmers and environmentalists. They fear that the dewatering activities of mines, particularly between Brits and Rustenburg, are depleting groundwater, their primary water source. Investigating the Crocodile River offers insights into the cumulative impacts of mining on water resources and ecosystems, highlighting the intricate balance between human development and environmental preservation.

Vaal River

The Vaal River has borne the weight of various mining activities and it remains a crucial water source for South Africa's industrial, agricultural, and domestic needs. These operations have continually strained the river's resources, with withdrawals to sustain mines and their associated settlements often leading to diminished water levels, jeopardising ecological integrity.

Emerging mines along the Tshwane–Rustenburg–Sun City axis, primarily driven by the escalating demand for platinum, have seen a surge in activity. However, the spectre of the "sunset clause" in the past Mining Bill played a significant role in this expansion. This clause, enacted at a specified time point, mandated that mining rights holders either utilise their rights or risk forfeiture. Consequently, there was a rush to exploit the region's resources before this deadline.

This rapid proliferation of mining activities catalysed substantial economic growth in the Rustenburg area. Consequently, there was an increased demand for both bulk and treated water, prompting mines to seek assistance from entities like Rand Water to meet their water requirements, further exacerbating the strain on the already overburdened Vaal River System.

5.4 Pollution and Contamination Risks

5.4.1 Chemical Pollution

Chemical pollution associated with CRMs mining in South Africa, particularly in platinum extraction, poses significant environmental and human health risks. This form of pollution primarily stems from the utilisation of hazardous chemicals such as cyanide and sulfuric acid in the mining and processing operations. Improper handling and disposal practices exacerbate the potential for soil and water contamination, thereby endangering ecosystems and human populations.

Cyanide, a commonly employed chemical in platinum extraction processes, poses a substantial threat to water sources due to its high toxicity. Accidental spills, leaks, or leaching from mine sites can result in the widespread pollution of nearby water bodies, endangering aquatic life and compromising the integrity of ecosystems. The utilisation of sulfuric acid in the mineral separation process further compounds the risk of chemical pollution, particularly through its potential to contaminate soil and water systems.

Furthermore, mining activities generate substantial volumes of waste materials laden with harmful and hazardous heavy metals (HMs), alongside noble metals. These HMs, when present in concentrations exceeding threshold levels, exert detrimental effects on both flora and fauna, including aquatic organisms. The long-term accumulation of these pollutants within ecosystems disrupts biogeochemical cycling processes and imposes a burden on environmental health.

The toxicity of these pollutant HMs disrupts the balance of essential nutritive elements within host plants, leading to damage and susceptibility to various diseases. Notably, trace amounts of toxic HMs such as cadmium pose significant health risks to exposed individuals. Therefore, harmful HMs above threshold levels in the environment contributes to environmental pollution and precipitates severe health complications for both human and animal populations.

Moreover, the mining and processing activities associated with platinum extraction result in the contamination of surrounding environments with a spectrum of metals, including chromium, copper, and nickel. Atmospheric deposition, wastewater discharge, and surface runoff serve as conduits for the dispersal of these contaminants, further exacerbating environmental pollution.

5.4.2 Land Pollution

Land pollution resulting from CRMs mining in South Africa poses significant environmental and socio-economic challenges. Beyond the immediate loss of land, which disrupts agricultural practices and jeopardises livelihoods, the encroachment of mining activities introduces hazardous pollutants into the surrounding environment, directly impacting nearby communities.

Contaminated soil near extraction sites becomes a repository for a plethora of waste materials, leading to soil degradation and erosion. CRMs, particularly PGMs, are often found in sediment fractions, with concentrations reported to be exponentially higher in mining areas compared to natural levels in the Earth's crust. For instance, platinum (Pt) concentrations in topsoil near smelters can be alarmingly elevated, reaching levels that are several orders of magnitude higher than background concentrations. This drastic increase in metal concentrations significantly alters the ecotoxicology of the affected environment, posing long-term risks to both terrestrial and aquatic ecosystems.

Land clearing associated with mining activities further exacerbates environmental degradation, leading to the loss of biodiversity and fragmentation of habitats. Moreover, the management of solid waste generated during mining operations presents a considerable challenge. The extraction of common minerals entails the handling of vast amounts of waste rock and tailings, necessitating meticulous planning and active management to mitigate adverse environmental and social impacts.

Tailings, the residual solid waste remaining after metal extraction, and waste rock, excavated during mining but devoid of economic metals, are two primary sources of environmental pollution. Their mismanagement can lead to catastrophic events such as tailings dam failures, as evidenced by historical disasters like the 1974 Bafokeng tailings disaster. Furthermore, the release of acidic mine drainage and other pollutants from these waste materials can contaminate land and water resources, posing serious health risks to local communities.

The environmental and health consequences stemming from solid waste pollution are keenly felt by mining communities, underscoring the urgent need for sustainable mining practices and robust regulatory frameworks. Addressing land pollution in CRMs mining requires a multifaceted approach encompassing effective waste management strategies, stringent environmental regulations, and proactive community engagement.

5.4.3 Water Scarcity, Pollution and Acid Mine Drainage

South Africa faces a major challenge with water scarcity, especially in regions critical for green hydrogen production. Producing green hydrogen requires significant amounts of freshwater, and around 85% of global green hydrogen projects for 2040 are planned in water-stressed areas (Stancioff, 2022). South Africa is projected to need the equivalent of 13,680 Olympic-sized swimming pools per year by 2050 (Groundwork, 2024). To address this, many projects will rely on desalination, which significantly increases costs. In South Africa, this issue is particularly important in platinum mining areas, where the rising demand for platinum used in green hydrogen technology could worsen water scarcity for local communities (Stancioff, 2022).

CRMs mining in South Africa poses significant risks of water pollution and contamination, primarily due to the environmental impact of solid waste generated during mining activities. One major concern is the release of pollutants from tailings and waste rock, which can have detrimental effects on both the environment and human health.

Environmental pollution stemming from solid waste from tailings and waste rock are felt by mining communities, both in terms of damage to land and water, as well as resulting health consequences. Water damage can come from AMD, which causes trace metals to leach out from the waste and into the water. AMD occurs when sulphide minerals in the waste are exposed to air and water, producing sulfuric acid. This acid is then carried from the mine through surface drainage or rainwater and deposited into local streams, lakes, rivers, and groundwater, severely damaging water quality.

The consequences of AMD can persist for extended periods, potentially lasting hundreds of years. This sustained contamination poses a significant threat to ecosystems and human populations relying on affected water sources for drinking, irrigation, and other essential purposes. Additionally, the presence of elevated levels of HMs such as lead, arsenic, and cadmium in water bodies can have severe health impacts on both aquatic life and humans, including neurological damage, cancer, and developmental disorders.

Furthermore, the discharge of untreated mine wastewater into surrounding water bodies can exacerbate the pollution problem, leading to further degradation of water quality and ecosystem health. Inadequate containment and management of mine waste can result in the release of harmful substances into the environment, posing ongoing risks to local communities and ecosystems.

5.4.4 Air Pollution

The extraction and processing of CRMs in South Africa pose significant challenges due to their consequential impact on air quality, primarily attributed to surface mining practices. Particulate matter, a ubiquitous by-product of various mining operations such as drilling, hauling, loading, and waste handling, represents a substantial fraction of airborne pollutants. These fine particulates, characterised by their high dispersibility and buoyancy, exhibit extensive transportability, disseminating over large distances and engendering widespread contamination.

The small size of these particulates exacerbates control efforts, particularly evident in filtration systems. Despite the initial deployment of drying processes and filters, the efficacy of such measures is compromised due to the obstruction of filters by fine particles, leading to heightened dust emissions and subsequent atmospheric pollution. Moreover, the occurrence of furnace blow-backs, precipitated by steam generation within furnaces, further compounds the atmospheric burden, augmenting hazardous emissions and deteriorating air quality.

In addition to particulate matter, emissions of sulphur dioxide and nitrogen oxides, inherent to CRMs extraction and processing, significantly contribute to atmospheric pollution. This pollution disproportionately impacts regions with elevated mining activity, precipitating adverse effects on respiratory health and exacerbating respiratory ailments like asthma. The reliance on fossil fuels for energy exacerbates this predicament, amplifying GHG emissions and exacerbating air quality degradation.

HMs represent another significant concern, with wind action facilitating their dispersion into the atmosphere. Emissions from mining activities, including wind-blown dust, material handling, and vehicular traffic, serve as primary sources of atmospheric HM pollution. The fine particulate fraction, particularly those with a diameter below 1 μm, poses acute health risks and accentuates atmospheric pollution.

The nebulous nature of fugitive dust, emanating from indeterminate sources, poses formidable challenges in pollution control. These elusive dust clouds evade conventional control measures, perpetuating their deleterious impact on air quality. The resultant haze induces diverse ecological repercussions, including damage to vegetation, agriculture, and adverse health effects on both livestock and human populations.

5.4.5 Health Risks of Mine Pollution and Contamination

With approximately 1.6 million individuals dwelling in informal and formal settlements situated on or in close proximity to mine dumps, the adverse health effects of pollution emanating from mining activities are of paramount concern, especially given that these communities often comprise historically disadvantaged and economically marginalised populations.

PGMs mines, prevalent in South Africa, are notorious for emitting high levels of hazardous substances such as carbon dioxide, sulphur dioxide, and dust particles. Sulphur dioxide emissions, in particular, pose a myriad of health hazards. Studies have established a direct correlation between exposure to sulphur dioxide and various respiratory ailments, including decreased lung function, respiratory illness, and alterations in pulmonary defences. Furthermore, individuals with pre-existing cardiovascular conditions face an elevated risk of exacerbation, while susceptibility to cardiovascular diseases and chronic lung disorders is heightened, particularly among vulnerable demographics such as children, the elderly, and individuals with asthma.

Moreover, particulate matter, categorised into PM10 and the more health damaging PM2.5, further compounds health risks associated with mining pollution. PM2.5, due to its smaller size, can penetrate deeper into the respiratory system, causing substantial damage to lung tissue and significantly increasing the likelihood of respiratory problems, cancer, and premature mortality. Vulnerable populations, including the elderly, children, and individuals with pre-existing chronic lung diseases or conditions such as asthma, are particularly susceptible to the adverse effects of particulate matter exposure.

It is imperative to recognise that there is no safe threshold for exposure to sulphur dioxide or particulate matter. Even at relatively low concentrations, these pollutants can have deleterious effects on human health, underscoring the urgent need for stringent regulatory measures and comprehensive mitigation strategies to safeguard the well-being of communities residing in proximity to mining operations.

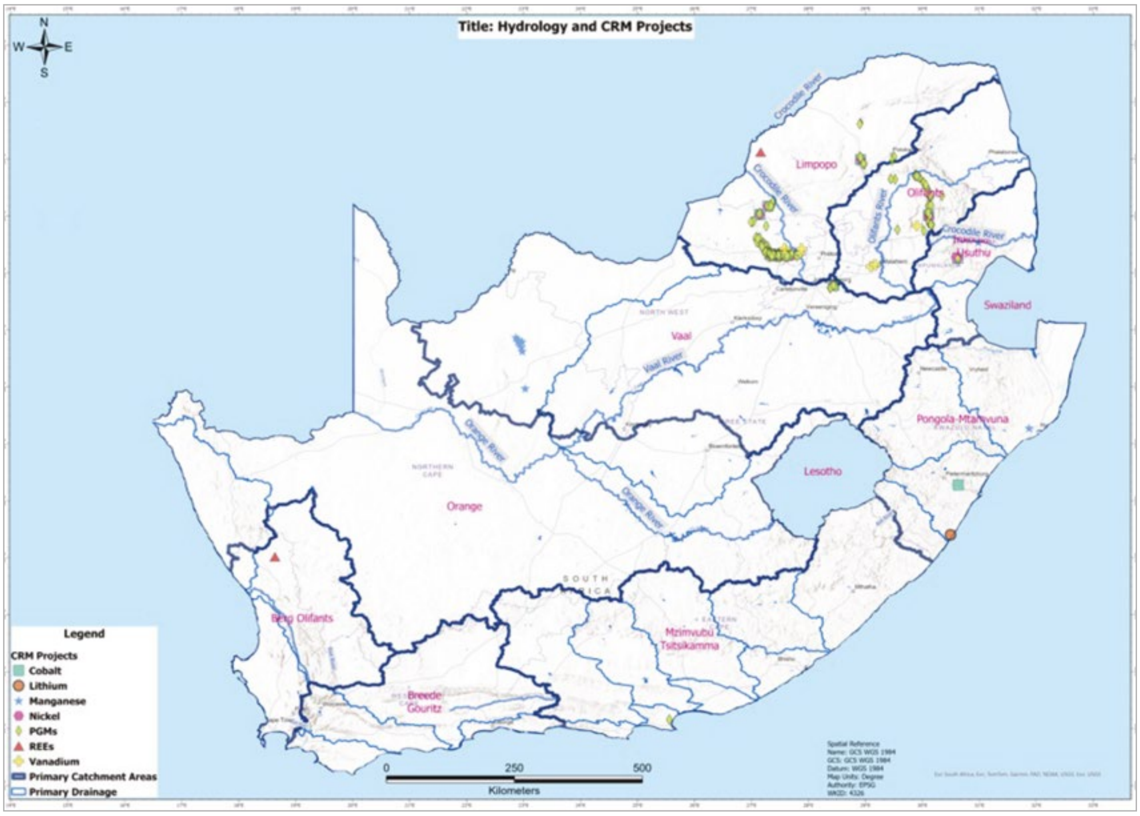


Figure 3: Primary catchments (names shown in pink) and CRM mining affected rivers in South Africa

5.5 Infrastructure Interactions

The following section displays the maps of existing infrastructure, including rail, power, and road infrastructure. Due to issues around the neglect of infrastructure maintenance in various areas around the country, it is important to note that the infrastructure depicted may not be fully functional and potentially in a state of disrepair that makes it functionally inefficient or unusable. This will be discussed further below.

Figure 4 illustrates the localities of CRMs projects and their relationship with renewable energy projects. The renewable energy-related CRMs in South Africa are cobalt, lithium, manganese, nickel, PGMs, REEs, and vanadium. PGMs are concentrated along the northeastern parts of South Africa, in the North West, Limpopo, Gauteng, and Mpumalanga provinces. Associated with the PGMs in the aforementioned provinces are vanadium projects. The KwaZulu-Natal, Free State, and Northern Cape provinces have fewer PGM projects. The Northern Cape is dominated by manganese projects; it has minor lithium, nickel, and REE projects. REE projects are in located in the Western Cape. Cobalt is sparse and located in the KwaZulu-Natal, Mpumalanga, Limpopo, and North West provinces.

Renewable energy (RE) projects are distributed nationally. The most abundant RE projects in South Africa are wind and photovoltaic projects. Wind energy projects are located along the coastal areas of South Africa, in the Western Cape, Eastern Cape, and Northern Cape, while photovoltaic projects are in the central parts of South Africa, in the Northern Cape, KwaZulu-Natal, North West, and Limpopo provinces. Concentrated solar power (CSP) and solar energy projects are in the Northern Cape province and petroleum projects are located in the Limpopo and Mpumalanga provinces.

The onboarding of renewable energy projects in South Africa is heavily constrained by the country's aging and limited grid capacity. The 2024 South African Renewable Energy Grid Survey revealed a planned 133 GW of renewable energy capacity at various stages of development, but integrating this capacity into the grid remains a significant challenge due to infrastructure limitations (Green Building Africa, 2024). Grid constraints have also directly impacted procurement processes, as seen in the seventh renewables bid window, where delays and uncertainties arose from insufficient transmission infrastructure (Engineering News, 2024). These challenges are particularly pronounced in areas with high renewable energy potential, such as the Northern Cape, where the grid struggles to accommodate additional capacity. To meet its renewable energy and decarbonisation targets, South Africa requires urgent investment in grid upgrades and expansions to support the growing demand for renewable integration.

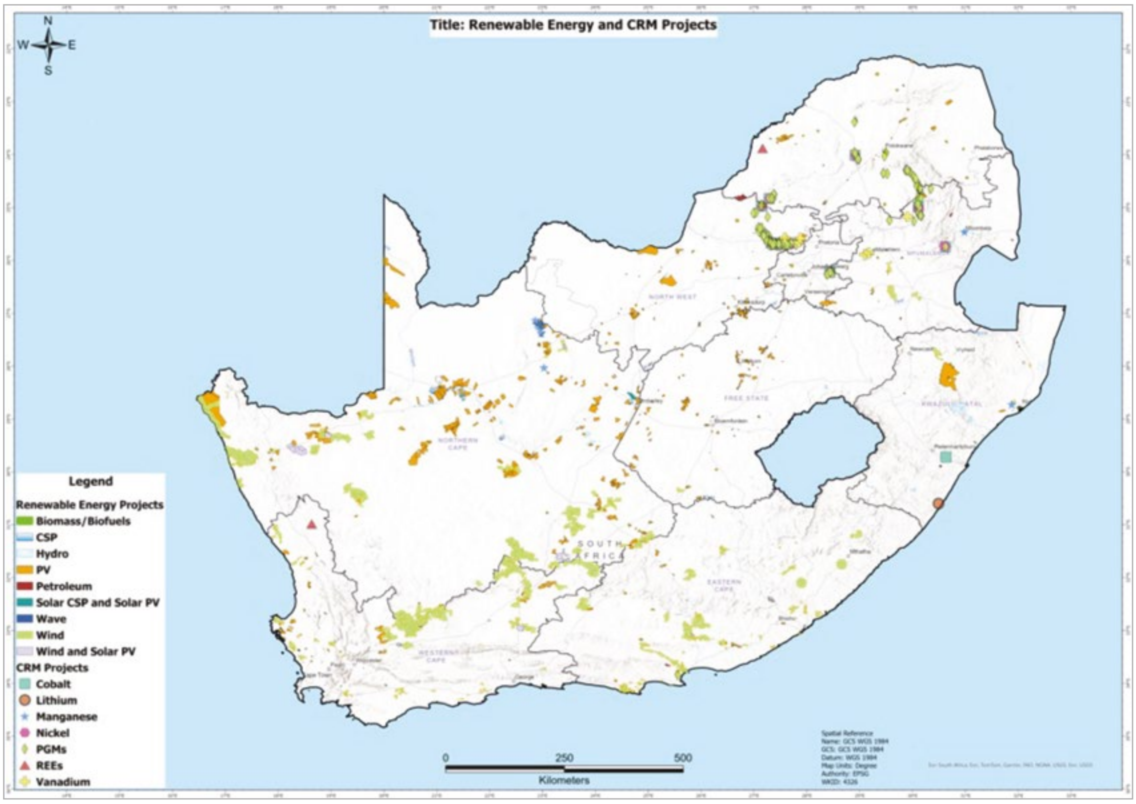


Figure 4: Renewable energy project applications as of Q3 2023

Figure 5 shows the locations of the national power grid and CRMs localities. The main transmission lines connect different provinces and within each province are high voltage lines connecting different communities. Approximately 42,000 MW of South Africa's electricity is generated by coal-fired power stations and approximately 95% of the electricity is generated by the state-owned and vertically integrated power company, Eskom. South Africa has several power stations with some generating over 1,000 MW and others having power generation capacities between 10 to 1,000 MW. Their substations are located in remote areas. Approximately 22,000 volts (22 kV) is the voltage at which the majority of Eskom's power plants produce electricity. Power lines are used to carry electricity from the power plants. Hence, high voltages are used to deliver electricity to customers, compensating for losses that occur over long distances and reducing the need for additional power lines. Typically, transmission towers are used to suspend overhead conductors for transmission lines. Underground cables are utilised in place of overhead wires in many urban locations. The overhead power lines carry electricity at voltages between 22 and 765 kV, as depicted in the diagram. Eskom has successfully run 765 kV transmission lines at high altitudes above sea level. Steel and aluminium are combined to create conductors in a variety of forms and dimensions. Bulk supplies of electricity at 22 kV are collected for primary distribution to towns and industrial areas, clusters of villages, farms, and similar concentrations of consumers when the electricity arrives at a distribution station. Transformers in the intermediate substations receive the electricity from lines and lower the voltage to 11 kV. The power is transmitted into the areas that need to be supplied via secondary distribution lines that emanate from these substations and end at distribution substations. Electricity generated at power stations is used as generated.

To attract renewable energy into the country, an independent power producer programme, the Renewable Energy Independent Power Producer Procurement (REIPPP) programme, has been introduced. South Africa has ongoing power outages referred to as “load-shedding”. It has developed non-hydro renewables with 8.7 GW of renewable energy planned to be installed between 2023 and 2032.

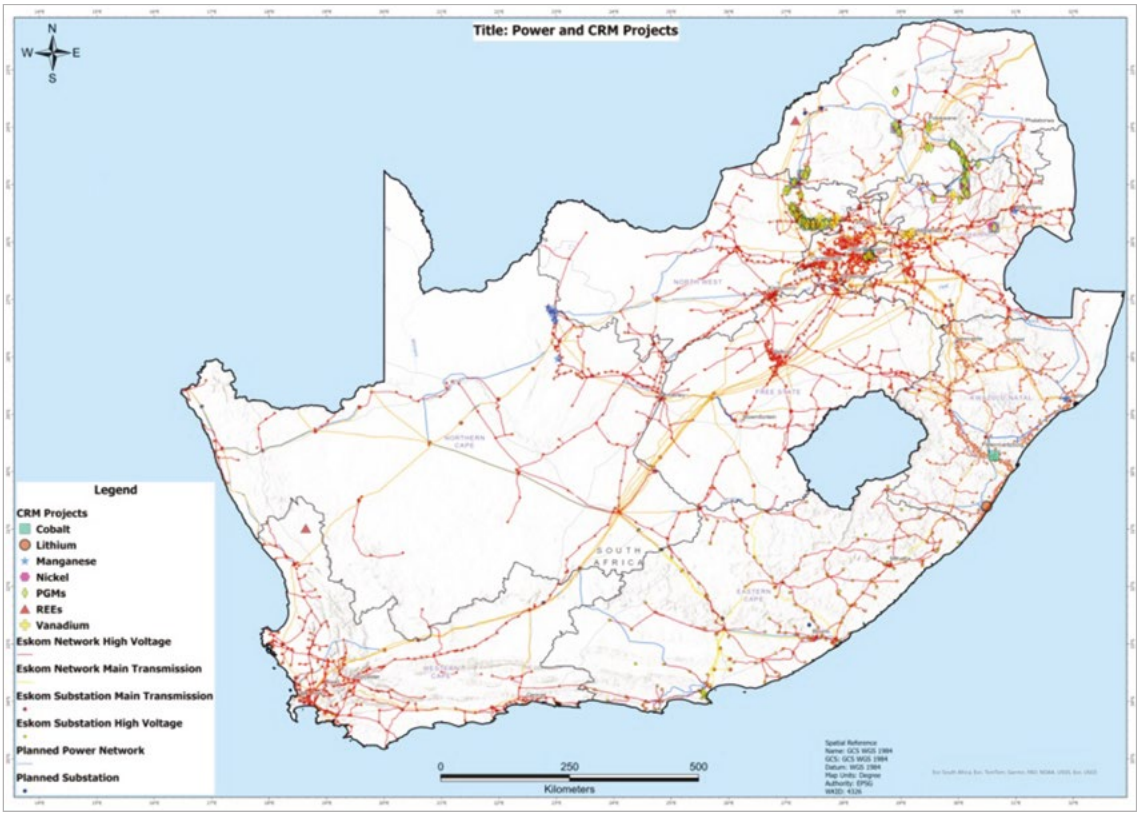


Figure 5: Power line network across South Africa

South Africa has a well-developed road network with several freeways, trunk highways, national roads, and regional roads. The road infrastructure overlaps with several development corridors, namely: the Maputo Development Corridor, North–South Corridor, and Trans-Oranje Corridor (Figure 6). The Maputo Development Corridor connects the northeastern provinces of South Africa to the port of Mozambique. It runs through industrialised Southern African regions and includes several road projects, including the N4 national highway. The South Africa corridor road links ports in Durban and Cape Town to Gauteng. It includes the N1 (Cape Town to Beit Bridge), N2 (Cape Town to Ermelo), and N3 (Cape Town to Johannesburg) national highways. In terms of road infrastructure development, the road network logically mirrors the population density of the country: the Northern Cape has fewer roads while Gauteng has the densest road network. South Africa's road network faces significant challenges, with approximately 80% of national roads and 40% of provincial roads exceeding their intended 20-year design lifespan as of 2022 (BusinessTech, 2022; Engineering News, 2022). A substantial maintenance and rehabilitation backlog exists, and although funding for road infrastructure has increased, the allocated resources remain insufficient to address these issues comprehensively within the next five to ten years.

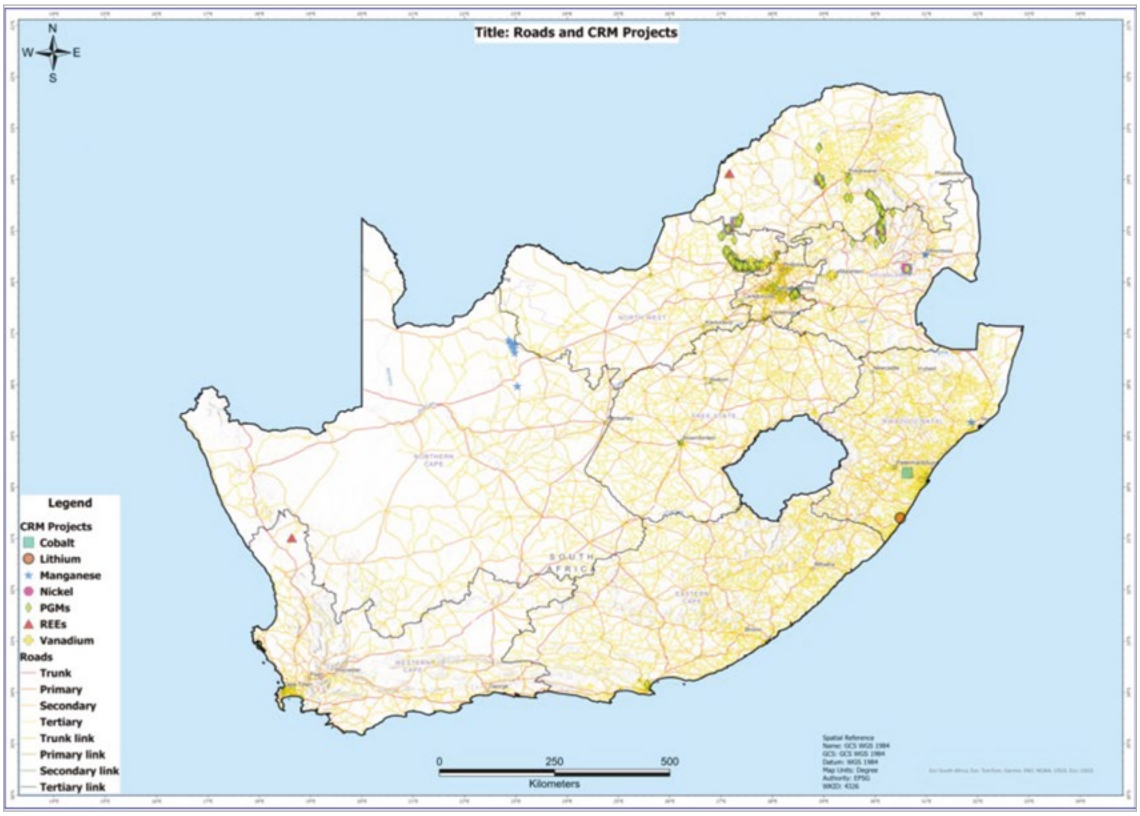


Figure 6: Road networks in South Africa

Figure 7 shows South Africa's rail network. In South Africa, the state-owned enterprise, Transnet Freight Rail (TFR), is the main operator of freight services. It manages South Africa's bulk cargo transport. TFR unveiled a new operating model that will decentralise important duties to guarantee a more adaptable rail freight network that is better suited to support South Africa's economy. TFR integrates its operations with Transnet ports, port terminals, pipelines, and rail engineering facilities in addition to operating a railway that is both vertically integrated and commercially separated. As such, rail freight corridors have been developed which include the North–South Railway Corridor (operational) and the Trans-Oranje railway (which is currently being upgraded). The Trans-Oranje railway is operated by the Walvis Bay Corridor Group and will link the ports of Walvis Bay and Lüderitz in Namibia through the Northern Cape Province to Johannesburg, while the North–South Railway Corridor has railways linking Durban (South Africa), Zimbabwe, Botswana, the DRC, and Zambia.

South Africa's rail network faces critical challenges due to decades of underinvestment, with the average fleet age between 30 and 40 years, nearing or exceeding its 46-year maximum lifespan (Daily Maverick, 2023). Vandalism and theft, particularly targeting copper cables, remain major obstacles, with PRASA reporting that 97% of its 2023 security-related incidents involved theft and vandalism (Wired, 2023). These issues have severely disrupted operations, including freight services, while delays in rolling stock availability further compound the challenges (Reuters, 2024). However, efforts to restore and modernize the network are underway, with PRASA having rehabilitated over 80% of railway lines by late 2023 and aiming for full recovery by the 2027–28 financial year (Citizen, 2023). Additionally, the government has committed R900 billion to rail infrastructure upgrades by 2027 to address these systemic issues and improve performance (Reuters, 2024).

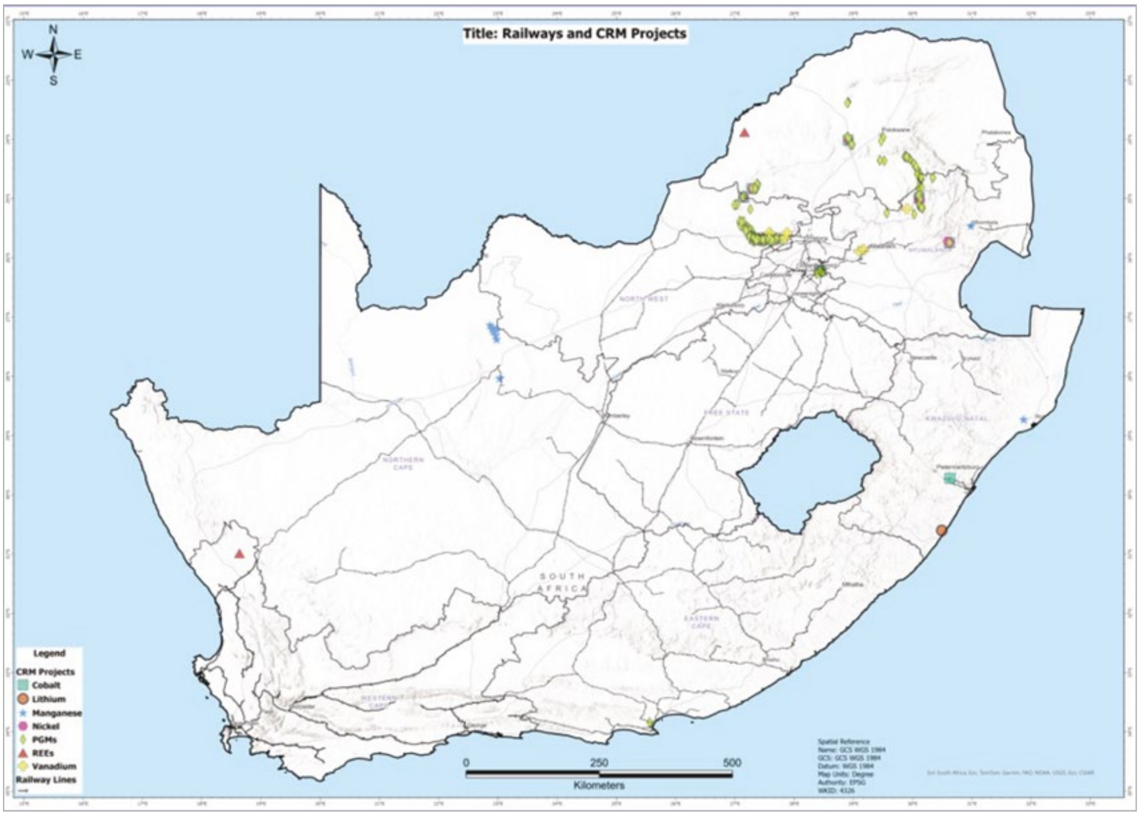


Figure 7: Railway network in South Africa

5.6 Community Interactions/Social Interactions

The socioeconomic impacts of mining certainly vary, as those most affected by mining tend to live and work in communities closer to mine sites (Bury, 2004). However, pinpointing these impacts in specific locations using GIS can be challenging. Despite a growing body of literature on the socioeconomic effects of mining, it often fails to address these impacts in spatial terms. This gap in understanding the spatial aspects of mining's social implications makes it hard to gather relevant spatial data on how mining affects communities and individuals. This difficulty arises because most studies on social impacts are qualitative, and translating this qualitative data into spatial visualisations presents challenges.

As a result, researchers often resort to using statistical data, such as demographic information tied to specific locations, to provide a broader context for analysing social processes (Lechner *et al*., 2018). They use maps and other visual tools to examine patterns and trends in these processes. While qualitative GIS methods hold promise for understanding the spatial dimensions of mining's impacts, publicly available datasets, like census data, are typically collected at large scale and are often aggregated, making it challenging to discern clear trends, especially at national level.

To overcome this limitation, it is valuable to explore available data while recognising that mining impacts can be inferred not only from census data but also from their effects on the socio-ecological environment. The socio-ecological environment refers to the intricate relationship between human societies and the natural world, encompassing the interactions between social and ecological systems. People rely on nature for their livelihoods, finding sustenance in activities like agriculture, forestry, and fishing. Nature also contributes significantly to human wellbeing, offering clean air, water, and recreational spaces like parks and forests. Moreover, biodiversity and ecosystem services play crucial roles in maintaining human health by regulating air and water quality and providing medicinal resources.

5.6.1 Biosphere reserves

Figure 8 shows the distribution of South African biosphere reserves and CRMs mining operations. In this figure, it is evident that there are several areas of overlap between biosphere reserves and mining operations in the northwestern portion of the country. We see that there is significant overlap of CRMs mines with the Magaliesberg Biosphere Reserve, and there is also slight overlap with the Kruger to Canyons and Vhembe Biosphere reserves.

Biosphere reserves, recognised internationally by UNESCO within the Man and the Biosphere (MaB) Programme, epitomise the pursuit of a harmonious relationship between humanity and the environment. This programme, operating at the intersection of natural and social sciences, is dedicated to fostering sustainable practices for biodiversity conservation and promoting a holistic understanding of environmental dynamics on a global scale. Central to the MaB Programme is the ethos of interdisciplinary collaboration, aimed at advancing knowledge, demonstrating best practices, and providing training in natural resource management. By facilitating scientific engagement in policy formulation, the programme endeavours to ensure the judicious utilisation of biological diversity while nurturing a deeper comprehension of environmental complexities. The genesis of the biosphere reserve concept can be traced back to the imperative of addressing the dual challenge of conserving planetary biodiversity and meeting the escalating material demands of a growing human populace.

However, this endeavour to reconcile conservation with human needs often confronts complexities, particularly evident in the realm of land use. Land-use conflicts, ubiquitous in settings where land serves multifarious purposes, assume heightened significance in ecologically sensitive zones such as biosphere reserves, endowed with cultural significance under the MaB programme.

The biosphere reserve framework delineates three distinct zones, each serving specific functions in the conservation and sustainable utilisation of natural resources. The Core Zone, characterised by stringent protection measures aligned with defined conservation objectives, comprises pristine or minimally disturbed ecosystems. Crucially, these core areas, singular or multiple, must collectively possess sufficient size and ecological integrity to serve as effective conservation units and benchmarks for long-term biospheric monitoring.

Surrounding the Core Zone is the Buffer Zone, delineated with precision to complement the core areas and often constituting a single administrative unit. Functionally diverse, the buffer zone accommodates activities ranging from conservation and research to environmental education, tourism, and recreation, all aimed at supporting the overarching goals of the biosphere reserve.

Extending beyond the Buffer Zone, the Transition Zone primarily serves developmental functions within the reserve, representing areas where human activities intersect with conservation imperatives. This tripartite zoning strategy underpins the sustainable management and stewardship of biosphere reserves, embodying the ethos of coexistence between human society and the natural environment within the framework of the MaB Programme.

Magaliesberg Biosphere Reserve

Biosphere reserves, as previously mentioned, are partitioned into three distinct zones, with the Transition Zone primarily earmarked for commercial and developmental endeavours, notably including mining operations. Consequently, within the vicinity of this biosphere reserve, numerous mining enterprises are operational, notably observed in a parallel swath of land situated on the northern periphery of the Magaliesberg Mountain Range, spanning the region between Tshwane and Sun City. Here, extensive mining undertakings, encompassing both open-cast and subterranean activities, primarily target the extraction of PGMs.

Reports from the Department of Water and Sanitation (DWS) in 2004 highlighted extensive land degradation near the Magaliesberg Biosphere Reserve due to mining activities. This degradation not only affects the appearance of the area but also poses threats to natural ecosystems and agriculture.

A major challenge in this area also includes the interactions between surface and groundwater. There is disagreement among water resource planners regarding the availability of water, with some arguing that much of the recharge comes from springs rather than surface streamflow. Farmers have also raised concerns about groundwater depletion due to mining activities north of the Magaliesberg Mountain Range.

Vhembe Biosphere Reserve

Figure 8 shows that there are several mining operations (specifically platinum mines) located close to the Vhembe Biosphere Reserve. The South African Government approved a right for a platinum mine in the Vhembe Biosphere Reserve, despite objections from a farming community of 500 whose homes are located on the mineral deposits. Concerns about potential degradation of land and livelihood disruptions become a pertinent aspect of mining.

Kruger to Canyon

Mining emerges as a notable industry within the Kruger to Canyon area, exhibiting a spectrum from small-scale subsistence operations to large-scale open-cast industrial mining. With an abundance of mineral resources, the region boasts a lengthy history of mining activity, yielding minerals such as gold in the Pilgrims Rest area and copper in the Phalaborwa area, alongside others like phosphate, andalusite, and mica. However, the exploitation of these resources has engendered significant environmental repercussions, notably evidenced in the strain on river systems due to heavy water abstraction, effluent discharge, and riparian zone degradation.

To address these impacts, mining operations are legally mandated to institute an environmental management plan/programme, delineating strategies for rehabilitation and closure. Within the Kruger to Canyon Biosphere, Palabora Mine is the largest operational open-cast mine in Southern Africa, situated in the northern expanse of the biosphere reserve. While smaller mines punctuate the surrounding areas, none rival Palabora Mine in scale. Operations such as the Bokoni Platinum Mine, situated close to the reserve, may exert influences on surrounding vegetation and water resources.

Despite occupying less than 5% of the total land surface within the biosphere reserve, the environmental consequences of mining activities can be locally severe. While the Palabora Mine's operations are anticipated to endure for at least another two decades, its eventual closure could portend significant repercussions for the regional social–ecological system. The cessation of mining activities may precipitate the emergence of 'new poverty' within the communities reliant on mining, potentially exacerbating dependence on rural resource economies. This transition could adversely impact settlement dynamics, communal land relations, and regional land cover.

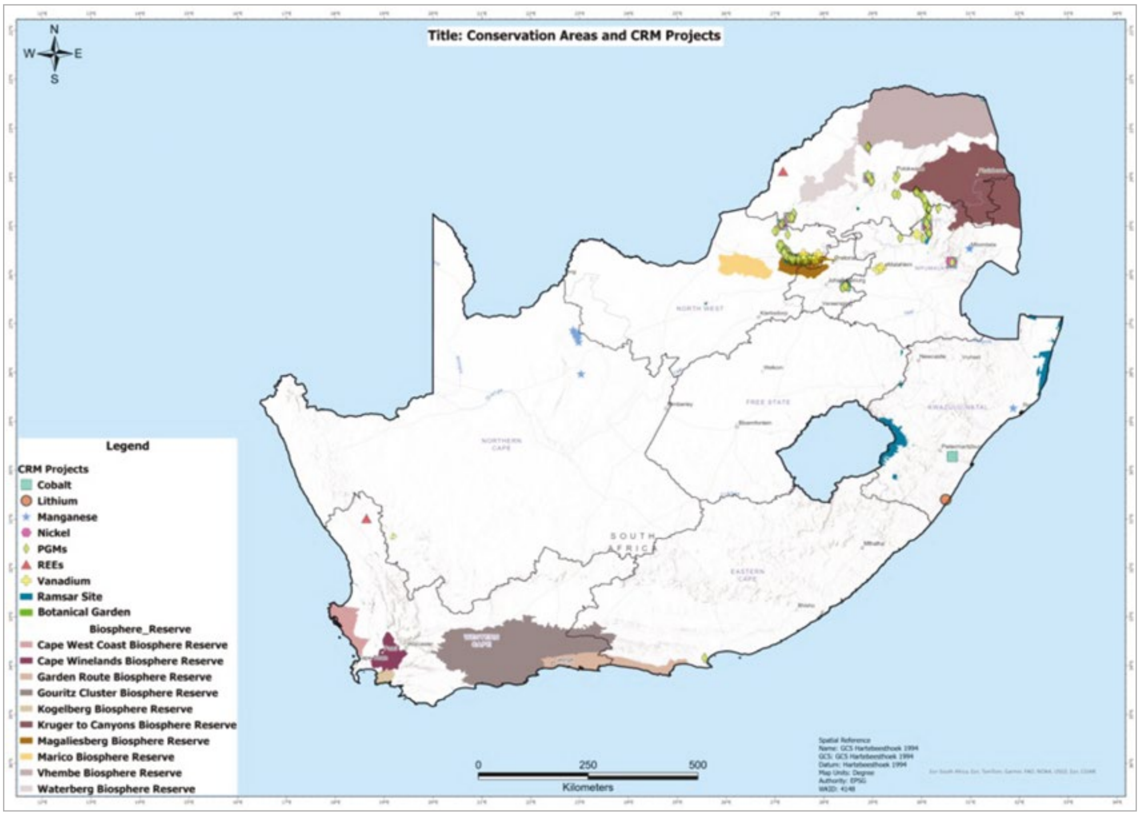


Figure 8: The spatial distribution of South African biosphere reserves alongside CRMs mining operations

5.6.2 Fossil Hominid Sites of South Africa (UNESCO World Heritage site)

Figure 9 depicts the various types of protected areas in South Africa. As seen on the map, one major area of overlap with these protected areas are found at various Fossil Hominid UNESCO World Heritage sites. There are several platinum mines in proximity to some of the fossil hominid heritage sites, including major mines such as the Marikana platinum mine. This juxtaposition of mining activities with sites of significant paleoanthropological importance often raises concerns about potential impacts on the environment, including water pollution and habitat destruction, as well as on the preservation of cultural and historical heritage. Striking a balance between economic development through mining and the conservation of natural and cultural heritage is a complex challenge faced by stakeholders in the region.

The fossil hominid heritage sites in South Africa bear profound social significance, serving as repositories of shared human ancestry. These sites, exemplified by the Cradle of Humankind and Sterkfontein, represent veritable portals into human evolutionary past, affording invaluable insights into the behaviours, lifestyles, and habitats of our ancient progenitors. Beyond their scientific import, these locales engender a sense of collective identity and pride, highlighting Africa's seminal role in the narrative of human evolution. They serve as educational bastions, igniting curiosity and fostering comprehension regarding our evolutionary trajectory among local communities and global visitors alike. Preservation and commemoration of these heritage sites transcend mere historical reverence; they are endeavours aimed at augmenting our contemporary comprehension of humanity and nurturing a profound appreciation for our interconnectedness across temporal and spatial dimensions.

In response to concerns raised by various stakeholders, the World Heritage Centre requested a study in January 2011 to assess the potential threat posed by effluent from abandoned and active mines to the World Heritage property. The study's findings highlight varying degrees of hydro-vulnerability among the cave sites, with some considered to be at minimal risk while others exhibit high vulnerability. Although the Sterkfontein caves are highly vulnerable, long-term geochemical studies suggest a mitigated impact on groundwater.

Nevertheless, the study underscores the necessity of sustained long-term monitoring and management of mine water. It concludes that natural treatment of AMD through neutralisation with dolomites is not a practical solution, emphasising the imperative to manage the risk of dewatering effectively.

It is clear from the above that CRMs mining has potentially significant impacts on the natural environment and the communities that are supported by it. The cases illustrated in the maps of this section show the areas where significant expansion of CRMs mining might impact the natural environment and communities disproportionately if not managed judiciously.

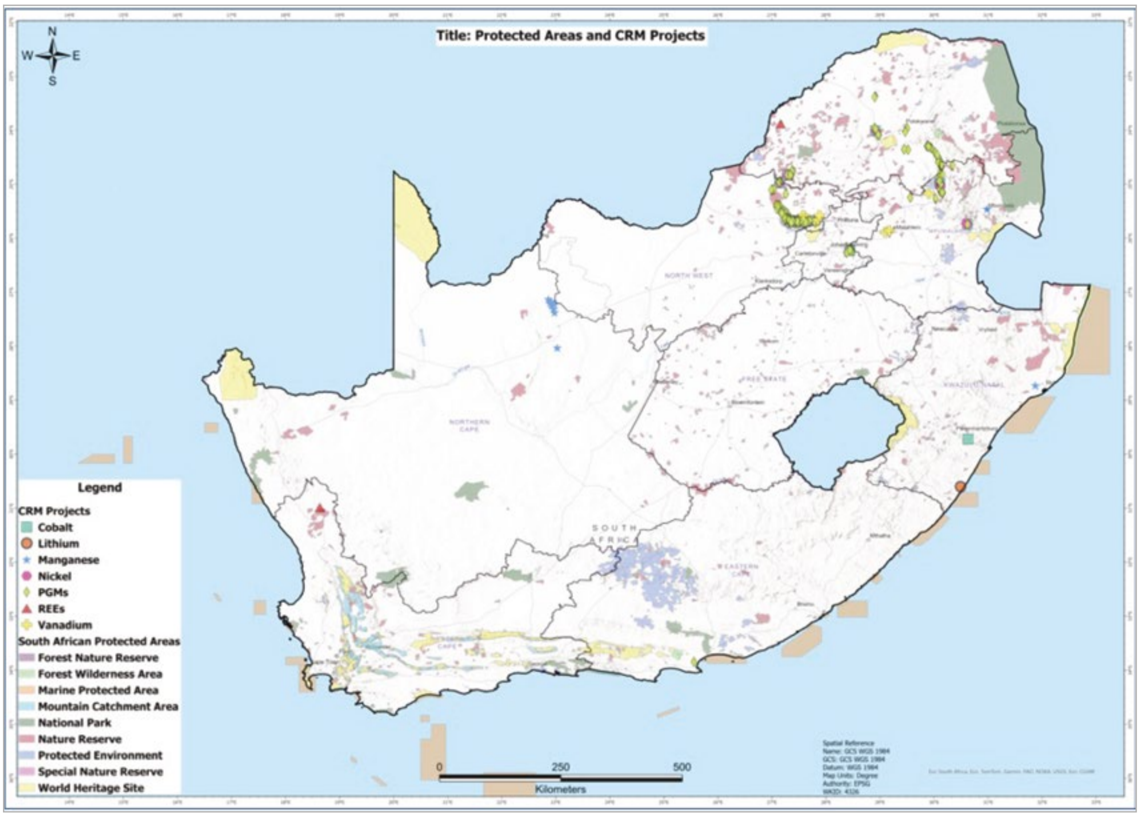
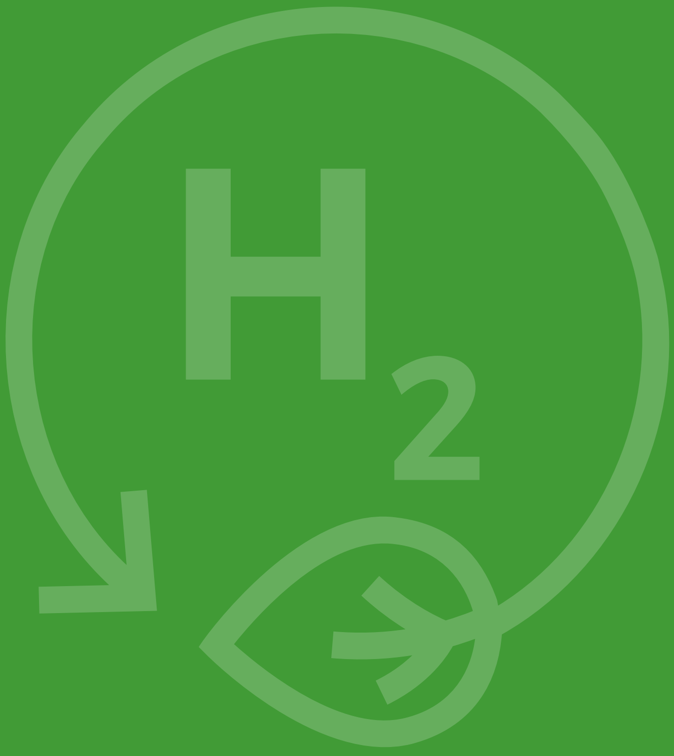


Figure 9: Distribution of protected areas in relation to CRMs projects

Chapter 6

CRMs Scenario Analysis and Risk Assessment



6. CRMs Scenario Analysis and Risk Assessment

According to new research, the global demand for CMRs is set to rise as the green hydrogen economy grows. The European Union (EU) has an ambitious goal of becoming the first climate-neutral continent by 2050. Renewable electricity generation will play a key role in reducing CO_2 emissions as it now accounts for almost a third of total electricity generation in the EU. Green hydrogen, produced by electrolysing water using renewable electricity, is a promising way to decarbonize a range of energy-intensive industries, along with energy storage, power to gas, and shipping. Thus, the global demand for CRM, including different types of renewable energy sources, is expected to increase in the coming years to produce the desired amount of green hydrogen. In the CRMs and hydrogen report published by the European Commission, two scenarios of renewable energy sources in producing green hydrogen have been derived from the integrated national energy and climate plans and the EU's long-term strategy.

In both scenarios, the total amount of electricity consumed in electrolysers significantly increases, leading to much higher levels of renewable energy being deployed solely for the purpose of hydrogen production. In the first scenario, renewable energy generation capacities are assumed to be dedicated to the electrolysers (i.e., actual generation is higher to account for capacity factors). This totals approximately 600 TWh, while in the second scenario, it is assumed that it is dedicated to actual renewable electricity generation, which totals approximately 700 TWh. This is a substantial increase compared to the estimation of 295 TWh of renewable energy consumed in 2019. The increased demand for CRMs in renewable energy largely hinges on solar and wind power technologies, which are the primary sources of renewable energy due to their low cost compared to other technologies and abundance of resources in the EU (Figure 10).

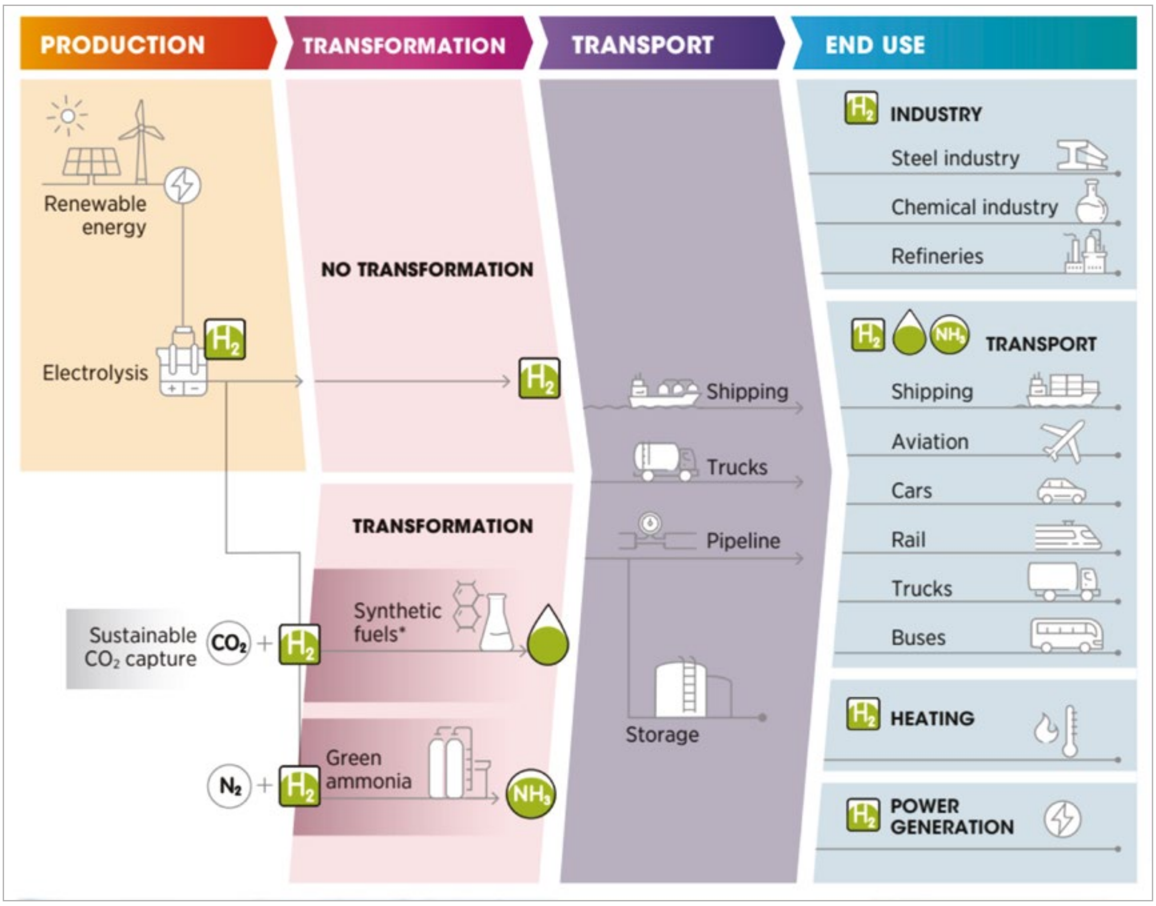


Figure 10 :The Green Hydrogen value chain

6.1 Baseline and Demand Scenario Analysis

The scenario analysis used the approach of using the International Energy Agency's (IEA) CRMs demand for green hydrogen based on the stated policies, announced pledges, and the net-zero emissions scenarios. By using these figures on CRMs demand as a baseline, the high- and low-demand scenario analysis was created by assessing South African critical minerals resources that would be needed to not only satisfy South Africa's green hydrogen production but global production demand from CRMs use.

To undertake the demand scenario analysis, an understanding of the demand drivers needs to be explored first. As captured in a report by the University Department of Energy (USDoE), total equipment and installation costs for alkaline and PEM electrolysers are estimated to be \$2300–3000/kW and \$4000–5000/kW which, at an average capacity utilisation of 70%, equates to \$3.3–4.3 and \$5.7–7.1 per kW of hydrogen production capacity. It has been reported that cell and stack replacement costs currently range from \$4.5–8.4 per kg H_2 and are considered high for current electrolysers. Ensuring high energy and resource efficiency with low environmental impact throughout materials extraction, processing, and component fabrication stages will require technologies tailored to the specific needs of the hydrogen energy industry.

There are two critical performance criteria: the use of energy (which relates to the choice of energy currency) and electrolyser durability. Reduced energy usage in electrolysers is closely related to cost, as these systems are still relatively inefficient, and the marginal cost of electricity is often the largest operating cost. While advancements in natural gas reforming and CO_2 capture and storage could reduce costs in the hydrogen production route based on steam methane reforming, it is likely that an increased environmental burden and carbon taxation will bias a transition to electrolysis.

Raw materials are central to the cost and environmental performance of all industrial processes. The evolution of hydrogen technologies toward decreased emissions and increased energy efficiency has, at a broad level, implied a transition from a resource and environmentally intensive "grey" pathway to a somewhat less carbon intensive "turquoise" route and then to "low" and "zero" CO_2 pure hydrogen production. Throughout, the degree to which materials and energy utilisation per unit of hydrogen output varies significantly.

Having described the dynamics that influence the demand for raw materials that feed into the green hydrogen value chain, it is necessary to discuss the key drivers behind critical minerals. These key drivers of CRMs demand for the green hydrogen economy are thus highlighted below.

6.1.1 Production of hydrogen

One of the first methods for electrolysis of water, alkaline electrolysis, has a long history and is a demonstrated and well-understood technology. The process takes place in an electrolysis cell with two electrodes (cathode and anode) separated by an electrolyte. When a voltage is applied across the two electrodes, the water splitting reaction occurs and gaseous hydrogen and oxygen are formed at the two respective electrodes. The electricity and heat needed in the electrolysis process are the primary energy requirements for water electrolysis. Typically, 4–5 kWh/Nm^3 of hydrogen of electricity and heat is needed for high-pressure electrolysis, whilst low pressure may be about 0.5–2 kWh/Nm^3 less. On-site generation of electricity and/or importing low-cost electricity may also be possible.

The green hydrogen production involves electrolysis of water using an electric current but at an industrial scale. Just like conventional hydrogen production, the crux of the production process is the source of energy. One of the key advantages of green hydrogen is the versatility of the source of energy used for its production, and this also holds the key for driving demand of CRMs. Fossil fuel-based hydrogen production is confined to the availability of the fossil fuel source, e.g., natural gas. It is also worth noting that renewable energy can be intermittent, and a low-cost, zero-emission energy storage solution may lead to arbitrage of renewable power and hence knowledge on CRMs demand drivers in green hydrogen production may allow location and timing optimisation of hydrogen production.

6.1.2 Fixed Costs of Production and Processing

Fixed costs are a crucial factor in investment decisions on either the initiation of a new source of CRMs or the expansion of an existing source or an alternative use of CRMs. Over the lifetime of a given resource, considering the time value of money, it is likely that the total sum of fixed costs will be the pivotal factor in the optimal use of CRMs and in determining the price of the product. Fixed costs are largely a function of the capital costs involved in the construction and development of processing facilities and in setting up or closing an operation. In CPRM2, we estimate net capital fixed costs of CRMs production in the range of -€80/t to +€1900/t, equivalent to a weighted average annual fixed cost rate of -€110/t to +€3600/t, considering the full range of CRMs, historical data on plant construction costs, and differing interest rates at different times and in different economies. Fixed costs are also incurred in the development of processing technology, which will vary in method and amount between different CRMs and will affect the relative supply of CRMs and derived products compared to alternative resources.

As with demand for all commodities, there are two types of cost involved in producing and supplying a quantity of a particular material at a specified time: processing and operating costs. Although the full accounting is complex, in general terms, processing costs represent the variable costs involved in turning raw material into a product, and operating costs represent the net profits of an operation compared to economic profits in alternative employment. Operating costs are subdivided into fixed costs and working costs. The former are incurred in running an operation whether it is profitable or not, while the latter can be recouped because they are time-related costs on variable inputs and/or represent the difference between the buying and selling price of a given quantity of a variable input. Fixed costs and working costs together determine the supply price curve. For a commodity with numerous potential suppliers, the supply price will be set by the most expensive source needed to meet the marginal demand, set in terms of price, for a commodity. This is particularly relevant to CRMs production and recycling, and it is therefore important to understand if the marginal demand for a particular CRMs is expected to lead to an expansion in supply from an existing source or sector, or from the development of a new resource.

6.1.3 Capital Costs

PEM electrolysers device/cell costs have decreased significantly over the last 20 years, associated with a decrease in the cost of PGMs. Furthermore, the evolution of fuel cell technology has had positive implications for the electrolysers industry, given that fuel cells and electrolysers share similar structured catalysts. This has led to a decrease in the platinum loading required in electrolysers and associated cost. An assessment of the main components of a PEM electrolyser was based on data developed in studies by the IEA and NEDO. The cost of alkaline electrolysers has traditionally been cheaper than PEM systems, however, PEM electrolysers have the potential to surpass them in cost effectiveness.

The capital cost of an investment is the cost required to actualise a project and bring it on stream. It does not encompass the cost of running the project but can overlap with the cost of developing technologies in a specific area. For the purposes of this study, capital costs of electrolysers and associated compressors/dryers have been estimated. Electrolyser development is currently focused on PEM and alkaline systems. There are a variety of different designs that can be developed under each category, but the most likely current candidates for large scale electricity conversion to hydrogen are PEM electrolysers because of their high efficiency. High temperature steam electrolysers are also an efficient means of hydrogen production but are not suited to the intermittent operation using electricity from renewable energy numbers outlined in this study.

6.1.4 Operating Costs

The main achievement of a model of this type is to appreciate the way in which costs might develop and flag the drivers of these changes and their relative importance in determining the overall level of operating cost. By doing this, we set the scene to consider the likely incentives for producing hydrogen from the various feedstocks in the future. This, in turn, will assist both policymakers and stakeholders in making decisions regarding supporting the implementation of hydrogen energy, the development of a supporting industry sector, including that for CRMs and potential chemical transient absorption systems (TaCs), and the prospects for hydrogen energy in facilitating the utilisation of non-CRMs resources. In the very early stages of this study, the intention was to ultimately develop an optimisation model from a combined multi-criteria decision analysis (MCDA) and cost minimisation approach, such that the dynamic movement in the diverse range of production technologies, including CRMs route, would be endogenously driven by evolving energy and industrial commodity markets and consistent with obtaining the long-term vision for hydrogen energy. Although still at a very early stage compared to that long-term vision, we believe the model and its results presented here will be a useful contribution.

6.1.5 Import and Export Tariffs

Most informative of all was a detailed USDoE-funded study to model specific CRMs import and use in electrolyser fuels. At the other end of the spectrum, the IEA prediction model for hydrogen supply and demand to 2030 provided highly complex but broad results for hydrogen price and a CRMs demand range, derived to meet supply with demand in the lowest possible cost scenario.

The studies or models used varied in depth and credibility. The Japanese Future Society Initiative report on green ammonia examined the extra cost of renewable ammonia production in Japan and found it was unlikely to be competitive with fossil alternatives until the 2030s. A more costly renewable ammonia production route was assumed to require a higher CRMs use per tonne. This model was relatively simple and speculative with its assumptions, with broader political and economic assumptions driving particular CRMs demand ranges. An EU hydrogen strategy study for the same fuel found the CRMs demand intensiveness per tonne of ammonia was derived in a complex fashion involving the relative costs of competing renewable and fossil fuel technologies.

The CRMs market's expected growing importance for green hydrogen production and use. A global lifecycle analysis for green hydrogen for each individual CRMs was not feasible for this study. Instead, a separate market-specific model or study was used to derive a hypothetical future CRMs demand range in green hydrogen.

6.1.6 Energy Demand

Energy is the principal driver of the model. It is a key to the production of hydrogen as it is the form of energy that will be used. However, for this model, conventional sources of energy such as coal, oil, and natural gas are not used for the production of hydrogen because a shift from conventional energy sources to renewable and other potentially sustainable sources is one of the main goals of the country, and the significant release of CO_2 and various other pollutants from the production of hydrogen from these sources. In fact, Japan's Basic Hydrogen Strategy states that the country's hydrogen is to be derived from renewables, nuclear, and fossil fuels with carbon capture and storage. This statement implies that the cost and availability of hydrogen are going to be in a state of flux in the foreseeable future. The period between 2020 and 2030 may be seen as a transition period as Japan aims to establish its hydrogen supply chain. It is anticipated that there will not be a large increase in the demand for hydrogen and the prices thereof will remain high, several times higher than the current price of hydrogen derived from natural gas. Industry will be the main consumer of hydrogen during this time period.

6.1.7 Logistics

A step beyond this and potentially a larger future use for energy storage is using hydrogen and derived products in place of natural gas as a reducing agent in various metallurgical processes, e.g., direct reduction of iron oxide to produce steel. Many of these processes are site and technology-specific, so a detailed analysis of the future trend and options for hydrogen in this application is not feasible.

Moving to an off-grid application of renewable hydrogen utilising excess or curtailed generation, hydrogen can be used as a feedstock in industry, and the Haber process can be used to produce ammonia. This is an energy-intensive process currently using steam reforming of natural gas, and numerous projects have looked into green ammonia production where the hydrogen source is water electrolysis.

A final issue to consider for hydrogen end use in transport is efficiency losses associated with reconversion back to electricity in fuel cells, and how this compares to the use of batteries in electric vehicles. This has been reviewed elsewhere for buses.

An often-cited issue with hydrogen is the difficulty of containment and embrittlement of metals, and while these issues are real, numerous experiments with hydrogen-fuelled passenger trains have been carried out. This involved the conversion of conventional internal combustion engine trains to hydrogen fuel cells, however, the overall energy efficiency of this system compared to electrification and using electricity directly would require detailed analysis.

The early development of renewable hydrogen could likely see much delivered in compressed form, and here freight efficiencies may be closer to those seen currently for compressed natural gas. Renewable hydrogen would likely be most efficiently distributed in liquid form, as the energy density of liquid hydrogen is more than twice that of compressed hydrogen.

In the entire supply chain, moving renewable hydrogen, and therefore renewable electricity, to demand centres may represent a major challenge. This may involve new purpose-built infrastructure, and particularly when considering hydrogen end-use in transport, may involve the generation of a parallel distribution system because the hydrogen infrastructure is not compatible with the existing hydrocarbon-based systems.

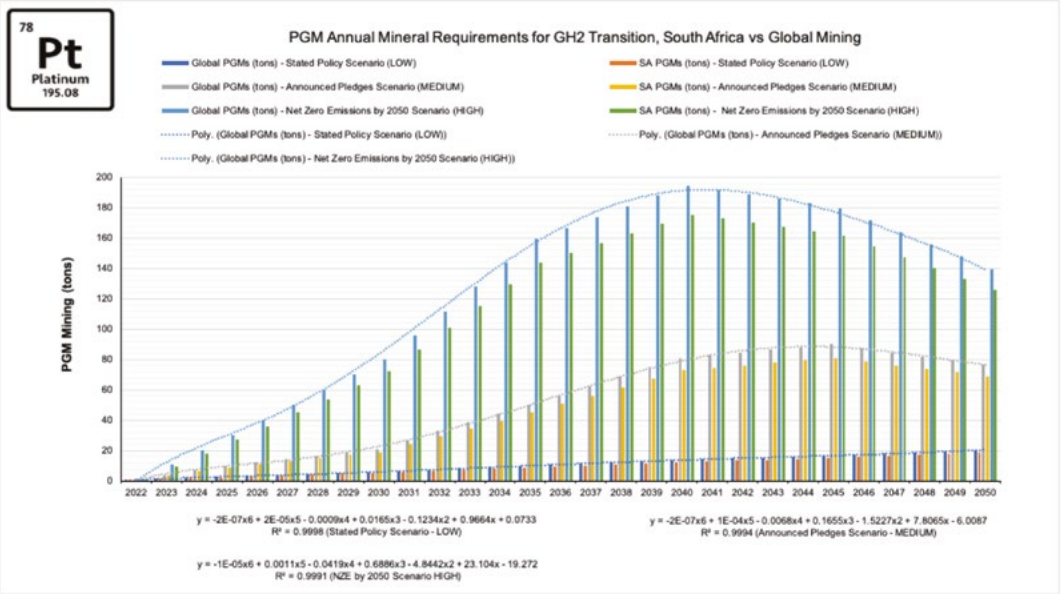
6.1.8 Baseline Infrastructure Requirements

The infrastructure for hydrogen production and delivery is not yet built, however, specifics regarding requirements have been in discussion for many years. It is known that hydrogen can be produced in many ways, however, capturing the carbon dioxide produced during the process is imperative. This dictates locating the “capture ready” storage sites and major transport facilities, clearly stating that planning the infrastructure is primary. From a delivery perspective, hydrogen is a clean-burning fuel; however, it has a lower energy content per unit volume than natural gas. This means that the pipelines, storage tanks, and shipping containers for hydrogen will be more voluminous or have less throughput than hydrocarbon equivalents. In the more distant future, hydrogen pipelines could add an entirely new transit method for energy transportation. The production process for hydrogen is not very different from what is being done today with natural gas reforming. This further supports the idea that transitioning to a hydrogen economy is attainable without requiring a monumental change in the infrastructure. This is not to undermine the cost associated with establishing such infrastructure, but it is suggested that given the proper incentives, policies, and a supportive timeline, the development of an infrastructure for hydrogen energy can be accomplished. This further reiterates the importance of public sector investment in the earlier stages of hydrogen development.

6.2 CRMs Demand Scenario Analysis Outcomes

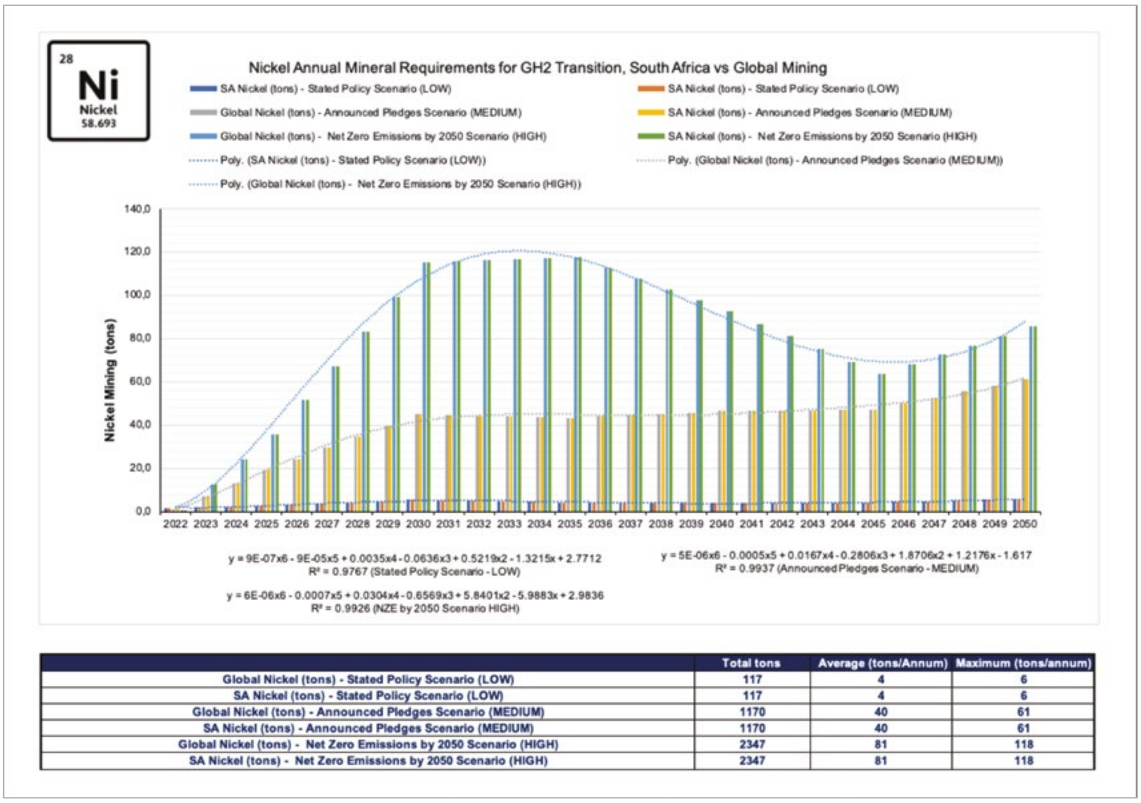
The scenario analysis as stated above used the IEA policy scenarios as benchmarks for the analysis. Both global and South Africa CRMs are used to project the demand in the various scenarios. Additionally, it was assumed that all declared mineral resources would be mined and projected across the policy scenario benchmarks. The main reason for using mineral resources was because production metrics could be sourced accurately and there is no predictive pre-cursor to estimating the rate at which mining production would increase over time.

The first set of graphs produced indicate critical raw material demand in the various policy scenarios and are highlighted below:



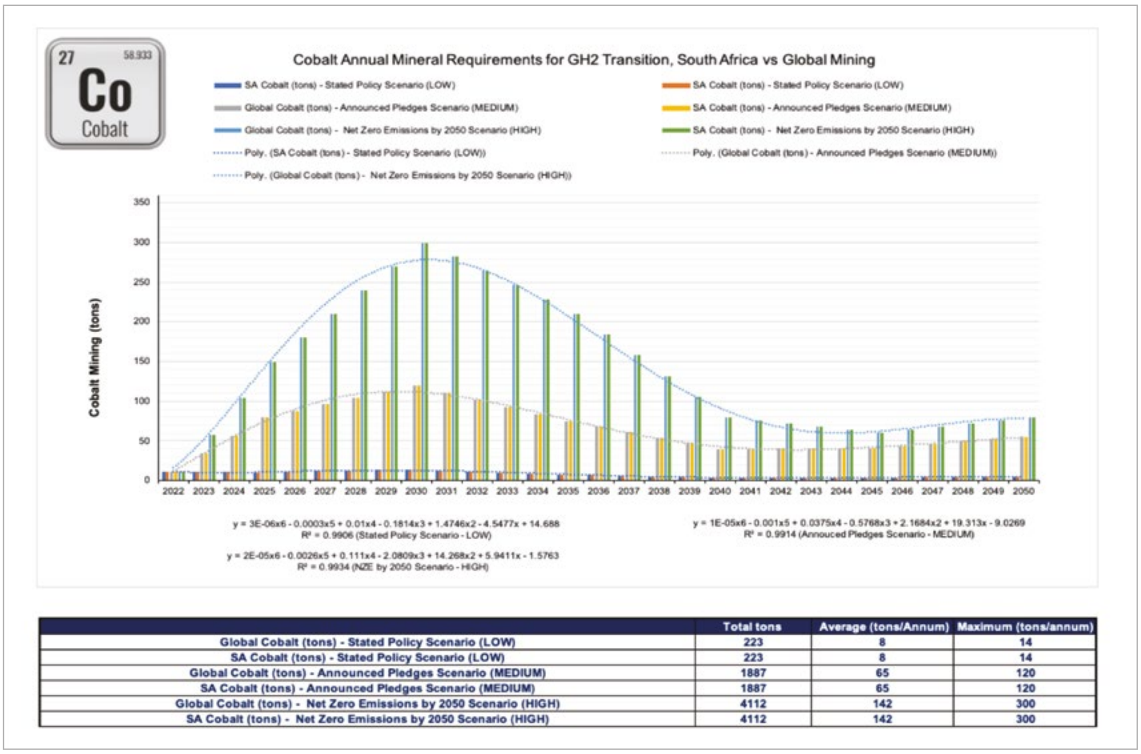
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global PGMs (tons) - Stated Policy Scenario (LOW)	307	11	21
SA PGMs (tons) - Stated Policy Scenario (LOW)	277	10	18
Global PGMs (tons) - Announced Pledges Scenario (MEDIUM)	1484	51	90
SA PGMs (tons) - Announced Pledges Scenario (MEDIUM)	1337	46	81
Global PGMs (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	3617	125	195
SA PGMs (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	3259	112	176

Figure 11: PGM demand outlook for meeting green hydrogen requirements across the modelled policy scenarios



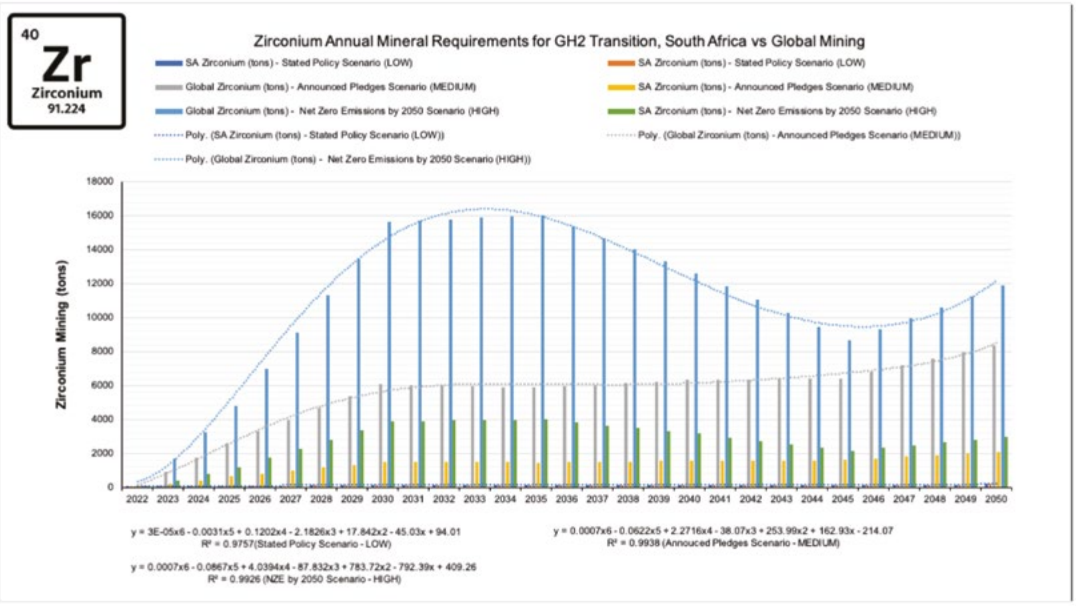
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Nickel (tons) - Stated Policy Scenario (LOW)	117	4	6
SA Nickel (tons) - Stated Policy Scenario (LOW)	117	4	6
Global Nickel (tons) - Announced Pledges Scenario (MEDIUM)	1170	40	61
SA Nickel (tons) - Announced Pledges Scenario (MEDIUM)	1170	40	61
Global Nickel (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	2347	81	118
SA Nickel (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	2347	81	118

Figure 12: Nickel outlook for meeting green hydrogen requirements



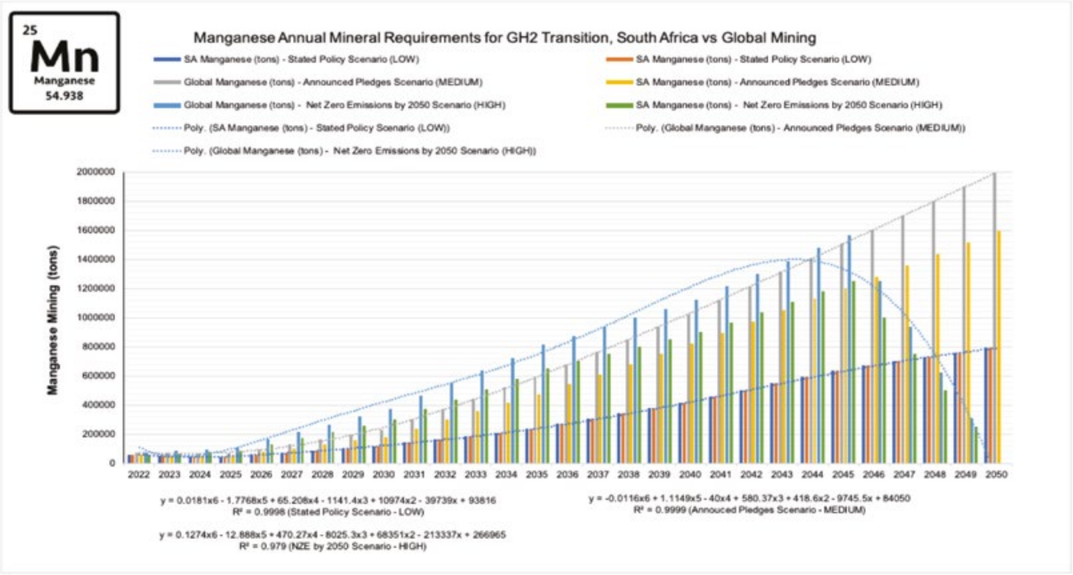
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Cobalt (tons) - Stated Policy Scenario (LOW)	223	8	14
SA Cobalt (tons) - Stated Policy Scenario (LOW)	223	8	14
Global Cobalt (tons) - Announced Pledges Scenario (MEDIUM)	1887	65	120
SA Cobalt (tons) - Announced Pledges Scenario (MEDIUM)	1887	65	120
Global Cobalt (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	4112	142	300
SA Cobalt (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	4112	142	300

Figure 13: Cobalt outlook for meeting green hydrogen requirements



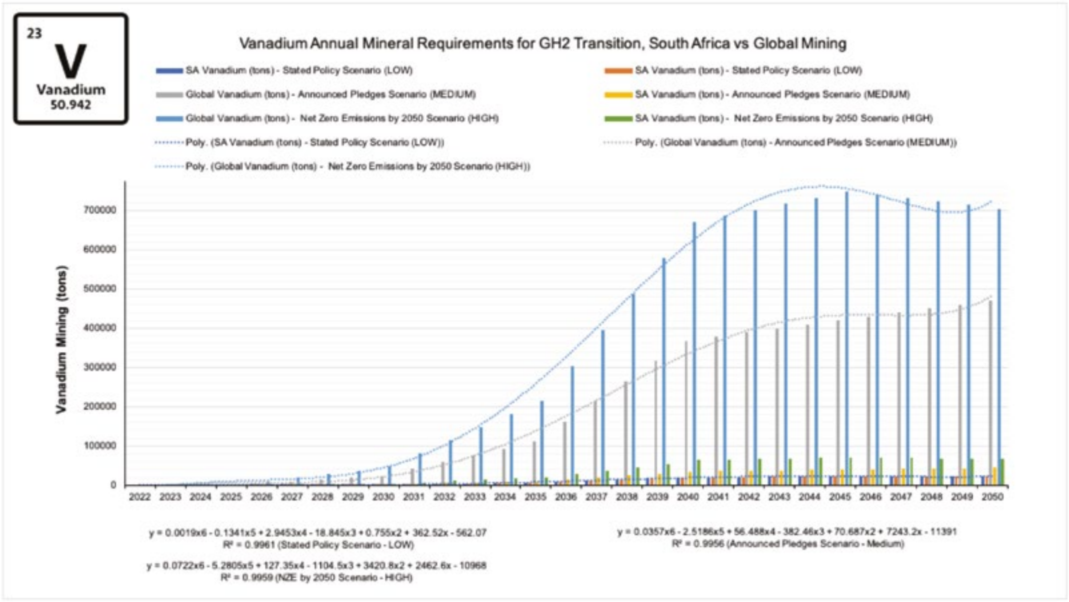
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Zirconium (tons) - Stated Policy Scenario (LOW)	15990	551	780
SA Zirconium (tons) - Stated Policy Scenario (LOW)	3998	138	195
Global Zirconium (tons) - Announced Pledges Scenario (MEDIUM)	159360	5495	8370
SA Zirconium (tons) - Announced Pledges Scenario (MEDIUM)	39840	1374	2093
Global Zirconium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	320070	11037	16050
SA Zirconium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	80018	2759	4013

Figure 14: Zirconium outlook for meeting green hydrogen requirements



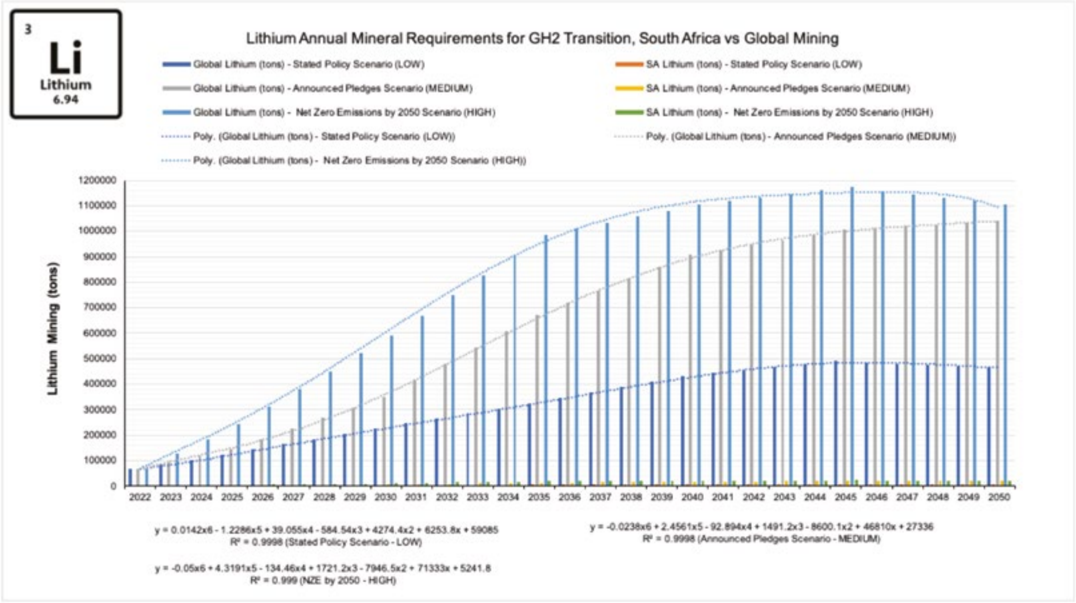
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Manganese (tons) - Stated Policy Scenario (LOW)	12232100	421797	993900
SA Manganese (tons) - Stated Policy Scenario (LOW)	9785680	337437	795120
Global Manganese (tons) - Announced Pledges Scenario (MEDIUM)	23229000	801000	1997300
SA Manganese (tons) - Announced Pledges Scenario (MEDIUM)	18583200	640800	1597840
Global Manganese (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	20039280	691010	1566100
SA Manganese (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	16031424	552808	1252880

Figure 15: Manganese outlook for meeting green hydrogen requirements



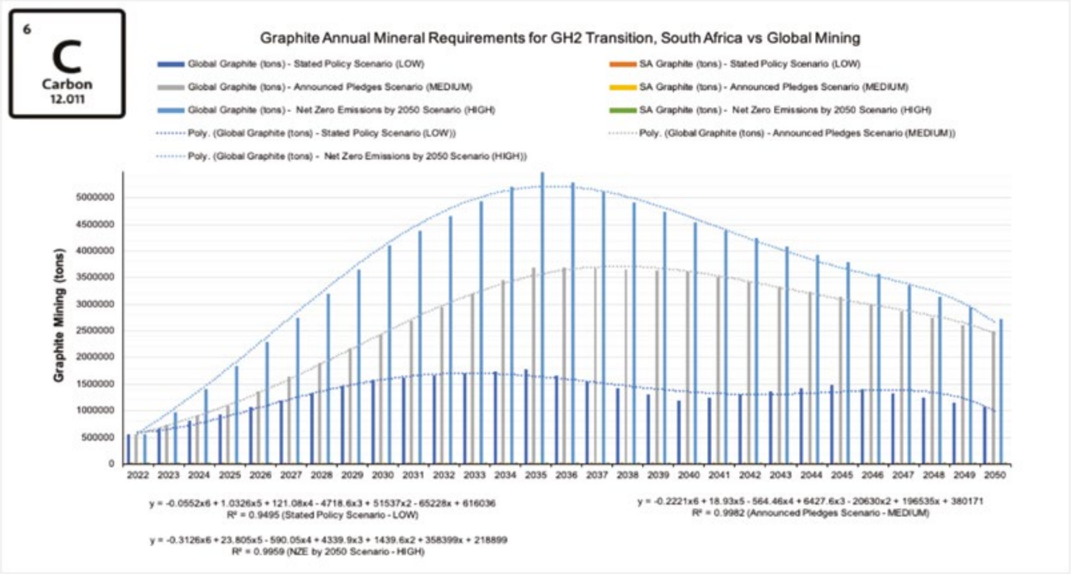
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Vanadium (tons) - Stated Policy Scenario (LOW)	3465430	119498	242890
SA Vanadium (tons) - Stated Policy Scenario (LOW)	329216	11352	23075
Global Vanadium (tons) - Announced Pledges Scenario (MEDIUM)	6030670	207954	470540
SA Vanadium (tons) - Announced Pledges Scenario (MEDIUM)	572914	19756	44701
Global Vanadium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	10516640	362643	747380
SA Vanadium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	999081	34451	71001

Figure 16: Vanadium outlook for meeting green hydrogen requirements



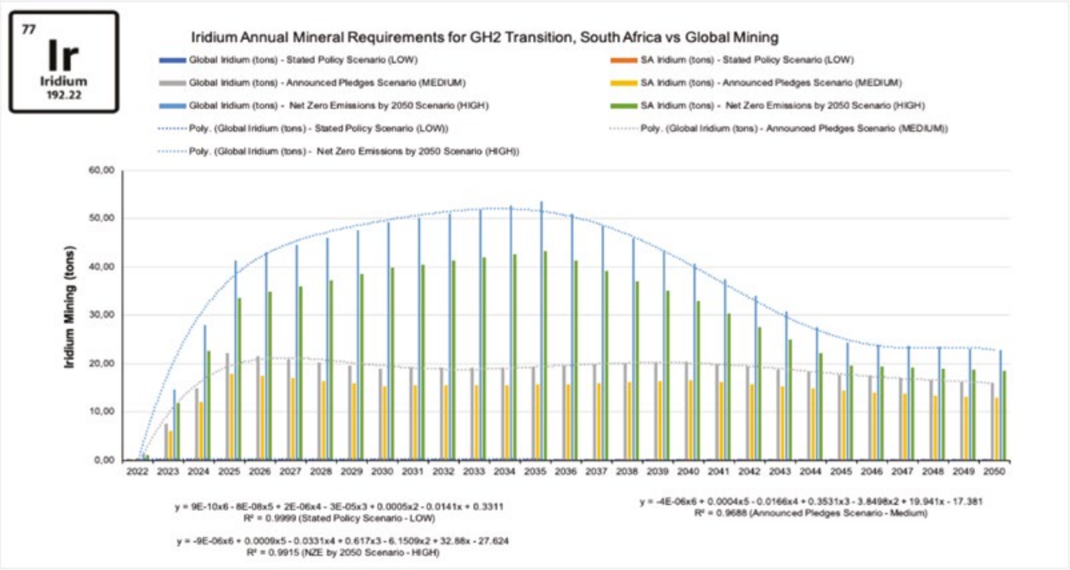
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Lithium (tons) - Stated Policy Scenario (LOW)	9412700	324576	490900
SA Lithium (tons) - Stated Policy Scenario (LOW)	188254	6492	9818
Global Lithium (tons) - Announced Pledges Scenario (MEDIUM)	18507300	638183	1039500
SA Lithium (tons) - Announced Pledges Scenario (MEDIUM)	370146	12764	20790
Global Lithium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	23699200	817214	1173000
SA Lithium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	473984	16344	23460

Figure 17: Lithium outlook for meeting green hydrogen requirements



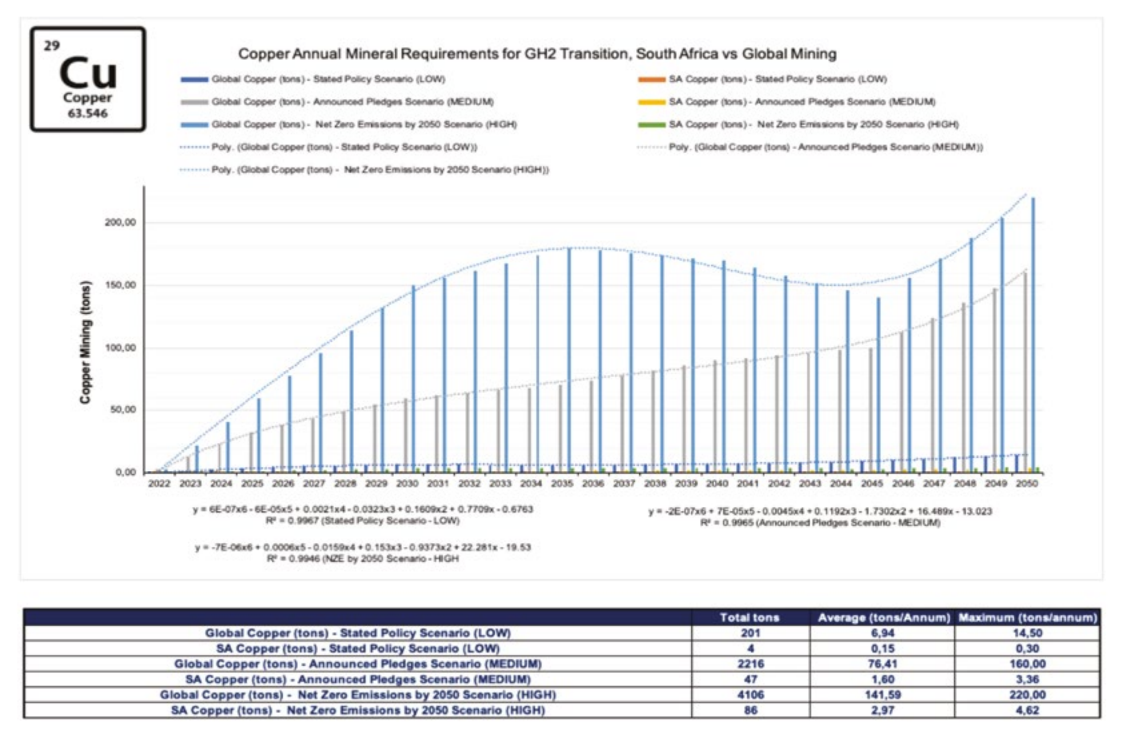
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Graphite (tons) - Stated Policy Scenario (LOW)	38386900	1323686	1781800
SA Graphite (tons) - Stated Policy Scenario (LOW)	116312	4011	5399
Global Graphite (tons) - Announced Pledges Scenario (MEDIUM)	77411800	2669372	3703100
SA Graphite (tons) - Announced Pledges Scenario (MEDIUM)	234558	8088	11220
Global Graphite (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	106301000	3665552	5486100
SA Graphite (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	322092	11107	16623

Figure 18: Graphite outlook for meeting green hydrogen requirements



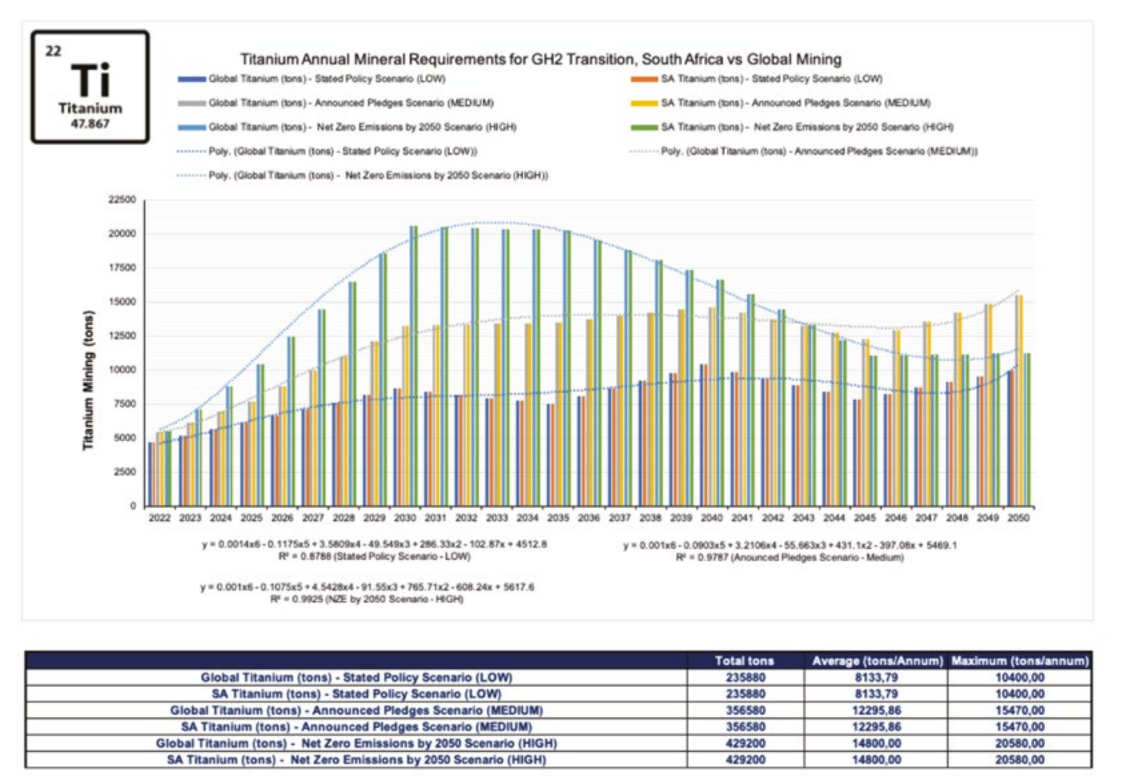
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Iridium (tons) - Stated Policy Scenario (LOW)	6	0,20	0,32
SA Iridium (tons) - Stated Policy Scenario (LOW)	5	0,17	0,26
Global Iridium (tons) - Announced Pledges Scenario (MEDIUM)	521	18,0	22,3
SA Iridium (tons) - Announced Pledges Scenario (MEDIUM)	422	14,5	18,0
Global Iridium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	1076	37,1	53,6
SA Iridium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	872	30,1	43,4

Figure 19: Iridium outlook for meeting green hydrogen requirements



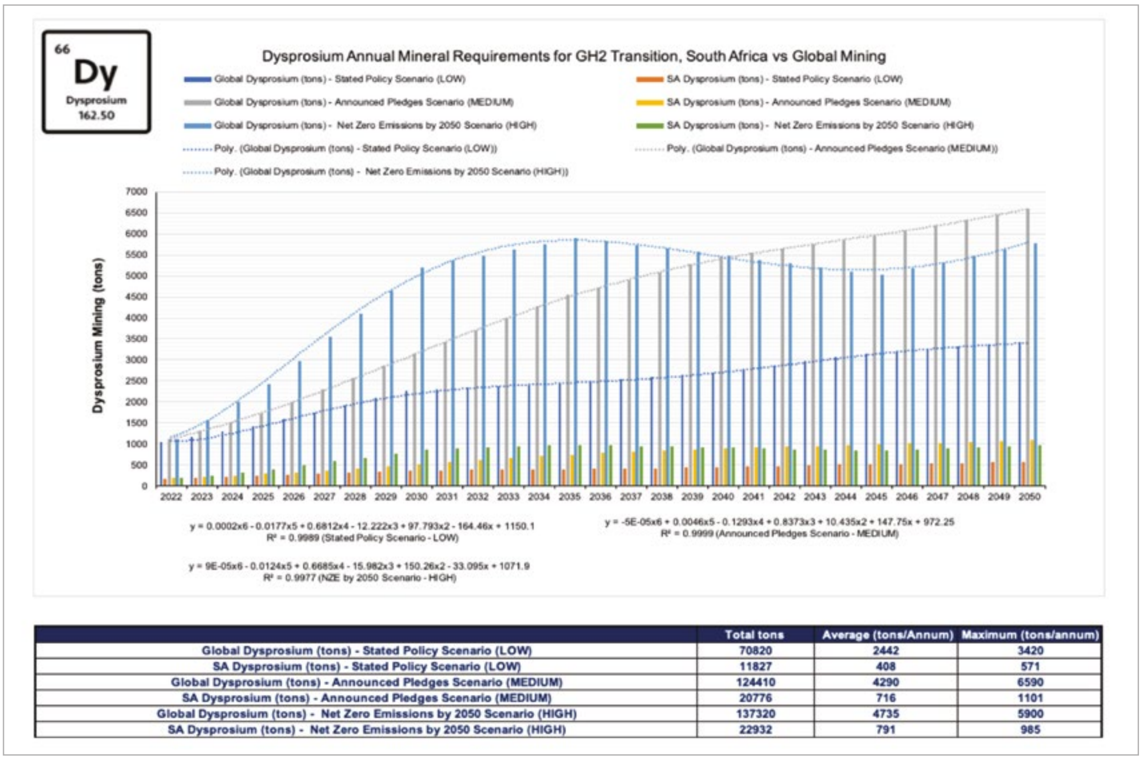
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Copper (tons) - Stated Policy Scenario (LOW)	201	6,94	14,50
SA Copper (tons) - Stated Policy Scenario (LOW)	4	0,15	0,30
Global Copper (tons) - Announced Pledges Scenario (MEDIUM)	2216	76,41	160,00
SA Copper (tons) - Announced Pledges Scenario (MEDIUM)	47	1,60	3,36
Global Copper (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	4106	141,59	220,00
SA Copper (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	86	2,97	4,62

Figure 20: Copper outlook for meeting green hydrogen requirements



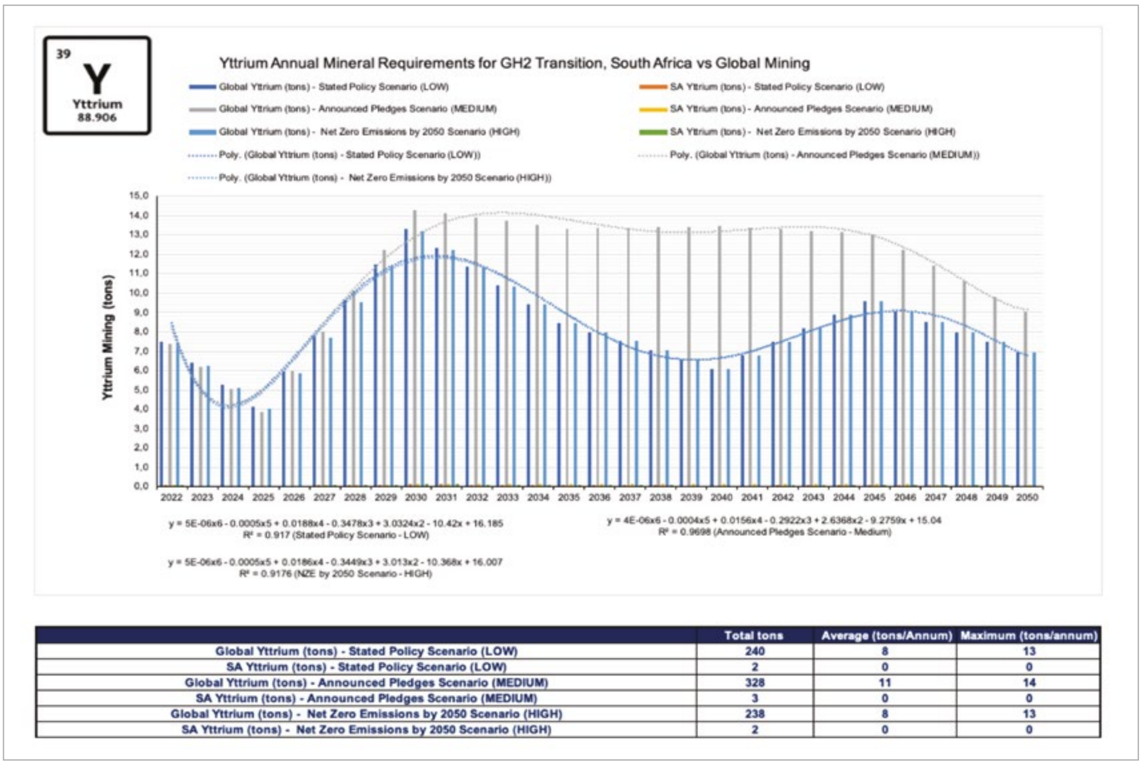
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Titanium (tons) - Stated Policy Scenario (LOW)	235880	8133,79	10400,00
SA Titanium (tons) - Stated Policy Scenario (LOW)	235880	8133,79	10400,00
Global Titanium (tons) - Announced Pledges Scenario (MEDIUM)	356580	12295,86	15470,00
SA Titanium (tons) - Announced Pledges Scenario (MEDIUM)	356580	12295,86	15470,00
Global Titanium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	429200	14800,00	20580,00
SA Titanium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	429200	14800,00	20580,00

Figure 21: Titanium outlook for meeting green hydrogen requirements



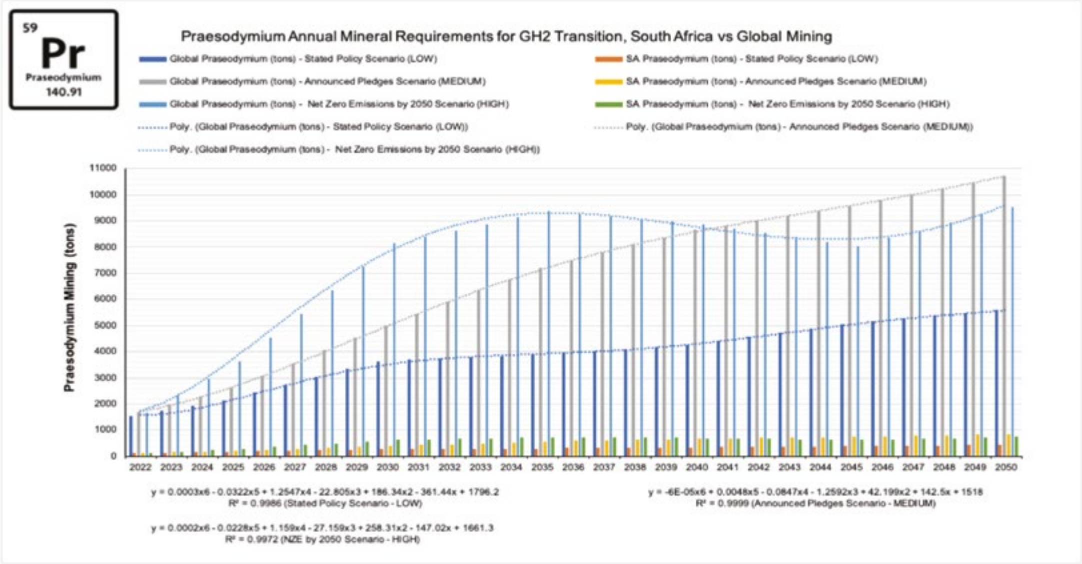
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Dysprosium (tons) - Stated Policy Scenario (LOW)	70820	2442	3420
SA Dysprosium (tons) - Stated Policy Scenario (LOW)	11827	408	571
Global Dysprosium (tons) - Announced Pledges Scenario (MEDIUM)	124410	4290	6590
SA Dysprosium (tons) - Announced Pledges Scenario (MEDIUM)	20776	716	1101
Global Dysprosium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	137320	4735	5900
SA Dysprosium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	22932	791	985

Figure 22: Dysprosium outlook for meeting green hydrogen requirements



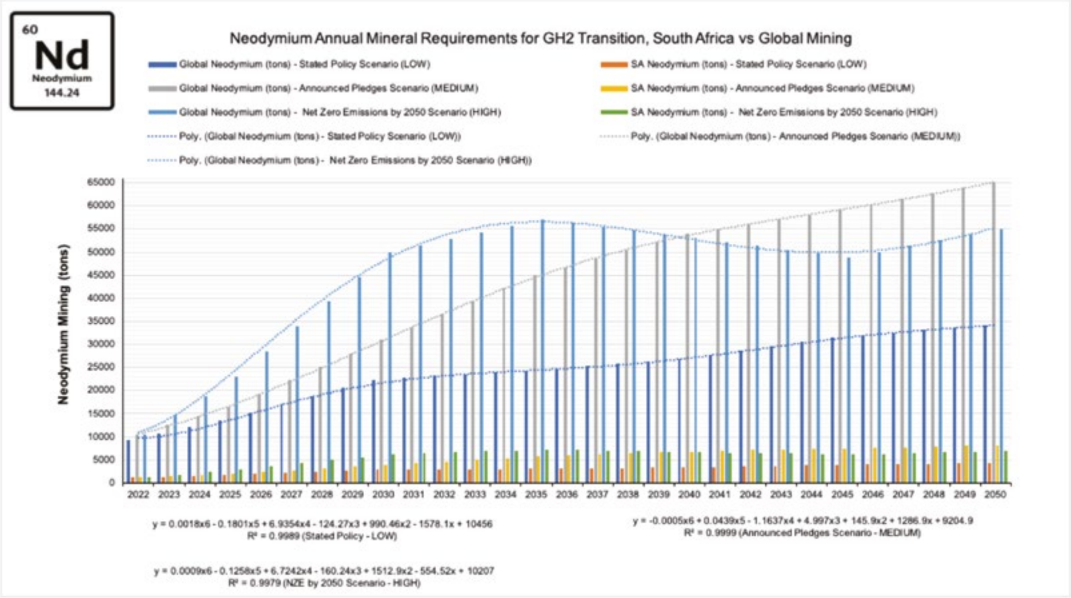
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Yttrium (tons) - Stated Policy Scenario (LOW)	240	8	13
SA Yttrium (tons) - Stated Policy Scenario (LOW)	2	0	0
Global Yttrium (tons) - Announced Pledges Scenario (MEDIUM)	328	11	14
SA Yttrium (tons) - Announced Pledges Scenario (MEDIUM)	3	0	0
Global Yttrium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	238	8	13
SA Yttrium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	2	0	0

Figure 23: Yttrium outlook for meeting green hydrogen requirements



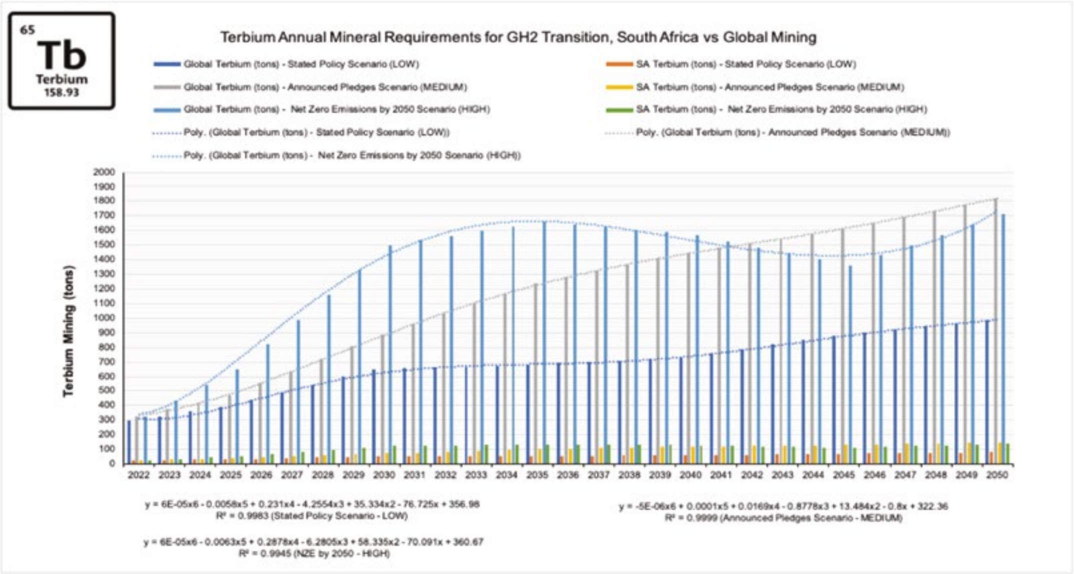
	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Praseodymium (tons) - Stated Policy Scenario (LOW)	112700	3886	5600
SA Praseodymium (tons) - Stated Policy Scenario (LOW)	8791	303	437
Global Praseodymium (tons) - Announced Pledges Scenario (MEDIUM)	198160	6833	10710
SA Praseodymium (tons) - Announced Pledges Scenario (MEDIUM)	15456	533	835
Global Praseodymium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	218750	7543	9540
SA Praseodymium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	17063	588	744

Figure 24: Praseodymium outlook for meeting green hydrogen requirements



	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Neodymium (tons) - Stated Policy Scenario (LOW)	701270	24182	34210
SA Neodymium (tons) - Stated Policy Scenario (LOW)	88581	3055	4321
Global Neodymium (tons) - Announced Pledges Scenario (MEDIUM)	1227920	42342	65110
SA Neodymium (tons) - Announced Pledges Scenario (MEDIUM)	155106	5348	8224
Global Neodymium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	1324470	45671	57190
SA Neodymium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	167301	5769	7224

Figure 25: Neodymium outlook for meeting green hydrogen requirements



	Total tons	Average (tons/Annum)	Maximum (tons/annum)
Global Terbium (tons) - Stated Policy Scenario (LOW)	19830	684	990
SA Terbium (tons) - Stated Policy Scenario (LOW)	1626	56	81
Global Terbium (tons) - Announced Pledges Scenario (MEDIUM)	33950	1171	1820
SA Terbium (tons) - Announced Pledges Scenario (MEDIUM)	2784	96	149
Global Terbium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	38840	1339	1710
SA Terbium (tons) - Net Zero Emissions by 2050 Scenario (HIGH)	3185	110	140

Figure 26: Terbium outlook for meeting green hydrogen requirements

The graphs above indicate the expected outlook on CRMs demand in a South African and global context based on: (a) the stated policy scenario, (b) announced pledges scenario, and (c) the net-zero by 2050 scenario. To produce the global outlook on CRMs demand, global resources of each critical mineral were used and extrapolated based on the different policy scenarios. The South African CRMs demand is based on the percentage of resources that South Africa has of each CRMs and is extrapolated as a percentage feeding into the global demand for CRMs within the various policy scenarios.

As these resources are modelled against the policy scenarios, three important trends are observed:

- The main trend is a “ramp-up” trend, where an increase in CRMs demand for a 10–15-year period beginning in 2022 is observed. The reason for the demand is attributed to the increase in mining and extraction activity because of policy commitments to curb GHG emissions and global demand for the green transition.
- The next two trends occur after the 10–15-year period from 2022, leading up to the 2050 net-zero where the CRMs demand declines or in some cases plateaus. The decline is expected and is attributed to improvements in processing technology for ore and tailings. The plateauing of some of the CRMs demand is due to the lack of substitution of CRMs in future technologies.

- Additionally, the decline in CRMs mined material could also be attributed to the expected increase in recycling of CRMs. As circular economy principles and commitments to recycling of CRMs get stronger, the decline in CRMs mining is expected within 20 years. However, shortly after the decline in CRMs demand, a small increase in CRMs demand is observed which is most likely attributed to a final ramp-up period in mining in order to meet the last set of net-zero policy requirements.

6.3 CRMs Demand and its Impact on the Environment (Energy, Greenhouse Gas Emissions, Water, and Land Disruption)

To provide a holistic examination of the impact dynamics around critical minerals, interactions between critical minerals and the environment are also considered in this report. Furthermore, the environmental impacts provide an outlook on sustainability challenges that will be brought on by CRMs mining driven by the demand for these CRMs in meeting the green hydrogen transition requirements.

The approach taken to address and highlight the impact on the environment, namely GHG emissions, water usage, energy demand, and land disruption, was by using the same IEA benchmark scenarios and the CRMs demand outlook and linking them to associated environmental needs of satisfying the IEA benchmark scenarios. The result is a highlighted view of the environmental impact borne out of meeting CRMs demand.

6.3.1 Greenhouse Gas Emissions Forecast

The first environmental impact scenario analysis is the GHG emissions impact because of green hydrogen transition CRMs demand. Using the same critical minerals mentioned above, each mineral's respective GHG intensity factor was multiplied by the corresponding mineral demand which resulted in a figure that provided an emission value associated to the mineral in terms of its equivalent tonnes of carbon dioxide. The summation of each of these emission values for the different critical minerals yielded the total emissions that would be produced against the various policy scenarios. These values are highlighted in the table below.

Table 1: Emissions attributable to CRMs mining under different production scenarios

	Total CRMs GHG Emission in tCO_2e (t/annum)	Average GHG Emissions in tCO_2e for CRMs (t/Annum)	Maximum GHG Emissions in tCO_2e for CRMs (t/annum)
Global CRMs GHG Emissions (tCO_2e) - Stated Policy Scenario (LOW)	956 097 058,38	32 968 864,08	50 312 491,29
SA CRMs GHG Emissions (tCO_2e) - Stated Policy Scenario (LOW)	92 690 333,85	3 196 218,41	6 849 469,61
Global CRMs GHG Emissions (tCO_2e) - Announced Pledges Scenario (MEDIUM)	1 910 433 102,63	65 877 003,54	104 793 881,01
SA CRMs GHG Emissions (tCO_2e) - Announced Pledges Scenario (MEDIUM)	210 262 005,64	7 250 413,99	15 618 263,25
Global CRMs GHG Emissions (tCO_2e) - Net Zero Emissions by 2050 Scenario (HIGH)	2 653 774 593,37	91 509 468,74	145 955 926,03
SA CRMs GHG Emissions (tCO_2e) - Net Zero Emissions by 2050 Scenario (HIGH)	294 235 337,43	10 146 046,12	18 518 823,45

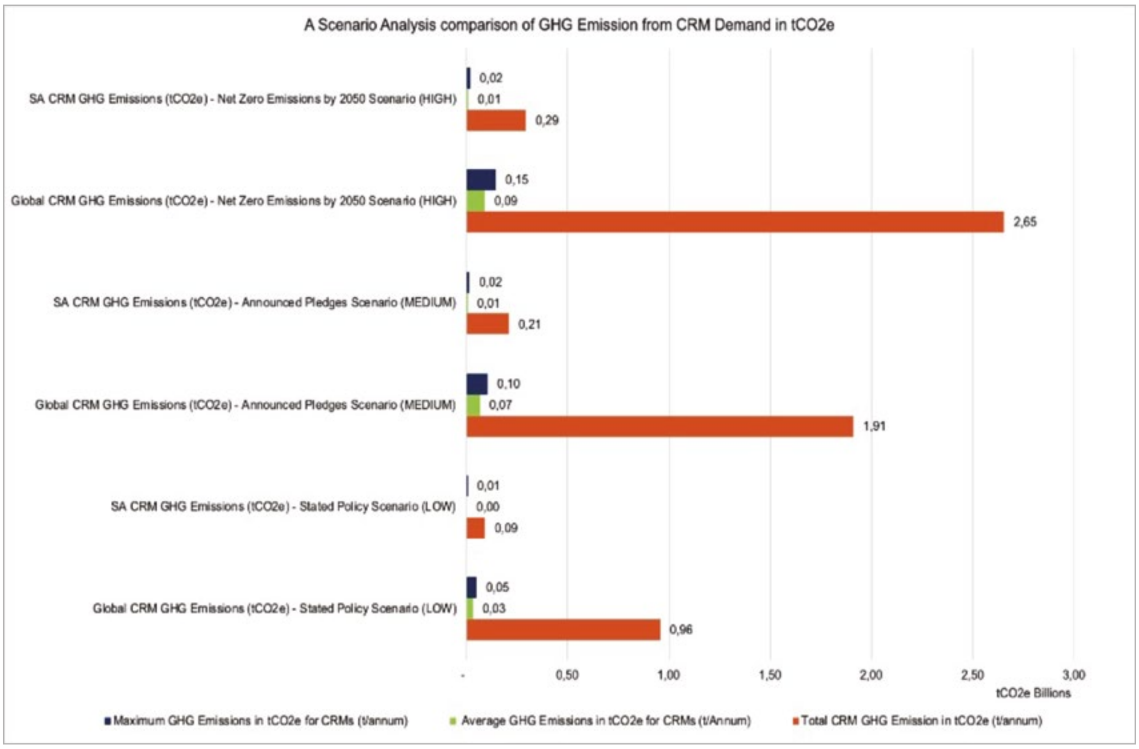


Figure 27: GHG emissions produced based on CRMs demand in tCO_2e

Figure 27 above highlights, as policy requirements become more stringent moving towards a net zero future, the total emissions produced from expected critical minerals mining activity for the green hydrogen transition increases.

6.3.2 Predicted Energy Demand

Similar to GHG emissions, energy impacted was measured using the same approach. Each critical mineral requires a certain amount of energy to mine it, whose energy value is presented by an energy factor. This energy factor is multiplied against the amount of mineral mined and produces a figure that is attributed to the total energy used in mining that specific mineral. By totalling the figures for total energy used for all the critical minerals, an overview of the energy requirements for satisfying CRMs demand for green hydrogen is produced. Table 2 shows the projected energy demand for CRMs production.

Table 2: Projected energy demand for CRMs production

	Total Energy Demand (GJ)	Average Energy Demand for CRMs (GJ/Annum)	Maximum Energy Demand for CRMs (GJ/annum)
Global CRMs Energy Demand (GJ) - Stated Policy Scenario (LOW)	4 910 823 441,36	169 338 739,36	298 528 143,76
SA CRMs Energy Demand (GJ) - Stated Policy Scenario (LOW)	961 339 787,77	33 149 647,85	69 858 958,47
Global CRMs Energy Demand (GJ) - Announced Pledges Scenario (MEDIUM)	9 366 684 820,59	322 989 131,74	604 765 175,66
SA CRMs Energy Demand (GJ) - Announced Pledges Scenario (MEDIUM)	1 984 399 952,81	68 427 584,58	149 090 234,89
Global CRMs Energy Demand (GJ) - Net Zero Emissions by 2050 Scenario (HIGH)	13 288 394 791,05	458 220 510,04	812 888 113,28
SA CRMs Energy Demand (GJ) - Net Zero Emissions by 2050 Scenario (HIGH)	2 554 437 514,20	88 084 052,21	166 470 561,22

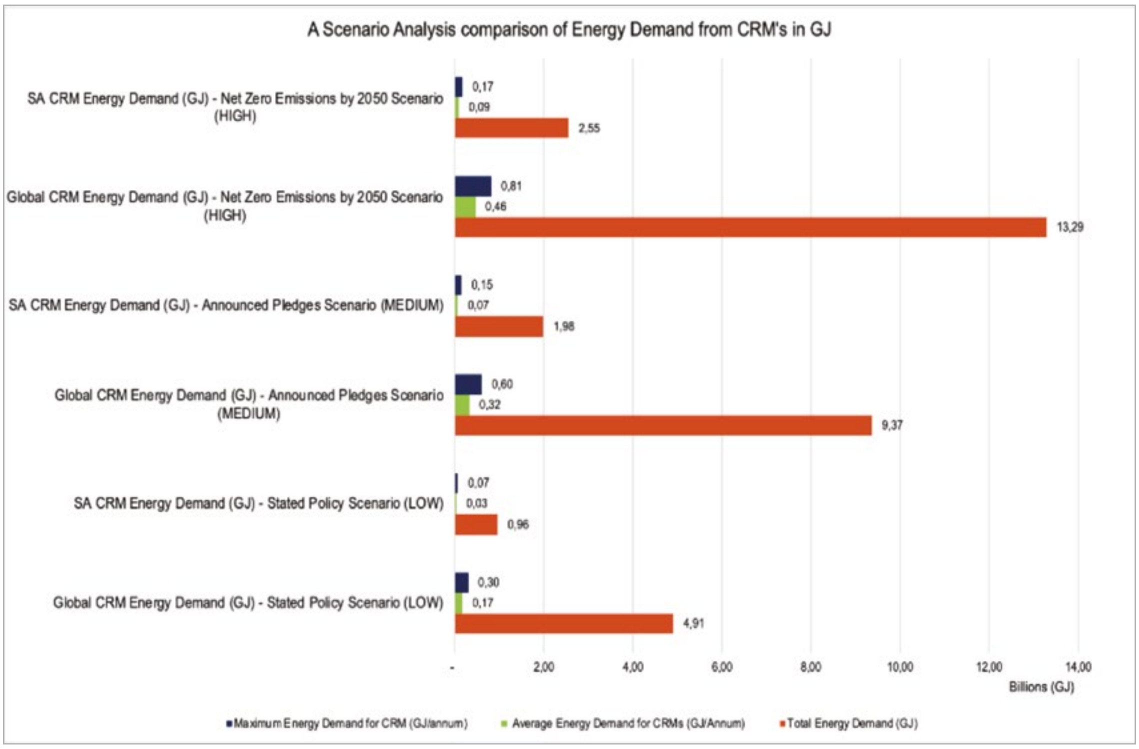


Figure 28: Energy demand attributed to CRMs mining for green hydrogen demand based on the IEA policy scenarios

Figure 28 illustrates that as the policy scenarios get more demanding on meeting net zero requirements, more energy is required to satisfy the demand for critical minerals. The total energy demand from the stated policy scenario to the announced pledges scenario increases by approximately 5 billion gigajoules; this figure indicates the intensity of mining activity required by 2040 to fulfil sustainability pledges. However, the total energy demand from the announced pledges scenario to the net zero emissions scenario only increases by approximately 3,9 billion gigajoules. The overall decrease in total energy demand from 2040 to 2050 is likely due to technological advances that improve processing of critical minerals and recycling.

6.3.3 Water Demand Forecast

To analyse the water demand impact associated with critical minerals according to the policy scenarios, average water usage factors per mined tonne of mineral was used. The water usage factors were multiplied against critical mineral demand to produce a total water usage estimate value per tonne of mineral mined. The sum of these values for each mineral thus produces figures for each policy scenario and are exhibited below.

Table 3: Predicted water demand for CRM production forecasts

	Total Water Demand for CRMs (m^3)	Average Water Demand for CRMs (m^3/ Annum)	Maximum Water Demand for CRMs (m^3/annum)
Global Water Demand for CRMs (m^3) - Stated Policy Scenario (LOW)	16 747 867 947,01	577 512 687,83	916 352 350,28
SA Water Demand for CRMs (m^3) - Stated Policy Scenario (LOW)	2 775 673 493,67	95 712 879,09	196 579 896,07
Global Water Demand for CRMs (m^3) - Announced Pledges Scenario (MEDIUM)	32 273 508 921,71	1 112 879 617,99	1 889 742 833,59
SA Water Demand for CRMs (m^3) - Announced Pledges Scenario (MEDIUM)	5 727 464 419,67	197 498 773,09	421 836 810,53
Global Water Demand for CRMs (m^3) - Net Zero Emissions by 2050 Scenario (HIGH)	39 703 914 163,83	1 369 100 488,41	2 037 824 611,99
SA Water Demand for CRMs (m^3) - Net Zero Emissions by 2050 Scenario (HIGH)	6 803 282 201,60	234 595 937,99	422 184 141,54

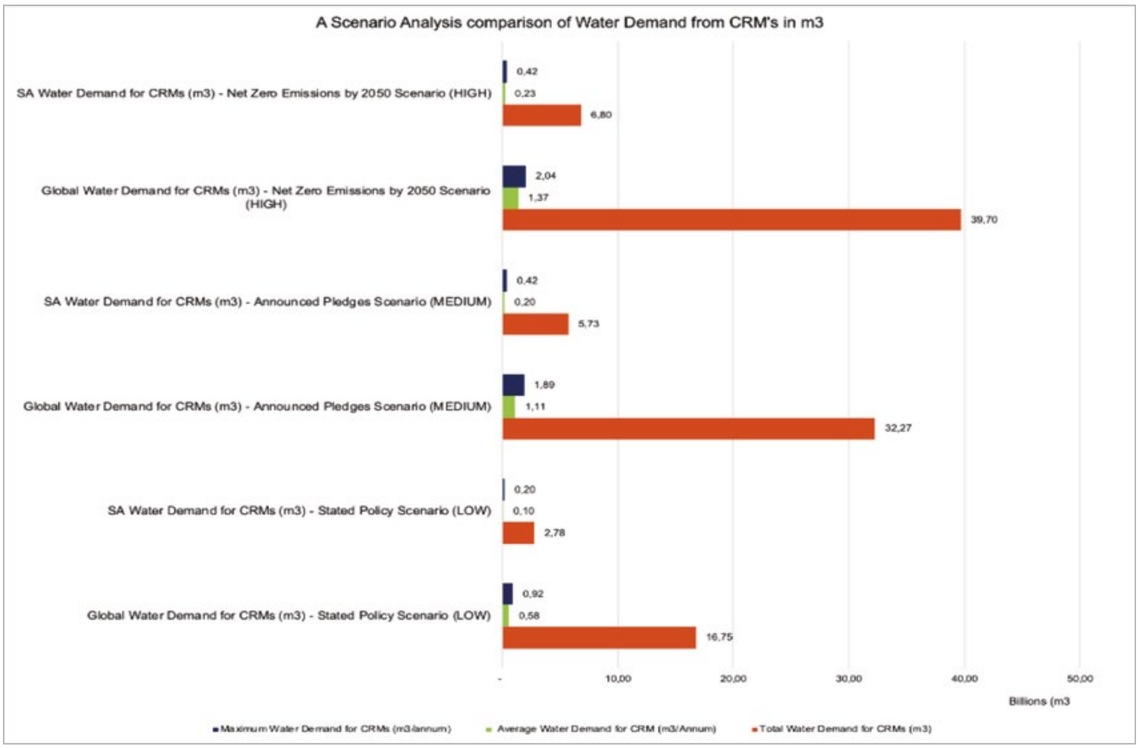


Figure 29: Water demand attributed to CRMs mining for green hydrogen demand based on the IEA policy scenarios

The result in Figure 29 above highlights the impact of water in relation to the demand for CRMs according to the IEA's policy scenarios. Firstly, a gradual increase in water demand is observed as CRMs demand increases to meet the policy requirements for the green hydrogen transition. This is true for both South Africa and globally.

6.3.4 Predicted Land Impacts

Finally, land impacts associated with CRMs demand are assessed. To measure the magnitude of land impacts, a rock to waste ratio is used as a proxy factor. The rock to water ratio does not estimate impacts associated with infrastructure but rather with mining; this is because the most intensive part of meeting the policy scenario will be mining and using rock to waste ratios that are well known and are readily available, land impacts can be assessed thereof. Using the rock to waste ratios multiplied by the demand for the specific mineral, a figure denoting the total amount of material used to mine for a specific mineral is produced. By adding these total amounts, land impact can be highlighted in tonnes of material produced as a result of mining CRMs for the green hydrogen transition.

Table 4: Predicted land impacts of CRMs mining

	Total RMR for CRMs (t)	Average RMR for CRMs (t/Annum)	Maximum RMR for CRMs (t/annum)
Global RMR for CRMs (t) - Stated Policy Scenario (LOW)	43 724 663 966,14	1 507 747 033,32	2 661 598 826,48
SA RMR for CRMs (t) - Stated Policy Scenario (LOW)	11 171 634 470,55	385 228 774,85	871 717 086,28
Global RMR for CRMs (t) - Announced Pledges Scenario (MEDIUM)	84 186 841 852,41	2 902 994 546,63	5 443 032 518,97
SA RMR for CRMs (t) - Announced Pledges Scenario (MEDIUM)	21 796 354 288,12	751 598 423,73	1 780 775 466,79
Global RMR for CRMs (t) - Net Zero Emissions by 2050 Scenario (HIGH)	102 333 839 311,57	3 528 753 079,71	5 910 381 725,28
SA RMR for CRMs (t) - Net Zero Emissions by 2050 Scenario (HIGH)	21 138 636 461,67	728 918 498,68	1 526 818 548,32

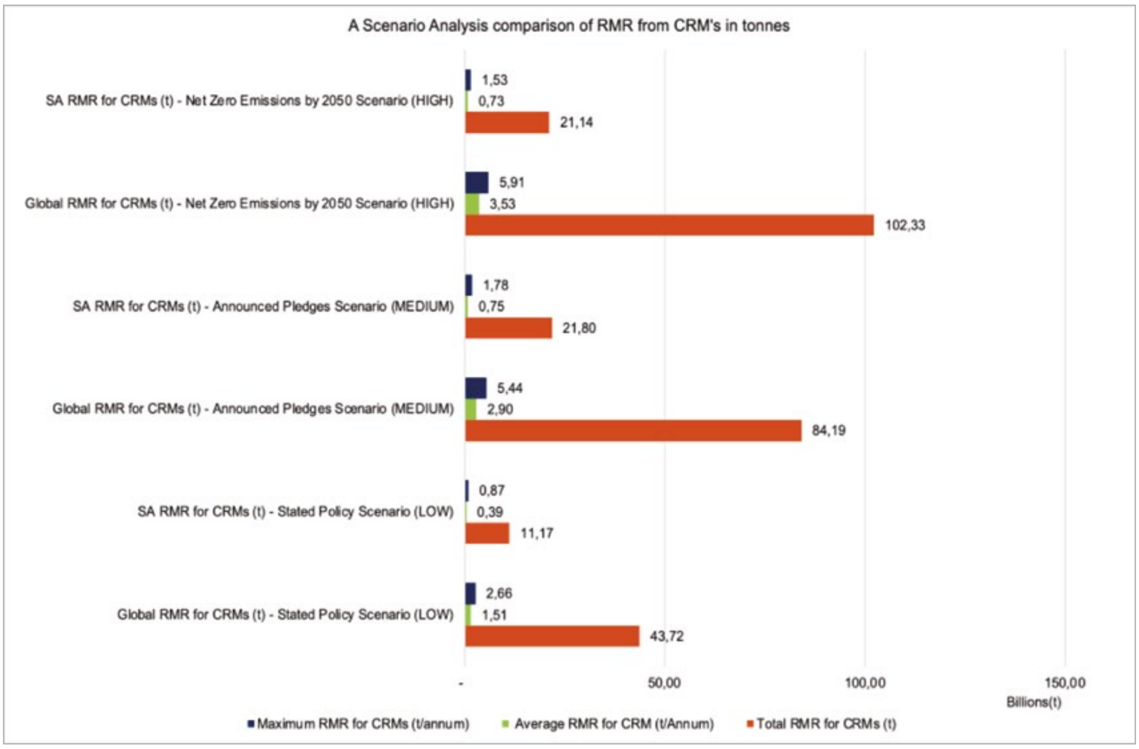
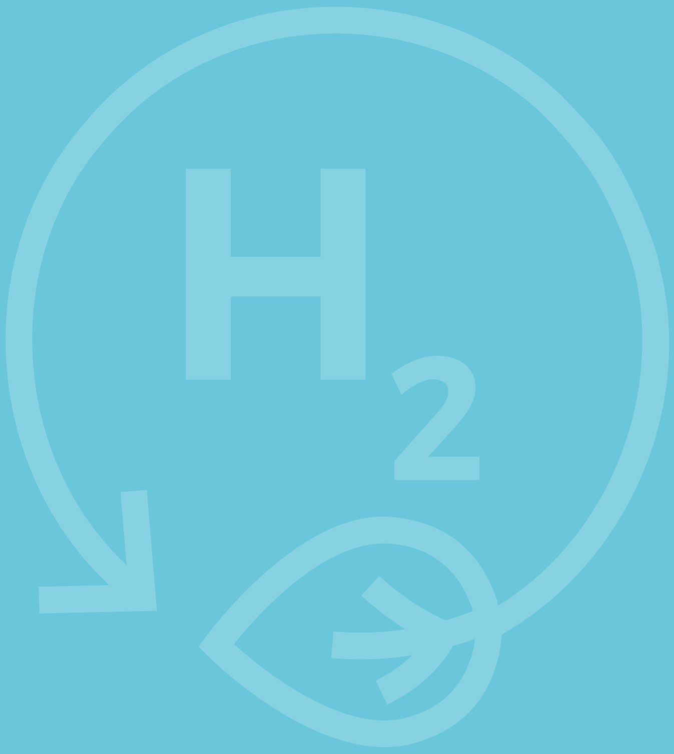


Figure 30: Land demand attributed to CRMs mining for green hydrogen demand based on the IEA policy scenarios

Figure 30 shows an increase in land use as green hydrogen policy requirements move towards a net-zero scenario. The intensity of mining increases sharply from the stated policy scenario to the announced pledges scenario due to demand for critical minerals in the short-term, but then the magnitude of the increase between the announced pledges scenario and the net zero emissions scenario is lowered. This trend is expected to be the outcome of an increase in recycling activity that promotes less land use closer to the net zero scenario.

Chapter 7

Socio-Economic Impacts of CRMs Mining



7. Socio-Economic Impacts of CRMs Mining

The mining industry plays a pivotal role in the economic development of numerous regions by providing substantial employment opportunities, contributing to community development, and supporting local businesses. However, the industry's considerable economic benefits are accompanied by significant negative social and environmental impacts, particularly in the areas of health, safety, and environmental degradation.

Globally, organisations like the United Nations (UN), the Stockholm Environmental Institute (SEI), and the International Institute for Environment and Development (IIED) have invested significant effort into documenting the broader impacts of mining, especially in relation to the green energy transition. This body of literature not only highlights the effects of mining on local communities but also underscores the potential for responsible mining practices when aligned with the SDGs. By adhering to international best practices, standards, and the overarching goals of the SDGs, the adverse effects of mining on both communities and the environment can be mitigated. This alignment promotes sustainable mining practices, creating pathways toward a more equitable and environmentally conscious industry.

7.1 Mining in South Africa: Economic Contributions and Challenges

Mining has long been a cornerstone of economic and technological development in South Africa, contributing significantly to the country's GDP and fiscal revenues. In 2022 alone, mining company tax contributions reached R74 billion, with royalties increasing to R14 billion. The sector's contribution to GDP grew by 4%, amounting to nearly R494 billion, which represented 7.53% of South Africa's total GDP (Minerals Council, 2023).

Despite these substantial economic gains, the mining industry faces equally significant socio-economic and environmental challenges. South Africa's rich mining legacy has also left a trail of adverse impacts. Mining activities are often associated with severe environmental degradation, including GHG emissions, biodiversity loss, land degradation, and water pollution (Kitula, 2005). These environmental issues have a direct effect on human health and exacerbate land scarcity, further hindering settlement development (Asare & Darkoh, 2001). Unsustainable mining practices pose long-term risks to both the environment and socio-economic growth (Anochie & Kathuria, 2021).

The challenges facing the sector extend beyond environmental concerns. Financial difficulties often impede mining companies' ability to comply with environmental regulations and support affected communities. Pressing social issues, such as child labour and the erosion of women's and indigenous peoples' rights, also remain critical concerns. Additionally, the industry's exposure to volatile prices, geopolitical tensions, and the pressure to expand into ecologically sensitive areas further complicates efforts to achieve a sustainable energy transition.

7.2 The Shift Toward Responsible Mining Practices

Historically, South African mining operations have tended to overlook the social and environmental repercussions of their activities. However, contemporary companies are increasingly recognising the need for community development strategies aimed at mitigating these negative effects and improving relations with affected communities. These strategies are designed to address the evolving social challenges facing the industry and reflect institutionalised motives to balance the economic benefits of mining with its social and environmental costs. Such initiatives are especially critical for supporting indigent and vulnerable populations who bear the brunt of mining's adverse impacts (Anochie & Kathuria, 2021).

7.3 Health and Safety Impacts of Mine Affected Communities

Mining operations cause significant environmental disruptions across South Africa which lead to severe health consequences for local communities. Common environmental challenges include land degradation, deforestation, and water pollution caused by the release of harmful chemicals and HMs. These environmental issues contribute to the deterioration of vital ecosystems that local populations rely on for water, food, and economic activity (UNDP, 2016; SEI, 2018).

In South Africa, the depletion of natural resources, such as water and soil nutrients, particularly affects agricultural productivity, which is often the backbone of rural livelihoods. This environmental degradation not only threatens food security but also has far-reaching effects on community health and well-being, exacerbating vulnerabilities in areas that are already struggling with resource scarcity (SEI, 2018). Indigenous and marginalised communities in South Africa face some of the most severe health and social impacts from mining. These communities often live close to mining operations, relying on local ecosystems for their livelihoods. The contamination of water sources and deforestation in these areas devastates their ability to sustain traditional lifestyles and leads to long-term health problems. For example, in South Africa's Limpopo Province, HM contamination from nearby mining operations has been directly linked to increased cases of respiratory illnesses, skin conditions, and other chronic health issues (Machete *et al*., 2017). According to a report by Chanda-Kapata (2020), respiratory diseases in school children, pre-term births in women, and increased hospitalisations and deaths in children and women living around dump sites have been observed.

The environmental degradation also worsens food insecurity and limits access to clean water, compounding health issues for these populations. Vulnerable communities often lack access to adequate healthcare, leaving them to manage the severe consequences of mining-related health complications on their own. Additionally, it has been observed that displaced communities in South Africa often have poorer nutritional and health outcomes which is particularly pronounced in children (Chanda-Kapata, 2020).

7.3.1 Water Contamination and Public Health Risks

Water contamination is one of the most severe health risks caused by mining in South Africa. The country's mining operations often result in AMD and the leaching of toxic substances, such as HMs, arsenic, and cyanide, into water sources. These pollutants, common in regions like Rustenburg, make water unsuitable for drinking, farming, and other essential uses. This contamination significantly increases the risk of waterborne diseases and disrupts access to clean water, which is already a limited resource in many rural South African communities (Singh & Singh, 2016).

Water scarcity resulting from pollution also impacts agricultural productivity and industrial processes, putting additional pressure on food security and the local economy. Communities that depend heavily on water for irrigation and livestock are left with few options, increasing their vulnerability to malnutrition and other health-related challenges.

7.3.2 Occupational Health and Safety risks of Miners

In mining-intensive areas of South Africa, poor air quality poses a significant health risk. Emissions of particulate matter from activities such as drilling, blasting, and ore processing release harmful pollutants into the air. In towns like Rustenburg, where mining is prevalent, prolonged exposure to dust and toxic gases results in widespread respiratory conditions, such as asthma and silicosis. These diseases are especially common among mineworkers but also affect surrounding communities (Singh & Singh, 2016).

The poor air quality not only puts immense pressure on local healthcare systems but also leads to long-term health problems that often go untreated due to inadequate medical infrastructure. These impacts are felt most acutely in poorer, rural areas, where health services are already strained.

Occupational health risks are rampant in the South African mining sector. Mineworkers are frequently exposed to highly polluted air resulting in respiratory diseases like tuberculosis (TB), silicosis, silico-TB, asthma, and chronic obstructive pulmonary disease (Chanda-Kapata, 2020). These diseases are prevalent among miners due to their long-term exposure to dust, pollutants, and unsafe working environments. Noise-induced hearing loss (NIHL) is also a significant issue. These occupational health problems have broader social impacts, as workers often bring illnesses home to their families and communities, further exacerbating public health challenges (Northam, 2023).

Miners working in operations that expose them to manganese dust and fumes are at risk of developing severe neurological conditions, such as manganism. Manganism, which presents with symptoms similar to Parkinson's disease—including slow motor movement, depression, and anxiety—affects many South African miners, especially those working in manganese-rich areas like the Northern Cape. Despite the severity of this condition, protection for workers is often inadequate, leading to long-term health issues that impact both the workers and their communities (South African Resource Watch, n.d).

The use of diesel engines is highly prolific in mines in the country which results in high diesel particulate matter pollution. Newer information on the specific amounts of diesel particulate matter is scarce, however, a study by van Niekerk *et al*. (2002) found that elemental carbon concentrations in two platinum mines exceeded the American Conference of Governmental Industrial Hygienists (ACGIH) guideline, and as well as the National Institute for Occupational Safety and Health (NIOSH) guidelines. Diesel particulate matter has been linked to cardiovascular dysfunction; ear, nose and throat irritation; asthma; nausea; and neurodegenerative diseases among mineworkers (Chanda-Kapata, 2020).

In addition to neurological disorders, South African miners face long-term damage to vital organs, including the kidneys, lungs, and liver, due to their exposure to dangerous chemicals in mining environments. The failure to provide adequate health and safety protocols leaves many workers vulnerable to life-threatening illnesses, which often go untreated or undiagnosed until the damage is irreversible.

Additionally, the influx of transient workers into South African mining towns facilitates the spread of communicable diseases, particularly HIV/AIDS. This influx often overwhelms local health systems that are underprepared to cope with rapid population growth and the resultant rise in disease transmission (SEI, 2018). Additionally, limited access to social services in a platinum mining area as well as long working hours and harsh working conditions have been associated with stress and poor health among mineworkers (Chanda-Kapata, 2020).

7.3.3 Social and Health Consequences of Climate Change Exacerbated by Mining

The South African mining industry is a significant contributor to the country's GHG emissions, which exacerbate climate change and its related health impacts. The reliance on coal-powered energy for mining operations amplifies South Africa's carbon footprint, contributing to rising temperatures, altered weather patterns, and increased natural disasters. These shifts particularly impact rural and indigenous communities, which are already vulnerable to environmental changes (SEI, 2018). Moreover, the coal mining needed to supply Eskom's coal powered fleet and as a result power the CRMs mining operations has been linked to coal dust-related pneumoconiosis in miners (Chanda-Kapata, 2020).

Climate change, driven in part by mining activities, leads to food insecurity, malnutrition, and the spread of diseases, further stressing the country's already fragile healthcare system. South Africa's mining sector, which consumes nearly a third of Eskom's coal-generated power, plays a crucial role in shaping the country's climate-related health risks (South African Resource Watch, n.d).

7.4 Employment, Development and Economic Impacts

The mining industry is associated with a range of socio-economic benefits, including infrastructure development, manufacturing growth, and employment opportunities. The Mining Charter emphasises BEE ownership, mandating a minimum of 30% BBEE shareholding for new mining rights. This provision is designed to empower historically disadvantaged individuals and promote economic inclusion. By advocating for local content and supplier development, CRMs mining significantly contributes to community upliftment, enhancing economic participation and creating employment opportunities.

Mining companies are often committed to improving skills and opportunities for mine communities and labour-sending areas. They often make substantial investments in local economic development initiatives, focusing on safety, security, health, environmental management, income-generating projects, education, and basic infrastructure (Northam, 2023). For instance, Northam Platinum's Corporate Social Investment (CSI) programmes support charities, non-governmental organisations (NGOs), research institutions, and social programmes in arts and education (Northam, 2023). Similarly, Anglo American emphasises sustainable community development through initiatives such as the Anglo-American South Africa Community Trust, which funds local development projects (Anglo American, 2023).

Another example of the economic and developmental impacts that mining companies can exert is through widespread use of community trusts, which are established to provide equity ownership to local communities and direct the financial benefits of mining towards sustainable development projects. These trusts can have a significant economic impact, provided they are well-governed and effectively managed.

For instance, Sibanye-Stillwater, a global precious metals miner, has consolidated its community trusts under the newly formed Sibanye-Stillwater Group Development Trust. This trust is responsible for implementing CSI programmes, ensuring that communities benefit from the mine's activities during its operational phase and after its closure. Additionally, at their Rustenburg operations, community trusts hold a substantial 26% shareholding, demonstrating a strong commitment to local economic participation. In Marikana, community ownership schemes like the Bapo ba Mogale Local Economic Development Trust ensure that local communities are direct beneficiaries of mining activities, focusing on projects such as regional agri-industrial development and community-based supplier support.

Similarly, Anglo American Platinum has launched its Lefa la Rona Trust as part of its Project Alchemy initiative. This trust acts as a vehicle for community development in areas surrounding its mines, such as Dishaba, Mogalakwena, and Rustenburg, contributing to health, education, and poverty relief programmes. Through these initiatives, the trust distributes economic benefits and aims to ensure long-term community upliftment.

Northam Platinum also highlights the role of mining in fostering local development. The Zambezi Platinum Trust, created to maintain BBEE credentials, includes community trusts such as the Northam Zondereinde Community Trust and the Northam Booysendal Community Trust. Despite criticism regarding its governance and allegations of fronting, Northam's efforts to invest in skills development and community projects highlight the potential for community trusts to create economic benefits.

Impala Platinum's engagement with the Marula Community Trust, aimed at the social and economic upliftment of the Tubatse community, demonstrates how mining companies support not just employment but broader socio-economic development. This trust focuses on education, enterprise development, and health, although financial challenges have delayed some of its intended impact.

Mining companies also provide extensive skills development and education programmes, including adult education and training (AET), scholarships, bursaries, internships, learnerships, and apprenticeships (Northam, 2023). These initiatives extend beyond employees to community members, enhancing their skills and improving employability. For example, AET programmes aim to improve literacy and numeracy skills, enabling community members to secure better job opportunities (Northam, 2023). Impala Platinum also offers vocational training and educational scholarships for local youth (Impala Platinum, 2023).

Notably, the mining industry generates numerous job opportunities, significantly reducing unemployment in local communities. Northam Platinum employs a large workforce and implements preferential procurement policies to source a substantial portion of capital goods, consumables, and services from BEE entities, fostering the growth of local businesses (Northam, 2023). This approach boosts the local economy and promotes the inclusion of historically disadvantaged individuals in the region's economic activities. Anglo American and Impala Platinum have similar initiatives aimed at supporting local suppliers and creating jobs in their operating communities (Anglo American, 2023; Impala Platinum, 2023).

In Rustenburg, which lies on the Platinum mining belt, mining employment increased from 46,000 in 1996 to 96,000 in 2012, although it dropped to 75,000 by 2019 (Marias *et al*., 2021). This significant increase in employment highlights the mining sector's role in job creation and economic development in the region. The average household income in Rustenburg in 2015 was R194,414, higher than the provincial average of R151,596 and the national average of R181,579 (Marias *et al*., 2021).

7.4.1 Distribution of Economic Benefits

Despite these contributions to the local economic development of communities, there is still a sense that indigenous communities often receive minimal economic gains compared to the substantial profits reaped by mining companies. Mnwana (2014) discussed how job creation in mining is typically limited to low-wage positions that do not offer long-term stability. Additionally, the shift from traditional livelihoods to mining-related jobs disrupts social structures and increases dependency on the cash economy, weakening community cohesion.

Moreover, the economic benefits that do accrue from mining are often short-lived and may not lead to sustainable development for the communities. Once the mining operations cease, the communities are left with degraded lands and limited economic opportunities. The boom-and-bust cycle of mining economies can leave communities worse off than before the mining began, with depleted resources and a degraded environment that is less capable of supporting traditional livelihoods (Machete *et al*., 2017).

In South Africa, an argument can be made that SLP guidelines and the BBEE scorecards are heavily based on how much companies spend rather than the impact or effectiveness of that spending (Corrigan, 2019). This focus on spending targets can result in two potentially negative outcomes. First, companies might direct more funds to projects that are easier to execute to meet spending targets. For instance, an analysis of AngloGold Ashanti's annual reports to the government disclosed actual spending on projects per year. When compared with initial SLP spending plans, it was evident that while total SLP spending was larger than initially planned, this was achieved through extreme overspending in some proposed activities that do not require long-term management or follow-up, such as small loans to local entrepreneurs and one-time infrastructure improvements (Corrigan, 2019). Conversely, there was extreme underspending in more challenging but potentially more beneficial activities, such as sustainable infrastructure development and local economic growth programmes that require community and local government participation (Corrigan, 2019).

Secondly, projects may be less efficient because operations focus on achieving total spending targets rather than maximising performance per dollar spent. This approach can be detrimental from a corporate perspective as it prioritises expenditure over the actual benefits and sustainability of the projects (Corrigan, 2019).

7.5 Community Participation in Decision Making

The importance of involving local communities in decision-making processes related to mining operations cannot be overstated. The IIED highlights that effective community participation ensures that the rights and interests of local and indigenous communities are respected, reducing the potential for conflict and fostering trust between the community and mining companies. Genuine involvement in decision-making processes can mitigate many of the social, environmental, and health impacts that are often associated with mining activities.

In the South African context, legal frameworks such as the Mineral and Petroleum Resources Development Act (MPRDA) and the Social and Labour Plan (SLP) system are intended to provide mechanisms for community consultation and participation. However, these frameworks often fail to translate into meaningful engagement, and local communities—particularly indigenous populations—remain marginalised. Free, prior, and informed consent (FPIC) principles, while recognised in policy, are not consistently implemented, leading to decisions that often benefit mining companies and government entities at the expense of community well-being (Mnwana, 2014; Chipagamante, 2020).

CSR initiatives are also designed to incorporate community needs and concerns. Yet, as research indicates, these initiatives are frequently seen as superficial or tokenistic, as they fail to address the fundamental power imbalances and environmental impacts that shape community perceptions of mining. Ensuring that community participation is not only a legal requirement but also an ethical priority is key to improving relations and outcomes for all stakeholders involved in mining activities (Northam, 2023; Impala Platinum, 2023).

7.5.1 Power Dynamics and Decision Making

Indigenous communities often face marginalisation in decision-making processes related to mining activities. Despite legal frameworks that mandate consultation and consent, such as FPIC policies, the actual implementation is often inadequate. Research indicates that community consultations are typically superficial and do not translate into meaningful participation or influence over decisions affecting their lands and livelihoods (Chipagamante, 2020; Mnwana, 2014). This lack of genuine engagement fosters resentment and resistance among community members, as they feel their rights and voices are ignored in favour of corporate interests (Mnwana, 2014).

In many cases, the power dynamics are skewed in favour of mining companies and government entities that prioritise economic gains over the rights and well-being of indigenous communities. For instance, in the Philippines, indigenous communities have reported that consultations are often conducted in a manner that is inaccessible and intimidating, further marginalising their ability to participate effectively in decision-making processes (Mnwana, 2014). The imbalance of power often results in decisions that benefit external stakeholders at the expense of indigenous rights and interests.

Anglo Platinum's operations at the Mogalakwena Mine in South Africa's Limpopo Province vividly illustrate the failure to properly integrate and respect indigenous communities in mining decision-making processes. The mine, one of the world's largest platinum resources, has been a focal point of substantial controversy due to its resettlement practices and poor community engagement strategies. These issues stem from a corporate focus that prioritises technical and logistical facets of operations over relational and communicative components essential to community relations (Farrell *et al.*, 2012).

The resettlement actions surrounding the mine were marked by conflict, with local communities feeling that their rights and needs were sidelined to expedite corporate operations. This has led to significant unrest and long-term damage to the company's reputation. Anglo Platinum's approach, while often meeting the minimum legal standards, did not equate to ethical or fair outcomes for affected communities, demonstrating a lack of genuine dialogue and consent from those impacted (Farrell *et al.*, 2012).

Furthermore, the company's insensitivity to the cultural and social dynamics of the Limpopo Province communities exacerbated tensions, highlighting a critical need for mining corporations to respect and integrate local cultural norms and practices into their operational strategies. The Anglo Platinum case underscores the importance of mining companies adopting more inclusive, respectful, and genuinely participatory approaches to community engagement, crucial not only for ethical reasons but also for the sustainability of their operations.

Corrigan (2019) highlights that in South Africa there are very few formal entry points for communities or local government to be directly involved in the SLP process, and the requirements for "consultation" are very vague. Moreover, communities are represented by a variety of actors, and the onus is often on the company to determine with whom to consult and who has the power to present a risk to the company. Often there is no standard process for engagement, and it is ultimately up to the community engagement coordinator. This means the communities directly affected are not involved in a uniform way. Even at the one point in the SLP process where local governments and communities have a formal voice (i.e., designing an Integrated Development Plan or IDP), municipalities often lack the capacity to ensure that IDPs reflect actual priorities (Corrigan, 2019).

These plans often do not include marginalised groups in their consultations, fully incorporate intergovernmental transfers, accurately budget projects, or collect enough information to make accurate forecasts about needs and costs. While companies must submit their SLPs to the national government, approved SLPs are often not even given to the local governments or communities, creating a significant barrier to achieving transparency (Corrigan, 2019).

This lack of transparency and genuine engagement in decision-making processes shows the power imbalances that exist, which often lead to decisions that do not favour indigenous or local communities.

7.5.2 Community Perceptions and the Social License to Operate

Community perceptions of mining are largely negative due to the adverse impacts on their livelihoods and environment. Research by Mnwana (2014) and Seloa and Ngole-Jeme (2022) suggests that CSR initiatives by mining companies are often perceived as insufficient and tokenistic. These initiatives, while intended to mitigate negative perceptions, do not address the fundamental issues of power imbalance and lack of meaningful engagement. The communities often view these efforts as superficial attempts to placate them without making substantial changes to the harmful practices of the mining operations.

CSR initiatives are frequently criticised for being more about public relations than about making real, substantive changes that benefit the communities. For instance, CSR projects that focus on building schools or clinics, while beneficial, do not compensate for the loss of land, environmental degradation, or the disruption of social structures. Furthermore, these projects are often implemented without genuine consultation with the communities, leading to solutions that do not fully meet the communities' needs or address their primary concerns.

Corrigan (2019) expands on this by highlighting the limitations faced by local actors in their ability to gather information and monitor the implementation of these CSR initiatives. These actors, along with the central government, are often underrepresented, understaffed, or underutilised, which further underlines the asymmetry of the regulatory relationship. This lack of capacity hampers their ability to hold mining companies accountable for delivering real community benefits. Although regulations may increase overall social spending, suggesting enhanced community benefits on paper, the absence of local involvement in the process raises questions about the actual impact of these expenditures (Corrigan, 2019). Authentic citizen involvement is crucial to making social spending more relevant to the needs of the community and ensuring that citizen expectations are realistic, thus strengthening a company's social license to operate (Corrigan, 2019).

7.5.3 Legal and Procedural Rights

The protection of procedural rights for indigenous people is crucial in mitigating the adverse impacts of mining. Legal frameworks such as FPIC are designed to ensure that communities have a say in projects affecting their lands. However, implementation is often inconsistent, leaving many communities vulnerable to exploitation and marginalisation (Mnwana, 2014). Ensuring robust legal protection and their enforcement is essential for safeguarding the rights and well-being of indigenous communities. Additionally, it is seldom that customary or traditional systems of legal practice are well implemented into the way both the state and mining companies approach the rights of indigenous people.

In South Africa, the post-apartheid mineral legislation, specifically the MPRDA, addresses these issues by establishing requirements for community consultations. Sections 10(1)(b), 16(4)(b), 22(4)(b), 27(5)(b), and 39 of the MPRDA mandate the government and mining companies to facilitate public participation or consultations with communities before granting mining and prospecting rights, ensuring that their concerns are addressed and integrated into mining operations. Despite these legal mandates, challenges remain in the effective integration and enforcement of these protections. The MPRDA attempts to redress economic inequalities, with the state as custodian of mineral resources, encouraging mining companies to convert community interests into equity. However, equity deals are often contested due to perceptions of state capture and prioritisation of elite interests, leading to a dominance of mineral rights by traditional capital structures (Ubink & Pickering, 2020). The state grants mining licenses and encourages mining companies to convert community interests and royalties into equity. However, many of these equity deals are contested by community members due to perceptions of state capture and the prioritisation of the black elite and traditional leaders, leaving the majority of mineral rights under the control of white capital (Ubink & Pickering, 2020).

The Interim Protection of Informal Land Rights Act (IPILRA) was enacted to protect people with insecure land tenure due to past discriminatory laws, yet it is often ignored in favour of the MPRDA. Traditional leaders claim the right to conclude deals based on customary law, however, these agreements are regulated by state law, leading to the corporatisation of traditional authority and a lack of transparency in revenue streams and community participation (Ubink & Pickering, 2020). This reality shows that there is a real challenge in the context of South Africa in not only integrating state law effectively to address community needs but also in the added complexity of a pluralistic legal system which ensures the accommodation of customary laws.

Globally, the impacts of mining on indigenous communities reflect similar patterns of exploitation, marginalisation, and environmental degradation. In Canada, tar sands extraction has led to the displacement of indigenous communities, cultural erosion, and health problems due to environmental pollution. In Latin America, precious metal mining has resulted in violent conflict, environmental degradation, and social upheaval. These issues are indicative of broader structural inequalities and power imbalances that need to be addressed through comprehensive and inclusive policies (Mnwana, 2014).

Despite these concerns, CSR reports suggest that local communities and indigenous groups are increasingly involved in decision-making processes related to mining activities. Mining companies engage with these communities through consultations to ensure their needs and concerns are addressed in the development and implementation of community projects. IDPs guide the alignment of community development projects with local needs and priorities, ensuring that the benefits of mining activities are shared equitably (Northam, 2023; Impala Platinum, 2023).

7.6 Displacement, Land-use Conflicts, and Cultural Heritage in Mining

Large-scale mining projects are widely recognised for displacing local populations, leading to the loss of homes, livelihoods, and community cohesion (Hilson, 2002; IIED, 2020; SEI, 2018). This displacement often causes significant long-term socio-economic disruption, especially when communities are not adequately compensated or relocated. The IIED (2020) stresses that when agricultural land, homes, and community infrastructure are lost due to mining activities, the social fabric of affected communities can be severely damaged.

A key challenge in mining regions is the emergence of land-use conflicts, as the demands of mining operations often clash with local land-use practices. These conflicts are particularly acute in developing countries, where regulatory frameworks are weak and government intervention is minimal. Competing interests between mining companies and local communities lead to the displacement of indigenous people and the destruction of livelihoods tied to the land, such as agriculture and small-scale fisheries. The social tension that arises from these conflicts can escalate into violence, especially in areas already prone to high conflict (Hilson, 2002).

Poor communication, environmental accidents such as chemical spills, and tailings dam failures frequently exacerbate these land-use conflicts. The displacement of local populations, contamination of water sources, and destruction of agricultural land disrupt not only the livelihoods of affected communities but also their social structures and traditional ways of life. This dynamic is particularly pronounced among indigenous people, who have deep cultural ties to their land. The loss of these lands undermines both their physical and spiritual connection to the environment, worsening social tensions (Hilson, 2002).

7.6.1 Cultural and Heritage Site Destruction

Mining operations frequently threaten the preservation of cultural and heritage sites, which hold significant value for local and indigenous communities. The UNDP emphasises that the loss of cultural heritage, whether through physical destruction or disruption of traditional practices, has profound social and psychological impacts on affected communities (UNDP, 2016). Mining often disrupts these cultural practices, leading to the erosion of cultural identities and the loss of intangible heritage (UNDP, 2016).

The SEI similarly highlights the importance of protecting archaeological and cultural sites in mining areas, noting that the destruction of these sites leads to the irreversible loss of historical knowledge and cultural heritage. Such losses not only have cultural ramifications but also weaken the social cohesion and identity that communities rely on for their resilience (SEI, 2018).

A notable example of this dynamic is found in the Bakgatla-ba-Kgafela community in the Pilanesberg region. Platinum mining has caused significant disruptions to sacred sites and traditional lands. The Heritage Impact Assessment (HIA) for the Pilanesberg Platinum Mine (PPM) revealed that key heritage resources, such as Late Iron Age stone-walled sites and an abandoned historical graveyard, have been adversely affected by mining activities. For instance, a stone-walled site was partially destroyed during road construction, and a graveyard had to be relocated due to mining operations (Pistorius, 2013).

7.6.2 Cultural Erosion and Fragmentation

The displacement of the Bakgatla-ba-Kgafela is not only a matter of physical relocation but also involves cultural erosion. The post-apartheid legislation, which has granted traditional chiefs increased power over communal land, has intensified land disputes, particularly regarding the control and distribution of mining revenues. Chiefs, as custodians of communal land, now wield significant authority over both cultural heritage and economic opportunities tied to mining. This dual role has led to internal community conflicts, particularly regarding transparency and fairness in revenue distribution (Mnwana, 2018).

The community has also experienced fragmentation, as younger generations grow increasingly disconnected from their cultural roots. With less access to ancestral lands and knowledge systems, the cultural practices tied to these landscapes are slowly eroding (Claassens & Matlala, 2014). The lack of meaningful consultation with community members about land use and mining agreements has deepened feelings of alienation, especially as traditional leadership is often seen as corrupt and unaccountable. Resistance to the role of chiefs in negotiating mining deals has further exacerbated tensions within the community (Mnwana, 2018). A study by Machete *et al.* (2017) on the environmental and social impacts of mining in Limpopo reveals similar trends. The introduction of mining can disrupt local economies and social dynamics, leading to increased inequality and social tensions. The displacement and resettlement of communities often result in the breakdown of traditional social networks and support systems.

Ultimately, the erosion of cultural heritage is not just a byproduct of physical displacement but reflects deeper tensions between traditional governance structures, modern economic pressures, and the survival of cultural practices in South African communities affected by mining.

7.7 Impact of Mine Closure

The closure of mines can also have severe negative impacts on communities, often exacerbated by poor planning and inadequate post-closure strategies. Mining operations typically lead to rapid economic and population growth, which bring about increased urban crime and social issues. However, insufficient attention is paid to the social disruption that can accompany mine closures (Marais *et al.*, 2021). Mining towns are characterised by high population growth, outmigration of residents, increased demand for short-term housing, and a predominance of young men. When mines close, these towns often experience significant social disruption, including elevated crime rates, which can surpass those of larger metropolitan areas. This disruption is partly due to the reluctance of mining companies and governments to address the decline and plan for the future, including the often-inevitable closure of mines. During periods of economic growth, there is often a lack of foresight regarding the eventual downturn, leading to challenges in developing strategies for sustainable decline. Material dependencies, such as infrastructure and mine dumps created during mining booms, further complicate these strategies. Additionally, it must be mentioned that the mining sector, particularly the PGMs sector, is vulnerable to market disruptions, including fluctuating commodity prices. This can result in job cuts. For example, Implats shed 13,000 jobs at its Rustenburg operations, and Lonmin cut 12,600 jobs as of 2019 (Marias *et al*., 2021). This economic instability has adverse effects on the local communities that depend heavily on mining for employment. Consequently, the social and economic burdens of mine closures are frequently transferred to the affected communities and households, leading to prolonged periods of instability and hardship (Marais & De Lange, 2021).

7.7.1 Gendered Impacts of Mining

The mining industry has long been a male-dominated sector, with women only recently entering the workforce, particularly in underground roles. Despite legislative measures aimed at promoting gender equality, women in the mining industry continue to face significant challenges and gender-specific impacts.

To address the historical gender inequities in mining, the South African government has implemented various policy instruments to support women in the mining industry. This includes adopting several international and continental protocols, including the African Union's (AU) Agenda 2063 and the UN framework for SDGs. These frameworks, along with the SADC Gender and Development protocol, focus on and commit to achieving full gender equality. As a signatory, South Africa is therefore bound to implement appropriate gender-focused programmes and interventions in line with these protocols (IGF, 2023).

South Africa's commitment to gender equality is enshrined in its Constitution, which was adopted in 1996. The founding principles of the Constitution include human rights, equality, and freedom for everyone in South Africa. Section 9 of the Constitution specifically protects the rights of all persons to equal protection and benefit before the law and to freedom from unfair discrimination based on gender, pregnancy, and marital status, among others.

To further support gender equity, South Africa has developed several national policies and frameworks. The National Policy Framework for Women's Empowerment and Gender Equality (2000) outlines the country's vision for gender equality and how it intends to realise this ideal. It details overarching principles intended to be integrated by all sectors into their specific policies, practices, and programmes. This policy also proposed a framework for intersectoral coordination, gender mainstreaming, and mechanisms for monitoring and evaluation.

The National Development Plan (NDP), published in 2012, serves as South Africa's implementation vehicle for achieving the SDGs and identifies the active participation and empowerment of women as essential for transforming the economy. The NDP includes several gender-specific focus areas, such as prioritising public employment for unemployed women, promoting and supporting women leaders across sectors, improving service accessibility for women, ensuring women's protection under the law, and facilitating access to HIV treatment and other healthcare services.

In 2014, the Department of Women was established within the Presidency to oversee the implementation of gender equality policies. This department was later expanded in 2019 to become the Department of Women, Youth, and Persons with Disabilities, aiming to accelerate socio-economic transformation through oversight, monitoring, evaluation, and influencing policy.

The National Framework on Gender-Responsive Planning, Budgeting, Monitoring, Evaluation, and Auditing (2018) was prepared by the Department of Public Services and Administration (DPSA). This framework proposes compulsory gender-focused training courses for all senior management and public servants to ensure gender-responsive governance. In collaboration with UN Women, the DPSA is also developing an e-learning platform to increase the reach of these training programmes.

The South African mining industry is regulated by the MPRDA, No.28 of 2002, which includes provisions for the acquisition of rights to conduct reconnaissance, prospecting, and mining. The MPRDA emphasises the need for transformation within the industry, including the increased participation of women.

To give effect to the broad policy objectives for transformation in the mining industry set out in the MPRDA, the Broad-Based Socio-Economic Empowerment Charter for the South African Mining Industry (Mining Charter) was established. Initially published in 2004, the Mining Charter has been amended several times, with the latest version, Mining Charter III, being released for implementation.

7.7.2 Physical and Psychological Impacts

Women in mining communities, especially those near platinum mines, are disproportionately affected by physical and sexual violence. According to a study by Médecins Sans Frontières (MSF), intimate partner violence (IPV) and non-partner rape (NP-rape) are prevalent among women in Rustenburg, a major mining area in South Africa (Zhang *et al*., N.D.). The lifetime prevalence of IPV was found to be 45%, while NP-rape was reported by 18% of women (Zhang *et al*., N.D.). These forms of violence have severe health consequences, including high rates of HIV, major depressive disorder (MDD), and induced abortions (Zhang *et al*., N.D.) In Rustenburg, where 72% of the world's platinum is produced, women have been found to face higher risks of violence and health issues due to the male-dominated and transient nature of mining communities.

The barriers to accessing healthcare further exacerbate the impacts of sexual violence. Many women are unaware of the available health services, and the coverage of sexual violence healthcare services is limited (Zhang *et al*., N.D.). Only 10 designated facilities in the Bojanala District, which has a population of over 1.5 million, provide varying levels of care for sexual violence survivors (Zhang *et al*., N.D.). Consequently, only a small percentage of women seek medical help, with 5% reporting to healthcare professionals and even fewer to counsellors or social workers (Zhang *et al.*, N.D.).

Additionally, the patriarchal culture prevalent in many mining communities often leads to the subordination of women. This cultural backdrop influences workplace dynamics, where women's contributions are often undervalued, and their issues trivialised. For instance, women working at Impala reported that male colleagues would laugh and boo when female committee leaders tried to speak during meetings (Ntswana, 2015).

Moreover, the burden of domestic responsibilities further complicates the lives of women miners. Many female workers are single parents or primary breadwinners, juggling the demands of work and home. The irregular and demanding hours of work in the mining industry often conflict with their domestic duties, leading to increased stress and fatigue (Ntswana, 2015).

7.7.3 Economic and Occupational Impacts

Women working in mines face numerous occupational challenges that stem from deeply entrenched gender discrimination. Historically, mining was an exclusive preserve of men, and it was only after the end of apartheid in 1994 that women were allowed to work underground (Ntswana, 2015). Despite these changes, women are still marginalised by their male counterparts, unions, and mine management. Female workers often encounter inappropriate working gear, lack of dedicated sanitation facilities, limited opportunities for job elevation, and instances of verbal and sexual abuse (Ntswana, 2015).

The 2012 platinum strike highlighted both the marginalisation and the resilience of women in the mining industry. Initially excluded from strike activities and decision-making processes, women gradually became involved in workers' committees. Their participation was crucial in advocating for their rights and addressing gender-specific issues. However, women's involvement varied significantly across different mining companies. At Impala Platinum, women were initially excluded but later included under pressure of their male colleagues (Ntswana, 2015). At Lonmin, women were co-opted into committees only after many male leaders were killed during the Marikana massacre (Ntswana, 2015).

In contrast, at Anglo American Platinum (Amplats), women were included from the beginning in the formation of workers' committees. This inclusion was seen as a recognition of the significant role women played in the workforce and their potential contributions to negotiations and decision-making processes (Ntswana, 2015). Despite these advancements, women's participation often remained limited to support roles rather than direct negotiation with management.

7.7.4 Impacts of Mine Closure on Women

The closure of mines has a significant impact on local communities, particularly on women. Women often endure most of the social and economic disruptions caused by mine closures. According to a study on the impacts of mine closures, women in mining communities face increased financial insecurity, as they are often employed in auxiliary roles that are among the first to be affected during downsizing (Sesele *et al*., 2021). The loss of income exacerbates their vulnerability, making it difficult to support their families and meet basic needs (Sesele *et al*., 2021).

Moreover, the social fabric of mining communities can be severely affected by mine closures. Women, who often play a vital role in maintaining community cohesion, find it challenging to cope with the increased social tensions and instability. The lack of alternative employment opportunities and social support systems further compounds their difficulties. The report highlights that women are disproportionately affected by the loss of community services and infrastructure that were previously supported by mining companies (Sesele *et al*., 2021).

The environmental impacts of mine closures also disproportionately affect women. Abandoned mines can lead to environmental degradation, including water pollution and soil contamination, which directly impact the health and livelihoods of women who rely on local natural resources. The long-term environmental damage can make it difficult for communities to recover and rebuild sustainable livelihoods (Sesele *et al*., 2021).

7.7.5 Efforts to Mitigate Gender Specific Impacts

According to CSR reports, the mining industry has made concerted efforts to address gender disparities and promote the inclusion of women. These efforts include increasing the representation of women in various roles within the industry, particularly in management and technical positions (Northam, 2023). Specific programmes target the inclusion of women, ensuring that gender diversity is maintained and promoted within the workforce. For instance, Northam Platinum's Women in Mining programme aims to increase the number of women in technical and leadership positions, addressing gender imbalances in the workforce (Northam, 2023). Anglo American and Impala Platinum have similar initiatives aimed at promoting gender equality and supporting the career development of women in the mining industry (Anglo American, 2023; Impala Platinum, 2023).

Training and development programmes also prioritise the participation of women, with a particular emphasis on black women, to enhance their qualifications and career prospects (Northam, 2023). These initiatives are crucial in empowering women and providing them with the skills needed to succeed in the mining industry. Moreover, policies and programmes are in place to support and protect women in the mining workforce. These include safety measures, health programmes, and support systems for those affected by gender-based violence or discrimination (Northam, 2023). Such initiatives are vital in creating a safe and inclusive working environment for all employees. The company's commitment to gender equality is also reflected in its adherence to the principles of the Mining Charter, which emphasises the importance of increasing female representation in the mining sector (Northam, 2023).

Chapter 8

The Security and Resilience of CRMs Supply Chains

8. The Security and Resilience of CRMs Supply Chains

The South African Hydrogen Society Roadmap is the defining strategy aimed at positioning South Africa as a global leader in the green hydrogen economy. The roadmap outlines ambitious objectives and initiatives across various sectors to achieve a sustainable and inclusive transition to a hydrogen-based economy. The roadmap provides a prospective overview of South Africa's green hydrogen value chain and showcases where its green hydrogen industry will fit on a regional and global scale.

The roadmap envisions a future where South Africa leverages its abundant renewable energy resources to produce and export green hydrogen. It emphasises the decarbonisation of energy-intensive industries, transportation, and power sectors, while fostering socioeconomic development and job creation. The objectives of the roadmap include:

- **Decarbonisation of energy-intensive industry** Achieve net-zero carbon emissions in energy-intensive sectors by 2050.
- **Green and enhanced power sector** Install fuel cells and hydrogen storage to support renewable energy and grid stability.
- **Decarbonisation of heavy vehicles, shipping, aviation, and rail** Target net-zero carbon emissions and increase fuel cell vehicle adoption.
- **Hydrogen generation, storage, and distribution** Improve infrastructure for grey, blue, and green hydrogen technologies.
- **Creation of an export market for SA green hydrogen** Identify export opportunities and engage potential partners and investors.
- **Centre of excellence in manufacturing for hydrogen products** Develop a manufacturing strategy aligned with industry masterplans.

The key plans to achieve this include:

1. Establishing 10 GW of electrolyser capacity at the Boegoebaai SEZ by 2025–2026.
2. Consolidating community-owned land for renewable energy use to support electrolyser power supply.
3. Partnering with the private sector to build a green hydrogen pipeline system.
4. Developing regulatory frameworks to support zero-emission transport across all modes.

5. Implementing refuelling station pilots for buses, heavy goods vehicles, and taxis.
6. Conducting feasibility studies to develop demand-driven business cases for municipal transport and heavy goods vehicles.
7. Creating an export market for green hydrogen through international partnerships and infrastructure investments.

The roadmap's initiatives are underpinned by a commitment to gender and youth inclusion, research, development, and innovation, and just transition principles, emphasising the socioeconomic benefits and job creation potential of the green hydrogen economy.

This roadmap is a bold and forward-thinking strategy that aligns with global efforts to combat climate change and transition to sustainable energy sources.

To supplement the Green Hydrogen Society Roadmap, the Department of Public Works and Infrastructure announced in December 2022 that South Africa has listed nine strategic integrated projects (SIP) with Infrastructure South Africa (ISA) that relate to green hydrogen. The list includes the following:

1. The Prieska Power Reserve in the Northern Cape
2. The Ubuntu Green Energy Hydrogen Project in Northern Cape
3. Boegoebaai Green Hydrogen Development Programme in the Northern Cape
4. Atlanthia Green Hydrogen in the Western Cape
5. Upilanga Solar and Green Hydrogen Park in the Northern Cape
6. Sasolburg Green Hydrogen Programme in the Free State
7. SASOL HySHiFT (Secunda) in Mpumalanga
8. HIVE Ammonia in the Eastern Cape

Hydrogen Valley Programme of Anglo-American and their JV Partners (nine projects) along the Limpopo, Gauteng to KwaZulu-Natal Corridor.

These projects are also supplemented by a pipeline of other projects related to the green hydrogen value awaiting registration with ISA, and this list includes:

1. Mainstream Renewable Energy Hydrogen in the Western Cape
2. AMSA Saldanha Steel Hydrogen project in the Western Cape
3. Enertrag Postmasburg Project (Ammonia) in the Northern Cape
4. HDF Energy Renewable Energy, IPM 1 in Mpumalanga
5. Enertrag Indigen Project (e-methanol) in the Eastern Cape
6. Isondo Fuel Cell MEAs Manufacturing in Gauteng g. Isondo / NCP Vehicles in Gauteng
7. Saldanha Bay Green Hydrogen Project
8. Project Phoenix Fuel Cell Manufacturing in Free State
9. Cape Stack in the Western Cape
10. Bambili Hyplat Fuel Cell Manufacturing.

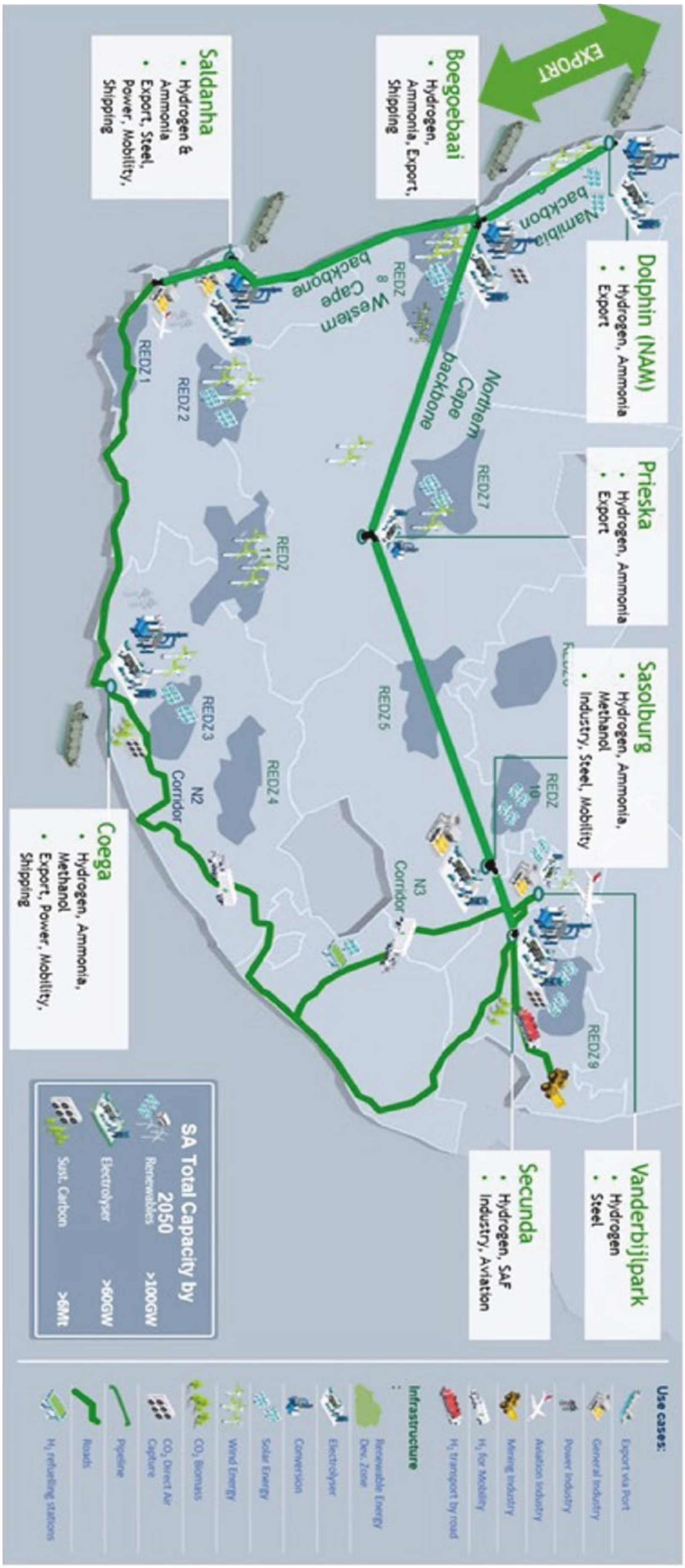


Figure 31: South Africa's green hydrogen project value chain (Source: NCGH2)

These 19 projects across South Africa demonstrate South Africa's intention to develop a green hydrogen economy and contribute to the global green hydrogen value chain.

The emphasis that green hydrogen requires industrialisation is something that has been picked up during our stakeholder engagements and is backed by supporting documents from South African Government entities. It is viewed that as defined by Infrastructure South Africa (ISA), green hydrogen is frontier 1 in the industrialisation and development of the South African economy, and the role of green hydrogen has expanded. Green hydrogen is now considerably viewed as a driver for green industrialisation.

The Hydrogen Valley Feasibility outlines a groundbreaking concept aimed at establishing a hydrogen valley in South Africa. This innovative initiative seeks to leverage hydrogen as a clean and sustainable energy source, with the potential to revolutionise the country's energy landscape. The proposed hydrogen valley is envisioned as a hub for hydrogen production, storage, and distribution, with the ultimate goal of driving economic growth and environmental sustainability.

The outcomes of this feasibility study are multifaceted, encompassing the identification of strategic locations for hydrogen infrastructure, an assessment of the technical and economic viability of hydrogen production, and an exploration of potential applications across various sectors. Moreover, the report delves into the socio-economic and environmental implications of establishing a hydrogen valley, highlighting the potential benefits for local communities and the broader South African society. The overarching purpose of this endeavour is to position South Africa at the forefront of the global transition towards clean energy, while simultaneously fostering job creation, industrial development, and energy security. By embracing the hydrogen valley concept, South Africa aims to unlock new opportunities for sustainable growth, reduce carbon emissions, and establish itself as a key player in the emerging hydrogen economy.

The HyShift Project is an aviation decarbonising project aimed at producing e-kerosene called sustainable aviation fuel (SAF). The consortium undertaking the HyShift project is led by Sasol but also includes Linde, Enertrag, and Hydregen. The project is located in Secunda and is focused on using Sasol's Fischer-Tropps process, a renewable energy input to produce e-kerosene. The SAF produced at Secunda will be used for refuelling Lufthansa and Swiss Air at OR Tambo as both airlines have committed to reducing their global aviation footprint.

These projects demonstrate the commitment of the South African Government and private entities in South Africa to cooperate and develop green hydrogen projects at scale. These initial projects have been brought past feasibility due to large collective efforts and growing collaborative initiatives to grow the green hydrogen economy in South Africa.

This has expanded by recent partnership agreements being signed by several South African provinces but also between South Africa and Namibia. These agreements aim to create linkages between the mining value chain (input of CRMs) and the green hydrogen value chain (project- and manufacturing-focused). The proposals aim to utilise local and regionally produced critical minerals in the manufacturing industry of the green hydrogen value chain to create a sustainable, industrialised green economy with the aim of bringing positive change to communities through job creation.

8.1 Resilience of South Africa's Green Hydrogen Value Chain

South Africa's ambition to become a global leader in green hydrogen is met with several significant supply chain barriers that slow progress and the development of its green hydrogen value chain. These barriers, which include long lead times for electrolysers, a shortage of skilled labour, inadequate project financing, limited local off-take opportunities, and insufficient energy transmission infrastructure are factors that weaken the resilience of the South African green hydrogen value chain.

- **Long lead time for electrolysers:** Electrolysers, essential for producing green hydrogen by splitting water into hydrogen and oxygen using renewable energy inputs, face extended lead times in the manufacturing, production, and shipping to the project site. These delays are a result of increasing global demand, technological constraints, manufacturing capacity, and logistical constraints. As a result, many South African projects may experience significant setbacks, impacting project timelines and increasing costs. This constraint can stall development and hinder South Africa's ability to rapidly scale up green hydrogen production within the compliance timeframes to meet international market demands.
- **Shortage of skilled labour:** The green hydrogen sector requires a specialised workforce with expertise in areas such as renewable energy technologies, chemical engineering, project design, health and safety, project maintenance, and energy systems management. South Africa faces a shortage of such skilled professionals, partly due to the scale of green hydrogen projects proposed and limited educational programmes specific to these project needs. This skills gap is a factor to consider in the long-term development of the green hydrogen industry.
- **Inadequate project financing:** Securing sufficient financing for green hydrogen projects remains a significant challenge. The high capital expenditure required for the installation of renewable energy, procurement of the electrolyser, infrastructure development, coupled with the uncertainty of the green hydrogen market has seen green hydrogen projects struggle to receive financing. The uncertainty surrounding the economic viability and long-term returns of green hydrogen projects further complicates financing efforts which are exacerbated by the high cost of capital.

Consequently, many promising projects struggle to move from conception to project development due to insufficient funding.

- **Shortage of local off-take opportunities:** Any commodity requires an off-take market, and this is no less true for green hydrogen. For the successful commercialisation of green hydrogen, a local market is needed to sustain the green hydrogen transition while also addressing socio-economic issues of an inequitable society in South Africa. However, South Africa currently experiences a shortage of local off-take agreements due to the relatively high cost of green hydrogen compared to conventional fuels and the slow adoption of hydrogen technology by local industries.
- **Lack of adequate energy transmission infrastructure:** The development of green hydrogen infrastructure is closely tied to the availability and reliability of energy transmission networks for the proposed energy wheeling that is being proposed in South Africa. South Africa's existing transmission infrastructure is often inadequate to support the large-scale deployment of renewable energy sources needed for green hydrogen production. This results in potential inefficiencies and seclusion of transmission networks that only service green hydrogen plants.

In conclusion, addressing these supply chain barriers is vital for advancing and unlocking the potential of South Africa's green hydrogen value chain.

8.2 Risks in South Africa's Critical Minerals Mining Value Chain

South Africa's critical minerals mining value chain faces several significant risks that threaten the stability and growth of the industry. These risks include challenges related to the export of CRMs through ports, energy security, the quality and quantity of known resources, financing for greenfields exploration, inadequate policy frameworks, and global market dynamics. Each of these factors plays a crucial role in shaping the competitiveness and sustainability of South Africa's mining sector:

- **Export of CRMs through ports:** The export of CRMs from South Africa is often hindered by logistical challenges at the Transnet ports. Inefficiencies in load management, ageing infrastructure, and poor coordination hamper the export of South African mined goods which impact global shipping networks and increase costs. These issues not only affect the timely delivery of commodities to international markets but also impact the country's ability to meet contractual obligations. Additionally, port-related disruptions can lead to financial losses and reduced competitiveness in the global commodity market.

- **Energy security:** Energy security is a critical concern for South Africa's mining sector, which needs stable and reliable energy supply. Loadshedding, increasing electricity costs, poor maintenance on outdated energy infrastructure, and the delays in bringing new energy infrastructure online have severe impacts on the mining value chain in South Africa.
- **Quality and quantity of mineral resources:** Due to a decrease in greenfields exploration in the past decade in South Africa, the quality (grade) and quantity (amount) of mineral resources have not been upgraded. A robust estimate of mineral resources is fundamental as it provides a pipeline of opportunity to the future success of mining operations. South Africa faces risks related to the depletion of high-grade ore bodies and the lack of discovery of new resources. Thus, the lack of future feedstock impacts the competitiveness of South Africa to feed into the global mining value chain.
- **Financing for greenfields exploration:** Securing financing for greenfields exploration has become increasingly challenging with South Africa receiving less than 1% of global exploration financing. The high costs associated with exploration and the lack of an enabling environment has deterred investors. Additionally, the unique challenges associated with labour, governance, and new energy projects face difficulty in advancing.
- **Policy:** Poor implementation policy frameworks and governance around mining present a significant risk to South Africa's mining value chain. The absence of clear, consistent, and supportive regulations and the lack of implementation of these policies create a poor enabling environment as well as an unstable business environment. Issues such as unclear land tenure rights, regulatory delays, and poor implementation of environmental regulations can hinder investment and operational efficiency. Effective policy frameworks are necessary to provide stability, promote responsible and sustainable mining practices, as well as attract both domestic and international investment.
- **Global market dynamics:** South Africa is part of an integrated mining value chain and is not shielded from fluctuating commodity prices, trade policies, and international competition, which impact South Africa's mining value chain. The volatility of global mineral prices can affect profitability and investment decisions. Moreover, shifts in global demand, geopolitical, and protectionist trade policies can influence market access and competitiveness.

In summary, the South African critical minerals mining value chain is at risk from various factors, including export challenges, energy security issues, concerns over resource quality and quantity, difficulties in financing exploration, inadequate policy frameworks, and volatile global market conditions. Addressing these risks through strategic improvements in infrastructure, energy management, policy development, and financial support will be crucial for ensuring the mining sector's security of supply and growth.

8.3 Enhancing the resilience of South Africa's Green Hydrogen Value Chain and Security of Supply of the South African Critical Mineral Value Chain.

South Africa's green hydrogen value chain faces significant supply chain challenges that hinder its growth and development. These approaches can help alleviate the constraints currently impeding the sector's progress:

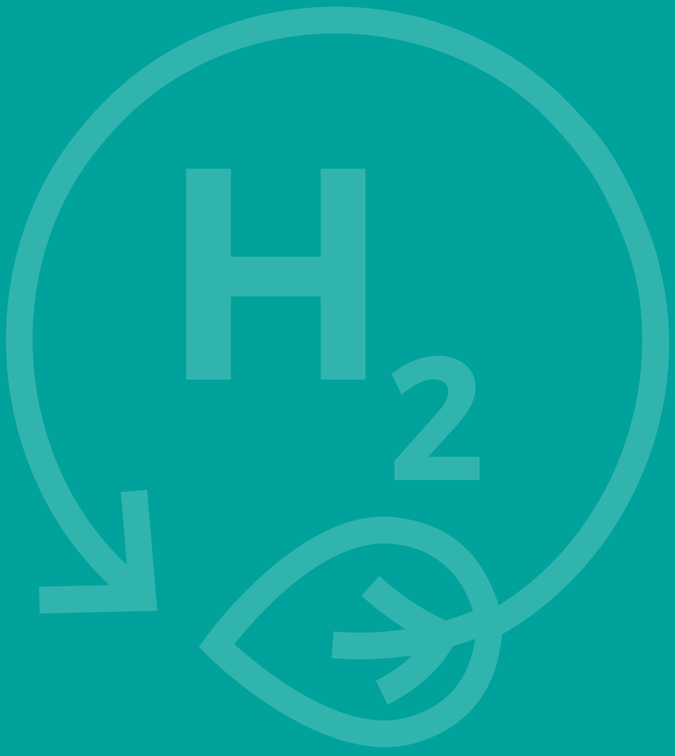
- **Local beneficiation through industrialisation:** Local beneficiation involves adding value to raw materials within the country rather than exporting commodities in native form. For South Africa's green hydrogen sector, this means developing and manufacturing critical components such as electrolysers and other component parts domestically. By investing in local industrialisation, South Africa can reduce dependency on imported technologies, optimise supply chains, and create high-value jobs. This approach can also drive innovation and technological advancements within the country, ultimately enhancing the efficiency and competitiveness of the green hydrogen industry.
- **Recycling of electrolysers:** Electrolysers are essential components for producing green hydrogen. They are capital-intensive and currently require replacement every 10–15 years. Implementing recycling programmes for component parts such as fuel cells stacks can address supply chain issues related to their procurement. By establishing facilities for the refurbishment and recycling of used electrolysers, South Africa can reduce the demand for new units and promote the circular economy domestically. Recycling not only helps manage costs but also promotes environmental sustainability by minimising waste and conserving resources. This approach can contribute to a more resilient and circular economy within the green hydrogen sector.
- **Support for junior exploration companies:** Exploration companies play a crucial role in discovering and developing new mineral assets that produce commodities that feed directly into the manufacturing node of the green hydrogen value chain. Supporting these companies through targeted financial assistance, technical guidance, and streamlined regulatory processes can enhance their ability to explore and develop new prospects. This support can lead to increased resource availability and reduce reliance on depleting deposits, addressing supply chain concerns related to the quality and quantity of raw materials. By fostering a dynamic exploration environment, South Africa can ensure a steady supply of essential minerals for the green hydrogen value chain.
- **Strengthening regional value chains using AfCFTA:** The African Continental Free Trade Area (AfCFTA) provides an opportunity to strengthen regional value chains by facilitating intra-African trade and cooperation. By leveraging AfCFTA, South Africa can collaborate with neighbouring countries to create integrated regional

resource supply chains for industrialisation of the green economy. This cooperation can enhance the availability of raw materials, optimise production processes, and expand market access. Regional partnerships can also facilitate the development of shared infrastructure, such as energy transmission networks and port facilities, addressing logistical challenges and reducing costs as well as provide regional markets for critical minerals.

By implementing the mitigating measures above, South Africa can begin the process of building a resilient green hydrogen value chain and ensuring security of supply of critical minerals in the critical minerals value chain.

Chapter 9

Sustainable Mining Practices



9. Sustainable Mining Practices

CRMs mining is energy-intensive, and traditionally, these operations have relied heavily on fossil fuels, including diesel generators for remote sites and coal-fired power plants, which contribute significantly to GHG emissions. Mining companies have increasingly turned to renewable energy as a sustainable and cost-effective solution to meet these energy demands while reducing their environmental footprint. HRES, which integrate solar photovoltaic (PV), wind turbines, and battery energy storage systems (BESS), have become a preferred method to power mining operations, reducing reliance on fossil fuels and ensuring continuous, reliable energy supply. This shift is largely driven by the environmental and economic benefits of renewable energy, including lower GHG emissions, reduced operational costs, and enhanced energy security, particularly in remote areas where grid access is limited (Nkambule *et al*., 2023).

One key advantage of renewable energy in mining is reduced operational costs over time. Although initial capital expenditure for renewable energy systems such as solar PV and wind turbines can be high, the long-term savings outweigh these costs. Renewable energy systems have no fuel costs and minimal maintenance expenses, providing cost stability over their 20–30-year lifespan. For mining operations, which are often located in remote areas where diesel fuel is expensive to transport, renewable energy systems offer significant financial benefits by reducing dependency on diesel generators (Limpitlaw, 2021). Furthermore, renewable energy contributes to a mining company's environmental, social, and governance (ESG) performance, enhancing its sustainability profile and compliance with international environmental agreements, such as the Paris Agreement (Glaister & Mudd, 2010).

Beyond the economic and environmental benefits, renewable energy has a role to play in post-mining land use. Old mining sites can be converted into solar or wind farms, generating long-term value for local communities and contributing to regional energy security. This approach enhances the sustainability of mining operations by reducing land degradation and providing a beneficial use for previously disturbed areas. By investing in renewable energy, mining companies can demonstrate their commitment to sustainability and community development while lowering their carbon footprint (Nkambule *et al*., 2023). However, the country's reliance on coal-fired electricity from the national utility, Eskom, presents significant challenges for mining companies that seek to reduce their environmental impact and improve energy security. Eskom's frequent loadshedding, due to insufficient electricity generation capacity, has disrupted mining operations and forced companies to seek alternative energy sources. This has led to the growing adoption of renewable energy, particularly solar and wind power, in South Africa's mining sector (Nkambule *et al*., 2023).

9.1 Examples in the South African Context

One of the key regions where renewable energy is being implemented is the Bushveld Complex, home to one of the largest platinum deposits in the world. PGMs such as platinum, palladium, and rhodium are essential for a wide range of technologies, including catalytic converters and hydrogen fuel cells. However, mining PGMs is energy-intensive, and many of the mines in the Bushveld Complex have traditionally relied on grid electricity supplied by Eskom. Due to the unreliability of Eskom's power supply and the environmental impact of coal-fired power, mining companies in the region have increasingly turned to renewable energy to power their operations. For example, Anglo American Platinum has begun investing in solar PV systems to meet part of its energy needs, reducing its reliance on Eskom and lowering its carbon emissions (Glaister & Mudd, 2010).

In addition to the Bushveld Complex, the Northern Cape, a region known for its high levels of solar irradiance, has become a hotspot for renewable energy projects in the mining sector. The Kathu Solar Park, one of the largest solar energy plants in the country, provides power to local mining operations. The Northern Cape's abundant sunshine makes it an ideal location for large-scale solar PV installations, which are increasingly being integrated into mining operations. For example, Gold Fields, a major mining company, has invested in a large solar PV project to power its South Deep Mine, located in Gauteng. This 40 MW solar plant is designed to meet approximately 20% of the mine's energy needs, significantly reducing its reliance on Eskom's coal-fired electricity and cutting its carbon emissions by over 100,000 tonnes per year (Nkambule *et al*., 2023).

Another notable example is the use of HRES at the Tharisa Mine, located in the North West Province. Tharisa is a chrome and PGMs mine that has adopted a hybrid system combining solar PV, wind turbines, and battery storage. This system allows the mine to operate independently of the grid during periods of loadshedding, ensuring that production can continue uninterrupted. The hybrid system has also reduced the mine's diesel consumption, further lowering its operational costs and carbon footprint. This approach demonstrates the potential of HRES systems to enhance energy security and sustainability in South Africa's mining sector (Limpitlaw, 2021).

South Africa's wind energy potential is also being harnessed to support mining operations. The Western Cape and Eastern Cape provinces, with their strong coastal winds, are ideal for wind power generation. Mining companies in these regions are increasingly investing in wind energy projects to diversify their energy mix and reduce their dependence on Eskom's unreliable power supply. Exxaro, a major South African mining company, has developed the Amakhala Emoyeni Wind Farm in the Eastern Cape, which generates 134 MW of wind power. This project not only provides clean energy to Exxaro's mining operations but also feeds excess electricity into the national grid, contributing to South Africa's broader renewable energy goals (Nkambule *et al*., 2023).

These examples highlight the increasing role of renewable energy in South Africa's mining sector, driven by both economic and environmental considerations. By adopting renewable energy, mining companies are not only reducing their operational costs but are also contributing to the country's broader efforts to reduce GHG emissions and transition to a more sustainable energy system. The integration of solar, wind, and HRES systems in regions such as the Bushveld Complex, Northern Cape, and Eastern Cape demonstrates the feasibility and benefits of renewable energy for mining operations in South Africa. With ongoing advancements in renewable energy technologies and the continued decline in costs, it is likely that renewable energy will play an even greater role in powering South Africa's mining sector in the future.

Chapter 10

Assessment of technological advancements that reduce reliance on critical minerals

10. Assessment of technological advancements that reduce reliance on critical minerals

Technology is a crucial aspect in the green hydrogen economy and its future. The main relationship of technology and green hydrogen is attributed to the influence it has on the need for critical minerals for electrolysers and fuel cells. The following section will explore the link between critical minerals and green hydrogen, global competing electrolyser and fuel cell technologies, as well as on-going trends within this space, and finally provide a brief update on certification progress.

The following sections highlight the crucial dependence of electrolysers and fuel cells on a range of critical minerals, potentially impacting their scalability and the transition to a green hydrogen economy. Green hydrogen, produced through electrolysis using renewable energy sources, is seen as a key enabler of decarbonisation in hard-to-abate sectors like heavy industry and transportation. However, the rapid scale-up of electrolysis capacity required to meet projected demand raises concerns about the availability of critical minerals essential for various electrolyser technologies.

Critical minerals are a key component in electrolysers and are a crucial aspect of the supply to grow the green hydrogen economy globally. Having established in previous chapters the overall need for critical minerals for the green hydrogen economy, the table below focuses on the specific node of the green hydrogen value chain, namely electrolysis which can be achieved using various technologies. The most common ones are highlighted below with key critical minerals and their requirement to produce a gigawatt of energy.

Table 5: Electrolyser requirement for a single hydrogen value chain node (Breakthrough Institute, 2024)

Technology	Material	Electrolyser Material Requirement (tons per GW)
Alkaline	Nickel	800
	Zirconium	100
	Aluminium	500
Proton Exchange Membrane (PEM)	Platinum	0.3
	Palladium	0.3
	Iridium	0.7
Solid Oxide Electrolyser Cells (SOEC)	Nickel	175
	Zirconium	40
	Lanthanum	20
	Yttrium	5
Fuel Cells	Platinum	0.29

It is important to note that the table offers a snapshot of critical mineral requirements for a singular node on the green hydrogen value chain. The relationship between critical minerals and green hydrogen via technology is expanded below.

10.1 AI and its Potential Contributions to Sustainability

Artificial Intelligence (AI) offers significant potential to advance sustainability in mining, both globally and in South Africa. By enhancing operational efficiency, reducing environmental impacts, and improving safety, AI can help mining operations meet sustainability goals, such as those outlined by the UN SDGs. Several case studies highlight practical applications of AI, particularly in countries like China and South Africa.

10.1.1 Operational Efficiency and Resource Optimisation

AI has demonstrated its ability to enhance operational efficiency by enabling real-time data analysis to optimise resource extraction and reduce waste. Predictive maintenance systems powered by AI, such as those used in large mining operations in China, help identify equipment failures before they occur. This pre-emptive approach reduces downtime and maintenance costs while boosting productivity (Corrigan & Laye, 2022; Liang *et al.*, 2024). In South African mines, AI has been applied to optimise ventilation systems, which are significant energy consumers in underground operations. AI helps regulate airflow more efficiently, reducing energy costs and emissions (Corrigan & Ikonnikova, 2024).

A specific case study from Goldspot Discoveries Incorporated illustrates how AI can aid mineral exploration. Goldspot uses machine learning models to analyse geological data, improving the accuracy of locating mineable prospects. This AI application, successfully used in Canadian gold mines, could be adapted for South Africa's gold reserves, increasing efficiency while reducing the environmental impact of exploration (Corrigan & Laye, 2022).

10.1.2 Environmental Sustainability

AI plays a critical role in promoting environmental sustainability in mining. AI-driven monitoring systems can continuously track environmental parameters such as water usage, carbon emissions, and land disturbance. In South Africa, water scarcity is a pressing issue, particularly in mining-intensive regions like Limpopo and Northern Cape. AI tools that optimise water usage can reduce the mining industry's water footprint by detecting leaks and managing consumption more effectively (Liang *et al.*, 2024).

A case study from China's Xingshan Iron Mine demonstrates AI's potential to minimise environmental impact by optimising energy consumption and managing water usage. The mine reduced carbon emissions and improved water conservation through the integration of AI (Liang *et al.*, 2024). In South Africa, similar AI systems could be employed to support the country's efforts to reduce GHG emissions under international agreements like the Paris Accord.

Moreover, AI-enabled autonomous vehicles optimise transportation routes within mine sites, reducing fuel consumption and emissions. Caterpillar's Autonomous Haulage System (AHS), used in mines in Australia, has resulted in a 15% reduction in fuel use, which can be similarly applied to South African open-pit mines (Corrigan & Ikonnikova, 2024).

10.1.3 Worker Safety and Social Responsibility

AI has proven effective in improving safety by automating hazardous tasks and reducing human exposure to dangerous conditions. In South Africa, where mining remains a high-risk occupation, AI-powered drones and robots are used to inspect hazardous areas, identifying risks such as gas leaks and unstable rock formations without endangering human lives (Corrigan & Ikonnikova, 2024).

Anglo American Platinum's Mogalakwena Mine in South Africa provides an example of AI enhancing worker safety. The mine uses AI-enabled drones for real-time monitoring of hazardous conditions, reducing risks to workers (Liang *et al*., 2024). The mine also employs autonomous vehicles, which have reduced the number of workers exposed to dangerous tasks, further enhancing safety (Corrigan & Laye, 2022).

10.1.4 Ethical Considerations and Multi-Objective Optimisation

Despite AI's benefits, its introduction raises ethical concerns, particularly around job displacement and data privacy. In South Africa, where mining is a major employer, there are concerns that automation could lead to job losses. However, AI also presents new job opportunities in high-tech fields such as AI system maintenance, provided that proper retraining programmes are implemented (Ge *et al*., 2023).

AI's capability for multi-objective optimisation offers a way to balance these competing concerns. Multi-objective optimisation allows AI to simultaneously consider economic, environmental, and social objectives, helping companies align operations with broader sustainability goals. For example, a study at the Sandaozhuang Molybdenum Mine in China used AI to develop a mine closure plan that minimised environmental degradation while providing economic opportunities for the local community (Corrigan & Ikonnikova, 2024). South African mines could adopt similar strategies to ensure post-mining landscapes are restored, in line with national regulations and community expectations.

In conclusion, technological advancements are crucial in reducing reliance on critical minerals and supporting the growth of the green hydrogen economy. Electrolyser and fuel cell technologies, essential for green hydrogen production, depend heavily on critical minerals, raising concerns about their availability as demand increases. Additionally, AI is enhancing sustainability in mining by improving operational efficiency, optimising resource use, and minimising environmental impacts. AI technologies, such as predictive maintenance and real-time monitoring, have reduced downtime, energy consumption, and emissions, while also improving worker safety through automation. However, AI's adoption raises ethical concerns, especially regarding job displacement in mining-dependent economies like South Africa. Despite this, AI's ability to balance economic, environmental, and social goals offers a path forward for sustainable mining operations. Ultimately, AI and renewable energy solutions could be key to ensuring the sustainable integration of critical minerals into the green hydrogen value chain and ensuring the green hydrogen economy meets future demands with less environmental and social impact.

10.2 Stakeholder Insights on Sustainable CRMs Mining Practices

The following section details the feedback and input received from the second validation workshop stakeholders on the topic of sustainable CRMs mining practices.

10.2.1 Water Resource Management and Mining Methods

Water scarcity remains one of South Africa's most pressing environmental concerns, and CRMs extraction for green hydrogen introduces additional demands on water resources. Since green hydrogen production is inherently water-intensive, CRMs mining operations must take a strategic approach to minimise their water footprint. There is a need to review and update South Africa's National Water Act to account for the additional pressures that increased CRMs mining and green hydrogen production will place on the country's already stressed water resources. This plan provides a crucial framework, highlighting areas where water resources can be conserved and managed more efficiently.

Participants in the workshop emphasised the need to align CRMs mining projects with the Master Water Plan to support sustainable water use. Specifically, they recommended exploring dry processing techniques and other water-saving innovations that can reduce the volume of water consumed in CRMs extraction. By prioritising these approaches, the mining industry can help mitigate the competition for scarce water resources, easing tensions with local communities that rely on these supplies for everyday needs.

10.2.2 Opportunities for addressing AMD

A unique opportunity exists within CRMs extraction to address one of South Africa's longstanding environmental issues, namely AMD. Workshop participants suggested that the increased demand for CRMs mining for green hydrogen could be leveraged to remediate AMD-affected waters. By treating AMD as part of CRMs mining operations, companies can convert contaminated water into a valuable resource for the green hydrogen ecosystem.

This approach not only transforms AMD from a liability into an asset but also aligns CRMs mining with broader environmental management goals. For instance, incorporating AMD clean-up into CRMs activities could reduce dependency on fresh water sources, contributing to water conservation and enhancing the environmental credibility of CRMs extraction projects. Through this synergy, mining operations can play an active role in sustainable water use while addressing one of South Africa's major ecological challenges.

10.2.3 Balancing Automation with Community Empowerment

As the extraction of CRMs expands, technological advancements and automation are becoming essential components of mining operations. However, in countries with high unemployment rates, such as South Africa, automation poses significant socio-economic challenges. Workshop participants emphasised the importance of balancing the efficiency gains from automation with community empowerment and job creation.

Automation in mining must be implemented thoughtfully, ensuring it fosters local employment opportunities. This involves prioritising the integration of local labour wherever possible, offering robust skills development programmes and designing roles that complement automated processes rather than replacing them entirely. By adopting this approach, CRMs mining operations can contribute meaningfully to the socio-economic development of surrounding communities. This not only ensures the benefits of mining extend beyond the extraction site but also fosters local support for CRMs projects by directly uplifting communities through job creation and economic opportunities.

A notable example of thoughtful automation implementation comes from Rio Tinto. The company introduced automation while partnering with educational institutions to retrain workers for higher-skill roles in operating autonomous equipment. Through a collaboration with South Metropolitan TAFE and the Western Australian Government, Rio Tinto developed Australia's first nationally recognised vocational qualifications in automation. These certifications aim to equip both current employees and new entrants with the skills needed to thrive in an automation-driven mining sector (Rio Tinto, 2020).

This proactive initiative highlights the importance of upskilling and reskilling the workforce to address automation-related challenges. By offering certificates and micro-credential courses focused on STEM education, Rio Tinto ensures that workers remain employable while enabling the industry to retain a skilled workforce in an evolving technological landscape (Rio Tinto, 2020).

10.2.4 Policy and Regulation Gaps

Participants identified several regulatory barriers that limit responsible CRMs extraction, with particular focus on spatial planning, land reform, and transparency policies. Clear and structured land-use guidelines are essential to direct CRMs extraction towards suitable areas, balancing mining activities with environmental preservation and community needs.

The National Environmental Management Act (NEMA) covers the environmental aspects of CRMs mining and already addresses many of the demands associated with sustainable mining practices. Rather than creating new legislation, participants emphasised the importance of small, targeted updates to NEMA to address specific gaps, especially those emerging from CRMs extraction and green hydrogen development. Moreover, stakeholders highlighted the need to improve implementation and enforcement of NEMA, recommending a review process to identify where execution could be strengthened. By ensuring robust implementation, gaps in environmental protections and community rights can be identified and addressed more effectively.

Additionally, participants noted that South Africa lacks a mining cadastre; a comprehensive spatial database for mining rights and land use. The lack of such an instrument, common in other countries, limits transparency and hinders effective land-use planning. Establishing a mining cadastre could help clarify spatial impacts, making it easier to assess the compatibility of CRMs projects with surrounding land uses and identify areas where mining activities may conflict with environmental or community priorities.

Finally, participants recommended updates to the National Water Act to address CRMs-specific water usage challenges, particularly given the significant water demands of green hydrogen production. Strengthening these regulations with targeted adjustments and improved implementation can create a cohesive, efficient framework for CRMs extraction, supporting sustainable development while ensuring that mining companies operate within environmentally and socially responsible parameters.

Chapter 11

Dependence on CRMs - a minerals intensive transition

11. Dependence on CRMs - a minerals intensive transition

To understand how important critical minerals are to the green hydrogen economy, it would be beneficial to provide an overview of the energy requirements that are needed. The illustration below provides a modelled expectation of how much energy is expected from green hydrogen based on electrolyser capacity.

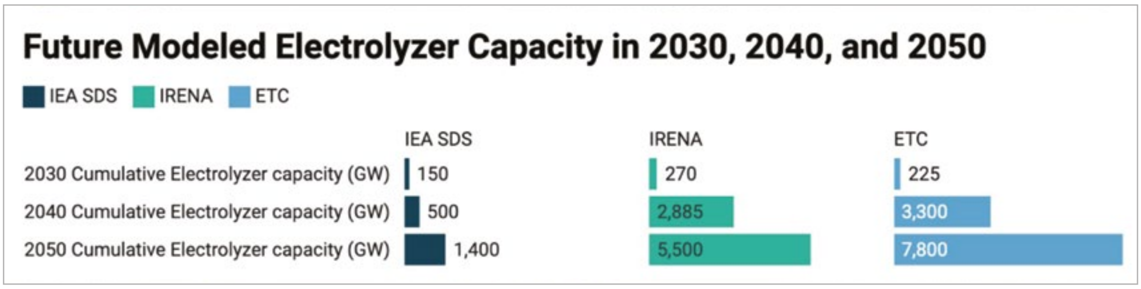


Figure 32: Future modelled electrolyser capacity (Energy Monitor, 2023)

As seen in Figure 32, the expected electrolyser capacity increases drastically between 2030 and 2050, citing the need for critical minerals to fulfil these intense energy requirements:

- Alkaline electrolysers (AE), a widely accepted technology and the most cost-effective type, utilising common metals like nickel and zirconium.
- PEM electrolysers, known for their higher efficiency, rely heavily on precious PGMs like iridium, platinum, and palladium.
- Solid oxide electrolysis cells (SOEC), operating at high temperatures with potential for even greater efficiency, require REEs such as lanthanum and yttrium.
- Beyond the electrolysers themselves, the renewable energy infrastructure needed to power them (solar panels, wind turbines) demands additional, significant quantities of critical minerals like silicon, copper, aluminium, zinc, and molybdenum.

11.1 Security of Supply - Concentrated Resources and Geopolitical Risks

A key point when linking critical mineral and green hydrogen is the security of supply for these critical minerals, particularly for PEM and SOEC technologies:

- The production of PGMs like iridium is highly concentrated, with a significant portion originating from a few countries like South Africa and Russia.
- Similarly, China dominates the production of REEs, accounting for approximately 95% of the global supply in 2022.
- This geographic concentration creates vulnerabilities to supply chain disruptions due to political instability, trade conflicts, or resource nationalism.

PEM electrolysers, which impact South African mining due to their need for PGMs, are favoured for their efficiency and compatibility with variable renewable energy sources. PEM electrolysers rely heavily on iridium, a product of PGM mining, for their anodes. With limited global production and concentrated production amongst a few mines, the potential for iridium scarcity looms large as its demand increases.

With all these challenges for security of supply and the additional scarcity of some critical minerals, it is important to examine the role of technology further, particularly in the green hydrogen space. It is noted that technology is a driver of efficiency and many forecast that technology will be instrumental in enhancing the efficiency of green hydrogen production and will lead to less reliance on critical minerals. Signs of improving efficiencies are already being seen globally; a good example of this is Toshiba, who has developed PEM electrolysis technology that reduces the need for iridium needs by 90%.

Globally, continuous innovation in material science and manufacturing processes will further alleviate pressure on critical mineral supply chains for green hydrogen. IEA has summarised how these different electrolyser technologies can be ranked depending on their level of maturity and highlights the ongoing efforts to improve technologies. It is worth noting that complete technological maturity for the various electrolyser technologies has not been achieved and is a crucial aspect to consider, especially when considering that these different technologies have different critical mineral requirements. Thus, the future need for critical minerals could be very different from today depending on which technology is taken up by the market and matures.

Continuous innovation in material science and manufacturing processes will further alleviate pressure on critical mineral supply chains. Further efforts using a multi-faceted approach to decreasing the reliance on critical minerals are highlighted below.

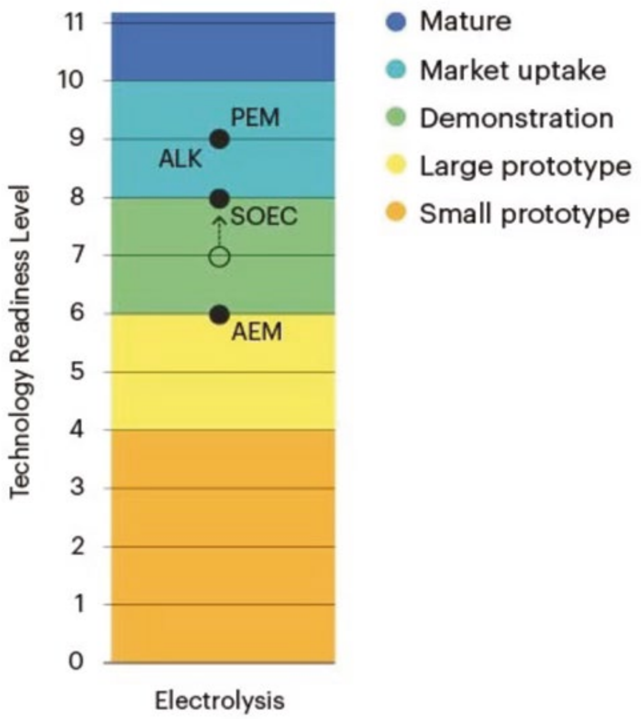


Figure 33: Illustration of different electrolysis technologies and their maturity levels in the market (IEA, 2023)

11.2 Reliance Mitigation - A Multifaceted Approach

Recognising these potential bottlenecks, there is a need for mitigating reliance on critical minerals to ensure the sustainable growth of the hydrogen economy. Based on the assessment and relationship between critical minerals and the green hydrogen economy, diversification measures need to be explored to avoid a scenario of over-reliance on specific critical minerals to the point where the value chains are monotonous and not resilient enough. To avoid this scenario, the following measures are proposed:

- Diversifying mining supply chains is crucial to reduce geopolitical risks and potentially lower costs.
- Ramping up domestic production in countries prioritising hydrogen deployment can enhance supply chain resilience.
- Supporting research and development to find alternative materials and improve efficiency is vital. This includes exploring REE-free magnets, PGM-free membranes, and reducing catalyst loadings.

- Optimising material use through innovative designs and manufacturing processes can minimise the overall demand for critical minerals.
- Recycling and reuse of critical minerals from end-of-life fuel cells and electrolysers can contribute to a more circular economy.

11.3 Fuel Cell and Electrolyser Trends – A Focus on a Changing Environment

Fuel cells and electrolysers are crucial aspects of green hydrogen production and are constantly evolving. An analysis by Startus Insights examined 446 start-ups and produced an illustration into the number of technologies that are being explored to drive innovation and improve technologies within the fuel cell space.

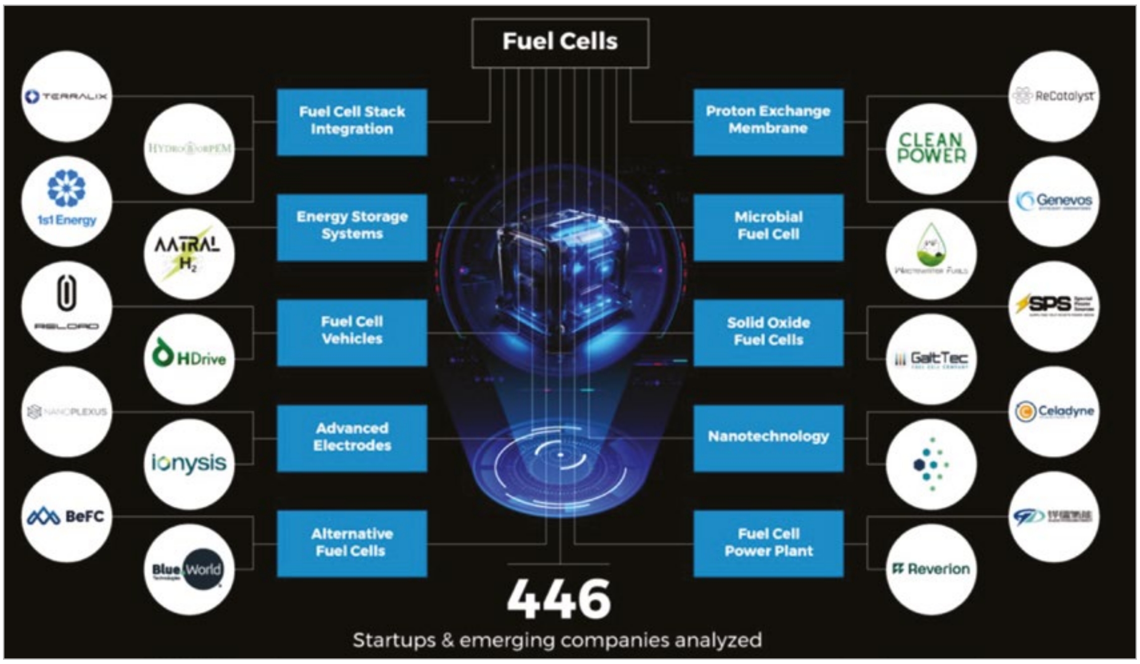


Figure 34: Fuel cell trends based on emerging technology (Startus Insights, 2024)

11.4 Fuel Cell Trends

To better understand the role of technology and innovation within the green hydrogen economy, it is important to understand trends within the fuel cell space that are currently being realised to improve efficiency and stimulate sustainable growth of the green hydrogen economy:

- **Fuel cell stack integration:** One of the major challenges hindering the widespread adoption of fuel cells is the degradation of membrane electrode assemblies (MEAs). Startups are working on developing more durable MEAs that can withstand higher temperatures and chemical degradation to improve efficiency and lifespan.
- **PEMs:** Improvements in materials science are leading to the creation of more efficient and durable fuel cell membranes. PEMs enhance conductivity and durability.
- **Fuel cell vehicles:** Fuel cell vehicles are gaining traction as a solution to range anxiety and slow charging times associated with conventional battery-powered vehicles. Advanced electrodes with nanostructured thin film catalysts are being used to increase the efficiency and lifespan of fuel cells for vehicles.
- **Advanced electrodes:** Research and development in advanced electrodes are focused on improving the efficiency and lifespan of fuel cells.
- **Alternative fuel cells:** Exploration of fuel cells beyond traditional types is leading to innovations in areas like lightweight drones, uninterruptible power supplies, and portable fuel cell generators.
- **Nanotechnology:** Nanotechnology is playing a significant role in improving the performance and durability of fuel cell components, including electrodes and membranes.
- **Solid oxide fuel cells (SOFCs):** SOFCs are well-suited for large-scale stationary power generation and combined heat and power (CHP) systems.
- **Energy storage systems (ESS):** Fuel cells are being integrated into ESS to provide a more sustainable and efficient alternative to conventional batteries.
- **Microbial fuel cells (MFCs):** MFCs offer unique applications in areas like wastewater treatment and small-scale power generation.
- **Fuel cell power plants:** Development and deployment of fuel cell power plants are contributing to the advancement of clean energy solutions.

11.5 Electrolyser Trends

Similar to the fuel cell trends, electrolyser trends are explored to better understand the progress that is being achieved to ensure technological efficiency and sustainability is improved.

- **Modelling and simulation:** Researchers are focusing on developing sophisticated models and simulations to better understand and optimise the performance of different types of electrolysers. These models help in analysing various factors influencing electrolyser efficiency and durability, such as operating conditions, materials, and designs.
- **Cost reduction:** Reducing the capital costs of electrolyser systems is crucial for wider adoption. Research is ongoing to develop more cost-effective materials and manufacturing processes for electrolysers, particularly focusing on reducing the amount of critical minerals used.
- **Increased efficiency and durability:** Technological improvements are leading to increased efficiency and durability in electrolyser systems, particularly PEMEL systems.
- **Reduced rare material usage:** Efforts are underway to minimise the use of rare earth materials in electrolyser components, especially catalysts. This is being achieved through nanostructure development and exploration of alternative materials.
- **Scaling Up:** Electrolyser systems are being scaled up to meet the growing demand for green hydrogen production. By 2030, 2–4 MW electrolyser stacks and 7 MW electrolyser systems are expected to be common and readily available to be installed.
- **Policy support:** Governments worldwide are implementing policies and providing financial incentives to promote the development and deployment of electrolyser technologies.

The trends associated within the electrolyser and fuel cell space speak to a larger effort which is focused on decarbonisation but also have complementary trends that help shape the green hydrogen economy.

- **Sustainability:** The focus on sustainability is driving innovation in both fuel cell and electrolyser technologies. This includes reducing the reliance on rare earth materials, minimising environmental impact, and improving the efficiency and durability of systems.
- **Legislation and certification:** As a growing industry, green hydrogen is not impervious to legislative requirements and certified efforts. Globally there are considerable efforts to ensure that the green hydrogen industry is fostered and allowed to grow through incentive schemes and bespoke financing arrangements. Additionally, to ensure green hydrogen is truly environmentally sustainable, certification must form

part of equation. The International Renewable Energy Agency (IRENA) highlights that they are currently 14 industry certification mechanisms that cover the green hydrogen value chain.

As technology improves and scalability is tested, there will be a decrease in subsidies, an increase in legislative requirements, and stricter certification mechanisms all contributing to ensuring that green hydrogen is sustainably produced.

11.6 Stakeholder insights on the role of technology

The following section details the feedback and input received from the attendees of the second workshop on the importance of technology to South Africa's green hydrogen plans.

11.6.1 Exploring South Africa's Competitive Advantage in the Green Hydrogen Value Chain

It was suggested that South Africa must assess the entire green hydrogen value chain from a broader perspective to include the dependencies and extended value chains that flow into the main green hydrogen value chain. As an example, to manufacture and assemble electrolysers would be a costly endeavour and would involve competing with already established industries in Europe and Asia. Thus, focusing on component part manufacturing, maintenance, and components that feed directly into the green hydrogen value chain such manufacturing pipeline and storage tanks would be a more appropriate approach.

11.6.2 Market trends in Technology

Participants in the workshop indicated that fuel cells and electrolyser technology is constantly evolving in line with the current report's assessment. Technologies that South Africa should also assess include loading and substitution (doping) which would reduce reliance on expensive critical minerals such as iridium and platinum. Another market trend that South Africa should be considering is nanotech research that focuses on using atomic scale coating of critical mineral needed on fuel cells or electrolyser component parts. This would also reduce the required volume of critical minerals.

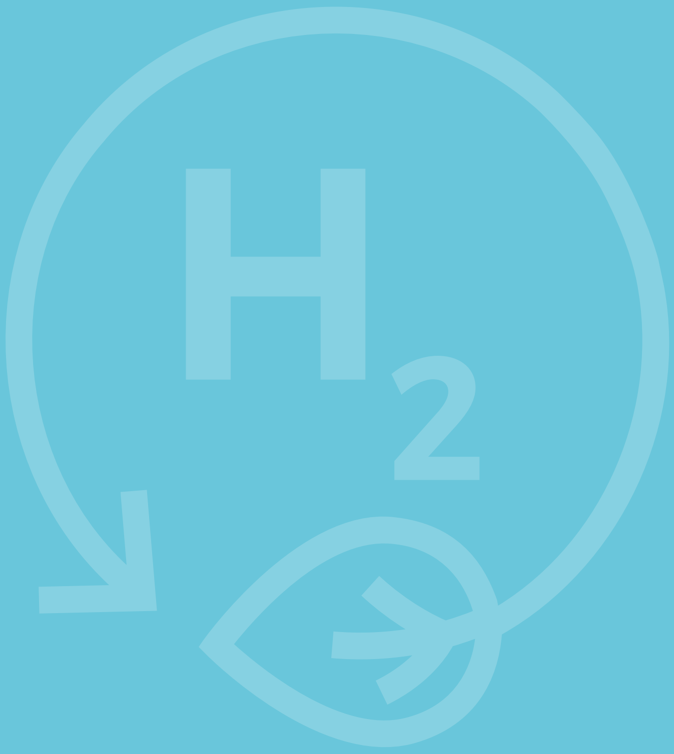
11.6.3 Women's role in the Green Hydrogen future

The workshop participants indicated that women have been prioritised to enhance their role and contribution in the green hydrogen economy with participation in HySA. Thus, the expectation is that the role of women will continue to develop and grow in the green hydrogen economy.

Overall, there was a consensus that South Africa has great initiatives and policies that aid in defining South Africa's vision for and positioning the country to develop a green hydrogen economy. HySA, the Decadal Plan, the expected Critical Mineral Strategy, the ongoing Global Competitiveness Assessment on Extraction of Critical Minerals in South Africa, and ongoing partnerships and collaboration agreements all position South Africa at the forefront to develop the green hydrogen economy. However, it was expressed that there is no clear implementation and direction on enhancing and building on this robust policy and initiative foundation to drive innovation in the development of technology that services the green hydrogen economy.

Chapter 12

Promoting the circular economy through recycling and CRMs optimisation



12. Promoting The circular economy through recycling and CRMs optimisation

Countries with CRMs recycling initiatives, particularly in Europe and Asia, have made significant strides in addressing the sustainability challenges posed by finite metal resources. The recycling of PGMs from automotive catalysts and electronic waste stands out as a key focus area globally. In contrast, South Africa, a major producer of primary PGMs, still faces significant gaps in its recycling efforts.

12.1 The Recycling Imperative

The recycling of these CRMs for the hydrogen economy is crucial for several reasons, as highlighted by sources such as the European Commission (2020), Ferro and Bonollo (2019), and Binnemans *et al*. (2013), who identify the following key factors:

- **Supply security:** CRMs such as REE, cobalt, lithium, and platinum are vital to key industries, particularly in green technologies like batteries and renewable energy systems. Recycling these materials ensures a more stable and sustainable supply chain, reducing dependence on imports from politically unstable regions.
- **Environmental benefits:** The extraction of CRMs from natural sources typically involves processes that could be harmful to the environment, such as mining and ore processing. By recycling CRMs, we can decrease the need for new mining operations, conserve natural resources, and lower carbon emissions.
- **Economic advantage:** Recycling CRMs offers economic benefits by reducing the costs associated with raw material extraction, refining, and transportation. Additionally, it opens new business opportunities in the recycling sector, supporting the development of circular economy models.
- **Waste reduction:** Many electronic devices and technologies contain CRMs, which often end up in landfills. Recycling these materials not only prevents waste but also allows for the recovery and reuse of valuable resources that would otherwise be discarded.
- **Sustainability:** The shift towards a low-carbon economy, particularly through green technologies like electric vehicles and wind turbines, is heavily dependent on CRMs. Recycling these materials contributes to long-term sustainability by reducing the environmental impact of their extraction and use.

The recycling of these CRMs is becoming increasingly more important as global demand for these minerals grows, especially in technologies like electric vehicles, renewable energy, and electronics. In the following sections we discuss global efforts, with a particular focus on South African efforts to recycle CRMs.

12.2 International Recycling Initiatives

The rapid advancement of novel technologies has significantly increased the global demand for CRMs. The extraction of raw materials has doubled since the 1990s, reflecting the growing need to meet current demands. For example, in 2019, the total raw material consumption per European citizen was approximately 14 tonnes, with 0.7 tonnes dedicated to metals, and by 2040, raw material extraction is projected to rise by 40% (Recycling Magazine, 2024). To support the transition to climate neutrality and ensure the long-term availability of essential materials, it is crucial to adopt strategies that prioritise the sustainable extraction of resources. This includes reviewing all geological resource activities to ensure their environmental, social, and economic viability. In this context, the EU has developed a list of CRMs that are critical to its economy and face high supply risks, a list that is regularly updated to reflect changing market conditions (Recycling Magazine, 2024).

Table 6: Raw materials identified as critical within the EU in 2023

2023 Critical Raw Materials (CRMs) (34)			
Antimony	Copper	Lithium	Scandium
Arsenic	Feldspar	Magnesium	Silicon metal
Aluminium/Bauxite	Fluorspar	Manganese	Strontium
Baryte	Gallium	Natural Graphite	Tantalum
Beryllium	Germanium	Nickel – battery grade	Titanium metal
Bismuth	Hafnium	Niobium	Tungsten
Boron/borates	Helium	Phosphate rock	Vanadium
Cobalt	Heavy REE	Phosphorus	
Coking Coal	Light REE	Platinum Group Metals	

As previously mentioned, CRMs are becoming increasingly important as it contributes to the security of raw material supply and promotes global material sustainability. Furthermore, recycling is anticipated to strengthen the competitiveness of economies such as that of the EU, as outlined in the European Commission’s circular economy action plan.

12.2.1 Europe

In the EU, PGMs recycling is supported by robust legislative frameworks and advanced recycling infrastructure. Key regulations, such as the End-of-Life Vehicle (ELV) Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive, mandate the recycling of automotive catalysts and electronic waste, both of which contain PGMs like platinum, palladium, and rhodium. These directives ensure that 85–95% of vehicle materials and a significant portion of electronic waste are recovered, driving high PGM recycling rates (Hagelüken, 2012; Ryan *et al*., 2010).

Europe's recycling infrastructure is among the most advanced globally, with companies like Umicore in Belgium and Johnson Matthey in the UK leading the industry. These companies operate state-of-the-art facilities capable of recovering over 95% of PGMs from recycled materials (Hagelüken, 2012). The recycling process typically uses pyrometallurgical and hydrometallurgical methods, both of which are highly efficient but complex. Despite high technical recyclability, challenges remain in collection and handling complex electronic devices (Tang *et al*., 2023).

Although PGMs recovery rates are notably high, the total volume of PGMs entering the recycling process is limited by various factors. Figure 35 below shows the recycling input rates of various materials in the EU metals like PGMs, while technically recyclable, are not processed in volumes comparable to metals like copper, tungsten, or aluminium. This disparity is due to economic challenges and the complexity of recovering metals from consumer goods such as electronics and vehicles (Tang *et al*., 2023).

The recycling of PGMs from end-use products like auto catalysts is highly efficient, with around 50% of these materials recycled globally (Ryan *et al*., 2010). However, for other applications, such as electronics, recovery rates remain much lower due to the complexity of extracting metals from small, mixed-use products (Hagelüken, 2012; Ryan *et al*., 2010). This disparity between technical capability and actual recycling volumes reflects the reality that although recovery systems are advanced, collection mechanisms and economic incentives are not always sufficient to ensure that these metals enter the recycling stream in large volumes.

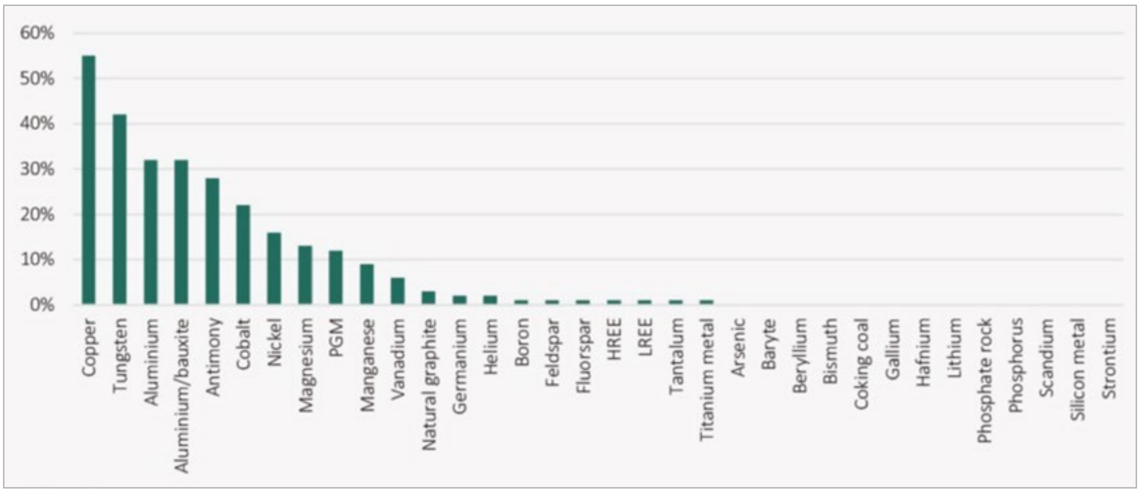


Figure 35: Recycling input rate of various metals in the European Union (from Righetti, Edoardo & Rizos, Vasileios (2024)

12.2.2 Asia

Countries such as Japan and China have also made significant progress in PGMs recycling. Japan has developed an advanced recycling industry, focusing on the recovery of PGMs from spent automotive catalysts and electronic devices (Tang *et al*., 2023). Hydrometallurgical and pyrometallurgical processes are employed to extract valuable metals, with recycling rates for PGMs being particularly high due to the concentration of these metals in used electronics and automotive parts. China, facing a shortage of primary PGMs resources, has similarly invested in recycling technologies as a way to secure a sustainable supply of these critical minerals (Tang *et al*., 2023).

Japan's model involves collaboration between government agencies, private companies, and research institutions to ensure that recycling systems are efficient and environmentally friendly. The use of hydrometallurgical techniques, which consume less energy than primary mining, has been especially effective in Japan, where energy costs are high and environmental concerns are a priority (Tang *et al*., 2023).

12.2.3 Recycling of CRMs in the SADC Region

There are very few CRMs recycling initiatives in the SADC region and they are mostly concentrated in South Africa. Where there are initiatives, these have not been well documented and published for international engagement. The only SADC countries outside South Africa that have initiatives related to the circular economy are Ghana, Namibia, and Zambia.

Ghana has been involved in circular economy initiatives with the EU, particularly through the African-EU cooperation framework. This includes discussions on waste management and the use of secondary raw materials. While Ghana is striving to adopt a circular economy model, challenges such as socio-economic and infrastructure limitations persist. However, the EU recognises Ghana's progress and has supported initiatives, particularly in recycling and waste management (European Commission, 2020; African Circular Economy Alliance, 2021).

Namibia signed a Strategic Partnership on Sustainable Raw Materials and Renewable Hydrogen with the EU in 2022. This agreement emphasises cooperation on sustainable extraction, processing, and recycling of CRMs to support a transition to renewable energy and a circular economy (European Commission, 2022). The partnership aligns with the European Green Deal and aims to enhance Namibia's industrial base while fostering technology transfer and capacity building.

Zambia signed a memorandum of understanding with the EU on 16 March, 2023, which included the promotion and investment in circular economy value chains for the recycling, reusing, and remanufacturing of CRMs, including through technology transfer between the EU and Zambia. This is a significant development and has implications not just for Zambia but for the SADC region as a whole, offering a strategic pathway for these countries to leverage their mineral wealth and become key players in the global CRMs recycling ecosystem.

12.2.4 Notable Recycling Initiatives Globally

The Heraeus Group, a German technology company, is a global leader in recycling PGMs, especially from automotive catalytic converters. Their facilities recover high-purity platinum, palladium, and rhodium from used catalytic converters, which are widely recycled due to their high content of valuable metals. PGMs recycling rates are quite high due to the value of the metals.

Companies like Umicore, a global materials technology company, focus on recycling REEs from end-of-life batteries and electronics. The recycling of neodymium, a critical REE used in magnets, is becoming more common in Europe and Japan.

Tesla and Redwood Materials in the U.S. are leading efforts to recycle lithium-ion batteries, recovering metals like nickel and cobalt for reuse in new batteries. Tesla aims to establish a closed-loop recycling process for its electric vehicles.

American Manganese Inc. in Canada has developed the RecycLiCo™ process to recycle lithium from spent lithium-ion batteries. The process extracts over 90% of lithium, cobalt, and nickel from batteries.

12.2.5 Global Challenges

The GIZ (2023) SADC Critical Transition Minerals report highlights that for newer technologies like electronics, batteries, and certain alloys, recycling remains a challenge due to the lack of technological advancements to recycle efficiently at scale and cost. As a result, recycling alone will not eliminate the need for continued investment in new resources. However, the IEA projects that by 2040, recycled materials from batteries—such as copper, lithium, nickel, and cobalt—could reduce the demand for primary supply of these minerals by approximately 10%.

Despite success, there are still challenges in recycling from other products like electronics where PGM content is lower and more difficult to extract (Recycling Magazine, 2024). The low concentrations of REEs in most products make it economically challenging to recycle them. Additionally, the technology for separating REEs from other materials is complex and energy intensive (Energy Monitor, 2023). One major challenge is the collection of end-of-life batteries, as there is no widespread system for gathering batteries from electric vehicles (EVs) at scale. The cost of lithium recycling remains a significant hurdle. Additionally, current processes are energy-intensive and expensive compared to mining virgin lithium (Energy Monitor, 2023).

12.2.6 South African Recycling Initiatives for CRMs

Existing South African CRMs Recycling Efforts

South Africa has several recycling initiatives and facilities that focus on CRMs essential for various industries, including the GH economy. These include the following notable facilities and initiatives:

Company	Focus	Key Materials	Website
AST Recycling	E-waste recycling and recovery of precious metals, especially from electronics.	Gold, silver, platinum (PGMs), palladium, copper. Not involved in REEs, nickel, or lithium, but recovery potential exists.	AST Recycling

Company	Focus	Key Materials	Website
Desco Electronic Recyclers	E-waste recycling company focusing on materials like copper, REEs, and other valuable metals. Expanding capabilities to PCBs and battery recycling.	Copper, REEs, and other valuable metals.	Desco
EnviroServ	Leading waste management company offering waste disposal and recycling services, including hazardous and industrial waste management.	Some CRMs-containing materials.	EnviroServ
E-Waste Technologies Africa	Focuses on recycling electronic waste, including lithium-ion batteries and obsolete electronics.	Lithium, PGMs (e.g., from circuit boards), nickel.	E-Waste Technologies Africa
Mintek	National mineral research organisation specialising in mineral processing and extractive metallurgy. Actively working on extracting CRMs from industrial waste and secondary sources.	REEs, nickel, cobalt, vanadium, platinum.	Mintek
SA Precious Metals	Specialises in refining PGMs and recycling end-of-life components containing these metals. Permitted to recover low-grade waste materials and develop specialty chemicals.	PGMs.	SA Precious Metals
Veolia South Africa	Specialises in recycling hazardous materials and alternative treatment methods for waste streams, including CRMs recovery.	Batteries, circuit boards, and complex waste.	Veolia South Africa
Isondo Precious Metals	Developing a recycling initiative focused on PGMs like iridium for green hydrogen production. Uses green chemistry for high-purity recovery of PGMs from secondary sources.	Iridium, platinum, and other PGMs (focus on iridium for PEM electrolysers in the hydrogen economy).	Isondo Precious Metals

Funding has been raised for the development of a SEZ. Bojanala SEZ is also known as the Platinum Valley SEZ, which clearly indicates its focus on mineral beneficiation of PGMs, including platinum, palladium, rhodium, osmium, ruthenium, and iridium, in the North West Province. The primary focus of the SEZ will be on PGMs beneficiation industries and key opportunities include catalysts (automotive catalytic converters), electrical and electronics components, biomedical and pharmaceutical products (cancer treatment and micro implants), high-performance alloys (labware, optical equipment and turbine blades), fuel cells, and jewellery.

12.2.7 The Gap in South Africa's CRMs Recycling

Despite being one of the largest producers of PGMs globally, South Africa lags behind in the recycling of CRMs, including PGMs. While recycling in other regions has been driven by legislative frameworks and economic incentives, South Africa's recycling efforts are still nascent, with several challenges impeding progress.

Lack of Infrastructure and Legislation

One of the major gaps in South Africa's CRMs recycling initiatives is the absence of a comprehensive legislative framework. Unlike the EU or Japan, South Africa lacks stringent recycling laws that mandate the recovery of materials from end-of-life products, such as vehicles and electronics. Consequently, the collection and processing of CRMs-containing waste remain fragmented and inefficient. This has resulted in low recycling rates, particularly for PGMs used in automotive catalysts and electronics (Ryan *et al*., 2010).

Furthermore, South Africa's recycling infrastructure is underdeveloped. While the country excels in primary PGM production, the facilities required for efficient CRMs recycling, such as smelters and refineries capable of handling complex waste streams, are limited. This contrasts sharply with Europe, where integrated smelting and refining facilities such as those operated by Umicore play a crucial role in ensuring high recovery rates for CRMs (Hagelüken, 2012).

Economic and Market Challenges

Economic factors also hinder the development of CRMs recycling in South Africa. The country's reliance on primary mining for PGM production means that the recycling of secondary materials has not been prioritised. Additionally, the fluctuating prices of PGMs and other critical metals make recycling less attractive for businesses, as the economics of collection, processing, and refining depend heavily on metal prices (Ryan *et al*., 2010). In periods of low metal prices, the profitability of recycling operations diminishes, further discouraging investment in recycling infrastructure.

In contrast, in Europe and Japan, government subsidies and tax incentives have been introduced to make recycling economically viable, even when metal prices are low. For South Africa to bridge this gap, similar economic policies would need to be implemented, providing businesses with the necessary incentives to invest in recycling technologies (Ryan *et al*., 2010).

Technological Challenges

South Africa also faces technological challenges in CRMs recycling. Hydrometallurgical and pyrometallurgical processes, commonly used in Japan and Europe for the recovery of PGMs, are not widely employed in South Africa's recycling sector. The lack of expertise and investment in these technologies means that even when materials are collected for recycling, the recovery rates are low. For example, global PGM recycling rates for spent automotive catalysts are less than 50%, and South Africa's rates are likely even lower due to the inefficiencies in the collection and processing stages (Tang *et al*., 2023).

To improve recycling outcomes, South Africa would need to invest in advanced recycling technologies, as seen in Belgium's Umicore facility or Japan's hydrometallurgical plants, which have been successful in extracting high yields of PGMs from complex waste streams (Hagelüken, 2012). Moreover, collaboration between the government, industry, and academia, similar to the Japanese model, could help bridge the technological gap by promoting research and development in CRMs recycling technologies (Tang *et al*., 2023).

While countries like Japan and members of the EU have made substantial progress in the recycling of CRMs, particularly PGMs, South Africa still faces significant challenges. The lack of comprehensive legislation, insufficient recycling infrastructure, and economic disincentives have all contributed to the country's lagging performance in CRMs recycling. However, by learning from international examples, South Africa has the potential to improve its recycling systems and secure a sustainable supply of CRMs for the future. By addressing these gaps through investment in technology, infrastructure, and legislative reform, South Africa could play a leading role in global CRMs recycling, complementing its position as a major primary producer of PGMs.

12.3 Stakeholder Insights on Recycling

12.3.1 Role of CRMs Recycling in the Green Hydrogen Economy and Mining-Value Chain

CRMs recycling supports the green hydrogen industrialisation goal by providing essential materials for renewable energy technologies, including electrolysers and fuel cells, which require PGMs and other CRMs critical to green hydrogen. CRMs recycling also reduces dependency on mining by reclaiming materials from end-of-life products, reducing mining's environmental footprint across the value chain potential.

The workshop participants noted that, within South Africa's green hydrogen economy, CRMs recycling can potentially play a vital role in supporting sustainable industrialisation and ensuring a stable CRMs supply. However, currently, the recycling of CRMs is not being prioritised in South Africa because of the various challenges discussed below:

- **High initial cost:** Establishing effective CRMs recycling facilities requires a significant investment in specialised technologies, infrastructure, and skilled labour. Entering the CRMs recycling market places South Africa at a disadvantage compared to countries with established recycling industries, especially in Europe, North America, and parts of Asia where the recycling infrastructure, technology, and regulatory frameworks are already robust.
- **Contained value:** The limited understanding of the contained value in recycling the CRMs slows down the rate at which it takes off in South Africa. Initiatives that advocate for and educate about the recycling of CRMs will assist in ramping up CRMs recycling.
- **Regulatory and policy gaps:** The recycling of CRMs involves navigating stringent environmental and waste management regulations, often lacking clarity on CRMs-specific requirements, specifically in South Africa.
- **Technical complexity:** Recycling CRMs, especially from complex products like electronics and batteries, requires advanced methods like hydrometallurgy and pyrometallurgy, which can be costly and energy intensive.
- **Limited feedstock:** South Africa lacks the necessary volumes of CRMs-containing waste, and this impacts the feasibility of large-scale CRMs recycling. This could be because of different factors such as the lack of necessary collection infrastructure and that South Africa's CRMs waste streams may be too small to attain economic critical mass.

While South Africa faces these hurdles, it could still carve out a niche by focusing on regional collaboration within the SADC area, targeting specific CRMs that are particularly important for the green hydrogen sector, and securing governmental support to accelerate CRMs circularity. This would ensure a stable feedstock and strengthen its CRMs recycling network.

12.3.2 Potential Environmental Impacts Associated with CRMs Recycling

Recycling CRMs is environmentally beneficial but poses specific challenges:

- **Waste and chemical use:** The recycling process can produce hazardous by-products and involve chemicals that, if mismanaged, could harm local ecosystems.
- **Energy use:** Recycling CRMs, particularly from complex products, can be energy-intensive, which could contribute to carbon emissions if renewable energy is not used. As a country currently struggling with a reliable energy supply, this will be a challenge for South Africa.
- **End-of-life waste management:** Improper handling of non-recoverable waste from CRMs recycling may lead to contamination and pollution.

12.3.3 Supporting South Africa's Green CRMs Recycling Hub

South Africa's potential to become a regional CRMs recycling hub depends on:

- **Government incentives and investment:** Financial incentives, such as tax breaks or grants, can stimulate investments in recycling technologies and encourage recycling practices across industries.
- **Innovation in recycling technologies:** Technological advancements, especially in hydrometallurgy and pyrometallurgy, would enable more efficient CRMs recovery from various waste streams.
- **Regional collaboration:** Partnerships with other SADC nations can create a larger CRMs waste feedstock and improve supply chains, making recycling economically viable.
- **Global and local demand for CRMs:** As demand for CRMs rises with green hydrogen and other renewable industries, South Africa's ability to provide recycled materials could bolster its position as a reliable CRMs supplier.

Chapter 13

Strategy framework for the implementation of a circular economy & critical mineral recycling optimisation

13. Strategy framework for the implementation of a circular economy & critical mineral recycling optimisation

For South Africa to initiate optimising critical minerals recycling and promote circular principles, an implementation strategy framework is crucial and should be built upon the foundation of the Just Energy Transition Implementation Plan (JET-IP). Using the JET-IP's framework and not deviating from its core ethos of socio-economic empowerment in a sustainable manner, the strategy for optimising critical mineral recycling through circular economy principles can be justified.

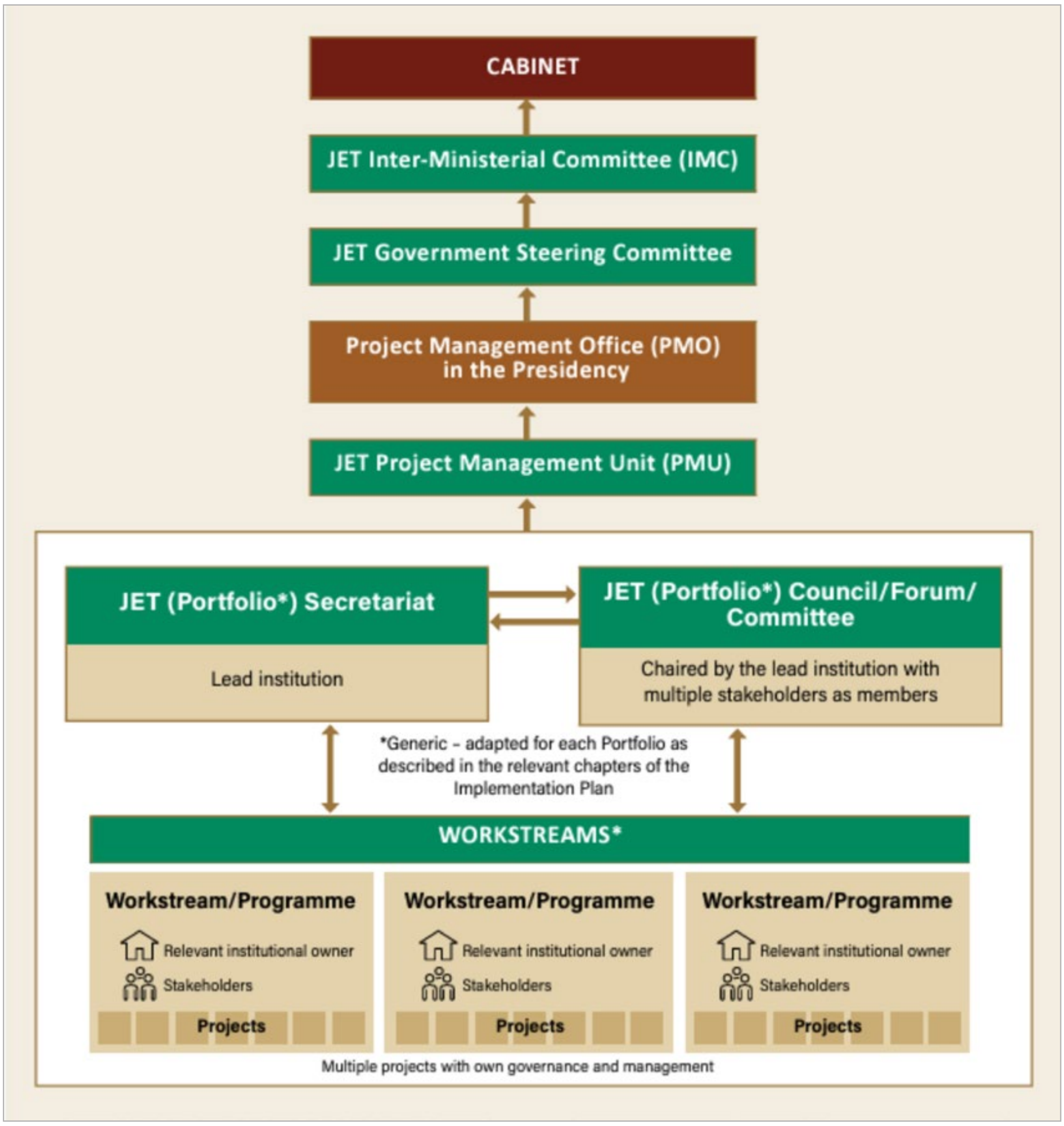


Figure 36: JET-IP Organisational Structure and Key Stakeholders involved in Implementation and Governance (from JET-IP, 2023)

The JET-IP organisational and governance structure involves an integrated approach and a mix of government stakeholders to ensure accountability and robust implementation with the Project Management Office within the Presidency in charge of overall growth and implementation of the JET. The governance structure also emphasises a collaborative approach to the management of project-related portfolio tasks. This ensures that both a top–down and bottom–up approach are synchronised to ensure effective implementation and communication is achieved in task execution.

The proposed strategy framework that follows would focus largely on developing implementation efforts to ensure sustainable critical mineral recycling and the promotion of South Africa's circular economy.

South Africa's Circular Economy Implementation Objective

Effective implementation, robust monitoring, and evaluation frameworks to track progress, identify challenges, and make necessary adjustments while promoting circular economy initiatives and offering a platform for the development of further circular economy initiatives is crucial to establish an accountable process and promote learning throughout the implementation process. The focus for critical mineral recycling would assess the opportunities that can be leveraged from already existing CMRs such as tailings, end-of-life component parts, and mineral dumps.

Strategic Development Actions

To implement an accountable process for promoting the circular economy and optimising critical minerals recycling, a strategy framework must be developed and defined to benchmark progress and a structure to implement the strategy must be outlined. These key facets are defined below:

- Develop a structure that complements existing public and private recycling efforts and centralises monitoring responsibilities to relevant lead institutions or stakeholders by focusing on opportunities and initiatives that are already in place.
- Define clear outcomes and impact indicators for circular economy portfolios, including critical mineral recycling with country targets. Driving research and innovation into advancing recycling can assist in reaching these targets quicker.
- Establish data collection mechanisms and reporting procedures that are centralised to ensure accessible participation.
- Implement a system for regular monitoring, evaluation, and engagement with stakeholders that promotes compliance and active promotion of circular economy principles in line with socio-economic upliftment.
- Regularly review progress, identify challenges, and make necessary adjustments to the implementation plan based on the monitoring and evaluation findings.

Key Factors that will help Promote the Circular Economy:

- **Strong leadership and coordination:** It is imperative that there is strong leadership from relevant government departments to provide clear direction, coordinate activities across portfolios, and ensure accountability for results. Together with mining stakeholders, innovators, entrepreneurs, and civil society, a public–private partnership can help bolster and accelerate government efforts to ensure critical mining recycling is realised.

- **Stakeholder engagement and collaboration:** Engaging communities, labour unions, businesses, and civil society organisations is essential for building consensus, addressing concerns, and ensuring that efforts to improve the circular economy are achieved through a consultative process.
- **Access to finance:** Securing adequate funding from international partners, the private sector, and government sources is crucial for implementing projects and initiatives.
- **Capacity building:** Investing in technical expertise, skills development, and institutional strengthening is necessary to support effective implementation.
- **Policy coherence and regulatory reform:** Creating an enabling policy environment through streamlined permitting processes, clear regulations, and supportive incentives is vital for attracting investment and promoting innovation.

By utilising these components, a strategy framework can be formulated for South Africa to enhance its sustainable initiatives, accelerate its transition to a low-carbon economy, and achieve the objectives to improve the South African circular economy.

13.1 Integrating CRMs Recycling with Circular Economy Principles in South Africa

13.1.1 South Africa’s Circular Economy Plans

Establishing a circular economy is essential for address the growing waste challenges, which are crucial for preserving resources and protecting the environment. The circular economy seeks to shift from traditional linear processes to circular value chains. This involves practices like sharing, leasing, repairing, refurbishing, repurposing, reducing, remanufacturing, upcycling, and recycling, rather than following the conventional take–make–consume–dispose model. It can also contribute to creating a sustainable and competitive economy (Hoosain *et al*., 2023).

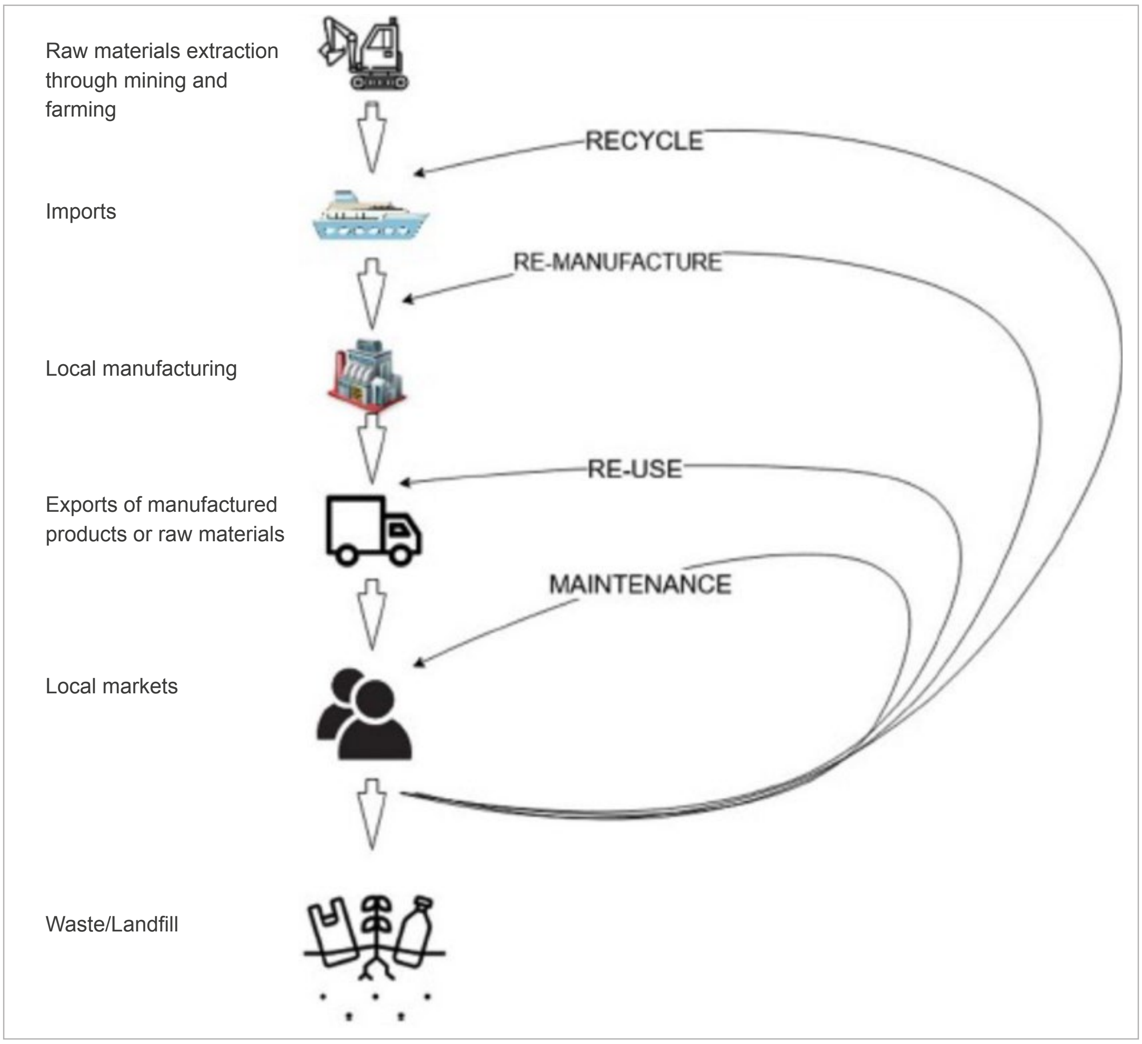


Figure 37: A typical South African circular economy approach (Hoosain et al., 2023)

The South African government approved the National Waste Management Plan (NWMP) for 2020. This policy aims to promote the waste hierarchy and circular economy principles, aiming to achieve socio-economic benefits such as job creation while minimising environmental harm. The NWMP provides technical interventions for the waste sector and aligns with the SDGs and the country's NDP (DFFE, 2020; Hoosain *et al*., 2023).

The country's National Waste Management Strategy (NWMS) also emphasises circular economy principles to minimise waste and promote recycling and resource efficiency. The CSIR report (2022) titled *"South Africa's resource availability as a driver for transitioning to a Circular Economy"* reports on the circular economy opportunities for the mining sector by keeping products and materials in use through various recycling initiatives. The report identifies the recovery of end-of-life products and/or e-waste (urban mining) using scrap metal in combination with primary concentrates to produce metals; secondary smelting of electronic scrap to recover valuable metals such as gold, silver, copper, and palladium; and optimising the recovery of co-products, e.g., a nickel mining company can increase the recovery of co-products such as PGM, cobalt, and copper as an opportunity for the mining industry. Through these efforts, alternate business models and subsequent jobs may potentially also be created. This can be achieved by establishing subsidiary companies focused on recovering and reprocessing scrap metal. As of 2018, less than 10% of e-waste was collected for recycling, with the majority being exported for processing abroad.

13.1.2 Challenges

According to Hoosain *et al*. (2023), although these strides are a great step forward, there are still major challenges as described in the report and by the national statistics (Department of Environmental Affairs Republic of South Africa, 2019; South Africa Department of Statistics, 2020). South Africa, and the African continent, have implemented policies and made commendable efforts toward innovation. However, these initiatives are often inconsistent. Several factors contribute to this, including limited funding compared to developed nations, differing public attitudes, corruption and criminal activities, and a lag in education (Hoosain *et al*., 2023).

13.1.3 Proposals for Efficient CRMs Recycling in South Africa

The efficient recycling of CRMs is crucial for the green hydrogen economy because many CRMs, such as those discussed above, a play critical role in hydrogen production, storage, and fuel cell technologies. Global demand for these materials is expected to surge as the transition to cleaner energy sources intensifies, making it vital to ensure a stable and sustainable supply. Efficient recycling minimises the environmental impact of mining and processing CRMs while reducing dependence on volatile supply chains, especially in politically unstable regions. By recovering CRMs from end-of-life products like fuel cells and electrolysers, industries can lower production costs and foster circular economy initiatives.

South Africa holds some of the world's largest reserves of PGMs, essential for clean energy technologies like fuel cells. The country's focus on recycling CRMs can boost its economic diversification by supporting new industries in the circular economy and creating green jobs. Moreover, South Africa's position in the SADC offers the potential to become a regional hub for CRMs recycling, thereby supporting the broader region's green energy transition.

Listed below are proposals that would help South Africa and the global community improve CRMs recycling, reduce environmental impacts, and secure critical materials for the green economy.

13.1.4 Expansion of PGM Recycling Initiatives

South Africa, as the world's largest producer of PGMs, can strengthen its recycling efforts by establishing specialised recycling facilities focused on reclaiming PGMs from spent catalytic converters and hydrogen fuel cells. Efforts such as those behind establishing SEZs can be expanded and scaled up to create a PGM recovery hub, supporting both the mining and hydrogen industries.

Efficiency: Essential in establishing a circular economy, where materials are continuously recovered and reused, reducing the need for new mining activities and enhancing resource efficiency.

13.1.5 Urban mining & e-Waste Recycling

Urban mining refers to the process of recovering metals from electronic waste, including smartphones, computers, and appliances. This is a rich source of CRMs like gold, silver, REEs, and cobalt. The recycling of WEEE containing valuable CRMs is necessary in terms of sustainability, the circular economy and the environment, and this method cannot be abandoned (Ouro-Salim, 2024; Recycling Magazine, 2024).

Efficiency: Research shows that e-waste contains significantly higher concentrations of CRMs than natural ores. Using modern recycling plants with integrated hydrometallurgy and electrometallurgy.

Recycling infrastructure for E-Waste

South Africa generates significant volumes of e-waste, which often contains valuable CRMs like REE, cobalt, and palladium. Investing in nationwide e-waste recycling facilities, along with implementing e-waste collection programmes, can help recover CRMs from discarded electronics. This would not only reduce landfill waste but also boost CRMs availability for the growing green hydrogen sector.

Efficiency: Infrastructure development would help increase recovery efficiency to be in line with countries that have a well-established e-waste.

Support for small-scale and informal recyclers

Many small-scale recyclers in South Africa collect and process valuable CRMs, but they often lack the resources or technology to recover materials efficiently. Providing support in the form of training, technology access, and financial incentives can improve their recovery rates. Initiatives like the South African Waste Pickers Association (SAWPA) could be leveraged to formalise and improve CRMs recycling efforts from grassroots levels.

Efficiency: By providing informal recyclers with training, technology, and support, South Africa could potentially increase their CRMs recovery efficiency. Formalising the informal recycling sector, as seen in countries like India and Brazil, has shown that efficiency can be significantly improved with government and industry support, leading to more sustainable recovery of CRMs.

Exploring New Recycling Technologies

Hydrometallurgy and Pyrometallurgy Approaches

Hydrometallurgy involves using aqueous chemistry (involving leaching) to recover CRMs, particularly for extracting metals like cobalt, nickel, and lithium from end-of-life batteries. This method dissolves the solid-metal fraction and results in a recycled metal solution for further separation (Recycling Magazine, 2024; Zhang & Xu, 2018).

Pyrometallurgy involves high-temperature processes for extracting metals, often used in recycling REEs and PGMs.

Efficiency: These methods are mature, with well-established industrial processes for CRMs like cobalt, nickel, and PGMs. However, newer, more environmentally friendly approaches like solvent extraction and ion-exchange are being integrated to reduce the environmental impact.

Bioleaching

Bioleaching uses microorganisms (bacteria and fungi) to extract metals from end-of-life products like e-waste and batteries. It is particularly effective for low-grade ores and materials like lithium, cobalt, and copper. This method has been shown to be more environmentally friendly than traditional methods and has high recovery rates (Recycling Magazine, 2024).

Efficiency: Bioleaching is energy-efficient and scalable, with up to 90% recovery of CRMs from complex materials like batteries and printed circuit boards (PCBs).

13.2 Stakeholder Insights on Circularity in South Africa

The following section details the feedback and input received from the attendees of the second workshop on the topic of circularity. The adoption of circular economy principles within CRMs mining could play a pivotal role in reducing waste and optimising resource use. Participants at the workshop emphasised practical, straightforward strategies to foster a culture of recycling and circularity in South Africa, suggesting that even modest initiatives could have a meaningful impact.

13.2.1 Exploring “Low-Hanging Fruit” for Recycling

Participants highlighted the importance of straightforward, accessible measures to encourage recycling. A notable example was a South African municipality initiative where free yellow bags were distributed for collecting recyclables, leading to an increase in public participation. Simple programmes like these demonstrate that providing resources and reducing barriers to recycling can cultivate a recycling culture, which is foundational for a circular economy. Further research and fact-checking on similar initiatives could help inform broader CRMs recycling efforts.

13.2.2 Learning from Other Sectors

To guide CRMs circularity, participants recommended examining existing recycling initiatives in other industries, such as plastics, lead-acid batteries, and tires. By understanding the successes and challenges within these sectors, CRMs stakeholders can adopt best practices and avoid potential pitfalls. Lessons learned from these sectors can shape effective strategies for CRMs recycling, providing insights into infrastructure, community engagement, and policy alignment needed for a circular economy.

13.2.3 Addressing Legislative Gaps

A critical barrier to CRMs circularity in South Africa is the lack of comprehensive legislation. Extended producer responsibility (EPR) was identified as an essential policy tool to ensure that CRMs producers are accountable for the entire lifecycle of their products. Implementing EPR would place the onus on producers to manage the recycling and disposal of CRMs products, incentivising them to adopt sustainable practices. Filling these legislative gaps could create a consistent framework that supports recycling, waste reduction, and sustainable production within the CRMs industry.

13.2.4 Early-Stage Circular Design and Economic Incentives

Circular economy principles should be embedded into CRMs-based products from the design phase, ensuring they are easy to dismantle, recycle, or repurpose at the end of their lifecycle. Participants advocated for economic incentives, akin to deposit-return schemes for glass bottles, where consumers pay a small fee on CRMs components and receive it back upon returning items for recycling. This system could drive circularity by rewarding consumers for responsible disposal while creating a steady stream of recyclable materials for CRMs producers.

14. Recommendations

Based on the study findings, the following recommendations chart a pathway to achieving a balanced and sustainable green hydrogen future:

- **Strengthen policy implementation:** Enhance the enforcement of existing frameworks, including the Mining Charter and NEMA, with robust monitoring and accountability systems to ensure sustainable practices and community engagement.
- **Promote technological innovation:** Invest in advanced technologies, such as artificial intelligence, to optimise CRMs mining processes, improve efficiency, and reduce environmental impacts.
- **Develop a national CRMs recycling strategy:** Adopt circular economy principles to enhance material recovery and reduce waste. This includes building recycling infrastructure, advancing recovery technologies, and addressing regulatory gaps to support efficient CRMs recycling.
- **Foster collaboration and capacity building:** Strengthen partnerships between government, industry, communities, and civil society to promote knowledge sharing, equitable benefit distribution, and local skills development for green hydrogen-related opportunities.
- **Diversify supply chains and explore alternatives:** Reduce dependency on single suppliers through diversified sourcing strategies and invest in research to develop alternative materials for green hydrogen technologies.
- **Address environmental impacts:** Implement sustainable water management practices to mitigate issues like AMD, ensure responsible land use, and protect biodiversity from mining-related habitat disruptions.

By adopting these strategies, South Africa can leverage its rich CRMs to drive a green hydrogen economy that supports economic growth while safeguarding social equity and environmental sustainability.

15. Conclusion

The transition towards a green hydrogen economy represents a critical juncture for integrating CRMs into cleaner energy systems. In South Africa, the extraction and utilisation of CRMs, particularly PGMs, underpin technologies such as fuel cells and electrolysers essential for hydrogen production. However, this development presents a complex interplay of economic, environmental, and socio-political challenges that require careful management.

CRMs mining provides substantial economic benefits, including contributions to GDP, tax revenues, and employment. The sector also supports local economic development and infrastructure improvements while playing a key role in global supply chains. These economic gains, however, come with significant environmental costs. CRMs extraction involves high energy and water demands and contributes to GHG emissions, habitat loss, and water pollution. Issues such as AMD, water scarcity, and land degradation have long-term consequences for ecosystems and communities, highlighting the need for sustainable approaches.

The environmental impacts of CRMs mining are evident in South Africa's grassland and savanna biomes, which are increasingly affected by mining operations. These activities intersect with biodiversity-rich areas, amplifying the effects of climate change and other land-use pressures. Hydrological systems face similar risks, with rivers such as the Limpopo, Olifants, and Crocodile experiencing pollution and resource depletion linked to mining. Effective mitigation strategies are needed to address these challenges while supporting industrial activity.

The socio-economic dimensions of CRMs mining reflect its dual nature. Mining activities provide employment and stimulate local economies but often impose significant costs on nearby communities. Health risks from pollution, displacement, and the loss of cultural heritage are common issues. Marginalised groups, including women and indigenous populations, are disproportionately affected, making it essential to implement inclusive policies and ensure communities benefit equitably. Strengthening community participation, upholding FPIC principles, and addressing unequal power dynamics in decision-making are necessary steps towards achieving fair outcomes.

Technological innovation offers potential solutions to align CRMs extraction with sustainability goals. Advanced resource extraction methods, supported by AI, can improve efficiency and reduce environmental impacts. Recycling initiatives, guided by circular economy principles, provide an opportunity to decrease dependence on virgin materials.

Developing robust recycling infrastructure and integrating sustainable design into CRMs-dependent technologies will be crucial for long-term resource management.

Infrastructure tailored to green hydrogen production highlights the complexity of the transition. Electrolysers, pipelines, and hydrogen storage systems require significant investment and coordinated planning. Challenges such as high capital costs, insufficient energy transmission infrastructure, and long equipment lead times will need to be addressed through targeted policies and financial incentives.

Balancing CRMs extraction and the green hydrogen economy requires a comprehensive and multi-layered approach. Policy frameworks must integrate environmental protection, industrial development, and social equity. Reforms to environmental laws, land-use plans, and water regulations will be necessary to align mining activities with both national and international sustainability priorities. Resilient supply chains and technological advancements will also play a vital role in ensuring the stability and sustainability of CRMs production.

In conclusion, integrating CRMs into the green hydrogen economy presents both significant opportunities and serious challenges. While CRMs mining offers economic and technological benefits, the associated environmental and social costs require focused attention and long-term planning. By adopting sustainable practices, fostering innovation, and prioritising fair socio-economic outcomes, the mining sector can play a meaningful role in advancing the energy transition. Achieving this will depend on effective collaboration between stakeholders, robust governance, and a consistent commitment to sustainability.

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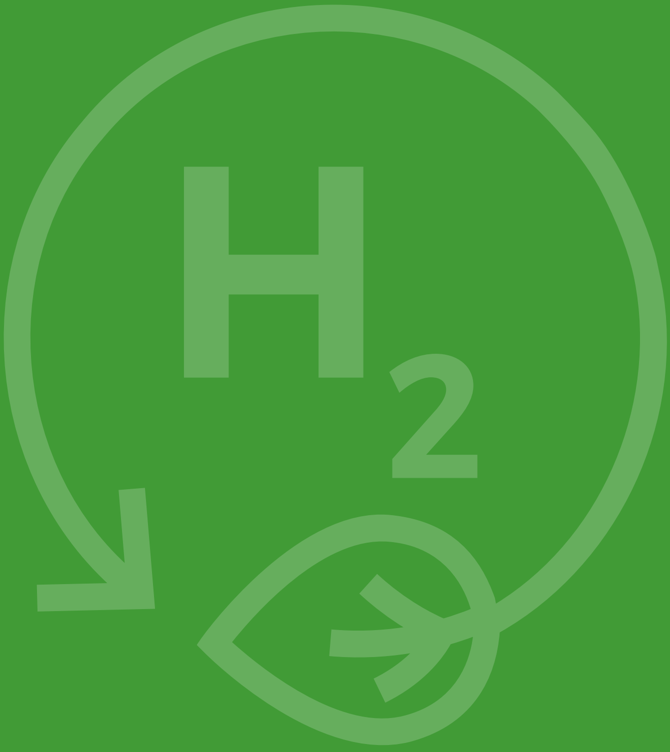

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