Mining Future Skills

MINING QUALIFICATIONS AUTHORITY

FINAL REPORT

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FOR

A STUDY TO EXPLORE THE STATE AND NATURE OF GREEN HYDROGEN TECHNOLOGIES AND IMPLICATIONS FOR SKILLS DEVELOPMENT IN THE MINING AND MINERALS SECTOR (MMS) IN SOUTH AFRICA

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EXECUTIVE SUMMARY

Introduction and background

The Mining Qualifications Authority (MQA) partnered the Wits Mining Institute (WMI) to conduct a study that provides insights into the state and nature of green hydrogen technologies and implications for skills development in the MMS (MMS) in South Africa. This report was developed by the Wits Mining Institute to present the findings of the study. The study aimed at exploring the state and nature of green hydrogen technologies and implications for skills development in the entire Mining and Minerals Sector (MMS) across nine sub-sectoral value chains. These sub-sectors include coal mining, gold mining, diamond mining, diamond processing, Platinum Group Metals (PGM), and cement, limestone, aggregates and sand (CLAS), jewellery manufacturing, Services Incidental to Mining (SITM), and other mining. As per the Terms of Reference, the study also focused on the state and nature of green hydrogen technologies and implications for skills development pertinent to the MMS. However, closely linked sectors with influence on the development of green hydrogen were also investigated in as far as collaboration opportunities are concerned.

Study aim and objectives

The aim of the study was to explore the state and nature of green hydrogen technologies and implications for skills development in the MMS in South Africa.

This aim was supported by the following objectives:

1) To identify the green hydrogen technologies implemented in the MMS
2) To establish the factors impeding the implementation of green hydrogen technologies in the MMS
3) To determine the nature of skills supply in relation to green hydrogen technologies in the MMS
4) To identify the skills demand associated with green hydrogen technologies in the MMS
5) To explore international mining-related experiences in the development of green hydrogen technology

6) To identify interventions that can be implemented by the MQA to facilitate skills development in the field of green hydrogen technologies within the MMS
7) To identify a green hydrogen technologies ecosystem for the MMS
8) To develop a framework of pathways for the development of green hydrogen technologies in the MMS

Approach to the study

The investigation into the state and nature of green hydrogen technologies and implications for skills development in the MMS required a description of the situation with respect to the opportunities and challenges, comparing the South African situation with other countries in Africa and other continents. Specific focus on sub-sectors was also important to understand and inform interventions, this included a review of case studies. The realisation that this is a nascent technological development resulted in this study anchoring research processes on the moorings of Actor Network Theory which looks at green hydrogen technological development as social and technological processes. This was important when exploring the benefits and opportunities of green hydrogen and the skills development implications.

Benchmarking developments in South Africa and other countries and across sectors required exploration of projects within sub-sectors and identification of the themes and commonalities among them to determine important drivers and challenges to draw implications for skills development. This implied that a mixed methods approach was most suitable for the study, combining qualitative, and quantitative methods. The study relied on archival data source, a review of the literature, notes from forums and relevant events, engagement with participants at the Energy and Mining Skills Forum (n=32), surveys involving representatives of the MMS sub-sectors and other stakeholders (n=46) and interviews with key informants (n=15) who completed the surveys.

Key findings and insights

The study revealed the following insights:

- The green hydrogen technologies are conceptualised as a value network rather than a value chain. A value chain perspective focuses on the main actors such as suppliers of renewable energy, electrolysers, fuel cell and water (upstream), production, transportation, and storage (midstream), and consumption (downstream). However, such a narrow perspective overlooks the important role that other services provide.
- Although a limited range of technologies are being implemented in the country, the study finds several green hydrogen technologies give significant potential in the future.
- There is over 1426 MW of investment in renewable energy capacity. This shows that although there is low preparedness in green hydrogen specific technologies, renewable energy investment is already underway.
- Current uses of green hydrogen in the MMS include for transport and power. Other applications include heat and industrial demonstrating the versatility of green hydrogen.
- The level of awareness and understanding of green hydrogen technologies, and therefore preparedness in the MMS in South Africa is very low.
- South Africa has made significant strides in developing a legislative framework to drive green hydrogen, but lack of coordination of efforts and perspectives was found to be a crucial blocker.
- Few projects globally have reached Final Investment Decision (FID) and in South Africa green hydrogen technologies are at embryonic stage.
- South Africa's MMS has huge potential to ride on the abundance of renewable resources in wind and solar to lead the green hydrogen technologies drive, but it needs to overcome several barriers to achieve that, including regulatory uncertainty, water scarcity, competition from other energy technologies, unreliability of electrolysers, high prices of green hydrogen when compared to, for example, grey hydrogen, high capital costs, and scalability issues.
- Green hydrogen technologies have potential for accelerating economic growth, and creation of jobs.

- Currently there are no green hydrogen skills gaps, yet the risks of future shortages and mismatches are apparent.
- Several competences and skills are anticipated to be lacking in future, specifically technical skills.
- There are several emerging skills that are essential for the green hydrogen technologies, including artificial intelligence and machine learning, digitalisation and internet of things, policy and regulatory frameworks, cybersecurity, and sustainability and lifecycle assessment.
- There is projected mismatch between certification needed for the hydrogen economy and qualifications/programmes in South African universities and vocational colleges.
- The need for increasing digital technologies in training, education and the workplace it is becoming more apparent.
- Workplace, education and training pathways are not keeping pace with industry and global trends.
- The demand for artisans and technicians will increase as the production of green hydrogen technologies gathers momentum. Technical and Vocational Education and Training colleges (TVETs) will play a crucial role, so will Universities of Technology and other learning institutions.
- South Africa has made significant strides in developing a legislative environment at the back of renewable energy and PGM endowments, and the MMS has joined other global MMSs in advancing green hydrogen technologies.
- The MQA could utilise skilling, upskilling, re skilling, cross skilling and multiskilling in line with different sub-sectors' likelihood of adopting green hydrogen technologies and the employee's skills transferability to green hydrogen technologies

Recommendations

Based on the findings from the study, the following recommendations are made:

Recommendation 1: Develop a green hydrogen workforce development plan

The is a need for MQA to develop a green hydrogen workforce development plan. The plan should be anchored on a solid vision for the sector's skills direction and aim to develop a workforce with the necessary skills to support the adoption of green hydrogen technologies important in the MMS. This study has identified the skills which will be important to take the sector forward. Although the study found that there are currently no skills shortages, the risk for future skills shortage is quite high and the sector will need to proactively prepare for the anticipated acceleration of the green hydrogen technologies, expected to generate 20 000 jobs per year by 2030 and 30 000 jobs per year by 2040 and a total of 380 000 jobs in total by 2050. This is approximately 80% of the current employment levels of the entire mining sector. The workforce development plan should utilise these estimates to inform skills development. This study has identified the green hydrogen technologies important in the MMS. MQA could build on these technologies to develop the needed skills. The following steps are important for MQA to develop a compelling vision.

i. The SETA should conceptualise a compelling and strategic green hydrogen technologies vision of the future the sector wants.
ii. The SETA should identify the type of skills that are needed to achieve this strategic vision (this study has identified them).
iii. The SETA needs to set out a plan to develop these skills.
iv. Implementing these skills strategies requires harnessing the energy and commitment of social partners and stakeholders, as there are limits to what the SETA can achieve on its own.

Activity	**Develop a *Mining Future Skills Development Programme* at three levels – basic, fundamentals and practice** **Lobby DHET to fill the gap of 21 qualifications missing in SA** **Develop a green hydrogen workforce development plan, include:** - **national and regional committee** - **a monitoring and evaluation framework** - **a learner and employed platform**
Timeline	1 to 2 years

Recommendation 2: Develop a green hydrogen technologies awareness and understanding campaign

This study found a very low level of awareness and understanding of green hydrogen technologies in the MMS. The MQA could create an awareness campaign to educate stakeholders about the basics, benefits and opportunities of green hydrogen technologies in the MMS. The challenges that are faced in the green hydrogen technologies implementation are important for stakeholders to know. Specifically, the campaign should focus on *problematising* the challenges that green hydrogen technologies seek to address which are summed as the energy trilemma of energy security, access, and sustainability. Second is for the campaign to *raise interest* for more sector and stakeholder participation which is a crucial condition necessary to build critical mass for the technologies to be economically viable. It is important for the sector to understand the benefits, such as employment creation and associated structural transformation, industrial diversification and economic growth, and assisting to decarbonise and meet their green targets. Additionally, for PGM mining sub-sector this generates alternative uses that sustains the sector. This helps to *enrol* more stakeholders to actively participate in building the green hydrogen technologies network. Over time, the campaigns will need to focus on mobilising participation of other sectors within the country and beyond to support the network to grow and finally *stabilise,* and for green hydrogen to become seen as the *institutionalised* energy resource to decarbonise the MMS which is one of the hard-to-abate sectors.

Activity	**Develop a green hydrogen awareness campaign in the MMS, include roadshows, digital newsletters, digital media, school hydrogen competitions**
Timeline	Annually

Recommendation 3: Create learning and career pathways that lead to new green hydrogen technologies opportunities

Key informants noted the many factors that highlight the need for improving learning and career pathways to new opportunities. This is underscored by the need for the sector to overcome the challenge and risk that comes with preparing youth for professions that do not yet exist and balancing that with opportunities that are envisioned in a fully hydrogenised MMS. This study has developed a matrix of four quadrants based on the sub sectors exposure to green hydrogen technologies and the compatibility or transferability of skills that employees already have or miss (Figure 37: *Exposure to green hydrogen transition, skills compatibility and skilling strategies*. We recommend that career pathways be based on that matrix. For example, the cement, mineral sands, PGMs mining, and gold mining sub-sectors are hard to abate and therefore more likely to lead the green hydrogen transition. The coal mining subsector is at high risk of scaling down as the economy decarbonises. Pathways need to take cognisance of these details in order to introduce specific interventions.

Recommendation 4: Create a framework to enable everyone to develop the green hydrogen skills needed in the future

The MQA is recommended to create a framework to enable the development of green hydrogen technologies skills for the future. This should be done by integrating formal learning, informal learning, and non-formal training to give everyone an opportunity to learn. The importance of investing in the integration of new entrants to green hydrogen technologies by supporting the recognition of previous qualifications, degrees and skills, as well as access to further education and training was also noted. This is important as there are no green hydrogen qualifications or degrees except for isolated modules in other programmes. Going forward, it is important to align the current qualifications and identify additional training that recognises current capabilities and competencies. The other challenge relates to the low value accorded to TVET qualifications. There is need for concerted efforts to collaborate with industry, stakeholders, and communities to build confidence to avoid a situation where TVETs do not have the required learner supply base. This due to no one wanting to take up courses or as graduates have no jobs due to being perceived to be unready for the job market. The framework should aim at capitalising the Not in Education, Employment or Training (NEETs). Such a framework should be inclusive to carter for women, the disabled and other marginalised groups.

Activity	**Create learning and career pathways that lead to new green hydrogen technologies and opportunities (lifelong and lifewide learning)** - **formal, informal and non-formal education and training, gamification**

	- **introduce games for basic, senior and young employees, integrated VR** - **Roadshows to recruit learners, train the trainer initiatives**
Timeline	2 to 3 years

Recommendation 5: Develop sector -led green hydrogen standards for the MMS

It is recommended that the MQA collaborate with industry stakeholders to develop standards for green hydrogen technologies in the MMS. This study found that the lack of standards and clear policies was a major challenge for the development of the green hydrogen technologies in the country and in the MMS. It is recommended that the MQA takes a leading role in advocating for sector-led green hydrogen standards for the MMS. This is achievable through partnering with the South African Bureau of Standards (SABS) and industry experts to align the standards with international best practices.

Activity	**Sector-led green hydrogen standards for the MMS should be established. Engaged stakeholders, unions, mining companies, OEMs, academics through virtual and provincial roadshows**
Timeline	Once-off

Recommendation 6: Develop a GLOCAL collaboration strategy and enrol international and local partners for green hydrogen

A GLOCAL collaboration strategy is centred on global collaborations that have local impacts. Such a strategy also focuses on collaborations with local actors including but not limited to SETAs. A typically example of a local partnerships is the MoU that the MQA, TETA and CHIETA formed recently to establish the Green Hydrogen Centre of Specialisation (CoS) at CSIR. However, the MQA could leverage the existence of the CoS to partner with international organizations and research institutions to leverage expertise and best practices in green hydrogen technologies. International collaborations and partnerships allow MQA to attend international conferences, engage with industry associations, and participate in global research initiatives. Collaborations should focus on the entire value network as it is important to build a comprehensive green hydrogen ecosystem in South Africa and globally for the MMS to thrive in these technologies. This study finds that the sector will not achieve green hydrogen transformation unless it collaborates with other sectors, including EWSETA, and merSETA. Green hydrogen technologies require usage of significant amounts of renewable energy, water and land, which makes the active participation of local governments important.

Activity	**Develop a GLOCAL collaboration strategy and enrol international and local partners for green hydrogen** **Develop a green hydrogen skills pact with local partners, leverage partner research to enrich initiatives** **Develop a green skills committee, leverage partner support to enrich initiative** **Develop a green hydrogen skills forum with local partners, leverage partner footprint to enrich initiative**
Timeline	Once off, by 2028

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/acronym	**Description**
ACED	African Clean Energy Development (Pty)
ADKAR	Awareness, Desire, Knowledge, Ability and Reinforcement
AMV	African Mining Vision
ANT	Actor Network Theory
AREP	African Rainbow Energy and Power
BEIS	Business Energy & Industrial Strategy
C	Coal
CG	Coal Gasification
Cl2	Chlorine Gas
CCS	Carbon Capture and Storage
CCU	Cabon Capture and Utilisation
CET	College of Education and Training
CH4	Methane
CHIETA	Chemical Industries Education and Training Authority
CLAS	Cement, Limestone, Aggregates and Sand
CO	Carbon Monoxide
CO2	Caborn Dioxide
CoS	Centre of Specialisation
CPPS	Cyber-Physical Production System
CPS	Cyber Physical System
CPMT	Cyber-Physical Machine Tool
DBSA	Development Bank of Southern Africa
DHET	Department of Higher Education and Training
DMRE	Department of Mineral Resources and Energy
DWS	Department of Water and Sanitation
DSTI	Department of Science, Technology and Innovation
ERA	Electricity Regulation Act

EWSETA	Energy and Water Sector Education and Training Authority
FID	Final Investment Decision
FTSE	Financial Times Stock Exchange
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GHT-DF	Green Hydrogen Technologies Development Framework
GLOCAL	Global and Local
GOs	Guarantees of Origin
GW	Gigawatt
H2	Hydrogen
H2O	Water
HAE	Hydrochloric Acid Electrolysis
HER	Hydrogen Evolution Reaction
HFCT	Hydrogen Fuel Cell Technology
HPP	Hydrogen Production Pathway
HSRM	Hydrogen Society Roadmap
HySA	Hydrogen South Africa
IEA	International Energy Agency
ILA	Individual Learning Account
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
ISA	Infrastructure South Africa
IPCC	Intergovernmental Panel on Climate Change
JET	Just Energy Transition
JSE	Johannesburg Stock Exchange
KIIs	Key Informant Interviews
LSP	Lephalale Solar Project
MCSA	Minerals Council South Africa
merSETA	Manufacturing, Engineering and Related Services Sector Education & Training Authority

MMS	Mining and Minerals Sector
MOOCS	Massive Open Online Courses
MoU	Memorandum of Understanding
MQA	Mining Qualifications Authority
NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
NC(V)	National Certificate (Vocational)
NDP	National Development Plan
NHFCT	National Hydrogen Fuel Cell Technology
NSDP	National Skills Development Plan
NATED	National Accredited Technical Education Diploma
NEET	Not in Education, Employment or Training
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OER	Oxygen Evolution Reaction
OPP	Obligatory Point of Passage
OQ	Occupational Qualification
PEM	Proton Exchange Membrane
PGMs	Platinum Group Metals
PPA	Power Purchase Agreement
POPIA	Protection of Personal Information Act
PPIAF	Public Private Infrastructure Advisory Facility
PPPP	Public Private People Partnership
RAS	Rapid Survey
RBM	Richards Bay Minerals
RED	Renewable Energy Division
SABS	South African Bureau of Standards
SADC	Southern African Development Community
SDG	Sustainable Development Goal

SETA	Sector Education and Training Authority
SEZ	Special Economic Zones
SMR	Steam Methane Reforming
STEM	Science, Technology, Engineering, and Mathematics
TETA	Transport Education and Training Authority
TNPA	Transnet National Ports Authority
TVET	Technical and Vocational Education and Training
UN	United Nations
WACC	Weighted Average Cost of Capital
WBL	Work-Based Learning
WEF	World Economic Forum
ZEHS	nuGen Zero Emission Haulage Solution

1. INTRODUCTION AND BACKGROUND TO THE STUDY

1.1. Introduction

The Mining Qualifications Authority (MQA) has partnered with the Wits Mining Institute (WMI) to conduct a study that provides insights into the state and nature of green hydrogen technologies and implications for skills development in the mining and minerals sector (MMS).

1.2. Background and context

The MMS in South Africa stands as a cornerstone of the nation's economy, presenting immense potential not only for driving economic growth but also for combating the entrenched challenges of poverty, inequality, and unemployment. The sector occupies a unique position within the South African context, contributing substantially to economic value through the extraction of minerals. More recently, the important role of the sector has been amplified by the realisation that global warming is causing unprecedented impacts on life on land (SDG-15) (Srivastava, Iyer-Raniga & Misra, 2024). The need for urgent intervention is espoused in SDG-13 on climate action (Bandyopadhyay & Maiti, 2022). However, the sector is at crossroads, faced with the trilemma of minerals access, accessing them in a cost-effective way and doing so sustainably. Thus, the sector has been grappling to increase productivity and becoming more environmentally sustainable. This has led to a focus on alternative energy sources to green the mining and minerals value chains. Green hydrogen has been proposed as a significant score for the country because of the opportunities to generate clean energy for green hydrogen production. Green hydrogen technologies go beyond just the chemical production to include the green energy sources technologies such as wind, solar, and geothermal. Together, these circumstances are a harbinger of an emerging mining and minerals sub-sector where MMS players are generating their own green hydrogen to power operations, including mining trucks. Similarly, riding on the abundance of PGMs (South Africa has over 80% of global known PGMs reserves) the country is presented with a huge opportunity to lead on their beneficiation in the production of green hydrogen technologies (Du Venage, 2020). This new trend has created a need for focusing on a comprehensive approach that integrates skills development as new jobs arise.

The African Union has acknowledged the central role that mining plays as a cornerstone of industrialisation and economic growth (Kay et al., 2012; Fernandes, 2014; Nkhonjera, 2022) by creating the Africa Mining Vision (AMV) aimed at promoting sustainable and equitable mineral resource development in Africa (Hilson, 2020). The overarching objective of the AMV is to foster knowledge and capacity building. In South Africa, the sector forms the economic bedrock and plays a key role in structural transformation from primary agricultural economy to a more diversified industrialised economy (Antin, 2013; Mavhunga, 2023).

The country's abundant PGMs, potential for green energy technologies including wind and solar, and intentional focus on green hydrogen to power the MMS puts South Africa in good stead to lead on green hydrogen technology development. Some mining companies in South Africa are already piloting these green hydrogen technologies. For example, Anglo American, a leading global mining company, has already made significant commitments to green hydrogen development. The company is focused on becoming carbon neutral by 2040 by producing green hydrogen through electrolysis using only renewable energy, developing fuel cell technology for heavy-duty transportation. To drive these initiatives, the Anglo American is partnering with other energy players and the government, thereby creating an important green hydrogen technologies ecosystem which requires corresponding skills development to fill emerging jobs.

These change drivers have significant implications for skills development as the sector currently battles a shortage of talent (Nwaila et al, 2022). A targeted focus on skills development is critical to catalyse economic and structural transformation within South Africa's MMS. There is an opportunity for MQA to play an important role of equipping mineral industry professionals with advanced skills and accelerate the creation of secondary economies in the green hydrogen technologies value chain (Molek-Winiarska and Kawka, 2024). The National Skills Development Plan (NSDP) complements the NDP by defining desired outcomes and establishing a framework for the development of a skilled workforce capable of advancing economic growth and social development (Alcock, 2022). To enable these initiatives, there is a need for an evidence-base to align the development of the green hydrogen technologies with a workforce that is proficient in these emerging technologies (Mishira & Mishira, 2023).

1.3. Problem statement

The world is grappling with the adverse effects of climate change such as floods, heat waves and droughts (Chipangamate & Nwaila, 2023). This has led to growing sentiments for global energy transitioning, viewed as essential for addressing these global environmental challenges and ensuring a sustainable future. The priority to mitigate climate change, stabilize energy prices, and manage the growing demands of the population and energy consumption has become increasingly urgent. South Africa is currently battling energy poverty yet demands to decarbonise the economy are growing. The contribution of the MMS to the decarbonisation of the economy is twofold. First, the industry is important for the mining and processing of green energy minerals, for which the country has some of the world's highest known reserves (examples include PGMs, manganese and chrome) (Gibson et al, 2023). Second, the sector contributes to carbon emissions through the mining and minerals beneficiation processes. This presents an opportunity for the sector to contribute to decarbonisation by greening operations. South Africa's mining sector is, therefore, at a critical juncture where the demand for critical minerals is escalating due to their centrality in powering green technology initiatives and decarbonising operations through energy transition. Green hydrogen is an important element of the green economy as it leverages green energy sources for hydrogen production.

Meanwhile, the ethical and responsible production of these minerals and downstream beneficiation of green hydrogen technologies is contingent upon a workforce adept in modern mining technologies and processes (Kalantzakos, 2023; Nalule, 2023; Shimaponda-Nawa and Nwaila, 2024; Asa'd and Levesque, 2024; Wen et al., 2024). Currently, the state and nature of green hydrogen is unknown and the implications for skills development are unclear. There seems to be an imperative to develop talent with a deep understanding of sustainability and the green hydrogen technological acumen to ensure minimal environmental impact (Chipangamate et al, 2023). The green hydrogen economy is creating an ecosystem around mining and minerals operations. These emerging trends require upskilling the current workforce while rapidly transforming our education system to cope with the changing landscape (Chikatamarla & Prasad, 2020).

1.4. Aim and objectives

The aim of the study is to explore the state and nature of green hydrogen technologies and implications for skills development in the MMS in South Africa. This aim is supported by the following objectives:

1) To identify the green hydrogen technologies implemented in the MMS.
2) To establish the factors impeding the implementation of green hydrogen technologies in the MMS.
3) To determine the nature of skills supply in relation to green hydrogen technologies in the MMS.
4) To identify the skills demand associated with green hydrogen technologies in the MMS.
5) To explore international mining-related experiences in the development of green hydrogen technology.
6) To identify interventions that can be implemented by the MQA to facilitate skills development in the field of green hydrogen technologies within the MMS.
7) To identify a green hydrogen technologies ecosystem for the MMS
8) To develop a framework of pathways for the development of green hydrogen technologies in the MMS

Several research questions have been identified as being crucial to the study. These have been grouped under three pillars, namely, state and nature of green hydrogen technologies, skills development implications, and green hydrogen technologies future pathways. The set of questions are noted below.

Pillar 1: Understanding the scope and nature of green hydrogen technologies in the MMS in South Africa

i. What is the scope of green hydrogen technologies in the MMS in South Africa?
ii. What is the nature of green hydrogen technologies in MMS in South Africa?
iii. How are other countries and sectors developing green hydrogen (international best practices) and what lessons could be drawn for the MMS in South Africa?

iv. What are the challenges and opportunities presented by green hydrogen technologies in MMS in South Africa?

Pillar 2: Explore implications of scope and nature of green hydrogen technologies on skills development

v. What are the current skills needs for the green hydrogen technologies in MMS in South Africa?
vi. What are the leading competences required for the development of green hydrogen technologies?
vii. What are the skills development needs to align with future green hydrogen technologies trajectory in South Africa's MMS?

Pillar 3: Design a framework of green hydrogen technologies and skills development pathways

viii. What pathways are available for the green hydrogen technological transformation in the MMS in South Africa?
ix. Under what conditions is such a transformation possible?
x. What skills development strategies are required for the green hydrogen technological transformation in the MMS in South Africa?

These questions guide the research, ensuring a focused and comprehensive approach to addressing the complexities and opportunities within South Africa's MMS. Figure 1 shows the interconnectedness of the areas of inquiry. The figure demonstrates that an exploration of the state and nature of green hydrogen technologies is the foundation for determining the skills needs and development strategies that will be required to advance green hydrogen technologies in the country. When these two pillars are combined, the study will be able to outline the various pathways possible for the desired outcomes.

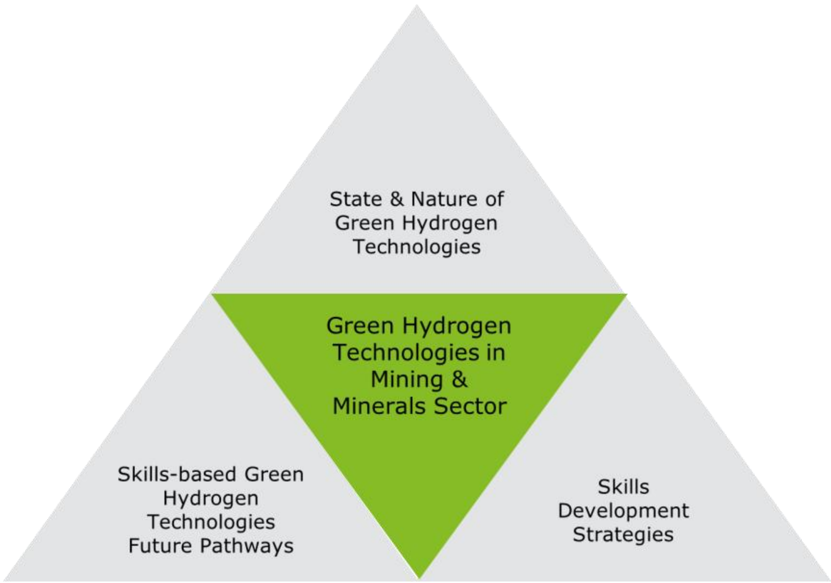

Figure 1:The three vital questions around green hydrogen technologies and opportunities for skills development. (Source: WEF, 2023)

1.5. Significance of the study

The contribution of the study is in the following areas:

Firstly, this study explored the state and nature of green hydrogen technologies and implications for skills development, providing direction on the key skills development strategies for the green hydrogen sub-sector. The MQA, other SETAs such as the Transport Education and Training Authority (TETA) and he Chemical Industries Education and Training Authority (CHIETA), and government departments, for example, the Department of Mineral Resources and Energy (DMRE) will be better informed as they utilise evidence-based decision making to plan and deliver programmes that respond to the practical needs on the ground regarding skills development and training. The study is timely, following the recent launch of the Green Hydrogen Centre of Specialisation at the CSIR in Pretoria.

Secondly, this study employs a transdisciplinary research approach to explore opportunities for multi-sector collaboration within and beyond the mining and minerals industry. The study involved researchers from different schools at the University of the Witwatersrand, including from School of Mining Engineering (Mining Engineers), School of Geosciences (Geoscientists), School of Chemical and Metallurgical Engineering (Chemical and Metallurgical Engineers), and the Wits Mining Institute (Social Scientists, Economists, and Environmentalists) and the Wits Centre for Researching Educations and Labor (REAL). Through fostering a cross-pollination of knowledge and resources, a cohesive ecosystem can be created that supports the MMS's growth and innovation through partnerships with other SETAs to advance the research and skills development pertinent to the green hydrogen technologies. Specifically, the Green Hydrogen Centre of Specialisation will benefit immensely from this study. It is also envisioned that the DMRE will utilise the research findings in decisions pertaining to the advancement of green hydrogen technologies.

1.6. Structure of the report

The report is structured into five chapters, and these are elaborated below:

Chapter 1 provides introduction and background to the study, presenting the aim, objectives and research question. The significance of the study is also included in the chapter.

Chapter 2 covers the literature and policy review. The literature review looks at the published work on the state and nature of the green hydrogen technologies, challenges and opportunities focusing on the South African MMS and benchmarking with global peers. The policy review looks at the development of policies in South Africa and elsewhere which are pertinent to green hydrogen technologies development. The skills development implications are also discussed from a literature and policy review perspectives. The chapter also covers the theoretical framework, where the Actor Network Theory is discussed alongside the Human Capital Theory and ADKAR Model.

Chapter 3 covers the research design, where the methodology is covered in detail. The application of qualitative and quantitative data collection and analysis is addressed.

Chapter 4 presents the findings covering the state and nature of green hydrogen technologies, challenges and opportunities, the findings regarding the policy framework. The implications on skills development are covered.

Chapter 5 outlines the conclusions and recommendations of this study.

2. LITERATURE AND POLICY REVIEW

2.1. Introduction

South Africa's mining sector is at a critical juncture where the demand for critical minerals is escalating due to their centrality in powering green technology initiatives and decarbonising operations through energy transition. Energy transitions typically progress in stages, starting with the shift from fossil fuels to renewable sources such as wind and solar (Kourougianni et al., 2024). Further advancement involves the use of more sophisticated integrations of technology, such as in green hydrogen (Hassan et al., 2023; DHET, 2024). It is estimated that in the 1.5°C Scenario, hydrogen is expected to account for 14% of final energy consumption by 2050, with 94% of it needing to be produced from renewable sources (IRENA, 2022). Hydrogen has significant potential for decarbonising the MMS and is crucial for achieving net-zero emissions (Hassan et al., 2023; DHET, 2024).

Green hydrogen technology is heavily reliant on critical minerals, including PGMs, for which South Africa has significant reserves. However, the country is not fully benefitting from the PGMs due to terms of trade imbalances associated with exporting partially processed or raw minerals. For example, the price of PGMs has been on a steady decline, causing viability challenges to the mining sector (Zhang et al., 2024). This presents the country with a significant opportunity to develop its green hydrogen technologies ecosystem and become a world leader. Meanwhile, the ethical and responsible production of these minerals and downstream beneficiation is contingent upon a workforce adept in modern mining technologies and processes (Kalantzakos, 2023). This era of 'Industry 4.0' is characterised by rapid technological advancements such as automation, data analytics, green energy, and environmental monitoring systems, which require a mixed breed of recent graduates and mature mining professionals (Nalule, 2023; Shimaponda-Nawa & Nwaila, 2024; Asa'd & Levesque, 2024; Wen et al., 2024). The imperative is to develop talent with a deep understanding of sustainability and the green hydrogen technological acumen to ensure minimal environmental impact (Lebrouhi et al., 2022). The green hydrogen economy is creating an ecosystem around mining and minerals operations. These emerging trends require upskilling the current workforce while rapidly transforming our education system to cope with the changing landscape (Sandri, Hayes & Holdsworth, 2024).

The practical challenge, however, is the limited knowledge of the state and nature of green hydrogen technologies in South Africa's MMS and the implications this could have on skills development (Panchenko et al., 2023). What has been clear from current studies are the skills gaps that exist in the green hydrogen technologies ecosystem (Sandri et al., 2024). The sector still battles with a myriad of challenges, including energy scarcity, viability problems, and knowledge/talent gaps, particularly in keeping pace with the modernisation of the industry (Chipangamate et al., 2023). As a country endowed with rich mineral resources, South Africa is at a crossroads, and the future prosperity of the MMS depends on its ability to adapt to new technologies, sustainable practices and leveraging downstream mineral beneficiation opportunities (Chipangamate et al., 2023). Sustainable mining operations of the future require an amalgamation of modern technology, green energy technologies and responsible mining that currently faces implementation barriers, such as limited upskilling opportunities for mining professionals and inadequate regulatory frameworks (Nakash, 2024). The harbinger of South Africa's benefiting from the mineral wealth is nothing other than the recalibration of the sector's approach to encompass a holistic view of sustainability, hinged on ongoing relevant skills development (Van der Walt et al., 2016).

From a theoretical standpoint, there is no established theoretical framework for analysing these important dynamics. This calls for the utilisation of a dynamic theory of technology development. To address this gap in literature, the current study builds on the Actor Network Theory (ANT) (Chipangamate & Nwaila, 2023) as a point of departure to infuse insights from the Human Capital Theory (Aslam et al., 2024) and the Awareness, Desire, Knowledge, Ability and Reinforcement (ADKAR) Model (Nagamalini & Wesley, 2024) to build a skills-based green hydrogen technologies development framework for South Africa. This is a novel hybrid framework addressing green hydrogen technologies development as a socio-technical change process where Human Capital 4.0 development through skills enhancement is integral in the context of Industry 4.0 and Mining 4.0 (Sishi & Telukdarie, 2020).

2.2. South Africa's Mining and Minerals Sector

South Africa holds the world's largest resources of economic minerals, including 91% of global PGMs (Cole, 2024), 80% of the world's manganese (South 32, 2024), 70% of chromium, and 11% of gold reserves (Minerals Council South Africa, 2023). The South African MMS has contributed significantly to the supply of minerals to various global economies and is one of the major contributors to the country's GDP, accounting for R1.18 trillion (about 7.53%) in 2022 (MCSA, 2024). To date, about 39 companies in the MMS constitute 31% of the Johannesburg Stock Exchange (JSE) market share (JSE, 2024) and provide employment to over half a million people (MCSA, 2024). The MMS in South Africa remains a backbone for the country's economic growth and poverty alleviation.

With the growing global demand for PGMs, driven by their use in technology, petrochemicals, vehicles, and pharmaceuticals due to their high melting point, corrosion resistance, and catalytic properties (Wildburn & Bleiwas, 2004; Zhang et al., 2024), South Africa's mining sector is set for growth. However, the sector is energy-intensive and relies heavily on energy supply from coal, a major contributor to global greenhouse gas (GHG) emissions. Energy from coal accounts for approximately 79% of South Africa's energy supply (Wright & Calitz, 2020). The MMS uses fossil fuels for activities such as mining, processing and transportation in primary and mineral production, thus contributing to global climate change (IPCC, 2023). Extreme weather events are ranked as the top global risk in the World Economic Forum's 2024 Global Risk Report (WEF, 2024).

Currently, renewable energy sources like wind and solar contribute about 1% to South Africa's energy mix (Stamm et al., 2023), highlighting the urgent need to increase their use. As a signatory to the Paris Climate Agreement, the South African government is committed to decarbonising its economy, as emphasised in reports by the Presidential Climate Commission, and policy initiatives, such as the White Paper on Renewable Energy Policy (2003), the Integrated Resource Plan (IRP) 2010-2030, and South African Hydrogen Society Roadmap (HSRM, 2021) which demonstrate the government's active role in promoting decarbonisation, with expectations for renewable energy to increase its share in the coming years.

The MMS must decarbonise its energy supply to reduce greenhouse gases (GHGs) and contribute to achieving net-zero CO_2 by 2050 (IEA, 2022). The sector has some of the hard-to-abate sub-sectors, such as quarrying and cement production. It is anticipated that by using green hydrogen produced by renewable energy, the South African MMS could achieve net-zero carbon emissions, as hydrogen is a carrier that can power the energy needed for extraction, transport, and processing (HSRM, 2021). The transition to green energy would not only help reach net-zero emissions but also positively impact other SDGs, such as clean, affordable energy (SDG 7), clean water and sanitation (SDG 6), life on land (SDG 15), decent work and economic growth (SDG 8) and good health and well-being (SDG 3). Moreover, adopting green hydrogen could stimulate the creation of new industries, particularly in hydrogen production using renewable energy, increasing demand for minerals like PGMs used in hydrogen storage cells and electrolysers.

While green hydrogen is currently expensive in South Africa, it is environmentally advantageous due to the country's abundant solar energy throughout the year, which can help reduce costs (Stamm et al., 2023). Additionally, water, a key component in hydrogen production, is often available in deep mining areas, where it poses challenges. This excess water could be repurposed for hydrogen generation using renewable energy sources like solar and wind. South Africa is already piloting the use of hydrogen-powered haul trucks in PGM mining. However, despite the accelerated green hydrogen technologies, integration could be hampered by high initial costs, poorly designed and unclear policies, and skills shortages as the sector is still grappling with hard-to-fill vacancies, some of which are applicable to green hydrogen technologies.

As the South African MMS transitions toward decarbonisation, the concept of a "Just Energy Transition" is vital. This approach ensures that employees and communities affected by decarbonisation, particularly those reliant on high-GHG industries like coal mining, and black and grey hydrogen, are not left behind. The Presidential Climate Commission emphasises the importance of an inclusive decarbonisation process that addresses poverty, inequality, and unemployment, which is important for communities around mining areas and those benefitting from the sector directly and indirectly.

2.3. Theoretical perspectives to understanding green hydrogen technologies and skills development

Before delving deeper into the literature and policy review, this section presents the theoretical framework that are utilised as a lens in the study.

Actor Network Theory (ANT)

Green hydrogen technologies are deeply rooted in the discourse of "energy transitions", a concept which has been used so narrowly in policy discussions that it may no longer be appropriate for capturing the broad socioeconomic consequences of energy systems change (Miller et al., 2013; Acheampong, 2023; Chipangamate & Nwaila, 2023). A review of literature in the MMS presents green hydrogen technologies as a double-edged sword, which, on the one hand, is a driver of climate change and sustainability through abating global warming (IEA, 2022). On the other hand, and from a more instrumental perspective, green hydrogen technology is seen as important for the MMS's efforts to build more resilient value chains in a world grappling not only with sustainability challenges but energy security and affordability (Chipangamate & Nwaila, 2023). These imperatives, dubbed the energy trilemma (security, access, sustainability) should be balanced to avoid the race to the bottom, where countries and private sector players are focusing on costs and survival and have little to no regard for environmental and social sustainability. It is no longer a question of choosing between people or planet or profit (3Ps), but sustainability has a role of protecting the benefits of all the 3Ps. This sort of plurality in transitions showcases both convergences and divergences in the approaches taken to address our twenty-first-century complex challenges (Hoppe & de Vries, 2018; 2019; Watari et al., 2021).

As Chipangamate and Nwaila (2023) posit, there are essentially two competing literature streams. The literature conceptualising energy transitions, such as green hydrogen technologies, as a struggle with sustainability and climate change mitigation has tended to focus more on the technology and how it can help reverse the effects of carbon emission (also see Energy Agency, 2021; Tzeremes et al., 2023). The second literature stream represents scholars who emphasise resilience and climate change adaptability. These scholars have tended to focus on how communities and stakeholders could be prepared to deal with the negative impacts of climate change, for example, farmers dealing with floods and droughts or employees dealing with job losses in the event of closures such as those associated with the transition from coal-fired energy plants (Owen et al., 2022; Valero et al., 2021) and adapting to new job opportunities arising from emerging energy systems such as green hydrogen plants (Ma et al., 2024).

This review, therefore, builds on Chipangamate and Nwaila (2023) in framing green hydrogen technologies as socio-technical systems where human and non-human actors interact to build a stable network. Thus, green hydrogen technologies are not merely created by innovators on the one hand and adopted by users on the other hand. Rather, they resemble struggles of co-creation among various stakeholders, referred to here as actors, following the Actor Network Theoretical perspective (Aka, 2019). This novel conceptualisation of the green hydrogen technologies development as a network-building process that involves the integration of all actors, human and non-human, provides new insights to unpack green hydrogen energy transition trajectories into the future (Marot et al., 2022). This has significant implications, including but not limited to ensuring the collective engagement of stakeholders at every stage of the green hydrogen technologies network-building process (Marcon Nora et al., 2023). The network building process encompasses various phases, namely problematisation, interessement or interposition, enrolment, and mobilisation (Akrich, 2023) and institutionalisation (Chipangamate & Nwaila, 2023). Chipangamate and Nwaila (2023) make a detailed presentation of the different phases of the network-building process, and it is not our intention to repeat them here except to posit that the development of green hydrogen technologies over time is anticipated to follow the phases as proposed in the literature. Although the original ANT has been criticised for ignoring social structures, such as policies (Akrich, 2023), this review addresses that concern by building on Chipangamate and Nwaila's (2023) framework that encompasses insights from institutional theory. Table 1 summarises the main assumptions of actor network theory (ANT).

Table 1: The five phases of the actor network theory as applied to green hydrogen technologies

Phase Level	Phase Descriptor	Phase description	Applicability to green hydrogen technologies
1	Problematisation	• Primary actor endeavours to identify the core issue at hand,	• Global warming and energy security • Green hydrogen is the answer to the problem (presenting it as the

Phase Level	Phase Descriptor	Phase description	Applicability to green hydrogen technologies
		• Determines the necessary knowledge claim required to address the problem, • Identifying the actors that are essential within the network	Obligatory Point of Passage (OPP)) • Partnerships for green hydrogen technologies
2	Interessement	• Primary actors actively work toward building the network • Actively engaging in negotiations with other actors, • Defining respective roles within the network • Those interested are 'locked-in'	• Anglo American negotiating with energy companies • Sharing of roles, e.g. Anglo American producing PGMs
3	Enrolment	• The actors involved willingly accept the roles assigned to them • They actively enrol themselves in the network. • They begin to act by practising the agreed roles • Communication channels are established	• E.g. Anglo American delivering a test haul truck • OEMs starting the fuel cell production
4	Mobilisation	• external actors, often referred to as allies, extend their support to the network • More allies join the network	• This is where international funders may join to support the initiatives of companies or governments

Phase Level	Phase Descriptor	Phase description	Applicability to green hydrogen technologies
5	Institutionalisation	• Crafting of policies and legal frameworks • The green hydrogen technologies are taken for granted • Stakeholders feel they co-own the green hydrogen technologies	• Most countries do not have clear policies to regulate green hydrogen technologies • There is need for health and safety policies considering the risks associated with green hydrogen

Source: Adapted from Chipangamate and Nwaila (2023).

The Human Capital Theory

This study builds on the human capital theory to explain the implications of green hydrogen technology development for skills development in the MMS. The key elements of the theory are human capital (skills, knowledge, experience, and health), investment (education, training, and development), and returns (increased productivity, earnings, and job satisfaction). However, in recognising the widespread effects of industry 4.0, this study builds on the work of Flores et al. (2020) who propose Human Capital 4.0 as a novel concept to describe human capital development in the era of digital transformation. The 4th Industrial Revolution (also known as Industry 4.0), is the new shift paradigm that embraces latest technologies to boost industrialisation at local and global scales, enabling a whole network of interconnected, dynamic, collaborative, fluid, self-organised and unique business services and manufacturing interactions (Sishi & Telukdarie, 2020). Various industries are integrating Industry 4.0 initiatives putting vast amount of effort into the adoption and implementation of Industry 4.0, giving birth to numerous research outputs in the form of both technological and human-focused approaches. The current study sees this as an appropriate lens to understand the dynamics unfolding in the MMS, also transitioning to Mining 4.0 (Lööw et al., 2019).

For this reason, the modern MMS would be better positioned to deal with this surging dynamic by embracing new developments ushered by Industry 4.0. This includes the cyber-physical production systems (CPPS), which are systems with collaborative and autonomous components that are connected to each other at the different levels of production and logistic processes (Monostori, 2014), Machine Tool 4.0 (the self-aware, self-maintained and self-optimised smart machine tool, which can provide assessment of its current and predictive used condition. Cyber-physical machine tool (CPMT) is proposed as a Cyber Physical System (CPS) application that integrates tooling, processing, networking and embedded computing to monitor and control machining process (Flores et al., 2020).

Industry 4.0 will not only change how the workforce interacts but will also impact the activities that individuals undertake, as they will need to become more coordinated, creative and strategic (Lööw et al., 2019). Thus, it will be important to realise that:

- the operational working level will be highly aided by cyber-physical systems,
- decision-making and planning processes will be highly decentralised,
- ongoing process integration and cross-functional perspectives will become the norm,
- quality and maintenance will become automated, increasing the complexity and dexterity to integrate and manage them) working life and partner networks will gain more flexibility and importance (Bonekamp & Sure, 2015).

Thus, the study further explores the state and nature of green hydrogen technologies and the implications for skills development, it is important to realise that the future workforce needs more than just proficiency in technical skills, but other skills including soft skills such as communication, critical thinking and leadership to be able to deal with the changing workplace. Employees who can embrace the rapidly changing digital landscape and adapt to the emerging cyber-physical space will thrive. This has significant implications on skills development. Skills development strategies must foster not only lifelong learning but lifewide learning where the workforce learns about technical and soft skills, including resilience in the face of rising mental health issues, for example. Therefore, this extended model of human capital theory may assist in conceptualising the skills development imperatives of the emerging green hydrogen technologies.

ADKAR model

The implications of the green hydrogen technologies development have change management implications. To explore the change management implications, this study leverages the Awareness Desire Knowledge Ability Reinforcement (ADKAR) Model (Jaaron et al., 2022). The model argues that development of change management strategy is based on the perspectives of Awareness, Desire, Knowledge, Ability, and Reinforcement. These aspects of the model are important for green hydrogen technologies development where skills development and training broadly are essential to generate the much-needed awareness, desire, knowledge and ability to execute the new technology at different stages representing the current state, transition phase and the future (Sulistiyani et al., 2020).

The model has had wide usage in diverse industries including construction (Jaaron et al., 2022), health, manufacturing, energy transition (Niesing & Grobler, 2013) and green human resources development (Osolase et al., 2022). In the context of green hydrogen technologies, the ADKAR model has numerous implications. For example, various stakeholder groups would require different emphasis on the different elements. When viewed in relation to the Actor Network Theory discussed earlier, different stages of the green hydrogen network building process require different focus on some elements. It is anticipated that during the problematisation phase, awareness of green hydrogen technologies will be important for various stakeholders. For employees, training focuses on raising awareness. As the network-building process progresses to interessement, the focus could be on enhancing desire and knowledge, while ability is more important as the technology is introduced and the workforce is trained on the job. Therefore, there could be a need for combining on the job training to gain practical experience, while building a strong foundation of knowledge may not be overlooked.

2.4. The state and nature of green hydrogen technologies

2.4.1. Green hydrogen production

Hydrogen is a clean-burning energy carrier with several applications in transportation, power generation, and industrial processes. While the literature on the interplay of hydrogen and power systems is vast and growing, in this review we focus on several recent papers that are closely related to exploring the state and nature of green hydrogen technologies in the MMS and implications for skills development. Notably, countries are actively exploring hydrogen as an alternative to fossil fuels, with several recent studies highlighting the possibilities, drivers and challenges for the power supply chain that countries need to address (Longoria et al., 2021). Literature suggests that hydrogen production technologies have different economic and environmental impacts (Abad & Dodds, 2020). Broadly, there are two methods of producing hydrogen namely, traditional and renewable which can be further split into several sub-groups. The traditional methods are based on steam methane reforming (SMR) which contributes up to 95% of global hydrogen production (IEA, 2022). The process of SMR involves high-temperature steam reaction with methane to produce hydrogen and carbon dioxide ($CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$). The other traditional method is coal gasification (CG) where hydrogen is produced by gasifying coal with oxygen and steam ($C + H_2O \rightarrow H_2 + CO$). Hydrogen can also be produced as a byproduct of chlorine production through a process of hydrochloric acid electrolysis (HAE) ($2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2$).

More recently, in response to the efforts to reduce GHGs, there have been calls for producing green hydrogen. Although these efforts are gaining traction, there has been varying definitions of green hydrogen, to the extent that the concept has been banded, even to the extent of some referring to it as a source rather than carrier of energy. A range of approaches have been taken to defining green hydrogen and guarantees of origin, varying from whether green hydrogen must be produced from renewable energy, on the boundaries of the carbon accounting system, the emission thresholds at which hydrogen is considered green, and on which feedstocks and production technologies are included in the scheme (Abad & Dodds, 2020). This definitional crisis is worsened because decisions on these factors are often influenced by other national and international standards, and the legal framework in which the green hydrogen supply chain operates. There has been a lack of policy or standards interoperability which in turn makes international trade, and the inclusion of hydrogen in energy policies, more difficult. Table 2 summarises some of the notable definitions of green hydrogen from literature.

Table 2: Definitions of green hydrogen

Definition	Production Pathway Consideration	Source
Any renewable energy sources with an explicit mention of low emission GHG intensity factors	Yes	Bleischwitz & Bader (2008); Galich & Marz (2012); Gazey et al. (2012); Viesi et al. (2017); DNV (2018)
Any renewable sources or any other net zero carbon energy through CCS and/or emissions offsets.	Yes	Government of Australia et al. (2017)
Any low carbon energy sources with low environmental impact	No	Çelik & Yıldız (2017)
Any sources (renewable or not) with an unspecified low emission intensity	No	Dincer (2012)
Any renewable and nuclear sources	Yes, but includes nuclear	Naterer et al. (2008)
Any renewable sources	Yes	Clark (2007); Rifkin (2002); Tada et al. (2012); Weidong & Zhuoyong (2012)
Any renewable energy sources with an explicit mention of air pollution, energy security and global climate problems	Yes	NREL (1995)
Renewable energy sources with focus on wind and solar	Yes	South Africa Government (2022)

What seems to be clearer and more universal in literature are the definitions of renewable hydrogen, as it constrains the eligibility of pathways to renewables sources, and 'black or brown' hydrogen as it is typically understood as hydrogen produced from fossil fuels feedstocks (Bellaby et al., 2012; Clark, 2007;), with some sources also including nuclear power sources in this group (Clark, 2007; Rifkin, 2002).

Despite the ranging definitions, a key theme could be discerned from the definitions as they mostly emphasise the use of renewable energy in the production of hydrogen. Thus, as opposed to the traditional hydrogen production methods, modern methods aim to green the processes. Alkaline electrolysis is the process involving splitting water into hydrogen and oxygen using electricity generated from renewable energy (2H20 -> 2H2 + O2). Similarly, proton exchange membrane (PEM) electrolysis splits water but more efficiently than alkaline electrolysis. Due to the growing solar energy production, two processes that leverage this new trend are solar-driven thermochemical water splitting (H2O -> H2 + 1/2O2) using metal oxides and nitride materials, and photoelectrochemical water splitting (H2O -> H2 + 1/2O2) using semiconductor materials at comparatively lower temperatures. Wind is the other renewable energy source that is gathering momentum in powering the electrolysis process. As more research is deployed, some emerging technologies include solid oxide electrolysis utilising high-temperature electrolysis for improved efficiency, liquid organic hydrogen carriers for hydrogen storage and transportation, and microbial electrolysis where microorganisms convert biomass for biological hydrogen production.

The diversity in the environmental impacts has resulted in the characterisation of different shades of hydrogen as summarised in Table 3.

Table 3: The hydrogen colour scheme and characterisation

Hydrogen scheme	Description of production pathways	Characteristics
Green Hydrogen	Renewable energy sources (wind, solar and hydro)	Zero emissions
Blue Hydrogen	Fossil fuels with carbon capture and storage (CCS)	Low carbon due to CCS technology

Grey Hydrogen	Fossil fuels without CCS	High carbon
Brown Hydrogen	From coal or lignite	High carbon
Yellow Hydrogen	From Nuclear	Low carbon
Turquoise Hydrogen	Methane pyrolysis	Low carbon
Pink Hydrogen	Nuclear with CCS	Low carbon than yellow
White Hydrogen	Biomass or biogas	Extremely low carbon

Having briefly looked at the basic hydrogen production processes, the following sections of this paper review the key role of renewable energy minerals with specific reference to PGMs such as platinum, iridium, ruthenium and palladium. Cobalt and nickel are also important elements in the green hydrogen production processes due to their properties that are also like PGMs. These metals have high catalytic activity, corrosion resistance and conductivity, properties important for electrolysis. They enable enhanced green hydrogen production by improving efficiency, increasing durability and reducing costs of installation and maintenance.

Table 4: Types of electrolysers, importance and crucial green metals

Application	Significance	Useful minerals
PEM electrolysers	Catalysts in proton exchange membrane (PEM) to enhance efficiency of the hydrogen evolution reaction (HER). Electrode durability and corrosion resistance	Platinum, iridium, ruthenium
Alkaline electrolysers	Nickel used as primary catalyst for hydrogen evolution reaction at the cathode. Cobalt is used as a co-catalyst to enhance HER activity. Nickel and cobalt also enhance oxygen production at the anode (Oxygen evolution reaction-OER)). Electrode durability and corrosion resistance.	Nickel, cobalt and platinum
Solid oxide electrolysers	Platinum: Catalyst for HER at the cathode Nickel: Primary catalyst for OER at the anode	Platinum, nickel, yttrium, ruthenium

	Yttrium: Stabilises zirconia electrolyte and enhances ionic conductivity Ruthenium: Co-catalyst to enhance HER activity Iridium: Enhances OER activity and stability.	
Fuel cells	Fuel cells to convert hydrogen into electricity, promoting efficiency in energy conversion	Platinum, palladium, iridium
Hydrogen purification	Removing impurities from hydrogen gas to ensure high purity	Palladium

2.4.2 Green hydrogen applications

Green hydrogen technologies are revolutionising various sectors of economies, and several applications have been deployed, shifting the ways of studying and experiencing energy (IEA, 2022). Some of the leading applications are in transportation, industrial applications, domestic use, seasonal energy storage, and power generation (Abad & Dodds, 2022)

Various modes of transportation have integrated green hydrogen as a sustainable mobility alternative. Some of the forerunners in this space are fuel cell electric vehicles (FCEVs) which have gained popularity in recent years, with companies such as Hyundai projecting to manufacture 500,000 hydrogen vehicles by 2030 (Aminudin et al., 2023). Other notable applications in this category include the drive towards smart cities where cities are adopting hydrogen powered taxis and waste collection (Dispenza et al., 2017). The MMS has witnessed a slow but steady increase in the integration of green hydrogen in mining vehicles (McLellan, 2009). Research has identified the usage of green hydrogen in trains, aircraft, lorries, and maritime, sub-sectors that are also closely relevant to mining and minerals.

Several industries are embracing green hydrogen technologies as a mechanism for sustainable energy security (McLellan et al., 2012). The chemical industry uses nitrogen in the production of ammonia and fertilisers (Mostafaeipour & Sadeghi Sedeh, 2019; Shariati et al., 2013). Meanwhile, the petrochemical industry has found applications in the production of petroleum products (Shariati et al., 2013), while the steel industry, to which the MMS is closely linked is exploring green hydrogen as a reducing agent to replace coal in iron production (Lumbers et al., 2022). Hydrogen has been used in the electronics industry as a protective and carrier gas, in deposition processes, for cleaning, in etching and reduction processes. Another example is its use in the metallurgic industry in the reduction stages and in the direct reduction of iron ore, which involves the separation of oxygen from the iron ore using hydrogen and synthesis gas (syngas) (Germscheidt et al., 2021).

Green hydrogen is also used as replacement for natural gas in industrial and domestic applications (Dodds et al., 2015). These applications involve green hydrogen networks providing electricity and heat to households without the common pollutant emissions. Green hydrogen's relatively high energy density has resulted in hydrogen attracting increasing attention in research, commercial and political spheres, specifically as a fuel for residential heating, which is proving to be a difficult sector to decarbonise in some circumstances (Longoria et al., 2021). It is important to recognise how hydrogen production is dependent on the power system, implying that any scale use of hydrogen for residential heating will impact various aspects of the power system, including electricity prices and renewable generation curtailment. Across various industries, including the MMS, green hydrogen technologies are also used to store energy for electricity generation when needed. This could be seasonal storage of excess energy generated from renewables (Hirscher et al, 2020). Such applications are also important for use of green hydrogen to generate electricity in fuel cells.

2.4.3 The benefits of green hydrogen technologies

Understanding the benefits of green hydrogen calls for a full appreciation of the global energy trilemma (Chipangamate et al., 2023). There essentially three competing objectives that the world is battling in efforts to achieve the affordable clean energy goal in line with SDG7. They focus on the energy security, access and affordability, and generating the energy in environmentally sustainable ways. This is the main area where green hydrogen technologies differ from other shades of hydrogen, for example, those that use coal as the main energy for hydrogen production (Germscheidt et al., 2021). Hydrogen is versatile because it has strategic application as a fuel, being applicable for direct combustion, by itself or in some blends with natural gas, and in fuel cells (FCs), where it can provide a reliable and efficient energy power, that can be used in stationary power stations and as a good candidate for transportation vehicles (Hirscher et al, 2020). Although hydrogen has several uses, application as a renewable fuel is the most promising application for the future, and its main advantage is related to its cleanliness and low greenhouse gas emissions (Germscheidt et al., 2021).

The benefits of green hydrogen in transport are well documented, whereas the benefits on power are less understood. Scholars have identified the ability to integrate variable renewable energy sources as a major benefit if production is sufficiently flexible in time (Stöckl et al., 2021). There seems to be a trade-off between energy efficiency and flexibility, such that more energy-efficient and less flexible small-scale on-site electrolysis is optimal. Less efficient and more flexible large-scale production allows for the temporally disentangling of hydrogen production from demand via storage (Stöckl et al., 2021). This has crucial implications for energy modelers and planners.

2.4.4 The challenges associated with green hydrogen technologies

Although hydrogen shows a bright future for energy security, it is an approach requiring scrutiny of the hydrogen production pathways (HPP) (Germscheidt et al., 2021). This is very important because the purification of hydrogen is the main determinant of how environmentally friendly it can be. The use of hydrogen is closely tied to the purity level, and consequently, the prices are different. For example, the traditional reforming processes produce hydrogen with purity ranging from 87% to 94%, whereas electrolysis delivers hydrogen with purity superior to 99.9%. To put this into context, the purity requirement of the hydrogen for fuel cell vehicles is grade 4, which means purity levels of not less than 99.999% (Germscheidt et al., 2021). The level of purity required for green hydrogen applications is very costly. This has crucial implications for the investments required to transition to green hydrogen.

Due to hydrogen having a low volumetric energy density, storing and transporting processes pose a challenge for hydrogen technologies and, therefore, a major limitation (Hirscher et al, 2020). For this and other reasons, hydrogen technologists have stored it in various forms including in high-pressure vessels, in liquid form (high pressure and low temperature), adsorbed in high porous materials, or liquid form as ammonia (Usman, 2022). These alternatives have significant cost implications requiring specialised storage and transport. It is always encouraged to aim for local production to decrease transportation costs, but this requires investments in proper infrastructure (Hirscher et al, 2020). In a study to explore green hydrogen technologies at scale in Canada's Atlantic Maritime, Maynard and Abdulla (2023) find that hydrogen production is at least four times more expensive than grid integration. Suggesting that projects could only be implemented by 2050 and at <2 $/kgH_2$ by assuming aggressive growth rates, learning rates, and electrolyser capital costs of 500 $/kW. Their analysis gives an appreciation of the effort, costs, and emission benefits of producing green hydrogen at scale.

Beside production costs, when planning production and logistical transportation for hydrogen through road, rail, or maritime it is important to consider the distance, suitable storage tanks, security, and laws. The other challenge rests on the diversification of industrial portfolio ranging from petrochemical and agricultural businesses (Mostafaeipour & Sadeghi Sedeh, 2019; Shariati et al., 2013).

As hydrogen is the smallest and lightest element in the periodic table (atomic ratio 53 pm and atomic mass 1.008), the storage poses significant challenges, yet the aspect of safety must be the key point for social recognition about the importance of hydrogen (Hassan et al., 2024). It is therefore necessary and important to ensure an essential feedstock for a sustainable industry and a safe product with a low risk of accidents. Socio-political scholars have also raised concerns that green hydrogen projects, if not well intentioned, could pose serious socio-political and techno-economic challenges to the three tenets of energy justice: distributive, procedural, and recognition justice (for example, see Patonia, 2025-pending). The scholar laments the risk of neocolonial resource extraction, uneven distribution of benefits, exclusion of local communities from decision-making, and disregard for indigenous rights and cultures. This could be exacerbated by other techno-economic factors such as water scarcity, land disputes, and resource-related conflicts in potential production hotspots.

2.5. Green hydrogen technologies policy frameworks

The green energy agenda has been on the global agenda for some time now. For African and other Global South regions, institutional policy framework voids have been identified as a major stumbling block (Chipangamate & Nwaila, 2023; Imasiku et al., 2021). Scholars argue that transitioning toward a green economy demands a significant overhaul of social and economic structures, updating the current infrastructure and technologies that were fossil fuel-based, and institutions concerning the green energy policy (Imasiku et al., 2021). Green energy policy encompasses any policy measure aimed at aligning the structure of a country's energy sector with the needs of sustainable development within established planetary boundaries (Pegels et al., 2018). The hydrogen policy frameworks in southern Africa have been a result of the realisation that grey hydrogen technologies, mainly utilising steam methane reforming (SMR) plants and coal gasification plants with coal and natural gas as the main feedstock are dominant (Imasiku et al., 2021). SMR produces hydrogen and carbon dioxide as a by-product. The cost that comes with the technologies for carbon capture and storage (CCS) and carbon capture and utilization (CCU) have prohibited the popularisation of blue and turquoise hydrogen in southern Africa. Unlike other forms of energy production, green hydrogen technologies are value chain based as they rely on feedstock which is important for hydrogen production pathways if the aim is to reverse the adverse effects of carbon emissions. Therefore, well-articulated policy frameworks are important to outline standards, protocols, incentives, and penalties for environmental sustainability in the green hydrogen economy.

South Africa has had energy regulation for a long time. Since the Energy Policy White Paper of 1988, several other policy documents have been penned to guide the energy policy in South Africa. The Electricity Regulation Act (ERA) 4 of 2006 is the existing legal and regulatory framework guiding South Africa and has informed new generation capacity regulations that demand an integrated resource plan (IRP) for long-term electricity sector planning. The government has used ERA as basis for conducting scenario analyses to establish the electricity demand requirements for an electricity generation-mix economy. The IRP that was revised in 2019 reflected the global drive for cleaner energy development. However, the IRP revision did not give explicit allocation for green hydrogen technology (Imasiku et al., 2021).

The country has attempted to bring impetus to green hydrogen by establishing the Hydrogen South Africa (HySA) strategy under the National Hydrogen Fuel Cell Technology (HFCT) that was approved by the South African cabinet in 2007 to achieve a 25% share of the global hydrogen energy products by 2020. Broadly, the country's hydrogen strategy is centred around the Hydrogen Society Roadmap which aims to make South Africa a major player in the global hydrogen economy. The key pillars of the strategy include export market creation, power generation decarbonisation, transport and industry decarbonisation, local manufacturing, investment and finance, economic development, (including skills), just transition and creating a clear policy and regulatory environment. A lack of green hydrogen policy framework and budget allocations are blamed, in part, for the dismal performance of the HySA strategy. As Chipangamate and Nwaila (2023) argue, a clear policy framework is antecedent to attracting meaningful financial investment for energy transition projects.

Namibia has been driving green hydrogen with intention. Its government established a Renewable Energy Division in 2009 after realising the important role that renewable energy development plays in achieving cleaner and affordable energy for all in line with SDG 7 (Moretti et al., 2022). Namibia's 1998 White Paper on energy policy guides the implementation of renewable energy and energy efficiency projects through enhanced research and development of renewable energy resources; renewable energy and energy efficiency public awareness; implementing the Namibia Off-Grid Master Plan and providing incentivised loans on solar energy technologies products (Imasiku et al., 2021). With specific reference to green hydrogen and green ammonia, the Namibian government announced the inclusion of the Harambe Prosperity II action plan as one of the priority areas targeted at bringing about economic growth and prosperity in the country. The plan was expected to attract a capital expense of N$27 billion over five years beginning in 2021. To date, several projects have been initiated (Moretti et al., 2022).

As shown in Table 5, several countries in the region have energy policies that are becoming more explicit about the importance of renewable energy, yet a specific focus on green hydrogen technologies has not yet been institutionalised.

Table 5: Review of energy policy frameworks in SADC countries

Country	Energy Policy Framework	Green Hydrogen Policy Framework
Botswana	• Electricity Supply Act: 1973;2007 • Vision 2036:1986; 2016 • Botswana Energy Master Plan:1996,2003, • Biomass Energy Strategy: 2009 • National Energy Policy: 2015 • National Development Plan II: 2017-2023	No specific reference to GH; Emphasis on renewables in general and mention of biomass and solar energy
Eswatini	• National Energy Policy: 2018	
Mozambique	• Electricity Law/Act of 1987 • Supports renewable energy independent power producers (IPPs) • Approved a regulation of feed-in tariffs regulations	Lacks a clear act on renewable energy, regulation of feed-in tariffs.
Namibia	• White Paper of energy policy: 1989 • Renewable Energy Division: 2009 • Harambe Prosperity plan II	

South Africa	• Electricity Regulation Act (ERA) 4: 2006 • Integrated Resource Plan (IRP): 2019 • Green hydrogen Commercialisation Strategy:2022	Has green hydrogen framework which needs more coordination and implementation
Zimbabwe	• Zimbabwe's National Energy Policy (NEP):2012 • National Renewable Energy Policy (NREP): 2019 • Zimbabwe's Vision 2030	No specific green hydrogen policy framework

2.6. Green hydrogen technologies in the mining and minerals sector

The advent of green hydrogen technologies has significant promise for decarbonising the MMS which has a considerable carbon footprint in its value chains. The sector is responsible for the growth of greenhouse gas emissions globally. The situation is amplified by the accelerated mining of critical minerals expected to grow by more than threefold in some instances (Chipangamate & Nwaila, 2023). The extraction and processing of these minerals are high carbon emitting and energy intensive (Nwaila et al, 2022). For example, lithium extraction has shifted from brine-based recovery to Hardrock mining which increases emissions, laterites such as nickel resources require more energy to produce, while copper, iron ore and steel refining and smelting operations consume large amounts of electricity, contributing to higher emissions (Norgate & Jahanshahi, 2011). It is expected that over the years, the sector can be fully decarbonized through energy efficiency in processes, electrification, and renewable energy with the proper investments. Green hydrogen technologies provide a versatile opportunity for accelerated sectorial transformation, especially in hard-to-abate sub-sectors including steel and iron making, cement and concrete production, lithium, and copper mining and quarrying, heavy duty transportation, aviation, shipping and maritime which are integral to the sector (Azadnia et al., 2023).

To date the MMS has seen a slow but steady increase in the integration of green hydrogen technologies to reduce GHG emissions and improve sustainability (Wang et al., 2023). Hydrogen is expected to contribute 12% to 20% of energy demand by 2050 which makes it an important component of the sector's energy transition (IEA, 2019). There are already some green hydrogen solutions that are beginning to emerge in the sector requiring support and development to overcome the barriers that will be encountered in implementation. For example, it is estimated that green hydrogen can replace diesel fuel in hauling vehicles, resulting in 30% to 80 % reductions in emissions (Anglo American, 2023). Replacing diesel fuel indirectly benefits the industry by removing diesel particulates and reducing ventilation load requirements in underground mining (Figueiredo et al., 2023). In addition to the use of green hydrogen for electricity generation to power mining operations, the technologies are used in processing low-carbon steel, aluminium, and other metals (Azadnia et al., 2023).

The socio-economic benefits of using green hydrogen for the MMS are multi-fold. This contributes to global decarbonisation, increased air quality for better health of society (especially around mining and smelting plants), enhanced energy security, and greater potential for cost savings resulting from reduced fuel consumption (IEA, 2019). Despite the potential, the acceleration of the technologies in the industry is hamstrung by difficulties in scaling up green hydrogen production, poor technical infrastructure for safe hydrogen transportation and storage, lack of the requisite skills and expertise specific to the green hydrogen technologies (Figueiredo et al., 2023). Although the challenges for acceleration are considerable, they are by no means insurmountable. Some leading examples of MMS applications include the Anglo American, FMG and BHP who are already exploring green hydrogen adoption in their operations (Geldenhuys, 2022).

To date, Anglo American has made the most significant strides in South Africa with their hydrogen project, focusing on partnerships for developing a hydrogen valley that clusters industrial and research initiatives to carry out pilot projects across the entire hydrogen value chain (Anglo American, 2023). It is estimated that the project has the potential to add between $4-9 billion to South Africa's GDP by 2050 and create 14 000 to 30 000 direct and indirect jobs per year (Geldenhuys, 2022). The project is driven by three Hydrogen Valley Hubs identified as Johannesburg, Durban, and Limpopo province to play a crucial role in integrating hydrogen into South Africa's economy. The nuGen Zero Emission Haulage Solution (ZEHS) is the world's largest hydrogen-powered ultra-class mine haul truck (with a 290-tonne payload capacity), aimed at reducing carbon emissions. It is anticipated that by investing in green hydrogen technologies at the Mogalakwena PGMs mine in collaboration with South Africa's Department of Science and Innovation, ENGIE, and Bambili Energy, Anglo American will achieve carbon neutrality across its operations by 2040. This is a significant milestone in reducing the company's carbon footprint because haul trucks represent up to 80% of diesel emissions at Anglo American's sites (Anglo American, 2023). To put this to perspective, diesel emissions from haul truck fleet account for c. 10-15% of the company's total scope 1 emissions. Table 6 shows some green hydrogen initiatives globally.

Table 6: Global examples of hydrogen technologies in the mining and minerals sector

Country	MMS Company	Partners	Green hydrogen solution
Australia	Fortescue Metals Group (FMG)	Australian Government is investing AU$70 million in Hydrogen projects	Green hydrogen project to power mining operations
	BHP	Fortescue Future Industries	Exploring green hydrogen opportunities
Canada	Teck Resources		Developing a hydrogen fuel cell power generation project
	Ballard Power Systems		Supplying hydrogen fuel cells for mining applications
	Alcoa and Rio Tinto		Green aluminium production
Germany	Thyssenkrupp		Developing green hydrogen production technologies for industrial applications
	Siemens Energy	Mining companies	Development of hydrogen-based solutions
	Salzgitter AG		Developing hydrogen-based direct reduction (H2-DR) to replace coal and natural gas in steel processing
Norway	Norsk Hydro		Developing Hydrogen-powered aluminium smelting
Chile	Anglo American Los Bronces Mine		Launching a hydrogen-powered haul truck trial
	Antofagasta Minerals	Engine	Develop green hydrogen projects

Country	MMS Company	Partners	Green hydrogen solution
South Africa	Anglo American	South African Government, Engie, Bambili Energy	Fuel Cell production, green hydrogen production, haul truck application
	Ivanhoe Mines	Sasol	Development of a green hydrogen project
Brazil	Vale		Investing in hydrogen-powered haul trucks
	Brazilian Government		Launching a green hydrogen development programme

2.7. Discussion and implications for skills development in the mining and minerals sector

The literature review has explored some of the nuanced dynamics pertinent to green hydrogen technologies development. What seems to be clear is the dire need for global economies to decarbonise in the wake of climate change induced crises such as droughts, floods, cyclones, heat waves and biodiversity loss (IEA, 2022). The route to decarbonisation is not an easy one as the world grapples with the energy trilemma of security, access and environmental sustainability considerations (Chipangamate & Nwaila, 2023). Hydrogen has been celebrated for long as the energy panacea to some of the hard-to-abate sectors like mining, heavy transport, quarrying, concrete and cement production (Wang et al., 2023). However, the Hydrogen Production Pathways (HPPs) become important if the aim is decarbonisation because grey hydrogen produced from fossil fuels is environmentally unfriendly (IRENA, 2023). Additional steps to clean it through Caborn Capture Use and Store (CCUS) are prohibitive due to costs associated with the technologies. This leaves the idea of water splitting using electrolysis as the main alternative for green hydrogen production. Therefore, the study and understanding of every HPP are essential for the development and advancement of green hydrogen to conquer a few primary challenges such as the choice of the feedstock (fossil fuel or water), the energy source needed to extract hydrogen from the feedstock, and the catalyst that is needed to overcome some kinetic and thermodynamic limitations that are present regardless of the process (Germscheidt et al., 2021).

South Africa, endowed with PGMs, an important ingredient in the production of fuel cells due to high corrosion resistance and durability, is in good stead to beneficiate the minerals and create a green hydrogen technologies ecosystem. The versatility of hydrogen gives it an edge as an energy carrier because it can be used for mobility in transportation, and in power generation, heat, and storage (IRENA, 2023). However, despite it being a promising energy solution, the technology faces some daunting challenges including costs, paucity of policy clarity and interoperability. There are not yet standardised formats, language and protocols, as much as there is lack of regulatory alignment in the global ecosystem. In most jurisdictions, there has been demonstration of ambition and political will which is seldom backed with implementation. In part, this is due to lack of coordination and collaboration at various levels.

For South Africa, already reeling with skills challenges, the green hydrogen technologies development calls for significant investment in skills development. At a time, the MMS is undergoing digital transformation (Nwaila et al., 2022; Chipangamate et al., 2023) which demands responsible modernisation (Chipangamate et al., 2023), the sector will need to focus of development of skills that enables it to deal with current challenges while preparing for the mining and minerals of the future. Industry 4.0 is posing disruptive challenges at different scales (i.e. business models, manufacturing processes, economy) which makes it necessary to upgrade the human force at different levels (i.e. technical, psychological, social) to meet those changes (Flores, Xu and Lu, 2020). Therefore, Human Capital 4.0 is proposed as a holistic shift in terms of competences, education, well-being and innovation that the workforce should exhibit for the era of Industry 4.0 (Chryssolouris et al., 2013). This implies that the future workforce will need to be highly adaptable, resourceful, resilient, and interdisciplinary for interaction and collaboration in the industrial marketplace. Thus, skills development will focus on several competences to ensure education and training are relevant, enduring and impactful. Following Flores, Xu and Lu (2020) is proposed Human Capital 4.0 with Competencies 4.0. Table 7 shows the key competencies for the green hydrogen technologies in the era of digital transformation.

Table 7: Key competencies for the green hydrogen technologies in the era of digital transformation

Item	Competences	Characteristics and skills	Sources
1	Sofy workforce (flexible and adaptable)	Flexibility and adaptability, social, communication, teamwork or cooperation, leadership, willingness to learn, self-development, negotiation	(Hecklau et al., 2017; Motyl et al., 2017; Flores et al., 2020).
2	Hard workforce: (professional and dexterous)	Industrial organisation, industrial processes, standards understanding, problem-solving techniques, designing with software, human-machine interactions, digital network settings, digital security and coding or programming	(Hecklau et al., 2017; Motyl et al., 2017; Mourtzis, 2018; Pinzone et al., 2017; Flores et al., 2020)
3	Cognitive workforce: (intelligent and analytical)	Verbal aptitude: vocabulary, spelling, and reading Numerical aptitude: math, arithmetic Spatial aptitude: coordination, memory, decision-making, problem-solving thinking, abstract reasoning, analytical thinking	(Hecklau et al., 2017; Flores et al., 2020).
4	Emotional intelligent workforce: (self-aware and empathetic)	Self-awareness, self-control, positive outlook, empathy, achievement orientation and motivation	(Boyatzis et al., 2017, Flores et al., 2020).
5	Digital workforce competence: digital literate and digital interactive	Programming, cybersecurity, digital networks, cloud computing, databases, web development and the management of Industry 4.0 technologies (i.e. IoT, big data analytics,	(Chryssolouris et al., 2013; Hecklau et al., 2017; Pinzone et al., 2017; Flores et al., 2020)

		3D printing, simulation, augmented and virtual reality, machine learning)	

For South Africa, these findings from literature have significant implications. Several scholars have highlighted a marked skills gap risk, highlighting the potential growth in demand for skills in the green hydrogen network. The network of green energy production, notably solar and wind energy has increased demand for green energy skills. For green hydrogen production the needed skills include in new areas such as electrolysis, fuel cell engineering and electronics. Engineers are expected to have capabilities in

- understanding of the hydrogen production process,
- appropriate selection, design and maintenance of equipment,
- diagnose and address production and process issues.

Meanwhile technicians and tradespersons are expected to have capabilities to understand:

- the hydrogen production process,
- appropriate selection, design and maintenance of electrolyser plant electrical equipment,
- appropriate selection, design & maintenance of electrolyser plant key instrumentation equipment.

There are capabilities required for specialists like economists and supply chain leaders who should not only understand the hydrogen production process but also demonstrate knowledge of the economics of green hydrogen and green hydrogen value chains. Management is also important in the running of green hydrogen entities. The top three capabilities required are understanding of the hydrogen production process, knowledge of hydrogen value chains, and maintenance of equipment and systems. In relation to all people across the value chain, including elementary skills, there is a need for capabilities to understand green hydrogen properties, behaviour and potential hazards created, and safety when working with or around hydrogen as the chemical is volatile.

Expertise in storage and transportation technologies is also expected to rise in demand, yet in South Africa these skills are in short supply or not readily available. The green hydrogen technologies space is nascent which makes it seem to have no shortages of skills, yet when viewed from a readiness perspective, it could be argued that the sector is not skills ready. This poses a significant risk resulting from skills demand outstripping skills supply unless targeted programmes are established to close these potential gaps. It is therefore important that capabilities are developed in advance in line with expected trajectories of green hydrogen technologies development. The green hydrogen value chain will require several hydrogen capabilities (core and cross cutting) including hydrogen properties, behaviour and potential hazards created safety when working with or around hydrogen, knowledge of hydrogen related regulations standards, and codes, understanding of electrochemical reactions, processes, and hydrogen production processes across the value chain and different levels of MMS organisations.

A different yet potentially damaging risk is that of job mismatch in the green hydrogen technologies, where individuals are employed in a job that does not match their skill profile. Reviewed literature suggests that this is not addressed by increasing the number of graduates from universities and training colleges. Workplace based learning or on-the job-training and retraining are possible strategies to address the challenges in the short term. In the medium to long term, there could be need to adjust the curriculum in university and college education to specifically include important materials relevant for the green hydrogen technologies.

This review of literature finds that the supply of these skills is mainly coming from chemical industry companies, of people with on-the-job training, or beneficiaries of upskilling and select skills development by SETAs, especially the Chemical Industries Education and Training Authority (CHIETA) and Energy and Water Education Training Authority (EWSETA). There is limited green energy training opportunities except for postgraduate research projects that seek to understand the skills gaps and opportunities for closing the gaps through training. It is observed that the petroleum and gas industries have skills that can be transferrable to the hydrogen economy.

On the academic front, it is found that there are no hydrogen related qualifications or programmes offered at undergraduate level and the challenge is worsened by lack of expertise to offer such courses. There is need to develop this expertise and ensure that funding towards skills development in hydrogen is commensurate with investment in infrastructure development. Even when the expertise are developed, there is a need for developing facilities for technology demonstrations. Currently there are very few local higher education institutes that have introduced hydrogen related topics in their institutions. There is need for these institutions to align with the country's strategic green hydrogen pathways. Therefore, the need for increased research focus on fuel cell innovation, green hydrogen production, storage and distribution, and demand patterns is crucial.

This study established that the demand for artisans and technicians will increase as the production of green hydrogen gathers momentum. Therefore, there is need to build capacity of TVET colleges to offer National Certificate (Vocational) (NC[V]), NATED and Occupational Qualifications. A focus on engineering will be important in providing foundational knowledge and skills necessary to support the green hydrogen technologies development in the MMS in South Africa. Training at TVET colleges should be targeted at developing the three important capabilities that cut across different roles and qualifications which are to gain understanding of hydrogen properties, identifying and managing hydrogen hazardous areas (safety & risk), and reading and interpreting technical drawings with hydrogen equipment. This is important at a time when the green hydrogen ecosystem is in the process of developing standards and guidelines to ensure uniformity. Currently, the challenge is that these standards and guidelines are not yet fully developed.

The MQA and other SETAs, for example, the Chemical Industries Education and Training Authority (CHIETA), Manufacturing, Industrial and Related Services Sector Education and Training Authority (merSETA), Energy and Water Sector Education and Training Authority (EWSETA), and Transport Education and Training Authority (TETA) could coordinate efforts in partnerships to develop occupational qualifications that equip leaners with hydrogen specific capabilities. In addition to technical qualifications, it is argued that soft skills are increasingly becoming critical skills for future employment, encompassing how individuals interact with others, and their intrapersonal skills that relate to self-awareness, self-management and resilience. These are currently missing yet very important in supporting the green hydrogen pathway in the MMS and therefore need attention. To curb the inherent shortage of human resources that have the requisite knowledge, skills, and industry experience to impart on students at schools, colleges of education and training (CETs), TVETs, and universities, it is suggested that collaboration between industry and education institutions be increased, relationships with public and private international institutions be embraced.

In line with emerging global trends, several countries are embracing workplace-based learning (WBL) in their programmes. In South Africa, some programmes already exist that have WBL opportunities, for example, mechatronics, electrical, mechanical engineers, and these could benefit from augmenting with hydrogen capabilities resulting in solid hydrogen gas (GH2) occupations. Thus, Apprenticeships, Learnerships, National N Diploma and Category C Student Internships could ensure that technical qualifications include work experience component, as a precondition for conferment of the qualifications. Similarly, Candidacy, Student internship (Graduate, Category A and Category B) could also ensure that candidates working towards professional registration are allowed to shadow experienced people in industry as the green hydrogen technologies gather pace.

2.8. Conclusions and further implications

This chapter has shed some light on four relevant aspects of green hydrogen technologies development: the South African context, a theoretical framework applicable to understanding the green energy technologies dynamics, the state and nature of green hydrogen technologies globally and locally, and implications for skills development in the era of Industry 4.0.

The study acknowledges the huge opportunity that green hydrogen technologies present in the decarbonisation of the economy, and socio-economic development to achieve SDGs at the back of a South African country endowed with mineral resources, including PGMs crucial for the green hydrogen technologies. However, much political will and limited implementation of green hydrogen strategies are seen, alongside high costs of technology and lack of clear policy frameworks as key blockers for the acceleration to achieve the net zero goal. A less discussed obstruction to the green hydrogen technologies is the skills gap that largely emerges from the poor coordination of planning, strategy, financing and rollout. Coordination is important in the context of green hydrogen as the hydrogen production pathways are crucial to achieving the decarbonisation agenda. For example, green hydrogen production requires coordination with green energy generation investments such as solar, wind and hydroelectricity. Where hydrogen is produced from fossil fuels followed by carbon capture, use and store, several other stakeholders are involved, requiring high levels of coordination.

Further, by leveraging the Actor Network Theory and ADKAR model, this paper provides a framework to explore in detail the green hydrogen technologies as a socio-technical process of change where conditions and circumstances are in the flow. Together, these dynamics, when gleaned at the back of the industry 4.0 revolution, have significant implications for skills development. Diverse competencies will need to be developed, ranging from soft, hard, cognitive, emotional and digital to address the technical, psychological and emotional levels of skills.

From a policy standpoint, it implies that a well-defined and stable policy framework is necessary to reduce uncertainty and risks for producers, helping the industry to make better-informed investment decisions. For South Africa, green hydrogen technologies present opportunities for economic growth and job creation in the medium to long term as demand expands. While international hydrogen trade might maximise economic growth in the future, it will not be possible unless consistent rules and regulations for green hydrogen standards and (Guarantees of Origin) GOs schemes can be agreed across regions or globally.

The review has unpacked numerous implications for green hydrogen skills development. The green hydrogen technologies are still various developmental levels but are expected to gather momentum. South Africa's MMS needs to develop the right skills to service the emerging energy resource for it to create decent work in line with SDG 4. The required occupations are evident in South Africa's MMS, but they are in small quantities. Although the country offers most of the basic required qualifications (higher education, TVET college system and occupational qualifications). It is evident that there is a need to augment for both occupations and qualifications offered. Further, the introduction of new qualifications and creation of new occupations is expected to close the anticipated gaps when green hydrogen gathers momentum. Currently, there are no skills shortages because the technologies are in development, but as the technologies grow in use, it is anticipated that there will be a risk of demand exceeding supply as technologies are established. It is evident that there is shortage of WBL opportunities which comes with a developing hydrogen industry.

To be ready for the expected growth, SETAs may need to push for the revision of curricula and aggressively focus on train the trainer initiatives where lecturers and trainers are trained to gain the needed capacity. The demand for specialized skills will however materialize before the longer-term project of updating curricula can be concluded. It is, therefore, imperative that the MMS develops continuing professional development (CPD) programmes to allow professionals to stay up to date with industry trends. Green hydrogen technologies are underdeveloped in South Africa, which gives credence to the promotion of learner and trainer mobility to other countries to hone their skills. From elementary education, students may be encouraged and coached to undertake STEM subjects in primary and secondary school. The students in STEM could be exposed to workshops, exhibitions and seminars focused on promoting green hydrogen as an industry of choice for students and workers in declining sectors.

3. APPROACH TO THE STUDY

3.1. Introduction

The following sections outline the research approach. This study utilises a pragmatic research philosophy which allows the research to utilise qualitative and quantitative methods. The sections are divided into research design and approach, data collection methods, data analysis, reliability and validity, ethical requirements, and limitations and challenges.

3.2. Research philosophy, design and approach

3.2.1. Pragmatism philosophy

The study followed a pragmatism philosophy where methods were selected for their effectiveness in answering the research questions. The philosophy focuses on practicality, utility and effectiveness in understanding reality. This study is, therefore, guided by the three core methodological principles that underlie a pragmatic approach to inquiry: (1) an emphasis on actionable knowledge, (2) recognition of the interconnectedness between experience, knowing and acting and (3) inquiry as an experiential process (Kelly & Cordeiro, 2020). The purpose of generating knowledge from a pragmatism perspective is to solve real world challenges to achieve practical goals (Ormerod, 2006). A key principle of pragmatism is pluralism, meaning that multiple methods are valuable (Kelly & Cordeiro, 2020). It gives the researcher the flexibility to utilise all the methods and perspectives that could address the research questions as opposed to obsession with paradigmatic debates which arise from the extreme philosophies of positivism and interpretivism (Kelly & Cordeiro, 2020).

In terms of epistemology, the philosophy rejects objectivity and embraces the idea that knowledge is context-dependent, shaped by individual perspectives and dynamics, allowing it to be revised as new evidence and perspectives emerge. These arguments are important when assessing the state and nature of green hydrogen and implications for skills development in the MMS in South Africa. This is because the green hydrogen technologies development is a practical process that requires thorough exploration involving gathering stakeholder perspectives and lived experiences. Additionally, multiple data points, for example, document analysis, quantitative surveys and interviews were important to understand the state and nature of these technologies.

3.2.2 Mixed methods research approach

A mixed methods research approach was utilized, and this provided an integrated approach with both quantitative and qualitative methods. The use of multiple methods was across data collection, analysis and presentation in line with pragmatism philosophy. Amongst the benefits of the mixed-method approach is that the strengths of one method offset the weaknesses of another (Kelly & Cordeiro, 2020). For example, qualitative methods do not provide generalisability of findings, which is provided by quantitative methods. On the other hand, qualitative methods allowed the researchers to generate new knowledge as interview participants were given the opportunity to express themselves freely. According to Creswell et al (2011) the use of several research methods fosters interdisciplinary collaboration leading to results that are comprehensive and convincing. More so, combining qualitative and quantitative methods increases confidence in the results and overall findings, and it is also a form of triangulation where results coming from the different methods can be cross-checked to ensure reliability and validity (Ormerod, 2021). The shortcoming of the mixed-method approach is potential conflict arising from theories underpinning the components of the study. For this reason, data analysis was done systematically to draw comprehensive and coherent conclusions. Data analysis started with the analysis of literature, quantitative analysis, followed by qualitative approach to corroborate the findings.

Mixed methods presented the most appropriate approach for exploring the state and nature of green hydrogen because green hydrogen is a developing technology that still has considerable questions to answer. This called for using qualitative methods of an explorative nature. Similarly, a detailed understanding of this emerging dynamic requires collecting and analysing quantitative data, regarding important skills, for example, and existing perceptions regarding the future potential pathways.

3.3. Data collection methods

Figure 2 shows the data collection and analysis framework. As captured on the figure, there were four phases moving from literature review to producing this final report. During ***phase 1***, review of relevant literature and reports, policies, plans on green hydrogen technologies and MMS skills planning was undertaken. A systematic literature review approach was followed, and this involved defining the research question, developing a protocol to guide the searches (i.e., capture key works from objectives and research questions, searching for reports, papers and policy documents, screening and selecting relevant literature, extracting information that aligns with components of the study objectives, synthesising and writing up the literature review chapter.

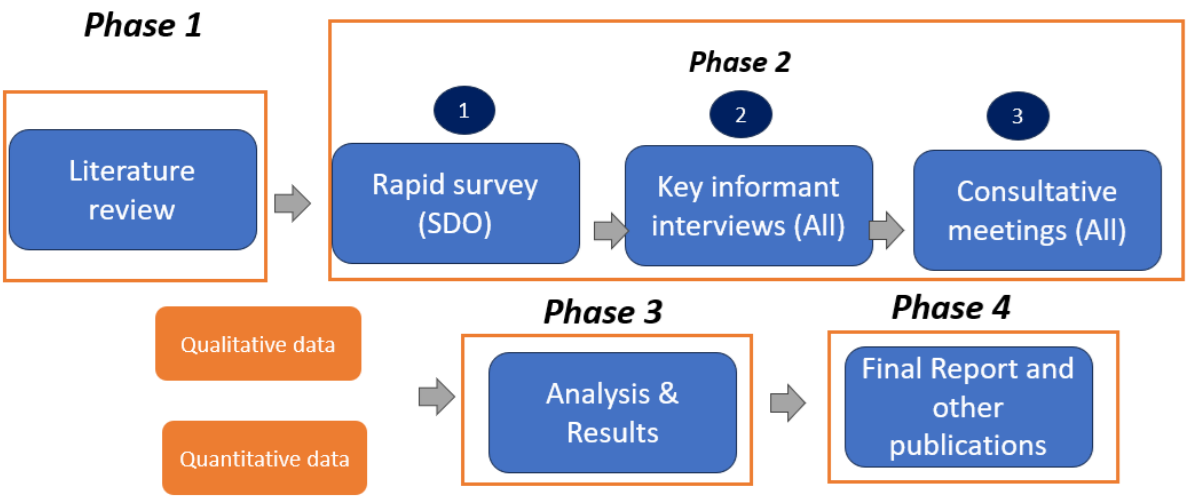

Figure 2: Data Collection and Analysis Framework

Phase 2 of the data collection and analysis framework involved the collection of primary data through rapid surveys, key informant interviews and consultative/stakeholder meetings. Rapid surveys were used to obtain insights on the experiences of the participants on the green hydrogen technologies (GHTs) and implications for skills development. The surveys targeted personnel responsible for green hydrogen planning and implementation working in MMS companies, GHT technical services, renewable energy companies, corporate services, and GHT planning personnel in these companies.

Human resources professionals and experts from the entire MMS were also sampled and labour representatives for their perspectives. Participants were drawn from a diverse range of companies including small, medium, and large-scale mines, OEMs and green energy suppliers and or funders. Academics and industry experts formed part of the sample.

A sample size of 46 participants was randomly selected from the total population of GHT specialists in MMS, original equipment providers (OEM) and other stakeholders. The sample was drawn from all the provinces of South Africa where projects are underway, or plans are in place to start GHT projects. For example, Anglo American are piloting haul trucking using green hydrogen, it was beneficial to include them. Transnet National Port Authority are advancing plans to leverage green hydrogen for their ships and other port facilities. For beneficiation, the Saldanha green steel project in the Western cape and the Sasolburg project in Gauteng were seen as promising examples and hence included.

The survey for quantitative data was administered using a structured questionnaire and this was completed online using Microsoft Forms to be cost and environmentally effective. The surveys were conducted alongside key informant interviews (KII). The KII were conducted using a semi-structure questionnaire and an interview guide informed by the research objectives. The interviews were conducted with the participants noted above and they were purposively selected. MQA also assisted with identifying target participants. Another component of the primary data collection was consultative meetings/stakeholder engagements. These included the official launch of the Green Hydrogen Centre of Specialisation where the MQA, TETA, and CHIETA signed a MoU to advance green hydrogen specialisation, the Energy and Mining Skills Forum in Mpumalanga, and stakeholder engagement sessions facilitated by MQA which were leveraged to obtain a deeper understanding of the state and nature of green hydrogen technologies and implications for skills development.

Figure 3 provides a summary of the representative sample which covered small, medium and large companies, and all the different subsectors, Gold Mining, services incidental to mining, PGM Mining, Coal Mining, Other Mining, Cement, lime, aggregates and sands (CLAS), Diamond Mining (2%), Diamond processing (2%), Jewellery (2%) of the MMS.

Figure 3: distribution of quantitative survey participants

The study ensured inclusivity with representation of both men (64%) and women (35%). For qualitative data the study utilised a questionnaire to ask semi-structured questions and at the end invited participants to share contact details if interested in participating in interviews. A total of 38 respondents from the total of 46 confirmed interest in participation. Table 8 summarises the breakdown of qualitative data contribution.

Table 8: Distribution of qualitative data informants

Group Number	Participant Group	Group Composition	Number of Participants
1	Energy and Mining Skills Forum (Mpumalanga)	MQA, EWSETA, DHET, DMRE, mining companies, 2 TVETs, Eskom, Mpumalanga Regional Training Trust, 3 District Municipalities, Provincial Government Departments (Basic Education, Public, Works, Roads and Infrastructure, Economic Development	32

Group Number	Participant Group	Group Composition	Number of Participants
		and Tourism), academics from Wits, UP and TUT)	
2	The official launch of Green Hydrogen Centre of Specialisation	MQA, CHIETA, TETA, DHET and CSIR stakeholders (Including MCSA, TVETS, and Universities)	3 (interviewed)
3	MMS companies	Mining companies' representatives	5
4	Academics	Academics from Wits, UP	3
5	Green Hydrogen Society	Experts	2
6	Women in Hydrogen (SA)	Women representatives in green hydrogen	2
	Total		**47**

3.4. Data analysis methods

Phase 3 of the research process covers data analysis and presentation of the results.

Qualitative data analysis: The data from archival documents, interviews and forums were transcribed and analysed using thematic analysis (Saldana, 2014). The analysis of qualitative data started with coding, where codes were developed to lead the analysis, the codes were developed into categories, which were then developed into themes. The analysis was applied to data that was generated from key informant interviews and reports from the forum and the official launch of the Green Hydrogen Centre of Specialisation (CoS) at CSIR.

Quantitative data analysis: Quantitative data analysis of reviewed literature, and policies, company documents, websites, and surveys were done by systematically examining numerical data to uncover perspectives, patterns, relationships, and trends. Once all the data descriptive statistical data analysis was done utilising Python. The analysis results are presented in this report (i.e., ***phase 4).***

3.5. Research reliability and validity

Research reliability and validity are important measures in research that ensure the quality and trustworthiness of the research and findings being presented. Various methods can be used to establish the validity and reliability of quantitative and qualitative research. In this study, reliability and validity were established through the use of the triangulation method. Different triangulation methods were used – data triangulation (i.e., the study used of multiple data), investigator triangulation (i.e., involved multiple researchers collecting and analysing the data), theory triangulation (i.e., application of multiple theories to test the findings) and methodological triangulation (i.e., the use of different approaches to collect and analyse data). This research study used multiple sources of data (i.e., secondary and primary data) as well as different investigators to collect, analyse and cross check the data. More so, two approaches (i.e., Rapid Survey (RAS) and Key Informant Interviews (KIIs) were used to collect the data, and these complemented each other. To ensure the validity and reliability of quantitative data, established research elements were used to collect data on different aspects of green hydrogen technologies.

3.6. Ethics requirements

In line with the statutes of the University of Witwatersrand, ethics clearance was obtained. This study was conducted in line with the following ethics guidelines: Human Research Ethics Committee (non-medical). The rigorous ethics process ensured that research did not violate the rights of the participants and aspects of confidentiality and anonymity both during data collection and in the final report were maintained, except for data in the public domain. Names of companies and participants were only used for data in the public domain.

3.7. Study limitations and challenges

The following are the limitations of the study:

- ***Access to data:*** The limitations of the current study are that it was assumed that all the targeted participants will participate in the study. There were issues of confidentiality and POPIA which affected access to certain data that was required for the study.
- ***Sample size and representation of targeted groups***: The sample size was significant to present credible findings. No major challenges were encountered during the study.

- ***Scope of analysis:*** Although there are so many other theories that could have been relevant to understanding green hydrogen technologies development and implications for skills development, this study focused on the Actor Network Theory (Chipangamate & Nwaila, 2023), Human Capital Theory, and ADKAR Model (Ali, 2021; Houben et al, 2020) to explore the state and nature of green hydrogen technologies and implications for skills development in the MMS.

3.8. Summary and conclusion

The study utilised mixed methods where qualitative and quantitative methods were used. Qualitative and quantitative data was collected from participants in the MMS companies and related stakeholders. To ensure credibility, triangulation of data sources was done.

The remainder of the report will focus on the findings of the state and nature of green hydrogen technologies and implications for skills development in the MMS in South Africa. The report focuses on major projects, challenges and opportunities presented for the MMS and ways to address them for creating a stable green hydrogen technologies network in the MMS in South Africa.

4. RESEARCH FINDINGS AND DISCUSSION

4.1. Introduction

This chapter presents the key findings of the research and discusses them in relation to literature and policy on the green hydrogen technologies and implications for skills development in the MMS in South Africa. Findings from recent past studies are also reported to underscore the green hydrogen development in the MMS in relation to major global and regional development. This is important for the MQA to implement the results not in isolation. The implications for skills development are also articulated as they relate to study findings. Figures, tables and case studies are utilised to paint a vivid picture of the state and nature of green hydrogen technologies development and implications for skills development.

4.2. Green hydrogen technologies in the mining and minerals sector

4.2.1. Green hydrogen technology development as a socio-technical network building process

The development of green hydrogen technologies has often been conceptualised as a value chain, suggesting that value is added from upstream, through midstream until it gets to downstream. This contemporary view of the green hydrogen technology posits that the value chain consists of upstream, constituted of the upstream resources, also known as feedstock. These could be the water needed for splitting in the production processes, and the renewable energy infrastructures needed to facilitate the water splitting. In other cases, more complex use of natural gas or fossil fuels combined with carbon capture use and storage (CCUS) to achieve low carbon hydrogen albeit at a higher production cost is also seen as a viable option in the production of low-carbon hydrogen. In the case of South Africa, which is seen as a water scarce country, desalination of seawater is the only feasible option. In that case, seawater and desalination facilities form part of the upstream resources. South Africa has coastal access which makes it a suitable candidate for seawater desalination in pursuit of green hydrogen production.

The objective of the South African government's green hydrogen commercialisation strategy is to produce green hydrogen, which is mainly focused on the water splitting technique, through desalination and electrolysis of seawater, using green energy. The main green energy sources to be utilised in South Africa are wind energy and solar energy. These energy sources are merited in the country due to the abundance of wind and solar opportunities all year round. Access to low-cost abundant renewable energy is crucial for competitive green hydrogen production. In addition to water and energy resources, the other important upstream components are electrolysers which are used for splitting water (H_20) into hydrogen (H_2) and oxygen (0_2) using electricity.

The midstream in the green hydrogen value chain is the green hydrogen production through electrolysis/water splitting. The hydrogen may be converted into ammonia for easy transportation or stored in a liquid or gaseous state. This is depicted in figure 4 as the grey segment. The third and final segment of the value chain is the downstream involving consumption, green products and export. The green final segment of Figure 4 shows the third segment of the traditional value chain.

However, this study finds this to be rather a simplistic view of the green hydrogen production process, especially at a time when the technology is grappling to establish itself as a significant contributor to the energy transition. This simplistic view overshadows several other processes and important actors who are necessary to drive the green hydrogen technology beyond the 'commercialisation valley of death'. This is defined as the tipping point where green hydrogen technology should eclipse for it to be commercially viable for production and utilisation at commercial scale. For this reason, this study finds that green hydrogen technology development is more of a value network with sidestream processes, than a linear upstream-downstream chain. This has significant implications to the scope for support and interventions necessary for scaling green hydrogen technologies as elaborated in the findings of this study. Figure 4 shows the layout of a typical MMS green hydrogen value network.

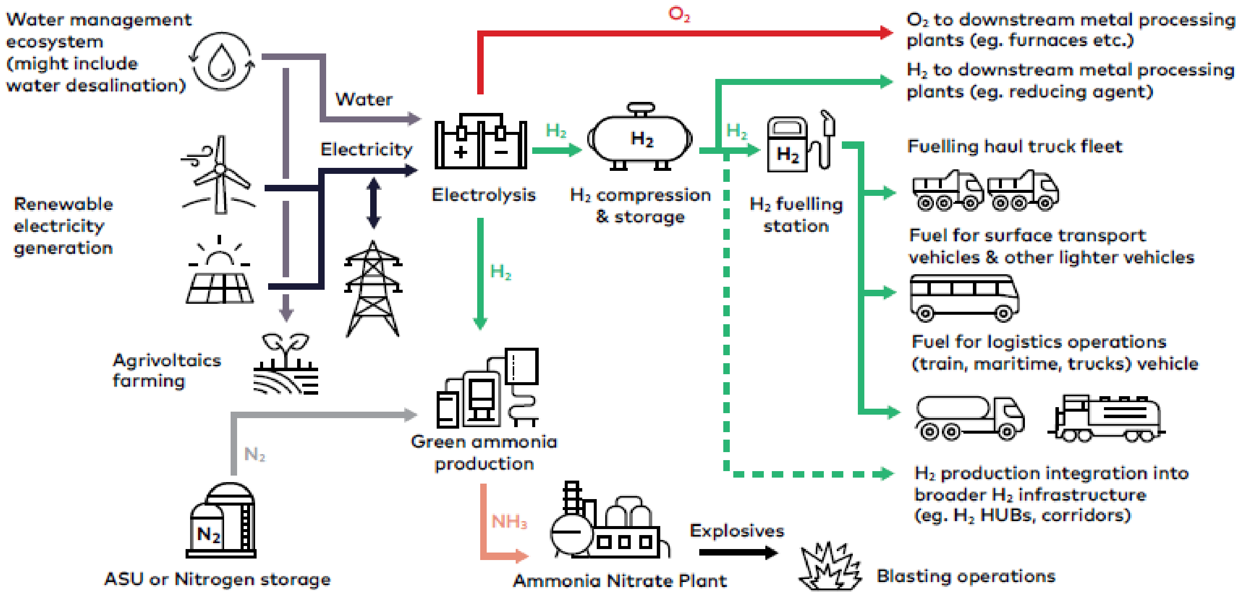

Figure 4: The green hydrogen value network (excluding the side-stream) (source: DSS, 2023)

The study findings concur with the postulations of the Actor Network Theory that development of green hydrogen technology could be seen as a socio-technical system involving bringing actors together to stabilise the network. The theory is seen as a useful lens to understand the development of technology through different phases of problematisation, interessement, enrolment, mobilisation, and institutionalisation (Chipangamate and Nwaila, 2023). The theory further assists to better understand the state and nature of green hydrogen technologies in the country's MMS as demonstrated in subsequent sections of this report. Table 9 summarises the key components of the green hydrogen value network

Table 9: Components of a green hydrogen value network

Stream	Components	Description	South Africa state & nature
Upstream	Renewable energy, water, and electrolysers	This is the supply side of the green hydrogen technologies	There is significant development of renewable energy in MMS. Electrolysers are not yet produced. There is potential due to PGMs.

Midstream	Electrolysis, storage, and transportation	This is responsible for the production, storage and distribution of green hydrogen	Production, and storage is limited to pilots
Downstream	Consumption	This is the final leg in the green hydrogen value network	There is not yet commercial consumption of green hydrogen
Sidestream	Support of the green hydrogen	This is where we find other stakeholders not directly linked to the production such as the MQA and training institutions, and other stakeholders	Learning institutions are not ready for the green hydrogen technologies

4.2.2. South Africa's green hydrogen technologies value network - Upstream technologies important for green hydrogen

South Africa is endowed with renewable energy resources, especially solar and wind energy. The country's geographical advantages make it a prime location for generating clean electricity, a crucial component in the production of green hydrogen. With high solar irradiance and vast, open landscapes ideal for wind farms, South Africa is well-positioned to harness renewable energy for electrolysis, which splits water into hydrogen and oxygen using electricity. South Africa's renewable energy potential is considered one of the best in the world, with estimates suggesting that the country could produce more than enough clean energy to meet its domestic needs and export surplus electricity to the rest of Africa and beyond.

Green hydrogen production requires significant amounts of electricity, and given South Africa's substantial renewable energy potential, there is an opportunity to produce hydrogen at a competitive cost. According to recent studies, green hydrogen in South Africa could be produced at one of the lowest costs in the world, making it an attractive proposition for both domestic consumption and export to international markets, particularly Europe and Asia, where hydrogen demand is expected to grow substantially.

As shown in Table 10 significant investments are either underway or planned to scale up renewable energy generation, particularly solar and wind. Table 10 shows Redstone Concentrated Solar Power Project is probably the largest renewable energy investment in South Africa, valued at R11.6 billion. The project is in the Northern Cape Province, where it is expected to power 200,000 households and reduce carbon emissions by 440 metric tons per year, when fully operational (DBSA, 2024). Meanwhile the South African Renewable Energy Project is another massive 5,000 MW wind and solar park, with a total project value of approximately $4.5 billion to produce 1800 MW of electricity from solar energy (ABIQ, 2024). The Richard's Bay Power Plant is a 3,000 MW combined cycle power plant project valued at $4 billion, scheduled for completion in mid-2028 (ABIQ, 2024). Another important renewable project is the kaXu Solar One which comprises a 100 MW concentrated solar power plant that supplies clean energy to over 95,000 households with a molten salt storage system that allows for 5.5 hours of energy storage (Roadlab, 2024). The other major investment in the Northern Cape is the Khi Solar One, a 50 MW concentrated solar power plant that reduces South Africa's carbon dioxide emissions by about 138,000 metric tons a year (Roadlab, 2024).

Wind energy opportunities are also available in South Africa. For example, the Garob Wind Farm is a 140 MW wind farm in the Siyathemba Local Municipality, near Copperton in the Northern Cape, using 46 turbines to generate around 573 GWh/yr and avoid the annual emission of around 600,000 tons of CO_2, the Nxuba Wind Farm, a 140 MW wind farm that generates 460 GWh/y of energy and mitigates the emission of about 460,000 tons of carbon dioxide per year (Roadlab, 2024). The availability of both wind and solar potential makes South Africa very competitive in the generation of renewable energy, a precondition for green hydrogen production. This is demonstrated by the example of the Kenhardt Project which is a hybrid renewable energy project consisting of solar and battery facilities, valued at over $4 billion (Roadlab, 2024). These projects demonstrate South Africa's commitment to transitioning to renewable energy sources and reducing its carbon footprint. The commitment is further demonstrated by the establishment of Special Economic Zones (SEZ) where green hydrogen could thrive. For example, the Boegoebaai Green Hydrogen Project is located in the Namakwa Special Economic Zone and is anticipated to use 3,000 MW of renewable energy to produce 100,000 tonnes of green hydrogen at an estimated build cost of $4 billion.

Table 10: Major renewable energy projects in the MMS

Project	Estimated investment	Energy source	Province
Redstone	R11.6 billion	Solar	Northern Cape
South African Renewable Energy Project	$4.5 billion	Wind and solar	Northern Cape
Xina Solar One	R12.4 billion	Solar	Northern Cape
Garob Wind Farm	R2.4 billion	Wind	Northern Cape
Nxuba Wind Farm	R2.4 billion	Wind	Eastern Cape
Khi Solar One	12.4 billion	Solar	Northern Cape
Kenhardt Project	R12.4 billion	Solar	Northern Cape
Boegoebaai Green Hydrogen Project	R300-400 billion	Green hydrogen	Northern Cape

Major renewable energy projects in the mining and minerals sector

South Africa's MMS is a leading example in integration of renewable energy in the energy mix as a broad decarbonisation strategy. Benchmarking against other African countries, this study established that some of the notable renewable energy projects are in South Africa's MMS. This provides the sector with huge opportunities to ride on the renewable energy infrastructure for the development of green hydrogen.

<u>Solar energy projects in the MMS</u>

Table 11 shows some of the leading solar projects by the sector. The Sibanye-Stillwater's Solar Project is a 175 MW solar project across its platinum group metal mining operations in South Africa, and it consists of an 80 MW solar PV project at its Rustenburg Platinum Mines Complex, a 65 MW solar PV project at its Karee Complex, and a 30 MW solar PV project at its Bushveld Complex (Sibanye-Stillwater, 2024). Similarly, Anglo American Platinum's Solar Project is a 100

MW solar PV plant at its Mogalakwena mine in Limpopo province, South Africa is expected to contribute to the company’s decarbonisation goal by 2040 (Anglo American, 2024). Another important investment in renewable energy is the Gold Fields' Solar Project which is a 40 MW solar PV plant at its South Deep gold mine near Westonaria, Johannesburg, which supplies the mine with a fifth of its power needs (Gold Fields, 2024). In the coal sub-sector, the following are noted:

Wind energy projects in the MMS

Taking advantage of the abundant wind resources, MMS companies are harnessing this resource to decarbonise their operations. For example, the study found that the Seriti Wind Power Station is a 155 MW wind power generation facility in Mpumalanga province, South Africa, to power Seriti Resources' coal mining operations (Seriti, 2024).

Hybrid power plants

Some MMS organisations are utilising a hybrid of energy sources. For example, Table 11 shows that the Juwi Solar and Wind Projects are 400 MW of engineering, procurement, and construction projects in advanced stages of development for mines in South Africa. Similarly, the Tronox Wind and Solar Plants are a hybrid of 200 MW wind and solar power plants to power Tronox's mines and smelters in South Africa (Toronox, 2024). Elsewhere on the African continent, the First Quantum Minerals Solar PV Park and Wind Farm is a hybrid of 230 MW solar photovoltaic facility and 200 MW wind farm to support First Quantum Minerals' Kansanshi and Sentinel mines in Zambia and is expected to reduce FQM's carbon footprint by 30% (Green Energy Africa Summit, 2022).

Viewed together, these projects demonstrate the MMS's commitment to transitioning to renewable energy sources and reducing its carbon footprint.

Table 11: Investment in renewable energy by different sub-sectors in the MMS

Project	Subsector	Energy Type	Capacity
Sibanye-Stillwater	PGMs	Solar	175MW
Anglo American Platinum	PGMs	Solar	100MW
Gold Fields	Gold	Solar	40MW
Sereti	Coal	Wind	155MW

Project	Subsector	Energy Type	Capacity
Exxaro Resources	Coal	Solar	68MW
Richards Bay Minerals	Mineral Sands	Hybrid/Wind and solar	288MW
Juwi Solar and Wind Projects	Sector-wide	Hybrid/Wind and Solar	400MW
Tronox Wind and Solar Plants	Mines and smelters	Hybrid	200MW

Figure 5 demonstrates that the CLAS subsector and PMGs are actively taking a lead in the development of renewable energy, with Gold Mining having the least of the studied sub-sectors.

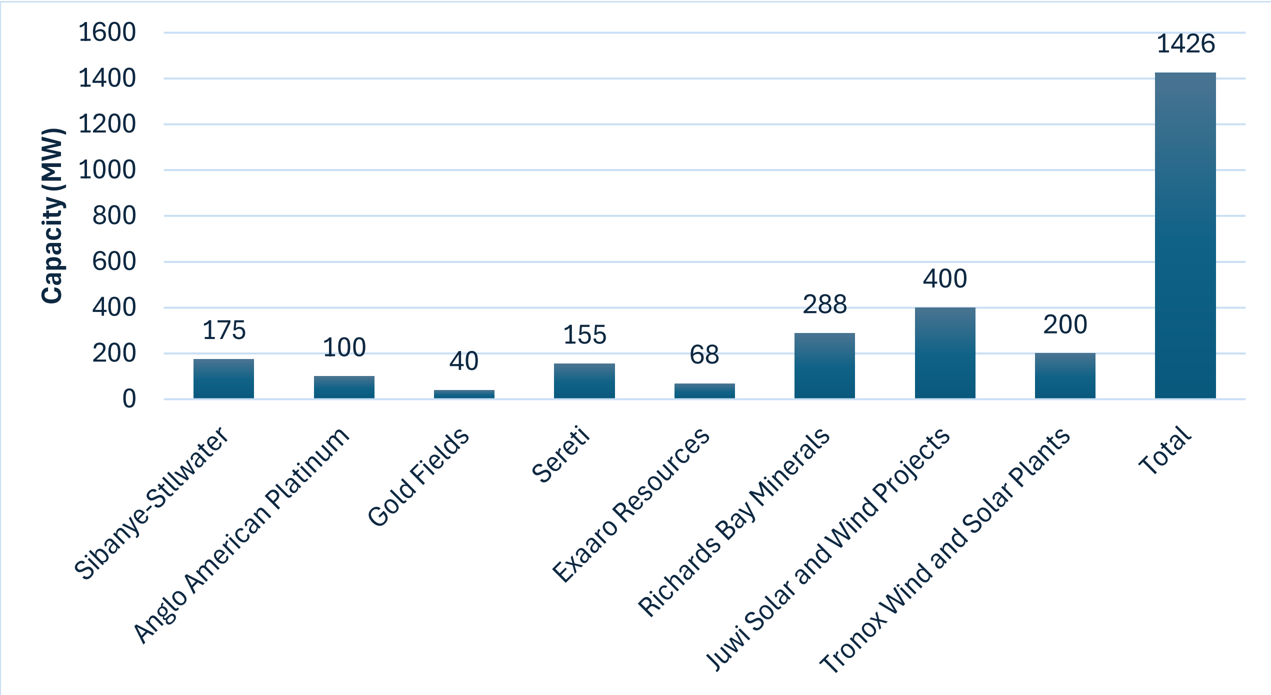

Figure 5: Renewable energy investment by subsector companies in the MMS

Similarly, Figure 6 shows the different renewable investment capacities that the different companies did in the MMS. Hybrid deployment combining wind and solar has the highest contribution (888MW) followed by solar (383 MW) and then wind (155MW).

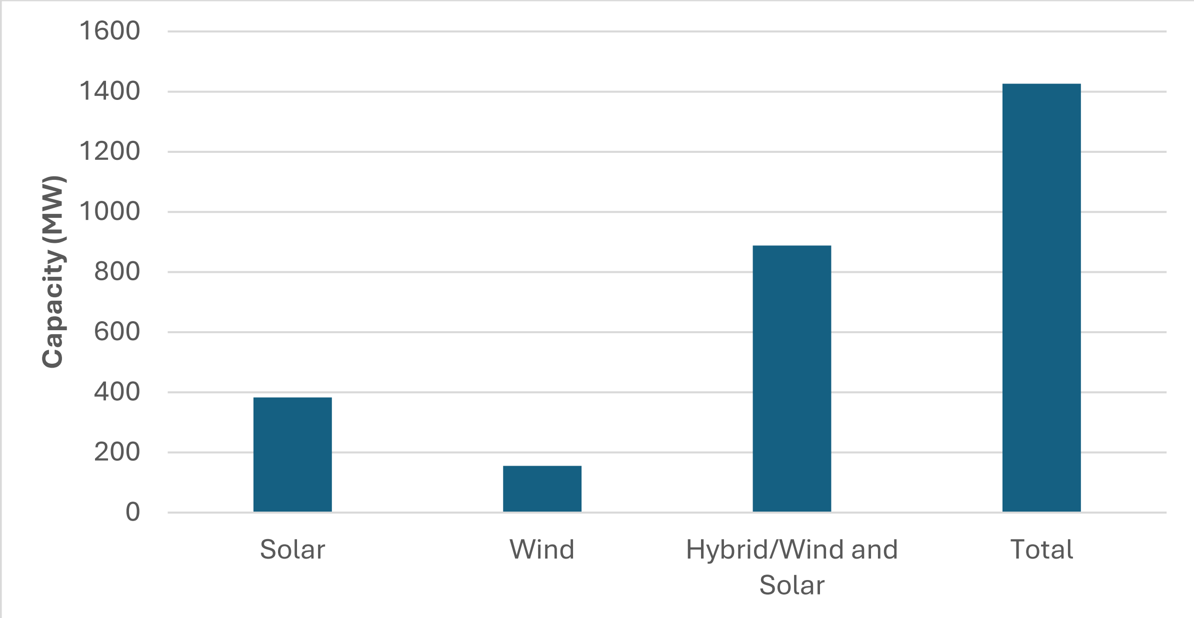

Figure 6: Renewable energy projects in the MMS

Major renewable energy projects by mining and minerals companies are underway across Africa. The following section presents some case studies of mining and minerals companies investing in renewable energy, which is important for green hydrogen technologies.

Case studies of companies in the mining and minerals sector deploying renewable energy

Case study 1. Mineral Sands Sub-sector

Richards Bay Minerals (RBM) is a world leader in heavy mineral sands extraction and refining. RBM mines mineral-rich sands in the northern KwaZulu-Natal province and produces materials used in a wide range of everyday products, from paints to smartphones. RBM is committed to sustainable practices and making a positive impact on the communities it serves.

Commitment to renewable energy for decarbonisation

"As a world leading mineral sands operation, we are determined to find better ways to produce the materials the world needs and decarbonizing our operations is one of them. Rio Tinto has committed to reduce Scope 1 and 2 emissions by 50% by 2030 and achieve net zero by 2050. The Khangela Emoyeni Wind Farm has the potential to reduce RBM's annual carbon emissions by 20% and reduce our existing reliance on traditional energy sources by 26%."

(Werner Duvenhage, Managing Director Richards Bay Minerals and Rio Tinto Iron and Titanium African Operations)

Proactive renewable energy initiatives

Richards Bay Minerals (RBM) signed a renewable power purchase agreement (PPA) with Khangela Emoyeni Wind Farm (Pty) Ltd to secure 140MW of wind energy from a wind farm situated in the Western and Northern Cape Province. The project is expected to reduce RBM's annual carbon emissions by 20%. When fully operational, the Khangela Emoyeni Wind Farm is expected to produce approximately 460GWh of renewable energy annually and, through a wheeling agreement with Eskom, will help power RBM's operations located in Richards Bay in KwaZulu-Natal. In 2022 RBM signed a similar agreement for the Bolobedu Solar PV plant in Limpopo with Voltalia, a renewable energy company. The Bolobedu solar PV project, is in progress and is anticipated to meet 17% of RBM's power consumption by generating up to 300GWh of renewable energy per annum. Combined, the Khangela Emoyeni Wind and Bolobedu Solar projects will supply approximately 42% of RBM's existing energy needs (Rio Tinto, 2024).

Partnering for renewable energy scaling

A common theme in this study for scaling renewable energy development is the crucial role that partnerships play in line with SDG 17. The parties to the 20-year PPA include African Clean Energy Developments (Pty) Ltd (ACED), The IDEAS Fund (managed by African Infrastructure Investment Managers), investment holding company Reatile Group, and Rand Merchant Bank. The EIMS Africa will be responsible for asset management for the project. As one of the partners reflected: "We are immensely proud to have achieved financial close and commenced construction on Khangela Emoyeni Wind Farm, with Rio Tinto's Richards Bay Minerals. Not only will it provide RBM with clean energy for their operations, but it will also help alleviate South Africa's power crisis." (James Cumming, General Manager at ACED)

Generating interest and legitimacy through communicating benefits

Jobs and skills implications - A key finding from this study is how the actors sought to communicate the benefits of these projects to gain wider interest as the renewable energy segment of the green energy technologies entered the enrolment phase of the network building process. This was evident in the communication by partners, for example: "Not only will it provide RBM with clean energy for their operations, but it will also help alleviate South Africa's power crisis." (James Cumming, General Manager at ACED).

A press release by one of the partners underscored the important role of these renewable energy projects in job creation and skills development: "The project presents opportunities for job creation, skills development, and knowledge transfer within local communities, surrounding the project sites, during both the construction and operational phases." (Rio Tinto, 2024)

<u>Case study 2. Coal Sub-sector</u>

Exxaro is one of South Africa's largest and foremost black-empowered diversified mining and renewable energy solutions companies. It is among the top five coal producers in South Africa and a constituent of the JSE's Top 40 Index. They are included in the FTSE/JSE Responsible Investment Top 30 Index and committed to embracing the principles of the Task Force on Climate-related Financial Disclosures (TCFD).

Commitment to renewable energy for decarbonisation

Organisations that have taken a lead in the renewable energy trajectory have invariably had senior management committed to the decarbonisation and solving the country's teething challenges. The CEO of Exxaro had this to say: "Our company is committed to sustainability and contributing to South Africa's energy security while powering better lives" (Exxaro's CEO, Dr Nombasa Tsengwa)

Proactive renewable energy initiatives

Exxaro has embarked on a utility-scale Lephalale Solar Project (LSP) involving an estimated R1.56 billion behind-the-meter solar PV plant located in the Waterberg District in Limpopo Province, covering an area of 236 hectares and with an installed capacity of 68 megawatts. The LSP aims to provide clean energy to Exxaro's Grootegeluk Mine in Lephalale and reduce carbon emissions. This is a proactive initiative near the Eskom Medupi and Matimba power stations which are expected to shut down by 2050. An important finding in this respect is the several years of planning that went into the fruition of the project. The project is scheduled for completion by the second quarter of 2025.

Partnering for renewable energy scaling

As in the RBM case study, the power of partnerships was highlighted as the main driver of success in this initiative. Exxaro Resources, through Cennergi, its subsidiary, entered a Public Private People Partnership (PPPP) with the Limpopo Provincial Government, and the communities representing the local people in the 4Ps to generate solar power through the Lephalale Solar Project (LSP). To underscore the important role of partnerships the Premier had this to say: “This is the path we have collectively chosen, embracing the principles of PPP, as we strive to overcome obstacles, uplift our economy, and create a brighter future. I call upon all stakeholders, including our communities, to rally behind this project. Together, let us turn our vision into reality,” (Limpopo Province Premier).

At the official launch of the project in 2023, Cennergi had this to say in underscoring the important role of partnerships: “In 2023, we received bank funding approval from Standard Bank and Nedbank, covering 75% of the required debt” (Managing Director of Cennergi, Leon Groenewalt).

Generating interest and legitimacy through communicating benefits

In advancing legitimacy perceptions of stakeholders, the partners communicated the various benefits that could arise from the project. These benefits include temporary and permanent job opportunities. It was highlighted that the project would generate between 400-500 temporary jobs during peak construction, and 50 permanent positions. Beyond the creation of direct jobs, more jobs will be created through commitment to local procurement. As part of their dedication to the local community, Cennergi will contribute 1% of its pre-tax revenue annually for the entire duration of the project. The crucial role of communication with stakeholders has important implications for soft skills development in the MMS to communicate not only the instrumental benefits but also the intrinsic and social benefits. For example, closely linking these projects with stakeholder experiences of climate change such as droughts, cyclones, and floods.

<u>Case study 3. Mineral Sands Sub-sector</u>

“*From Mine to Pigment*” captures the wide scope and vertical integration of Tronox’s global operations. They mine titanium-bearing mineral sands and operate upgrading facilities that produce high-grade titanium feedstock materials, pig iron and other minerals, including the rare earth-bearing mineral, monazite. The company is focused on driving sustainability by realising that the mark it leaves behind extends beyond the minerals it extracts or the products it manufactures. The company thrives to operate safely and responsibly to safely deliver high-quality titanium dioxide (TiO_2) pigment, specialty TiO_2 and zircon products.

Commitment to renewable energy for decarbonisation

Organisations that have taken a lead in the renewable energy trajectory have invariably had senior management committed to the decarbonisation and solving the country's teething challenges. This is demonstrated by the senior executive's pronouncement of their commitment: "Not only is Tronox demonstrating our commitment to emissions reduction by switching from coal-based to renewable power in South Africa, but we are also implementing innovative technologies at our operating sites to protect our land, water, air and ecosystems while also investing in our products, people and communities." (Tronox's Chief Sustainability Officer and Head of Investor Relations, Jennifer Guenther).

The mining and processing company has enjoyed superior support of the board and senior management: "Tronox's renewable energy project with SOLA Group will reduce our global carbon emissions by approximately 13% compared to our 2019 baseline and has the full support of our Board of Directors and senior management," (Melissa Zona, Tronox Holdings plc's Senior Vice President, External Affairs and Chief Sustainability Officer.)

Proactive renewable energy initiatives

Tronox has consistently invested in renewable energy focused on multiple wind and solar projects in South Africa. Their projects include the SOLA Group project, a 200 MW solar power agreement with SOLA Group that was fully implemented in April 2024. The project includes two solar photovoltaic plants in Lichtenburg, North West province, that generate 593 MW and 721 MW of clean energy annually respectively. The power is transmitted to five of Tronox's sites through the Eskom grid. Similarly, Tronox is in another long-term power purchase agreement (IPPA) with NOA Group for approximately 497 GWh of energy. The project is expected to be fully implemented by the end of 2027. The Tronox initiative is South Africa's largest operational wheeling project, which adds 256 MW of renewable energy capacity to the national grid. The project powers Tronox Mineral Sands' operations in KwaZulu-Natal and the Western Cape.

Partnering for renewable energy scaling

Tronox entered into a long-term power purchase agreement with the South African independent power producer, SOLA Group, to provide 200 MW of solar power to Tronox's mines and smelters in the Republic of South Africa. These partnerships are made possible by a wheeling agreement with Eskom that allows the energy to be wheeled on the grid. The funding partner, Nedbank argued that: "As a growing number of organisations seek to take advantage of the government's relaxation of the thresholds on private energy generation, Nedbank is committed to continuing its leadership role as a preferred funding and advisory partner. As such, we invite our clients to partner with us in pioneering bespoke solutions driven by innovative ecosystem thinking." (Nedbank)

The deal, in which Nedbank CIB acted as joint mandated lead arranger, saw the provision of debt funding of over R3 billion. The project will comprise a total of 387 000 solar panels mounted on trackers that change position as the sun moves. This solar PV project was designed and developed by the SOLA Group and African Rainbow Energy and Power (AREP). It's this type of ecosystem thinking, rooted in deep cross-sector expertise, that radiates sustainable impact across business ecosystems into the world.

Generating interest and legitimacy through communicating benefits

Some of the benefits that are proffered in the Tronox initiatives to advance legitimacy perceptions of stakeholders include sustainability through greening operations. Solar energy equipment suppliers have demonstrated appreciation of the scaling of renewable in MMS.

"We are delighted to see that large scale energy consumers like Tronox are making use of the opportunity to convert to clean and cost-effective energy," (Chris Haw, Director and co-founder at the SOLA Group).

In terms of implications for green energy technologies, these sentiments have both positive and negative connotations. They are positive because they provide the much-needed upstream precondition for green hydrogen. However, the declining cost of solar renewable energy must be met with declining costs for green hydrogen to be competitive as an energy resource with a compelling business case because solar energy is promoted and legitimised as a low-cost green source of energy: "These types of projects are the fastest way to bring new generation capacity online and not only contribute to closing the electricity supply gap in our country, but also support the much-needed transition to clean energy and modernization of our electricity grid.” (Chris Haw, Director and co-founder at the SOLA Group).

A common theme that underscores the three case studies is the important role of clean energy in the decarbonisation agenda of MMS actors. Specifically, Tronox's energy-intensive operations benefit from these projects in several ways: The projects are expected to reduce Tronox's global carbon emissions by an estimated 13% compared to its 2019 emissions baseline in addition to making electricity more affordable and secure for Tronox. For South Africa, when the latest Tronox renewable energy project is completed, approximately 70% of Tronox's South African electricity needs will be met by renewable energy, and in-country emissions will be reduced by 54%.

4.2.3. South Africa's green hydrogen technologies value network - Hydrogen production using electrolysis (Midstream)

South Africa is increasingly committed to developing green hydrogen production, primarily through electrolysis, supported by its rich renewable energy potential in solar and wind. The country's Hydrogen Society Roadmap has set ambitious goals, including installing 10 gigawatts (GW) of electrolyser capacity by 2030 and expanding to 15 GW by 2040 (Figure 7). These installations will focus largely on the Northern Cape, a region with ample solar resources, to establish a reliable and competitive green hydrogen industry.

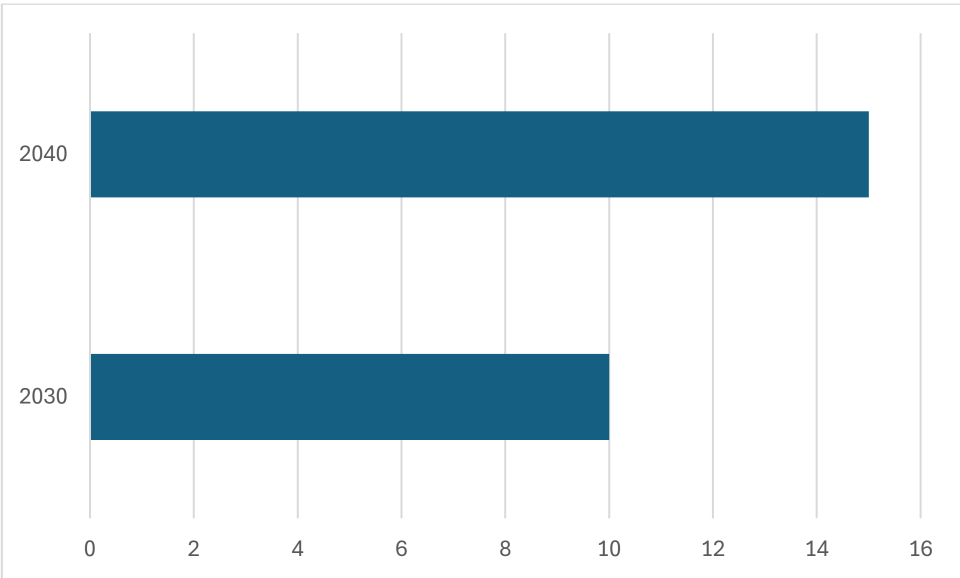

Figure 7:Electrolyser capacity projections for South Africa

Several green hydrogen projects have already been launched to showcase the feasibility of green hydrogen, such as the Hydrogen Valley initiative (Figure 9), which aims to create a hub for hydrogen production, transportation, and utilization along an industrial corridor. The concept involves clustering several industrial and research initiatives to carry out pilot projects across the complete hydrogen value chain. The Hydrogen Valley is expected to span across three hubs: Johannesburg, Durban, and Limpopo, with the latter being centred around Anglo American's Mogalakwena PGMs mine. This project has the potential to create a significant number of jobs, with estimates suggesting around 14,000 to 30,000 direct and indirect jobs per year. Figure 8 shows the Green Hydrogen Valley in South Africa.

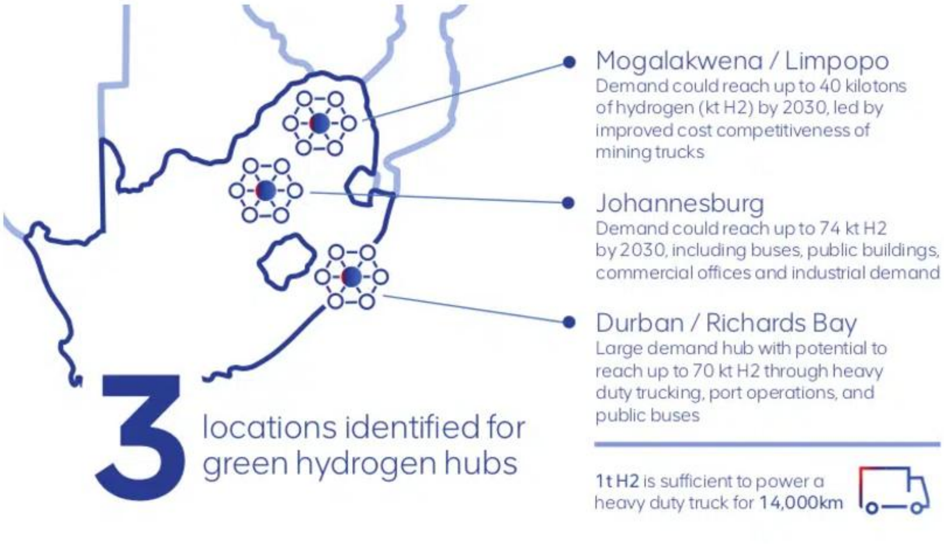

Figure 8: The Hydrogen Valley (Source: Hydrogen Council, 2022)

The South African government has shown significant support for the Hydrogen Valley initiative, with the Department of Science and Innovation launching a feasibility study to identify opportunities for green hydrogen production and utilization in 2021. The government has also committed to investing in infrastructure development and providing incentives for private sector investment in the hydrogen sector. Additionally, South Africa's wealth of platinum group metals provides a unique advantage, as these metals are essential in electrolyser manufacturing, giving South Africa the potential for localized production of key hydrogen technology components. However, the country still faces challenges, particularly with securing financing for large-scale infrastructure and maintaining a stable, renewable energy supply to support the hydrogen economy.

With government backing and international partnerships, South Africa aims to position itself as a significant player in the global green hydrogen market by creating export opportunities and supporting its domestic industries in decarbonization efforts. It is anticipated that the green hydrogen economy will play a significant role in South Africa's economy (Figure 9).

Figure 9: The green hydrogen economy contribution to South Africa's economy by 2050 (Source: Hydrogen Council, 2022)

The Green Hydrogen Valley initiative is promising as South Africa secured substantial funding for various green hydrogen initiatives from both international and domestic sources. A significant contribution is a R628 million grant from the European Union (EU). This grant, aimed at establishing South Africa's green hydrogen value chain, is expected to leverage an additional R10 billion in private and public investments across production, transportation, storage, and downstream industries

In addition to the EU grant, the SA-H2 Fund, created in partnership with Invest International and Sanlam, supports South Africa's green hydrogen projects. This fund mobilizes both local and international capital to drive infrastructure development, create jobs, and stimulate sustainable economic growth through green hydrogen projects

These commitments reflect a strong focus on scaling green hydrogen as a strategic sector, with funding directed toward infrastructure and feasibility studies to position South Africa as a competitive global player in green hydrogen production. Table 12 shows the benefits that are proffered as legitimation strategies in the enrolment of green energy actors to build the network around the Hydrogen Valley.

Table 12: The role of green hydrogen technologies in a decarbonising MMS

Strategy	Description
Job creation	The project is expected to create a significant number of jobs across the hydrogen value chain
Economic growth	The initiative has the potential to contribute significantly to South Africa's GDP.
Reduced carbon emissions	The use of green hydrogen can help reduce South Africa's carbon emissions and contribute to a cleaner environment.
Increased energy security	The Hydrogen Valley initiative can help reduce South Africa's reliance on imported fossil fuels and improve energy security.

This study has established empirical evidence that the MMS expects the government to play an important role in funding green hydrogen technologies development.

Major hydrogen projects in South Africa

South Africa has several significant green hydrogen projects underway; each aimed at leveraging renewable energy resources to produce hydrogen for both domestic and export markets. Here are some of the most notable initiatives:

Prieska Power Reserve (Northern Cape)

This project is expected to produce green hydrogen and ammonia starting in 2026, powered by solar and wind renewable energy sources. The project, valued at approximately R9.7 billion, aims to create over 10,000 jobs throughout its phases. It has been granted strategic status as a part of South Africa’s Green Hydrogen National Programme, allowing for expedited regulatory approvals.

Boegoebaai Green Hydrogen Hub (Northern Cape)

Sasol, in partnership with the Northern Cape government, is developing this hub, with a projected production capacity of 400,000 tons of hydrogen annually. Requiring around 9 GW of renewable energy, this hub will serve as a production and export facility for hydrogen and ammonia. It is expected to create thousands of direct jobs and help position South Africa as a significant global hydrogen player.

Coega Green Ammonia Project (Eastern Cape)

The Hive Hydrogen consortium, which includes international partners, is developing a large-scale ammonia production facility near Gqeberha. This project is supported by extensive solar and wind power initiatives and aims to produce around one million tons of green ammonia annually. Hive has been advancing the project alongside Japanese firm Itochu, with potential investment and offtake agreements in place. The project holds strategic status and is projected to stimulate local economic growth and employment.

Hydrogen Valley Initiative

Stretching across Limpopo, Gauteng, and KwaZulu-Natal, this initiative is designed to integrate hydrogen into various sectors, including mining, industrial applications, and mobility. Conducted in partnership with Anglo American, ENGIE, and Bambili Energy, the project could create between 14,000 and 30,000 jobs per year, with the potential to add R66 billion to R150 billion to the GDP by 2050.

These projects demonstrate South Africa's strategic focus on green hydrogen riven by both economic opportunities and its climate commitments, with the government actively prioritizing these projects through its Green Hydrogen National Programme and the Just Energy Transition Investment Plan. These projects, collectively valued at hundreds of billions of rand, aim to secure the country's position as a competitive player in the global green hydrogen economy.

Transnet National Ports Authority (TNPA) is taking significant steps in advancing South Africa's hydrogen industry through its ports (Figure 10). TNPA recently issued a Request for Information (RFI) to gauge market interest in developing facilities at its commercial seaports for hydrogen-related projects, including green hydrogen, green ammonia, green methanol, and grey hydrogen. This initiative spans seven ports: Cape Town, Durban, East London, Mossel Bay, Ngqura, Port Elizabeth, and Saldanha Bay.

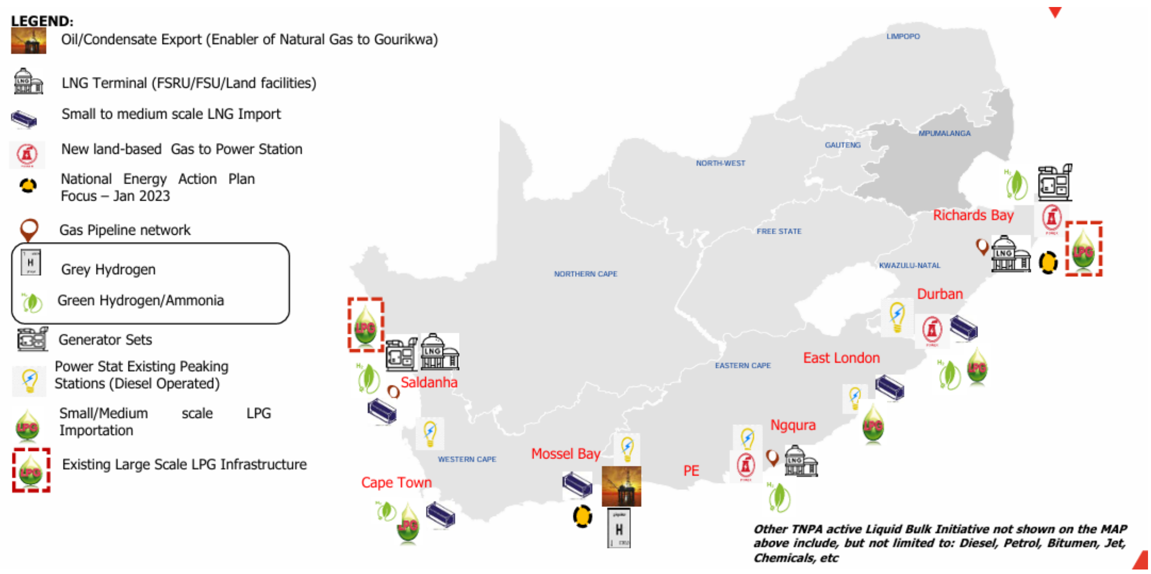

Figure 10: TNPA's green hydrogen ambition should benefit the MMS (Source: TNPA,2024)

The TNPA's initiative aligns with South Africa's Hydrogen Society Roadmap and the National Development Plan 2030, which aim to build a more sustainable and inclusive energy sector. TNPA's role would involve constructing, financing, and managing these facilities, creating infrastructure to support both the import and export of hydrogen fuels. This project also forms part of South Africa's broader goal to support decarbonization and renewable energy at its ports, potentially enabling cleaner marine shipping and fuelling options for the future.

There is a total of 17 hydrogen related projects registered with Infrastructure South Africa (ISA) (Table 13). By obtaining such registration, projects ensure that they do not delay the processing of permits.

Table 13: Hydrogen related projects registered with the Infrastructure South Africa (Source: TNPA, 2024)

Hydrogen related projects successfully registered with Infrastructure South Africa (ISA). These include component manufacturing, production and export activities.

Project	Province
Atlanthia Green Hydrogen	Western Cape
Mainstream Renewable Energy Hydrogen	Western Cape
AMSA Saldanha Steel Hydrogen project	Western Cape
Saldanha Bay Green Hydrogen Project	Western Cape
Enertrag Indigen Project (e-methanol)	Eastern cape
HIVE Ammonia	Eastern cape
The Ubuntu Green Energy Hydrogen Project	Northern Cape
Enertrag Postmasburg Project. (Ammonia)	Northern Cape
Boegoebaai Green Hydrogen Development Programme	Northern Cape
Upilanga Solar and Green Hydrogen Park	Northern Cape
Isondo Fuel Cell MEAs Manufacturing	Gauteng
Hydrogen Valley Programme of Anglo-American & their JV Partners (9 projects) along the Limpopo, GP to KZN Corridor	Gauteng
Bambili Hyplat Fuel Cell Manufacturing	Gauteng
Sasolburg Green Hydrogen Programme in the Free State	Free State
Project Phoenix Fuel Cell Manufacturing in Free State	Free State
SASOL HySHiFT (Secunda) in Mpumalanga	Mpumalanga
Hydrogen Valley Programme of Anglo-American and their JV Partners (9 projects) along the Limpopo, Gauteng to KwaZulu-Natal Corridor	KwaZulu Natal

The TNPA has recently called for bids for the development of green hydrogen projects, and the interest was fairly encouraging. Table 14 shows the breakdown of bids. A total of 10 bids were received for the 5 ports of Durban (2), East London (1), Cape Town (2), and Saldanha (5).

Table 14: Bids received by TNPA show high interest in green hydrogen in South Africa (Source: TNPA, 2024)

Port	No. of Bids	Hydrogen commodity type	Volume
Durban	2	Green Ammonia, Green Methanol and/or Grey Hydrogen and other	TBC
		Green Ammonia, Green Methanol and/or Grey Hydrogen and other	TBC
East London	1	Green Ammonia and Green Hydrogen	650- 6,500 tons/year
Cape Town	2	Green Ammonia	360 000 tons/year
		Green Ammonia, Green Methanol and/or Grey Hydrogen and other	TBC
Saldanha	5	Green Hydrogen and Green Ammonia	100 tons/day - 2500 tons/day
		Green Ammonia, Green Methanol and/or Grey Hydrogen and other	TBC
		Green Hydrogen	32,139 tons/year
		Green Ammonia	440,000 tons/year
		Green Methanol and Green Ammonia	500,000 tons/year

Major green hydrogen projects in the mining and minerals sector

South Africa's MMS is on the cusp of a green hydrogen revolution! The country has the potential to become a leading producer of green hydrogen, with the Hydrogen Economy projected to contribute 3.6% to South Africa's GDP and create 380,000 jobs by 2050. There are huge opportunities for the MMS to ride on the emerging green hydrogen technologies wave and the strong government commitment to support the development of a green hydrogen economy.

Case study of the Saldanha Ecosystem

The World Bank has leveraged support from the Public Private Infrastructure Advisory Facility (PPIAF) and PROBLUE, the World Bank's blue economy programme, to assist South Africa in exploring the requirements for establishing green marine bunker fuel value chains at the ports of Saldanha and Boegoebaai. The study revealed that supplying ammonia as ship fuel in Boegoebaai, Saldanha, and Cape Town will require up to 120,000 tons of green hydrogen by 2035. Additionally, both projects have the potential to develop into green hydrogen hubs, each offering a unique value proposition.

The port of Saldanha is an ideal location to aggregate demand from multiple hydrogen users, which can help to reduce investment risk. For example, the conversion of the mothballed Saldanha Steel plant to run on green hydrogen shows promise. This project has the potential to become one of the largest first-mover projects in Sub-Saharan Africa, creating over 8,000 direct and indirect jobs in the next few years. By 2027, the facility could start producing green direct reduced iron (DRI) for the European steelmaking market.

The Boegoebaai mega project in contrast will boost the country's position as a mega exporter for green molecules. The Northern Cape provincial government has set out an ambition to develop a 40 GW electrolysis capacity, producing around four million tons of green hydrogen annually. This will require around 80 GW of renewable energy. Boegoebaai, located 20 kilometres south of the Namibian border, offers ample available land for the gradual expansion of solar parks and wind farms. The site provides favourable conditions for developing a vertical hydrogen value chain, including domestic production of photovoltaic modules and electrolysers. Mining contributes 28 percent to the Northern Cape's GDP (WB, 2023). The new port at Boegoebaai will not only facilitate the export of green molecules but also enable the cost-effective export of minerals like manganese, a critical mineral for the energy transition. South Africa is the largest manganese producer, serving around 25 percent of global demand.

Challenges and Opportunities:

- Access to low-cost and abundant renewable energy is crucial for competitive green hydrogen production
- Reductions in electrolysis facilities costs are needed to make green hydrogen more viable
- The mining sector's role in green hydrogen production will drive demand for minerals like PGMs

4.2.4. South Africa's green hydrogen technologies value network - Hydrogen consumption in the MMS (Downstream)

Several sub-sectors have potential to deploy green hydrogen to lower carbon emissions. Although the cement subsector is one of the most hard-to-abate sectors earmarked for the green hydrogen technologies, in South Africa the sector has lagged behind other sectors. Elsewhere initiatives are underway to pilot innovations. Globally, cement companies are exploring the use of green hydrogen to reduce carbon emissions. Key examples include:

- Hanson UK's Ribblesdale Plant (UK): This site conducted a successful trial using a hydrogen-fuel blend with bio-derived components like meat and bone meal and glycerine, demonstrating a shift to net-zero fuel mixes. Supported by the UK's Department for Business, Energy & Industrial Strategy (BEIS), the trial showed that this approach could save up to 180,000 tonnes of CO_2 annually if fully implemented. This is part of broader UK industry efforts to meet net-zero targets.
- Cemex's Partnership with HiiROC (Mexico and Global): Cemex has been actively involved in green hydrogen initiatives, increasing its investment in HiiROC, a company that develops green hydrogen technology. This partnership aims to incorporate hydrogen as a fuel in cement production processes to further decarbonize their operations across locations.

- Limak Cement and Air Liquide (Turkey): Limak Cement partnered with Air Liquide to incorporate green hydrogen as a fuel in its production. The project, focusing on decarbonization at Limak's Ankara facility, is expected to help reduce emissions and is part of Turkey's broader sustainability goals.

These initiatives illustrate a growing trend in the cement industry to use hydrogen and other renewable fuels to reduce reliance on traditional carbon-heavy processes, aligning with global sustainability targets.

Green hydrogen is increasingly being tested as a fuel alternative for mining locomotives, offering a pathway to reduce reliance on diesel and decrease emissions in mining and heavy freight operations. Here are some key projects globally:

- Fortescue Metals Group in Australia: Fortescue has begun testing hydrogen and ammonia fuel systems in its mining locomotives, aiming to decarbonize its rail fleet. They are exploring various configurations and plan to roll out hydrogen-powered locomotives across their mining operations by 2030 as part of a broader carbon neutrality target. Fortescue is also examining other green technologies for mining equipment, including haul trucks and drill rigs, to reduce emissions from mining operations.
- Anglo American and Aurizon in Queensland: Anglo American and Aurizon, Australia's largest rail freight operator, are conducting a feasibility study for hydrogen-powered trains on heavy-haul routes. This initiative focuses on using hydrogen fuel cell and battery technology in Queensland's mining freight corridors, with the potential to deploy hydrogen-fuelled locomotives for transporting materials like coal, minerals, and agricultural goods.
- HyRail Namibia: In Africa, the HyRail Namibia project aims to launch the continent's first hydrogen-diesel hybrid locomotives. This initiative, funded partly by Germany, involves converting two traditional locomotives to run on a dual hydrogen-diesel fuel system. The project, led by the consortium Hyphen Technical and supported by Namibia's state-owned rail company TransNamib, seeks to establish green hydrogen as a viable rail fuel and eventually expand the conversion to the broader locomotive fleet in Namibia.

These projects reflect the mining sector's broader efforts to embrace green hydrogen as part of the transition toward cleaner, more sustainable operations in regions with high emissions from rail and freight activities. Such developments support the long-term goal of reducing carbon footprints in mining logistics worldwide.

South Africa's competitive advantage in fuel cell production and deployment in mining and minerals sector trucks

South Africa is well positioned to lead in the green hydrogen revolution as the leading producer of PGMs and other minerals important to producing fuel cells. The country has received support from government, the global community and private sector players for example the work of Anglo American in this space has been relentless.

Case study. PGM mining Sub-sector

The following extract from Anglo American gives a picture of who they are: "We are a leading global mining company, and our products are the essential ingredients in almost every aspect of modern life. Our portfolio of world class competitive operations, with a broad range of future development options, provides many of the future-enabling metals and minerals for a cleaner, greener, more sustainable world and that meets the fast growing everyday demands of billions of consumers."

Commitment to renewable energy for decarbonisation

Organisations that have taken a lead in the renewable energy trajectory have invariably had senior management committed to the decarbonisation and solving the country's teething challenges. This is expressed in the broader strategy of the organisation. This is demonstrated by Anglo American's strategic position regarding green hydrogen: "We believe that hydrogen - a clean, versatile energy carrier of almost infinite supply - has a significant and wide-ranging role to play in achieving a low-carbon future."

Proactive renewable energy initiatives

Anglo American sees hydrogen as having great potential to drive decarbonisation within their operations. Recently, they unveiled First Mode's nuGenTM hydrogen-powered ultra-class mine haul truck, capable of carrying a 290-tonne payload at their PGMs mine in Mogalakwena, South Africa.

The innovation was developed by their own Technical Development team, in partnership with First Mode, the truck is part of First Mode's nuGenTM's Zero Emissions Haulage Solution (ZEHS) that includes the capability to produce green hydrogen in the future.

The pilot for the nuGenTM Zero Emission Haulage Solution is a hydrogen-powered ultra-class mine haul truck. It is an ambitious project that marks the first time a truck of that size and load capacity (a 220t truck with a load capacity of 290t = a total laden weight of 510t) has been converted to run on hydrogen that will be produced on-site in hybrid combination with a battery.

The nuGenTM truck is retrofitted from a diesel-powered vehicle. The truck uses a hybrid hydrogen fuel cell providing roughly half of the power and a battery pack the other half, to allow energy recovery from braking.

Hydrogen enters the fuel cell from the tank and mixes with oxygen to create water in a chemical reaction catalysed by platinum. This generates electricity that is used to power the motors that drive the wheels. The only emission from the vehicle is water vapour.

The 2-megawatt hybrid battery/hydrogen fuel cell powerplant, which replaces the diesel engine installed, has been designed by Anglo American and their partner First Mode in Seattle, USA.

The power management and battery systems in the truck have been developed to improve overall efficiency by recovering energy when the haul trucks travel downhill, through regenerative braking.

Harvesting the regenerative energy created when driving downhill, this reduces the need for external energy. This energy, stored in the battery, together with the hydrogen extends the truck's range and reduces the out of cycle time for the trucks, since hydrogen refuelling is significantly faster than recharging batteries.

As part of the integrated nuGen™ solution, Anglo American have also built a zero emission vehicles hydrogen production, storage, and refuelling complex at Mogalakwena that incorporates the largest electrolyser in Africa and a solar PV field to support the operation of the haul truck.

ENGIE is the hydrogen producer and supplier in this proof-of-concept project.

Partnering for renewable energy scaling

In South Africa, Anglo American joined forces with the Department of Science and Innovation, Engie, and Bambili Energy, to carry out a feasibility study that looked at the possibility of setting up a "hydrogen valley" anchored in the platinum group metals-rich Bushveld geological area.

Generating interest and legitimacy through communicating benefits

Some of the benefits that are proffered in the Anglo American initiatives to advance legitimacy perceptions of stakeholders include sustainability through greening operations. Green hydrogen technologies are projected as crucial in the decarbonisation of the hard-to-abate MMS. The partnership carried out a feasibility study to generate scientific evidence for deployment of green hydrogen: "The study's findings revealed the multiple benefits that the (green hydrogen valley) project could help unlock, including adding more than $3.9bn to the country's GDP by 2050, and creating more than 14,000 jobs per year, across the entire hydrogen value chain." (Anglo American).

Anglo American demonstrates optimism in the success of green hydrogen technologies: "In the coming years, we are planning to convert or replace our current fleet of c.400 diesel-powered trucks, fuelling them with green hydrogen. This will help us to remove up to 80% of diesel emissions at our open pit mines and move us closer to our 2040 carbon neutrality goals."

What is clear from the Anglo American analysis of the state and nature of green hydrogen technologies, it requires the entire ecosystem to pull in one direction. The company opine that: "As the case for hydrogen as an alternative energy source gathers momentum around the world, costs will continue to fall, and infrastructure will improve. And because it requires no charging time, unlike electric battery systems, using hydrogen means mines can enjoy clean power with no loss of productivity – an attractive option that could see hydrogen's involvement in the mining industry grow significantly in the years ahead." (Anglo American)

In terms of implications for green energy technologies in the MMS, these sentiments reflect a huge need for collaboration, with each player focusing on their comparative advantages as the technology is complex and requires multiple competencies. However, what is clear are the subtle battles among actors with differing persuasions. For example, the solar actors speak highly of their technology, whereas the hydrogen actors highlight only their advantages and optimism: "PGMs are used as catalysts in Fuel Cell Electric Vehicles, which offer many benefits to the transport sector, including refuelling times comparable to internal combustion engine vehicles, long ranges, and space and weight efficiency."

To institutionalise green hydrogen, the hydrogen council was formed and several legislative frameworks introduced. Further, the introduction of commemorations, such as the National Hydrogen and Fuel Cell Day are important additions to the national calendar to institutionalise green hydrogen technologies. Now in its eighth year, the aim of the day is to raise awareness of the role hydrogen can play in helping the world to reduce its carbon emissions and transition to cleaner, greener transport and energy systems (Anglo American).

The MMS is expected to play an important role by using an integrated approach including investing in new technologies, supporting entrepreneurial projects, and advocating for policy frameworks that enable a supportive long-term investment environment for hydrogen to deliver on its potential. Specifically, the PGM Mining sub-sector and jewellery manufacturing have a huge incentive to support the green hydrogen technologies efforts.

4.3. Green hydrogen technologies opportunities and challenges in the mining and minerals sector

4.3.1. South Africa's opportunities in the world of green hydrogen technologies

South Africa, a country historically known for its rich mineral resources, particularly coal, has increasingly become a focal point in the global transition toward renewable energy. As the world confronts the urgent need to reduce greenhouse gas emissions and mitigate climate change, green hydrogen technologies present a promising solution. Green hydrogen, produced through the electrolysis of water using renewable energy, holds significant potential as a clean energy carrier for sectors that are hard to decarbonize, such as heavy industry, transportation, and power generation. This section presents the findings on South Africa's opportunities to play a leading role in the global green hydrogen landscape, considering its resources, policy initiatives, challenges, and opportunities for growth in this emerging sector.

South Africa's Global Role Potential

Globally, the demand for green hydrogen is expected to rise in the coming decades as countries seek to decarbonize their economies. South Africa's low-cost production potential, combined with its renewable energy resources and developing policy framework, positions the country as a potential global leader in green hydrogen. The country can play a crucial role in supplying hydrogen to international markets, particularly to hydrogen-demanding regions such as the European Union and Asia.

In the context of Africa, South Africa can also serve as a regional hub for green hydrogen production, helping to drive energy security and economic growth across the continent. The African Union's Agenda 2063 recognizes the potential of renewable energy in driving sustainable development, and South Africa's green hydrogen ambitions align well with these regional goals. The UNCTAD (2024)'s study demonstrated that South Africa had a huge potential to lead in green hydrogen due to the abundance of renewable energy potential and PGMs.

Policy Initiatives and Strategic Vision

Recognizing the potential of green hydrogen, South Africa has begun developing a robust policy framework aimed at fostering the growth of this developing sector. The government has embraced green hydrogen as part of its broader energy strategy, acknowledging its potential to diversify the energy mix, create jobs, and reduce carbon emissions. The National Development Plan (NDP) and the Integrated Resource Plan (IRP) both include measures to encourage renewable energy adoption and to position South Africa as a leader in green hydrogen production.

In 2020, South Africa unveiled its Hydrogen South Africa (HySA) strategy, a roadmap to establish the country as a global leader in hydrogen technology. The strategy envisions the development of hydrogen hubs and the integration of hydrogen into various sectors, including transportation, industry, and power generation. Furthermore, the country's National Treasury has been exploring funding mechanisms for green hydrogen projects, with a focus on facilitating both local and international investments.

In 2023, South Africa also signed a Memorandum of Understanding (MoU) with Germany, one of the world's most advanced green hydrogen economies, to cooperate on green hydrogen development. This partnership is expected to involve knowledge sharing, joint projects, and technology transfer, as well as helping South Africa gain access to European markets for its hydrogen exports. Figure 11 shows the major milestones that South Africa has gone through to advance the development of green hydrogen. In 2024, the MQA, CHIETA, and TETA entered a partnership to establish the Green Hydrogen Centre of Specialisation to advance research and skills development in the country.

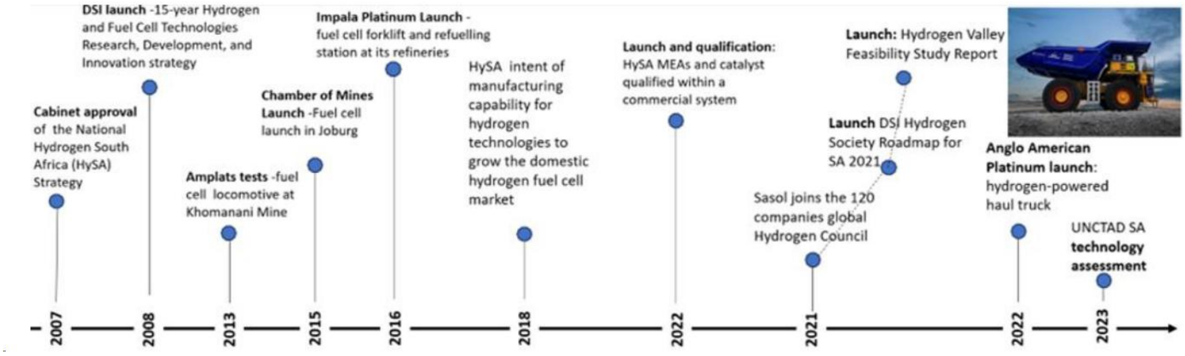

Figure 11: The green hydrogen legislative environment and major developments in South Africa (Source: UNCTAD, 2024)

Economic and Employment Opportunities

The development of a green hydrogen economy presents significant economic opportunities for South Africa. The country's existing infrastructure, such as ports and industrial hubs, can be leveraged to create a robust hydrogen export network. In particular, the Port of Durban and the Saldanha Bay Industrial Development Zone are seen as key locations for green hydrogen production and export. South Africa could position itself as a global hydrogen supplier, especially to European countries like Germany, which are investing heavily in hydrogen technologies to meet their ambitious decarbonization goals.

The study found that a significant percentage (80%) of respondents agreed (56%) or strongly agreed (31%) that green hydrogen technologies have the potential to create jobs (Figure 12). This shows the high expectations that are within the people for the contribution of green hydrogen technologies in job creation.

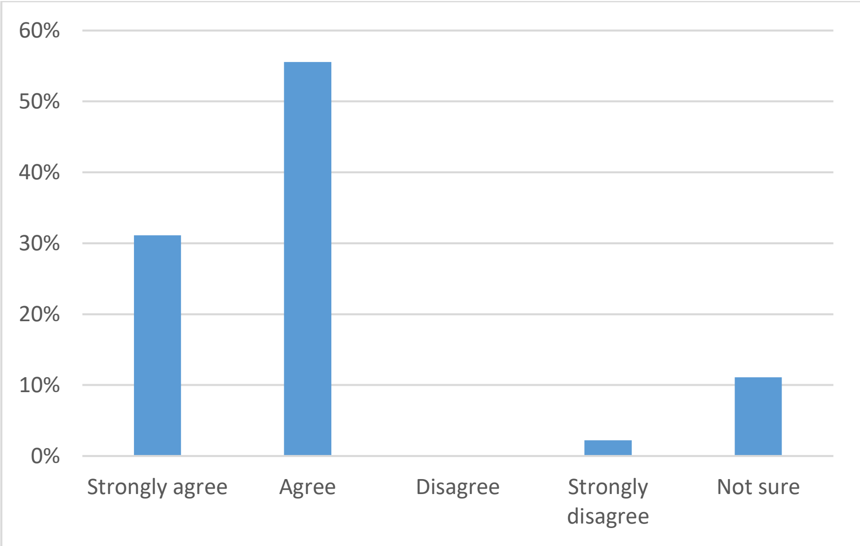

Figure 12: The perceived potential of green hydrogen technologies to create jobs in the MMS

This demonstrates that in addition to export potential, green hydrogen could stimulate job creation across various sectors. Jobs will be created not only in the production of hydrogen but also in the development of supporting industries, such as renewable energy, electrolysis equipment and fuel cell manufacturing, and hydrogen storage and transportation technologies. The establishment of hydrogen production facilities and the scaling of renewable energy projects could significantly boost employment, particularly in areas like the Northern Cape, where renewable energy projects are already underway.

4.3.2. South Africa's challenges in the implementation of green hydrogen technologies

Low level of awareness and understanding

Quantitative analysis of data found that the level of awareness and understanding of green hydrogen technologies in the MMS was very low. This is attributed to the developing state and nature of green hydrogen technologies. Figure 13 shows that only 38% of the surveyed participants had either a high (29%) or very high (9%) level of awareness when it comes to green hydrogen technologies.

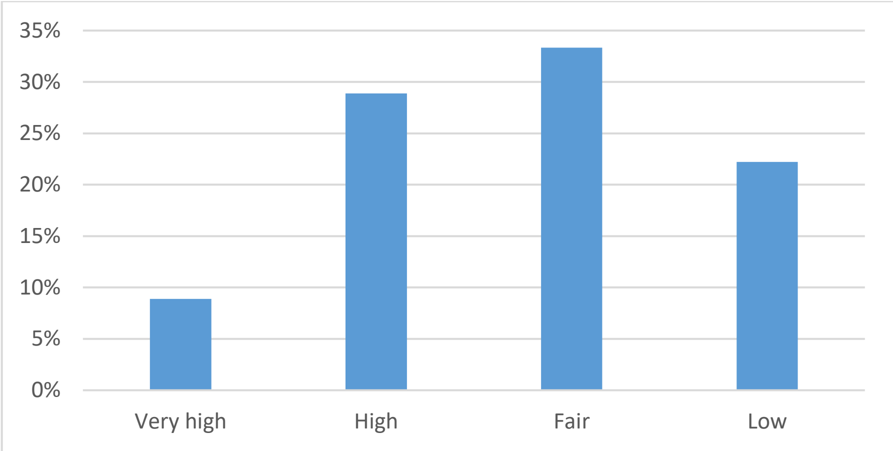

Figure 13: Green hydrogen technologies awareness in the MMS in South Africa

These findings are echoed by a recent study by the United Nations Conference on Trade and Development. The study by the United Nations Conference on Trade and Development found that of the 21 participants interviewed, seven could identify specific policies and related instruments that linked to or could affect green hydrogen production and commercialization. However, only those from government departments and Eskom were able to make some general statements about the effectiveness of the policies. All the interviewees concurred that there was a high level of policy illiteracy, or lack of awareness and familiarity with, different policies and instruments (UNCTD, 2024). The study reported a respondent who noted that there "are now many policies, strategies and regulations covering the hydrogen economy, but the detail of each policy remains hidden in the documents because the government is not raising public awareness."

The same could be said of the level of understanding of green hydrogen technologies. Only 38% agreed they had a high or very high understanding of green hydrogen technologies. This shows a low level of preparedness of the MMS to adopt green hydrogen technologies. Figure 14 shows the level of understanding of green hydrogen technologies in the MMS.

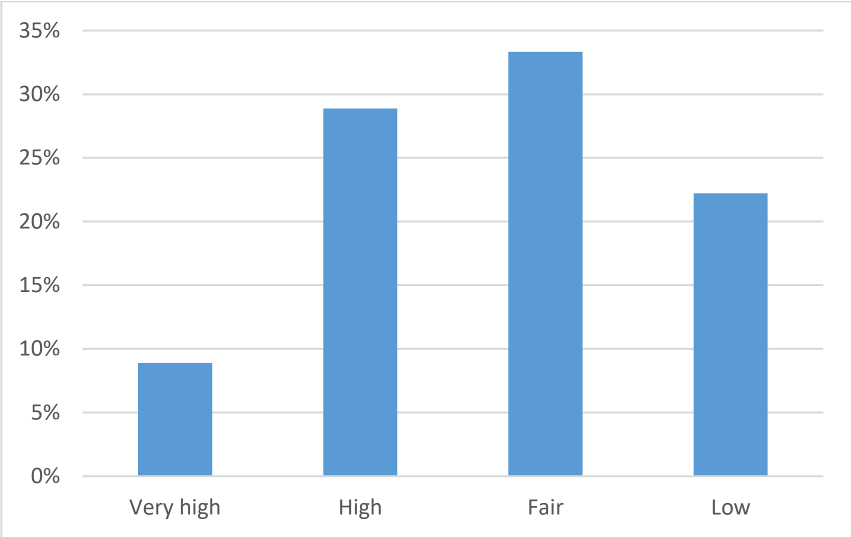

Figure 14: Level of understanding of green hydrogen technologies in the MMS in South Africa

In terms of the effectiveness of the legislative instruments, a significant percentage of interviewees (70%) opined that South Africa's National System of Innovation (NSI) was weakened due to poor coordination within and between government departments, and poor institutional linkages, both within the public sector and between public and private sectors. Interviewees from the public universities observed that HySA required better coordination between the DSTI and DMRE as well as strengthening of linkages among the HySA CoCs (UNCTAD, 2024). The study finds that there are considerable R&I capabilities in the country related to green hydrogen and electrolyser technologies. However, there are growing fears that the general economic decline in the MMS could erode R&D investment and reverse the little gains accumulated so far. These findings have implications for skills development. In addition to developing technical skills, there is a need to focus on soft skills development.

Regulatory uncertainty

These findings echoed what we find in the current study on the backdrop of most of the participants viewing legislation as an important blocker to green hydrogen technologies. Figure 15 shows that only 6% disagreed that regulatory uncertainty retards their efforts in adopting green hydrogen technologies. A total of 40% agreed that uncertainty regarding legislation retards development of green hydrogen technologies. Reiterating the low level of awareness, 53% were not sure of the implications of the legislative framework on green technologies development (Figure 15).

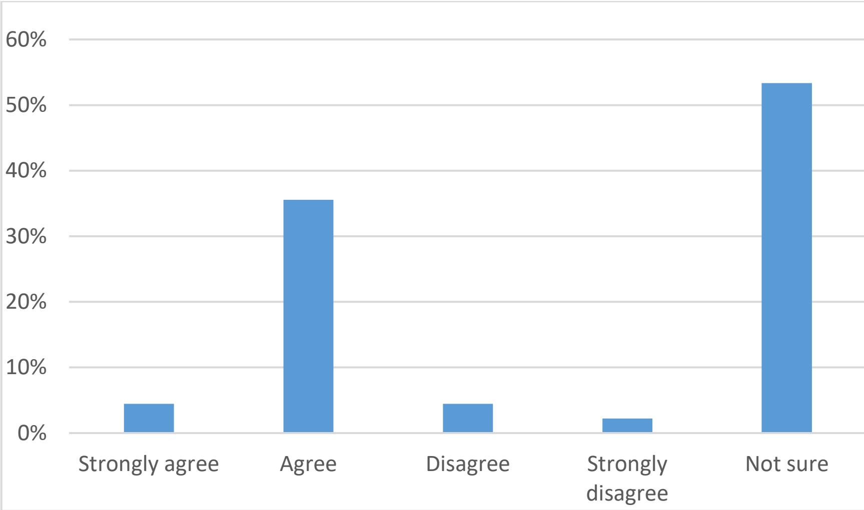

Figure 15: Regulatory uncertainty as a blocker of green hydrogen technologies uptake in the MMS

Skills gaps in upstream renewable energy technologies

This study combined surveys, key informant interviews and document analysis to identify some of the skills gaps in upstream renewable energy technologies, namely wind and solar sources.

South Africa's solar and wind energy sectors are facing significant skills gaps, hindering the country's transition to renewable energy. The main challenges lie in the lack of technical skills, particularly in the areas of engineering, construction, and maintenance. Table 15 shows the skills gaps in upstream renewable energy technologies

Table 15: Skills gaps in upstream green hydrogen value network

Skills Gaps	Description	Source
Engineering and technical	Insufficient expertise in designing, installing, and maintaining solar and wind energy systems.	(Meyer & Sunjka, 2019)
Project management skills	Limited experience in managing large-scale renewable energy projects.	(Meyer & Sunjka, 2019)
Operation and maintenance	Shortage of skilled personnel to ensure the efficient operation and maintenance of solar and wind energy infrastructure	(Meyer & Sunjka, 2019)

The skills shortage is attributed to various factors, including the historical legacy South Africa's education system not keeping pace with the growing demand for renewable energy skills (Meyer & Sunjka, 2019). Recently, it has been observed that there is a growing brain drain where skilled professionals are often attracted to opportunities abroad, exacerbating the skills shortage. Closing the gaps has been made difficult due to the limited training and development (Meyer & Sunjka, 2019). The different education and training institutions are insufficient and have limited training programmes to develop the necessary skills for the renewable energy sector. According to Meyer and Sunjka (2019) very few degrees or diplomas are currently offered at South African tertiary institutions; there is a greater emphasis on short courses, which does not aid the transfer of skills. The REIPPPP was launched in South Africa in 2011, as a programme for privatisation in the South African electricity supply sector. But there has long been a mistrust of renewable electricity in many sectors of government that has hampered this programme.

To address these challenges, it is essential to develop and implement effective training programmes, promote collaboration between industry stakeholders, and encourage investment in renewable energy education and training initiatives (Meyer & Sunjka, 2019). According to Meyer and Sunjka (2019) the challenge is worsened due to lack of training and skills transfer which does not take place regularly, particularly at the management level. This argument was raised in interviews as well as in literature, making it a strong challenge. This has the potential to worsen at the latter levels of South Africa's Renewable Energy

Independent Power Producers Procurement Programme (REIPPPP) process, where local sub-contractors need to act as sole contractors and not under the auspices of the large multi-nationals (Meyer & Sunjka, 2019).

Water stewardship and green hydrogen potential for South Africa

South Africa's ambitious plans for green hydrogen production face significant challenges, particularly due to high water requirements for hydrogen production. Green hydrogen is produced by electrolyzing water, splitting it into hydrogen (H2) and oxygen (02), which requires a steady supply of purified water and substantial energy, ideally from renewable sources. This study finds that for a water-scarce country like South Africa, this presents several specific challenges:

- Water Scarcity: Several regions of South Africa face chronic water shortages, and recent droughts have intensified concerns. Hydrogen production could place additional stress on already limited water resources, especially in regions with limited rainfall and high water demands from agriculture, industry, and urban areas. This is especially considering that producing 1kg of hydrogen requires at least 9 litres of purified water.
- Infrastructure and Cost: Green hydrogen requires significant investments in water treatment infrastructure to ensure the water used is sufficiently purified for electrolysis. This purification process adds to the cost and complexity of hydrogen production, potentially limiting its economic feasibility in areas with scarce or poor-quality water sources.
- Competition for Water Resources: With many communities in South Africa already facing water shortages, prioritizing water for hydrogen production could raise social and political concerns, especially if this competition leads to higher water prices or reduced water availability for households and agriculture.
- Location Constraints: The best sites for solar and wind energy in South Africa, which are needed for green hydrogen production, are often in arid regions like the Northern Cape. These areas have excellent renewable energy potential but lack adequate water resources, requiring either water to be transported or the use of desalination which are both expensive options.

To address these challenges, South Africa may consider alternative water sources, such as seawater desalination, or develop efficient water recycling systems. Desalination could be a viable option along coastal regions, but it would raise costs and energy demands. It costs about $0.50 to $1.50 per 1000 litres of water, which adds to the cost of green hydrogen production. However, other studies, for example the UNCTD (2024) support our findings on the important role of paying attention to the country's water scarcity. According to UNCTD (2024) it is concerning that there is no proper alignment between the JET-IP initiatives, spearheaded by the Presidential Climate Commission, and HySA led by the DSTI. One interviewee in the study remarked: "There seems to be no clear match between DSTI programmes for green hydrogen and the JET-IP… in terms of a policy position on the sustainability of hydrogen energy in South African context of water scarcity."

The MMS is already creating innovative mechanisms to embrace water stewardship, with the ICMM having introduced water stewardship principles in an effort for the industry to be a responsible citizen in host communities. The introduction of green hydrogen will increase demand for water if the hydrogen is produced locally, otherwise this entails producing hydrogen in regions with adequate water sources and transporting the hydrogen to the mine sites. Mining is concentrated in the Northwest, Mpumalanga and Limpopo Provinces and Northern Cape which are also experiencing water scarcity. It will be important for the MMS to embrace water stewardship principles.

Low electrolysers deployment in South Africa

South Africa's green hydrogen sector is still in the early stages of electrolyser installation, focusing on pilot projects and feasibility studies rather than large-scale capacity. Notable projects include a planned 60 MW hydrogen production site by Sasol in Gauteng, as well as green ammonia and hydrogen projects across the Northern Cape and Western Cape, where the government has designated these as priority projects. While targets for electrolyser capacity are ambitious, with proposals suggesting up to 40 GW by 2050, current installed capacity is limited as the country continues to work on building the necessary infrastructure and funding pathways to support future expansion.

The government and industry partners are developing green hydrogen hubs, such as those in Boegoebaai and Prieska, to build capacity and attract international investment for scaling up in the next decade. This staged approach aims to capitalize on South Africa's solar and wind resources for green hydrogen production, which has strong potential in the Northern Cape due to high renewable energy availability.

A recent study by the United Nations Conference on Trade and Development (UNCTAD) (2024) examined the state and nature of electrolysers for green hydrogen production and concluded that there are only pilot projects in South Africa. This is due to the realisation that there are no operational projects yet that are either manufacturing or deploying commercial use of electrolysers for green hydrogen production. The study findings provide important insights on the state and nature of green hydrogen technologies in South Africa. Findings show that the abundance of resources, including PGMs is a source of competitive advantage for the South Africa (Figure 16).

A question was asked in the study to gather participants' views or perceptions about South Africa's main competitive advantages in the international electrolyser market. It was generally reflected that the country has natural, scientific and technological opportunities to enter that market as shown in (Figure 16). According to the survey, 92 per cent of respondents opined that South Africa's PGM deposits provided it with an important or very important comparative advantage, while 76 per cent and 62 per cent of the respondents stated that technological knowledge and highly qualified personnel, respectively, are important or very important comparative advantages for the country.

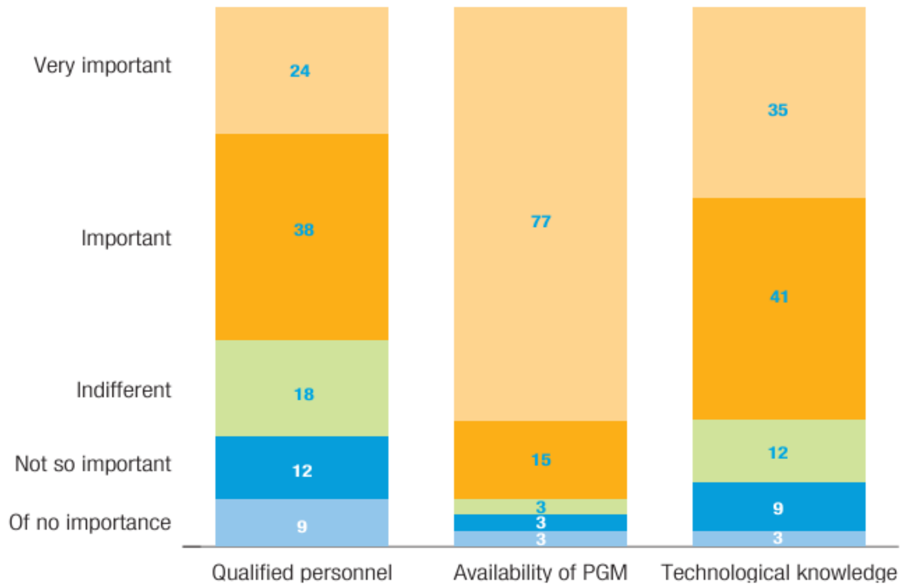

Figure 16: South Africa's comparative advantages in electrolysers (percentage of respondents) (Source: UNCTAD and DSTI Survey Results, 2024).

Figure 17 shows that energy security and lack of specific qualifications are major challenges in the development of electrolysers in South Africa despite the advantages associated with PGMs availability. This finding underscores the idea that PGMs alone are not enough to generate the advantages for South Africa. There are some disadvantages that must be dealt with.

When asked what they thought about South Africa's main disadvantages in international electrolyser markets, 71% of the respondents considered energy costs and security as an important or very important disadvantage. Similarly, more than half of the respondents, or 53%, indicated a lack of specific qualifications as an important or very important disadvantage (Figure 17).

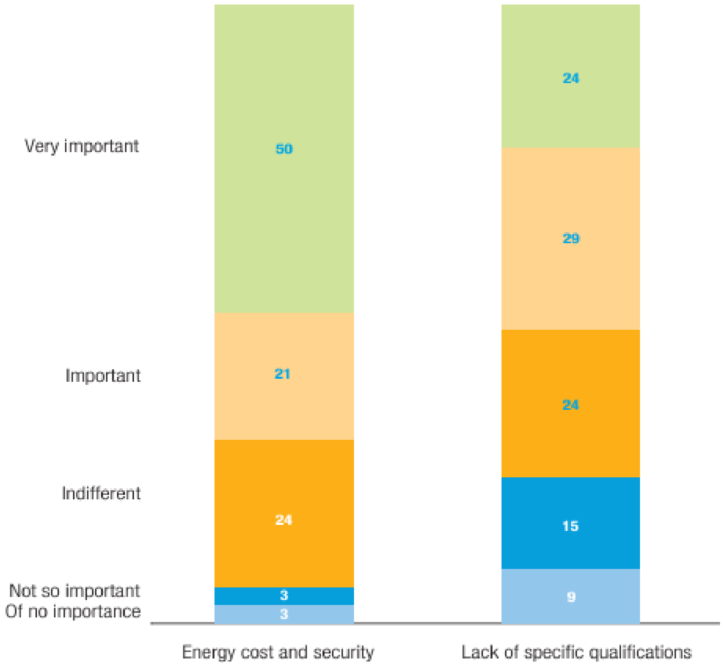

Figure 17: South Africa's main disadvantages in the international electrolyser markets (Percentage of respondents) (Source: UNCTAD and DSTI Survey results, 2024)

Regarding strategies to strengthen the country's Research and Innovation (R&&I) capabilities in electrolyser technologies. The study asked the question: "What should be done to strengthen knowledge creation and applications related to electrolyser technologies in South Africa?" A significant percentage (38%) of the respondents thought that increasing research capacities at universities and science councils was very important, while some considered improving relations between public research and the business community as very important (56%), and half of the respondents believed that attracting foreign direct investment in electrolyser and associated technologies was very important (50 per cent). A significant proportion of respondents (71 per cent) suggested that strengthening local and regional synergies in the hydrogen valleys and hubs was very important, while 53 per cent believed that promoting South Africa's international cooperation in R&I on electrolyser technologies was very important (Figure 18).

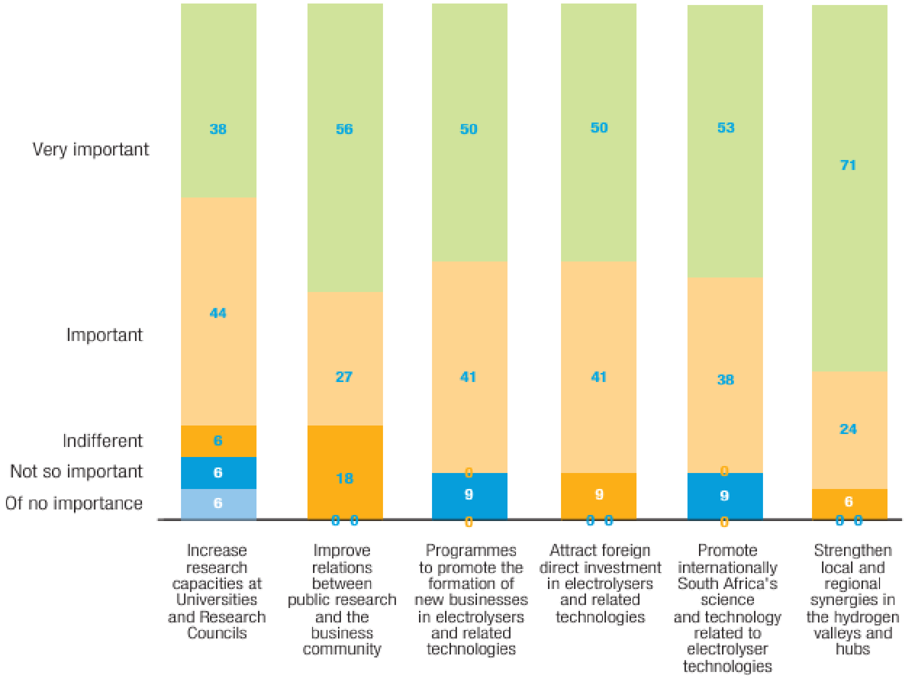

Figure 18: Strengthening knowledge creation and application in South Africa (Source: UNCTAD, 2024)

The UNCTAD (2024) study, in addition to surveys, utilised interviews with various stakeholders to understand their perceptions on the state of green hydrogen in general and electrolysers in particular. The interviewees were from government departments (the DSTI and DMRE), public universities (University of Cape Town and University of Pretoria), funding agencies (Technology Innovation Agency and South African National Energy Development Institute), one State-owned enterprise producing and distributing electricity (Eskom), the Presidential Climate Commission and an independent consultant/doctoral student of energy technologies (UNCTD, 2024).

Green hydrogen production requires extensive infrastructure, including electrolysers, renewable energy plants, and specialized storage and transportation systems. In South Africa, where much of the energy infrastructure is currently centred around coal, shifting to green hydrogen will require significant capital investment. The upfront costs for renewable energy installations and hydrogen production technology remain high, making the financial feasibility of such projects a critical challenge for both government and private sectors. One interviewer mentioned the potential cost escalation due to inefficiencies: "Producing green hydrogen could be expensive. Imagine, the costs of electrolysis and renewable electricity. This makes it less competitive when compared with fossil fuels."

High upfront costs

South Africa's energy grid is currently under strain, primarily due to heavy reliance on coal-powered plants and frequent power outages. Building a hydrogen network will place additional demand on an already fragile system, which could hinder consistent and efficient hydrogen production. Establishing a green hydrogen economy thus requires substantial upgrades in energy infrastructure, such as expanding grid capacity and creating dedicated renewable energy sources for hydrogen production. This has issues with efficiencies - "The process of converting electricity to hydrogen and then back to electricity or other energy forms can be inefficient and sometimes results in considerable energy losses." Figure 19 shows that high upfront costs retard green energy uptake in the MMS.

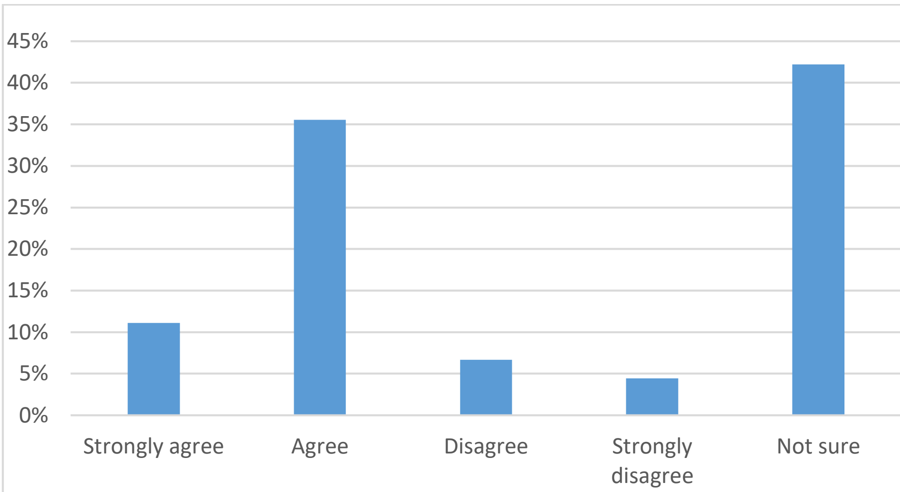

Figure 19: High upfront costs are retarding green hydrogen in the MMS

Of the survey participants only 11% either disagreed (8%) or strongly disagreed (4%) that their organisations were deterred from embracing green hydrogen due to high upfront costs (Figure 20). As many as 42% were not even sure, indicating a sector with a low level of green hydrogen awareness.

The other challenge that has been observed is safety. Green hydrogen is highly flammable and has a low energy density by volume, necessitating complex and costly storage and transportation solutions. South Africa lacks a comprehensive infrastructure for hydrogen storage, pipelines, and fuelling stations, which would be essential for a stable hydrogen supply chain. Developing these facilities is crucial but expensive, as it requires specialized technology to handle hydrogen safely over long distances.

Similarly, South Africa's regulatory landscape for hydrogen production and usage is still under development, which can slow progress on major projects. Clear policies on hydrogen production, transport, and export are necessary to attract investment and foster confidence among stakeholders. Additionally, environmental regulations related to hydrogen production and renewable energy projects must be streamlined to support the sector's growth. Currently there is a high level of uncertainty. When asked about the role of regulatory uncertainty, only 6% of respondents either disagreed (4%) or strongly disagreed (2%). As many as 53% of respondents were not even sure about the role of regulation and policy in their business.

Although currently there are no visible skills shortages related to green hydrogen, there are risks of shortages of critical skills in the future. Meanwhile, building a green hydrogen MMS requires specialized knowledge in hydrogen production, electrolysis technology, and renewable energy integration. South Africa currently faces a shortage of skilled professionals in areas related to green hydrogen technologies, which could slow down the adoption and scaling of hydrogen infrastructure. Training programmes and partnerships with international hydrogen experts will be essential to build a competent workforce. When asked about the future risk exposure to skills shortages, as many as 58% of respondents either agreed (47%) or strongly agreed (11%), while as many as 38% of respondents were not sure (Figure 20).

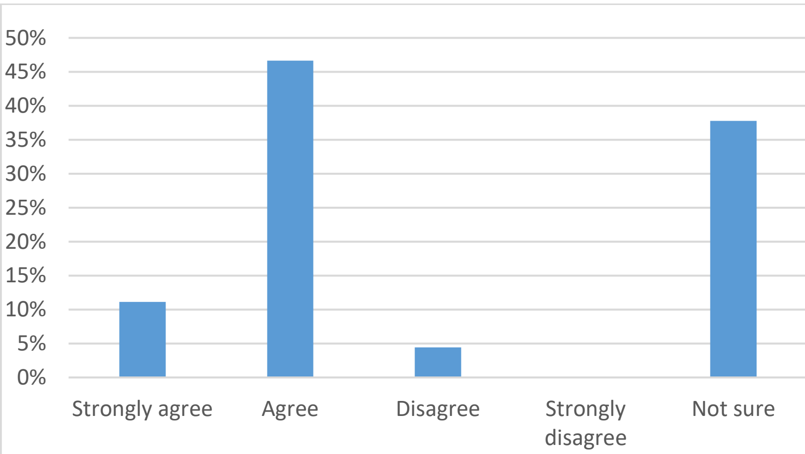

Figure 20: Potential skills gaps in future

Other risks impending green hydrogen technologies implementation

A working paper published by the OECD (2023) utilises financial market data to address the knowledge gap concerning the range of Weighted Average Cost of Capital (WACC) for green hydrogen projects. It also conducts a survey among investors and financiers to identify key risk factors contributing to the high WACC. The key risks that have been identified (Figure 21) include offtaker risks, lack of credible offtakers, price uncertainty of green hydrogen, and the absence of hydrogen trading markets. These risks are closely connected to the available risk mitigation strategies and tools proposed in the paper (Lee, & Saygin, 2023). It is important to understand the risks associated with green hydrogen technologies development because although 1046 projects were announced by January 2023, valued at USD $320 billion, showing a growth of 35% from May 2022, only 10% of these projects have passed the "commercialisation valley of death". Of these, 90% have not reached Final Investment Decision (FID). Globally, only about 20 clean hydrogen projects in emerging and developing economies outside China have reached the final investment decision (FID) stage (ESMAP, OECD, Global Infrastructure Facility, and Hydrogen Council, 2023).

Early-stage technologies such as green hydrogen are often confronted with a significant hurdle known as the "Commercialisation Valley of Death." This phase occurs between the pilot/demonstration and commercialisation stages of technological development and represents a gap in funding between venture capital investments and later-stage project finance and debt/equity investors (Jenkins and Mansur, 2011).

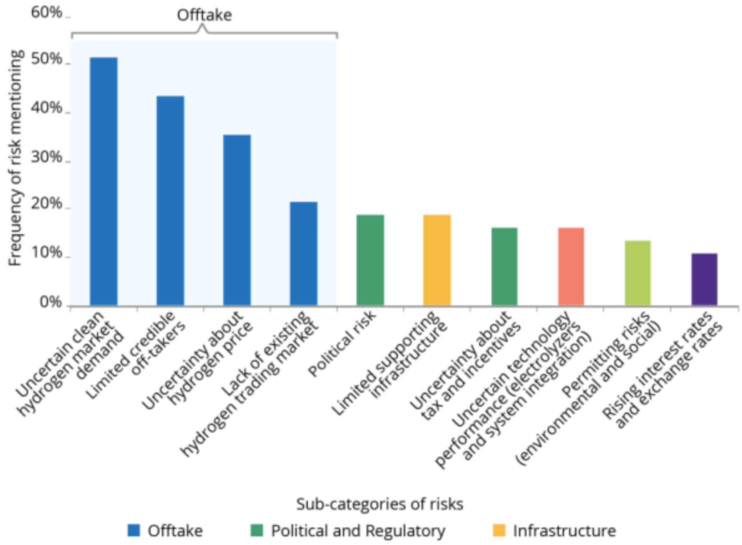

Figure 21: Key perceived risk factors associated with green hydrogen projects based on surveys and case studies (Source: Lee & Saygin, 2023)

Mitigating risks requires policies to be tailored to market maturity and respective needs. This has implications for South Africa's MMS in the early market stage. There is need for policy support focusing on demand creation, regulatory clarity and revenue stream support. Several interview participants mentioned that: "South Africa still needs improvement as it faces regulatory and policy challenges because there are many players in the green hydrogen system who need to be coordinated".

For mature projects at the stage of final investment decision, policies can ensure certainty in off-take volumes and pricing through mechanisms such as feed-in tariffs, carbon pricing and auctions. While tailored policy support to mitigate high risk factors are essential for market creation and growth, they also carry the risk of market distortion and discouraging private sector involvement. Long-term solutions that build on better enabling conditions are needed to create an environment that can mobilise private capital and reduce dependency on the limited availability of public finance (Lee, & Saygin, 2023, Chipangamate & Nwaila, 2023). Figure 22 shows how different risk mitigation strategies could also contribute to the decline of the leveraged cost of hydrogen from US$5/kg to $3/kg.

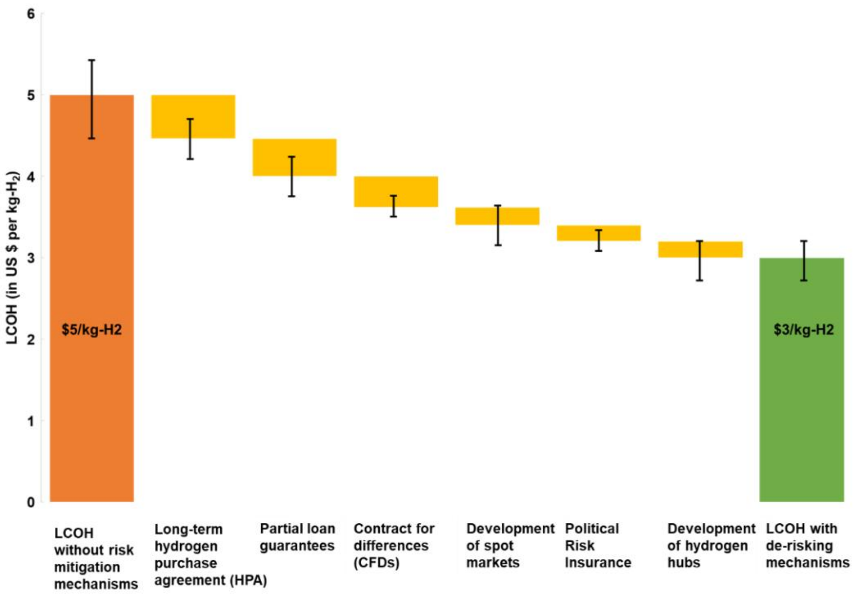

Figure 22: Green hydrogen derisking mechanisms (Source: Lee & Saygin, 2023)

South Africa has progressed in the development of a green hydrogen commercialisation strategy, a governance mechanism in the form of a roadmap and the existence of a regulatory framework (that is aligned with national targets), and the improved quality of the licensing and permitting process. South Africa has identified some critical projects to facilitate smooth permitting on the Hydrogen Valley. However, there is still need for more work to develop technology and industrial development to enhance technical know-how, experience, and capacity-building. This is where the MQA could play an important role in skills development and awareness building for the sector. A key informant mentioned that: "…. the green hydrogen education is lacking, very few people know about the benefits of implementing green hydrogen."

Enabling market measures, highlighting the potential to achieve a sustainable green hydrogen market that would not rely on support and subsidies in the long-term, for instance through the presence of demand for green products. Further, there is a need for De-risking investment mechanisms and financing solutions, exploring factors that could affect financial risk perception among investors and describing the ability of the financial ecosystem to invest in local green hydrogen projects. There is a need to reduce the cost of green hydrogen if it will be an important resource for the MMS which is bent on achieving both the decarbonisation targets and shared value for all stakeholders, which rest on a business case. Figure 23 shows the different prices for varying hydrogen types.

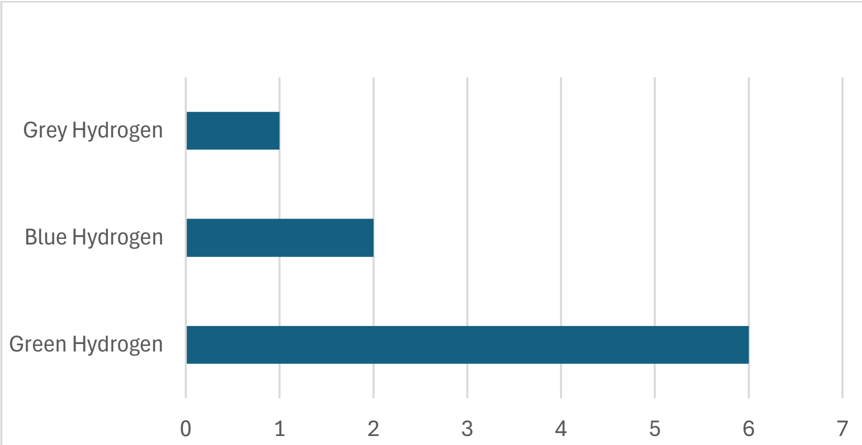

Figure 23: Price of different hydrogen types, in USD (Source: Lee & Saygin, 2023)

It is important to remember that the costs associated with green hydrogen production are influenced by two key factors: a) the levelised cost of renewable electricity and, b) the capital cost of electrolysers. These factors, in turn, are influenced by a combination of the availability of renewable energy resources, capacity factors of renewable power plants and electrolysers, and the cost of capital. South Africa has the potential to excel in all factors, but this largely depends, in part, on the global trajectory regarding electrolysers. Figure 24 shows how the cost of green hydrogen is anticipated to decline from $5/kg_H2 in 2020 to about $/kg_H2 in 2050. Figure 24 shows that a significant reduction in costs will come from the anticipated decline in electrolyser costs, followed by declining energy costs, improved electrolyser efficiency, full load hours increase, and weighted average cost of capital (WACC) improvements. These projections have significant implications for South Africa due to the current energy shortages. A business case for green hydrogen requires that those drivers are developed in the country.

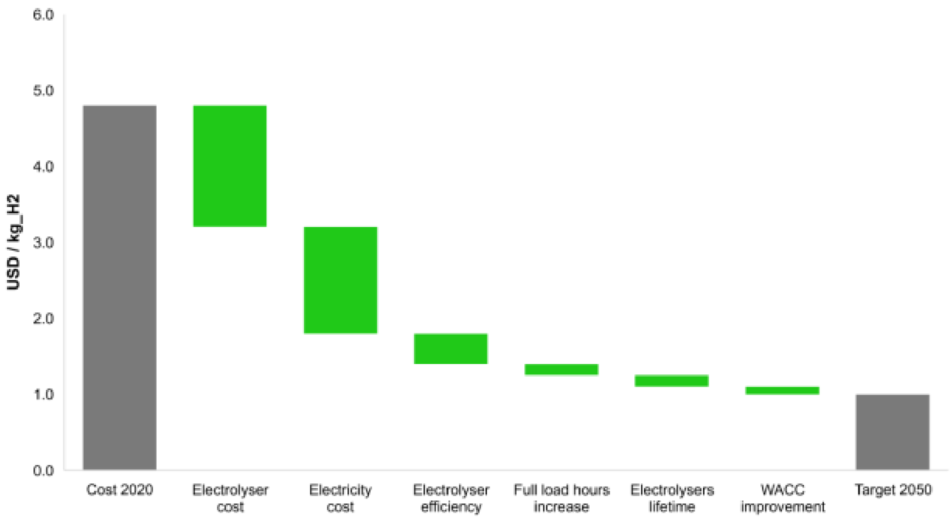

Figure 24:Drivers of green hydrogen cost decline over time (Source: Cordonnier & Saygin, 2022)

4.4. Path forward for South Africa's green hydrogen technologies and skills development

For South Africa to realize these opportunities, a coordinated approach involving public and private sector collaboration is essential. The findings suggest that South Africa's MMS has huge potential based on the abundance of renewable resources and government commitment. However, to achieve green hydrogen technologies network stabilisation where supply and demand for green hydrogen are balanced, there are key steps to be taken.

4.4.1. Advocating for awareness and sustainable Industrial Policy for green hydrogen technologies

Additionally, while the South African government has shown political will, the pace of regulatory and policy development can sometimes be slow. Ensuring the timely implementation of the HySA strategy and attracting both domestic and international investment will require efficient and clear policy frameworks, financial incentives, and guarantees. Survey participants seemed to concur that policy is important in advancing green hydrogen technologies. Figure 25 shows that a significant percentage of participants regarded the policy as important for advancing green hydrogen uptake in the MMS.

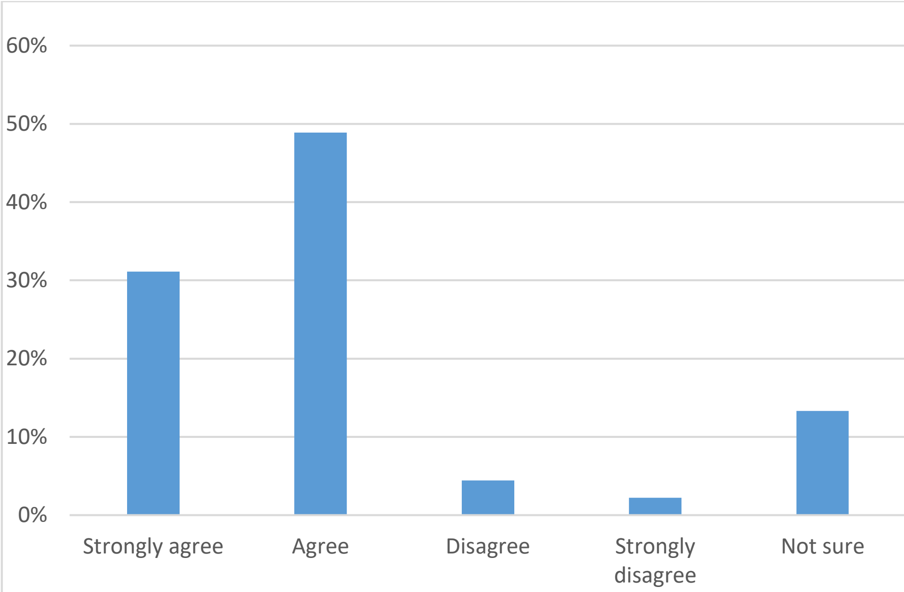

Figure 25: The role of policy in advancing the MMS green hydrogen technologies uptake

As figure 25 shows, as many as 80% either agreed (49%) or strongly agreed (31%) that a conducive policy framework will drive green hydrogen development. One interview participant even advocated for more coercive regulatory environment: “Maybe we should try a command-and-control regulatory instrument requiring all organisations to use some sort of green hydrogen technology.”

South Africa will need to some important steps to establish a comprehensive regulatory framework, consolidating the many policies and instruments, including reviewing the HySA strategy, the JET and other hydrogen-related policies and strategies (UNCTAD, 2024). Advocacy is even more important because of the low level of awareness in the MMS in South Africa. Key informant participants echoed that: “…. for me I think the issue in our sector is awareness. There is limited public awareness and understanding of green hydrogen technologies which can lead to scepticism and resistance to the adoption of green hydrogen”

At an Energy and Mining Skills Forum held in Mpumalanga, several participants expressed scepticism advocating instead for focusing on the development of abundant coal deposits. One delegate argued that: “There is a need for funding coal production because we have plenty of it in South Africa. Do you know that people want to kill mining in South Africa? They are agreeing to kill mining.”

These sentiments demonstrate what Chipangamate and Nwaila (2023) describe as ‘lock in effect’ where stakeholders are unwilling to change to alternative energy resources and have genuine fears. The MMS needs to ensure the skills development is in line with the pace of awareness. Programmes and training initiatives may risk limited uptake. A participant in interviews opined that: “Communities must also be well informed and taught about green hydrogen because they are quite not aware about green hydrogen”.

4.4.2. Developing green hydrogen technologies infrastructure

Despite the tremendous potential, the MMS in South Africa faces several challenges in establishing itself as a green hydrogen leader. First and foremost is the need for substantial investments in infrastructure. While the country has a wealth of renewable energy resources, there is a need for enhanced grid infrastructure to ensure that electricity from solar and wind farms can be reliably transmitted to electrolysis plants. The lack of large-scale, cost-effective hydrogen storage and transportation infrastructure also remains a key challenge.

Further, the study finds that design, construction, and completion risk is much higher in green hydrogen projects than in other energy resources. Moreover, accurately estimating project design costs is difficult when there is insufficient data for investment appraisal (ESMAP, OECD, Global Infrastructure Facility, and Hydrogen Council, 2023). Construction and completion risk pertains to the possibility of a project not meeting its budget and schedule expectations which is costly.

Consequently, lenders may demand significant maintenance reserves and manufacturer warranties may require the backing of insurance or other financial instruments to offer credit support. This is also due to the complexity of green hydrogen projects and the associated high level of construction and completion risks.

For the MMS to accelerate green hydrogen technologies, there is a need for increased investments in renewable energy and developing specialised infrastructure for hydrogen storage and transportation. This will call for unique skillsets.

4.4.3. Investing in Research, Innovation and Technology

Technology risk has been identified as a major challenge in green hydrogen technologies development. For example, electrolysers are a critical technology to produce green hydrogen from renewables. However, due to its limited deployment, the technology's performance, durability, and asset lifetime, it still needs to be tested. The absence of information on performance increases the cost of finance. In addition, the asset lifetime of electrolysers will raise risks related to the interplay of electrolyser degradation and the replacement cycle - "There is a need for investment in research and development where the South African government can provide funding for R&D initiatives to improve efficiency and reduce the cost of green hydrogen technologies because at the moment it is too expensive."

This is why there is a need for skills development related to economists and financial analysts who appreciate the unique green energy risks. Interviewees opined increasing investments in the HySA CoCs and ensuring their sustainability is crucial. Further, there are fears around cybersecurity threats as the green hydrogen technologies integrates into the grid for wheeling arrangements - "As green hydrogen technologies become more integrated with the grid and other systems, they may be vulnerable to cybersecurity threats. Remember to integrate the systems you need digital systems in place. Do we have those skills?".

4.4.4. Collaborating to build a stable green hydrogen technologies network

What is evident from research is that green hydrogen projects are intricate, involving various stakeholders in a complex supply network. Specifically, vertically integrated green hydrogen projects, which incorporate renewable power for electrolysers and support infrastructure for mid- and downstream processes, pose challenges due to the limited transaction experience of sponsors and financiers in this field. At a policy level, interviewees underscored the important need for the various government departments, MMS actors, and communities. An interviewee mentioned that: "As you may know, green hydrogen projects are complex, and in South Africa, for example, water scarcity, and energy poverty are real challenges. This means that the Department of Water and Sanitation, DMRE (the Department of Mineral Resources and Energy) and communities should put their heads together".

The need for increased collaboration has implications for skills development by MQA and other SETAs. For green hydrogen technologies development requires SETAs and academic institutions to collaborate for research and innovation for the MMS to take a lead in the technologies. One interviewee had this to say: "…for me the low hanging fruit is collaboration among academics, SETAs, research institutions like CSIR, Mandela Mining Precinct, mining houses, and TVETs to develop the needed skills".

A recent study by the UNCTAD (2024) highlights the need for raising public awareness of the benefits and costs of green hydrogen and electrolysers. The study found that the need to manage the social and economic transition away from coal is important in South Africa. South Africa is heavily reliant on coal for electricity generation, and the shift to renewable energy and green hydrogen will disrupt traditional industries. Workers and communities dependent on the coal sector will require reskilling and support to transition into the new green economy. This concern is very valid because in an Energy and Mining Forum attended by the research team in Mpumalanga as part of this study, participants in Mpumalanga were very protective about the need to preserve the coal industry. One participant said: "We do not want to see a repeat of the Komati power station. People are suffering because there are no livelihoods. People who lost their jobs in mining have been approached sometimes to do farming, but what if my skills are in mining?"

This finding corroborates the UNCTAD (2024) study which found the was need for strengthening coordination among various actors in the hydrogen energy ecosystem and the National Systems of Innovation (NSI) in general. An interviewee in this study had this to say: "… this is why I think public-private partnerships will be necessary to derisk investments in capacity development. This is where collaboration between the government, local municipalities and private sector companies can help to accelerate the development and deployment of green hydrogen technologies."

4.4.5. Investing in education, training and skills development

Several interviewees in the MMS believed that the industry is currently facing skills shortages in fields related to green energy technologies and there is a huge risk that if the technologies were to be commercialised, gaps would be inevitable. One interviewee believed that the sector's challenges in getting and retaining talent for engineers and technicians was uninspiring - "…right now we are sitting on over 56 unfilled vacancies for technicians in all our operations. Although we do not currently have green energy in our energy mix, we can imagine that it will add a layer of complexity if green hydrogen were to be introduced".

However, there was no consensus on the skills development pathways for the green hydrogen technologies, with interviewees differing on perspectives. One interviewee was very critical of the technology thinking that: "Before we can talk or think about skills development let ponder about where is the green hydrogen technology to talk about? The production of green hydrogen is very expensive, and batteries have already occupied that space in transport…it will be risky to train people for jobs that are not yet here. Maybe the way forward is multiskilling rather than specialised green hydrogen skills".

The other major challenge that has been identified is the lack of capacity for the trainers themselves at different levels from junior to senior school and tertiary institutions of learning. One interviewee argued that: "…I think there are two important interventions that the MQA could do in the mining industry. One is for starting to focus on the junior levels because by the time someone is metric, they have already decided about the pathway they will follow. Encourage STEM subjects from junior levels. They now call them STREAM because arts are also important in there and so is reading. R is for reading and A is for Arts. The second is perhaps to focus on training the trainer initiatives because even the teachers and trainers in tertiary institutions may also need new skills".

This finding has important implications for building technical expertise and other soft skills through training. The UNCTAD (2024) also found international partnerships to be important in addition to training. They also recommended developing and promoting explicit policy actions for the creation of skills and jobs for the youth through investments in green hydrogen and electrolyser technologies.

The complexity of green hydrogen technologies puts the need to develop soft skills at the centre of skills development. For example, the supply risks associated with the need to integrate upstream partnerships for water supply, renewable energy and technical partners such as OEM for electrolysers and fuel cells may require competencies and skills that are ordinarily beyond the purview of MMS. This may involve the wheeling agreements with utility companies which calls for strong negotiation and critical thinking skills. Such skills have been described as important in the current and previous studies yet missing in the MMS senior management.

In conclusion, South Africa faces considerable challenges in building a stable green hydrogen network but also stands to gain significantly from the transition. By leveraging its natural resources, establishing international partnerships, and investing in infrastructure, and talent, South Africa can position itself as a leader in the global green hydrogen economy, advancing both economic and environmental goals.

4.5. Skills supply and demand dynamics for green hydrogen technologies in the mining and minerals sector in South Africa

Preceding sections of this report have looked at findings regarding the state and nature of green hydrogen technologies in South Africa, broadly, and then zeroed in on the MMS. To provide perspective, the report presented findings to benchmark development against peers globally and on the African continent. Generally, it was found that green hydrogen technologies presented both challenges and opportunities. To subvert the challenges and capitalise on opportunities, findings underscored the important role that a skilled and well competent workforce could play. Implications for the MQA, highlight the need for the SETA to pay attention to developing a clear vision for the sectorial future skills needs, creating learning and career pathways that lead to new opportunities, enabling everyone to develop the skills for the evolving green hydrogen technologies. These three focal points are the foothold upon which the MQA may transform the green hydrogen technologies skills performance. Subsequent sections look at each of the three pillars in turn.

4.5.1. Supply and demand imbalances

This study found that although there are currently no skills shortages related to green hydrogen technologies, there are fears of future skills mismatch as the technologies gain traction. Survey results showed that 58 % believe that there will be skills shortages, some agreed (47%) and others strongly agreed (11%) that there will be future green hydrogen skills shortages in their organisations (Figure 26). Again, as many as 38 % were not sure, while only 4% disagreed.

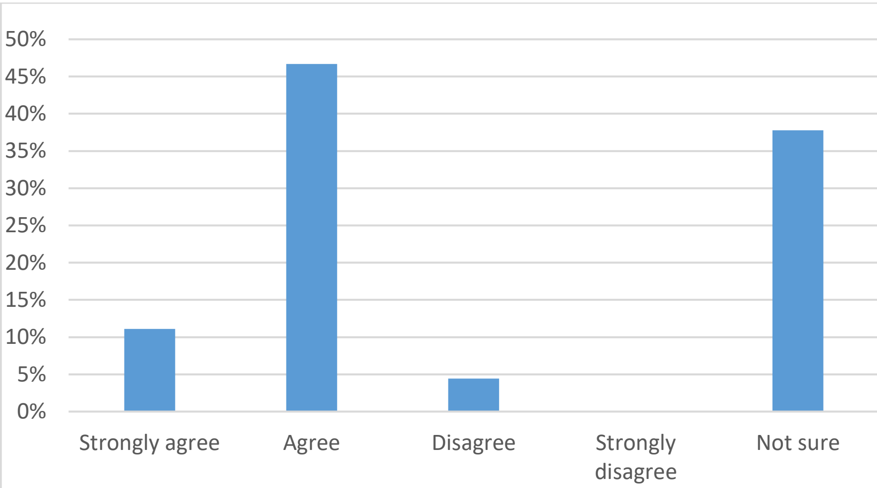

Figure 26: Anticipated skills gaps in the green hydrogen technologies in the MMS

By zooming in on the specific competencies and skills, it was found that several capabilities are important but at risk of shortages unless proper coordination is done. Figure 27 shows the percentage of respondents who selected different categories. Participants were allowed to select more than one competence (Figure 27). Findings note that understanding hydrogen properties (46.67%) is perhaps the most important competence at risk of shortage, followed by calibrating, testing and maintaining of equipment (37.78%). Knowledge of power electronics was also seen as an important competence with 35.6 %. Overall, it was found that all competencies listed attracted at least 17.8% being fuel cell knowledge. This particular competency was seen as less likely to be in short supply due the technology being tested already at one of the mining companies in South Africa.

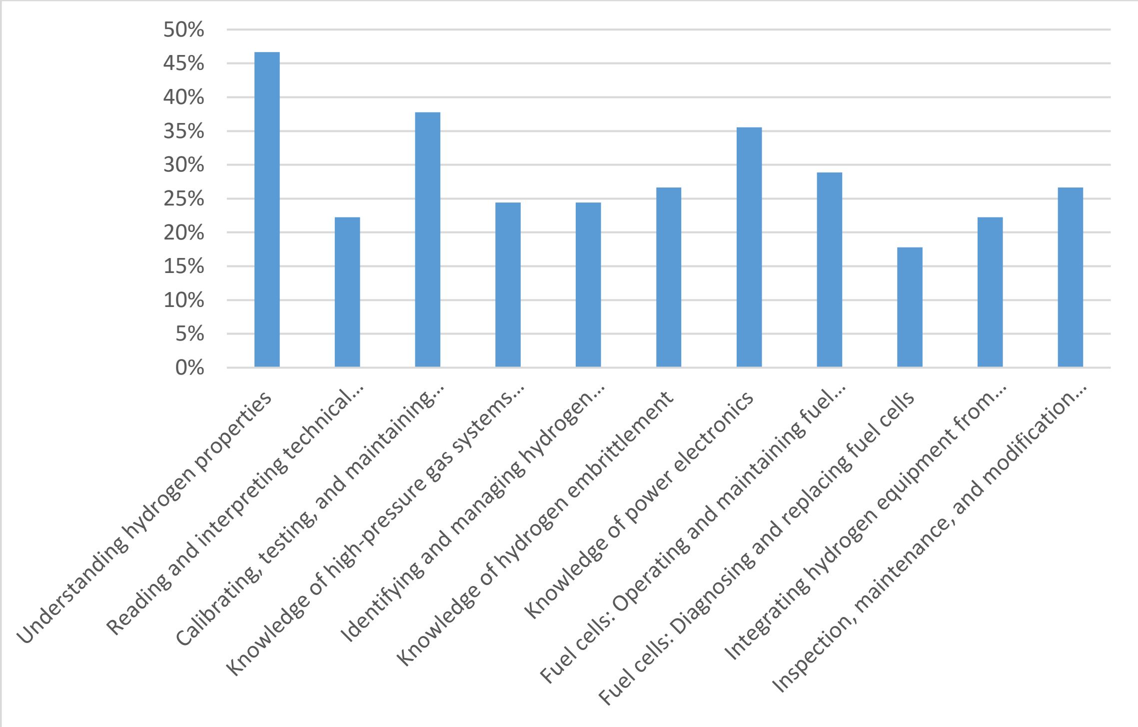

Figure 27: Competences that will be needed in the MMS but at risk of shortages in future (Note: competencies add to more than 100% due to multiple answers)

In terms of skills, it was noted that technical skills were very important, but it was crucial for the sector to also be attentive to business skills and soft skills as shown in Figure 28.

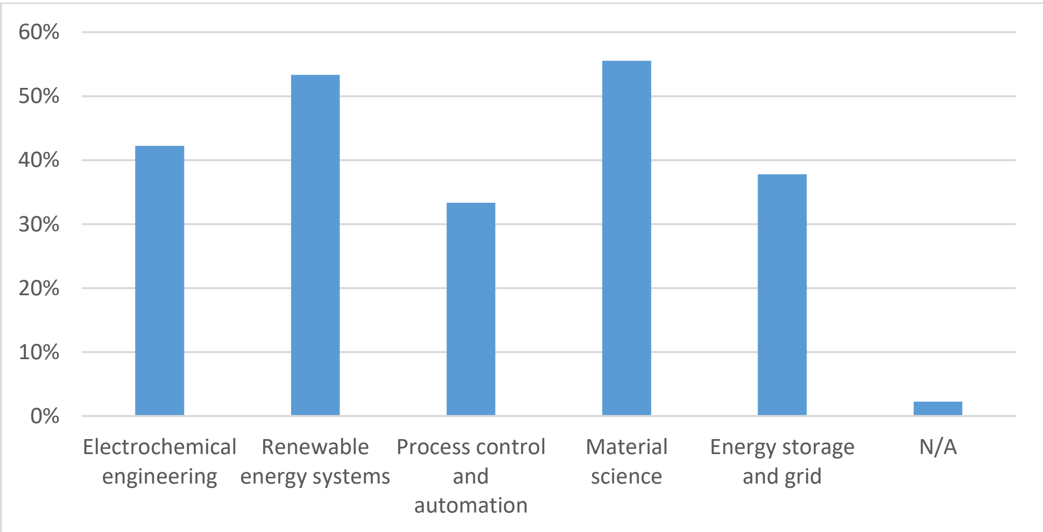

Figure 28: Important technical skills at risk of shortages in the future (Note: Adds to more than 100% due to multiple answers)

The study has found that business skills will also be important but unless developed, they are also at risk of shortages in the future. This presents the MQA with opportunities to address these challenges proactively. Figure 29 shows the important skills at risk of shortages in the future. Figure 29 shows that financial analysis (51%) and economics (44%) will be the highest risk skills. This perhaps suggests the complexity of the green hydrogen technologies development as the MMS seek a business case for the integration of green hydrogen in the sector.

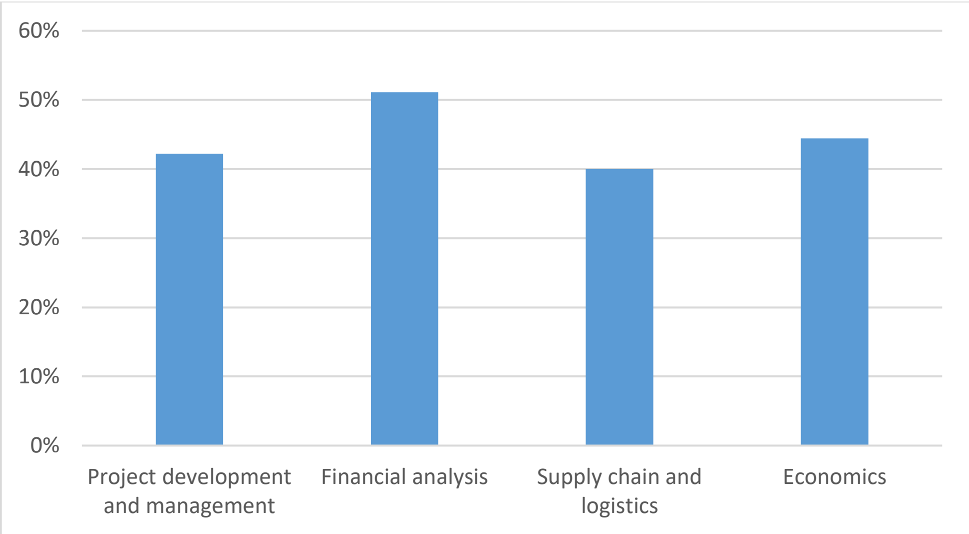

Figure 29: Important business management skills at risk of shortages in the future (Note: Adds to more than 100% due to multiple answers)

The current study echoes findings from other recent studies that sift skills will need to be particular attention need to be paid to soft skills. Figure 30 shows that adaptability and continuous learning (44%), communication and stakeholder engagement (42%), problem solving and analytical thinking (40%), and collaboration and teamwork (36%) will be very important and at risk of shortages in future.

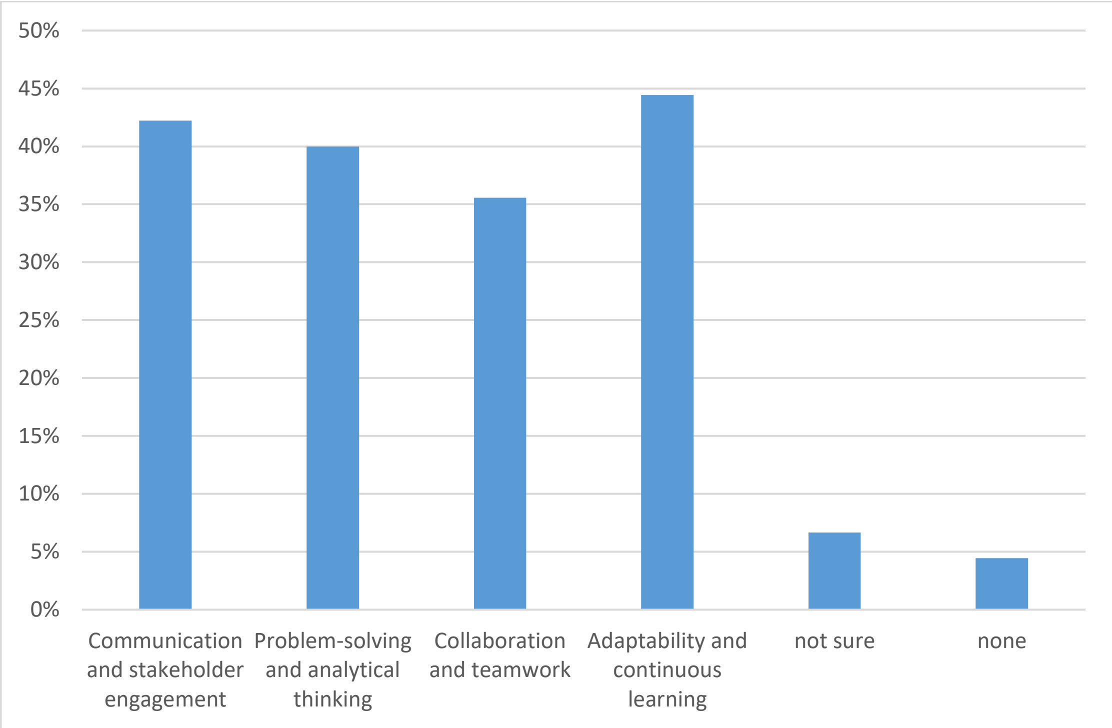

Figure 30: Important soft skills at risk of future shortages

Having identified some important soft skills that are at risk of future shortages, the study also investigated the importance of some emerging skills. Figure 31 shows that AI, Digitisation and IoT, and policy and regulatory frameworks skills will be important.

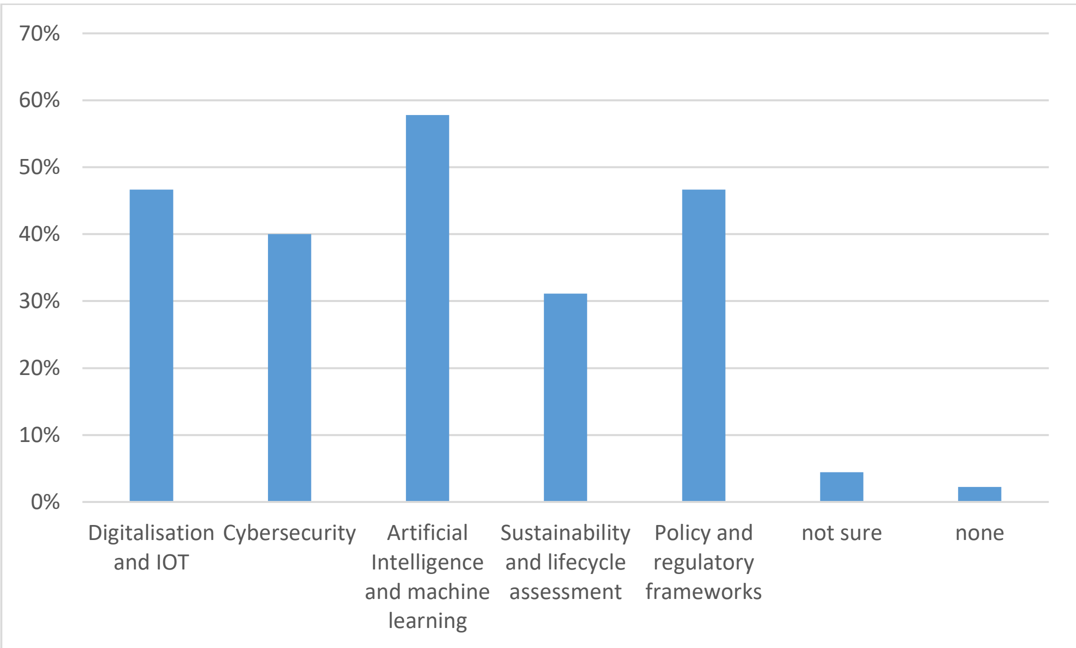

Figure 31: Emerging green hydrogen skills

To understand the implications of these skills of the future for the green hydrogen technologies, this study examined the different certifications needed for the hydrogen economy, qualifications/ programmes in South African Universities, to identify hydrogen qualifications missing (Figure 32). It was found that the Bachelor's and Diploma in management and support were well covered. Implying that the MQA will need to focus on implementation of digital components in those programmes. Engineering Diploma, and Bachelor's had the highest deficits. There is need for special targeting of grants and bursaries in this area as these were found to be important in the future of green hydrogen technologies.

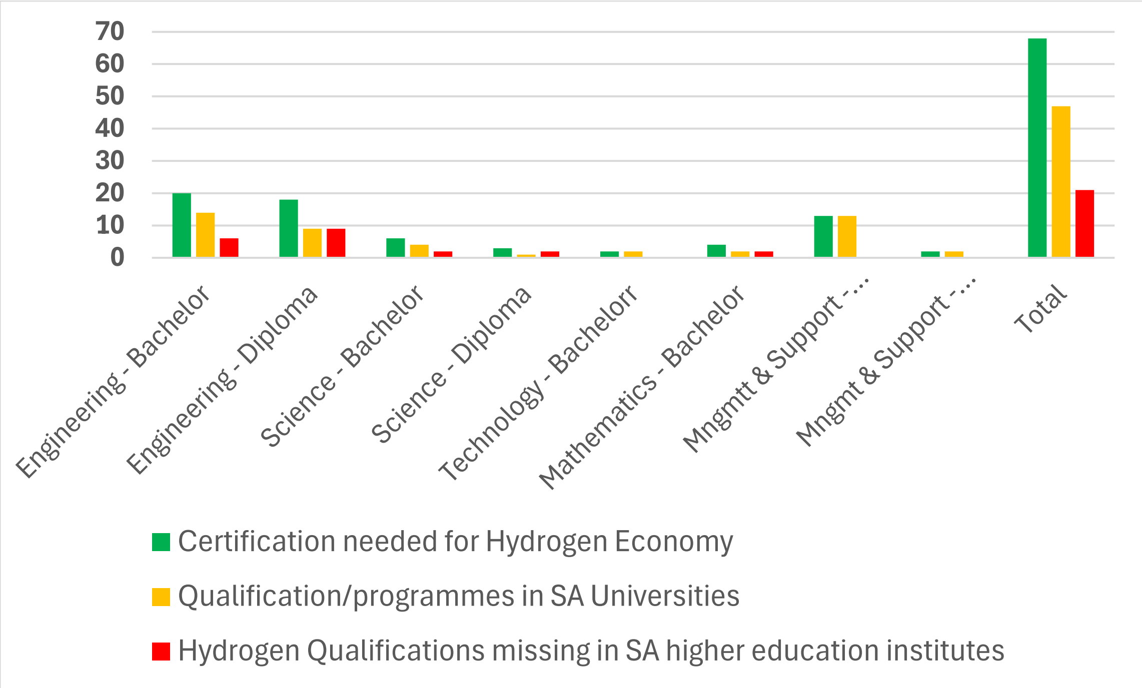

Figure 32: Certification/Qualification mismatches in South Africa (Source: Various studies in South Africa)

4.6. Green hydrogen technologies skills development pathways for the MQA and other stakeholders

4.6.1. Developing a vision for the sectorial future skills needs

This study has exposed the opportunities due to the abundant renewable energy resources within most MMS proximity. However, the study has also found that although availability of renewable energy resources and PGMs is an important precondition for sustainable and cost-effective green hydrogen production, translating those opportunities into practical benefits for the sector is not straightforward. This is due to the identified challenges associated with green hydrogen technologies in general and other challenges that are peculiar to South Africa. These challenges include high cost of the technology, high cost of green hydrogen production, lack of a ready market for commercial green hydrogen, competition from other energy solutions, technology risks, supply risks, lack of expertise and water scarcity. A recent study by WEF (2023) found that in South Africa, 68% of surveyed companies mentioned power storage and generation as the technology with the most likelihood to drive industry transformation with significant expected impact on job creation (Figure 33).

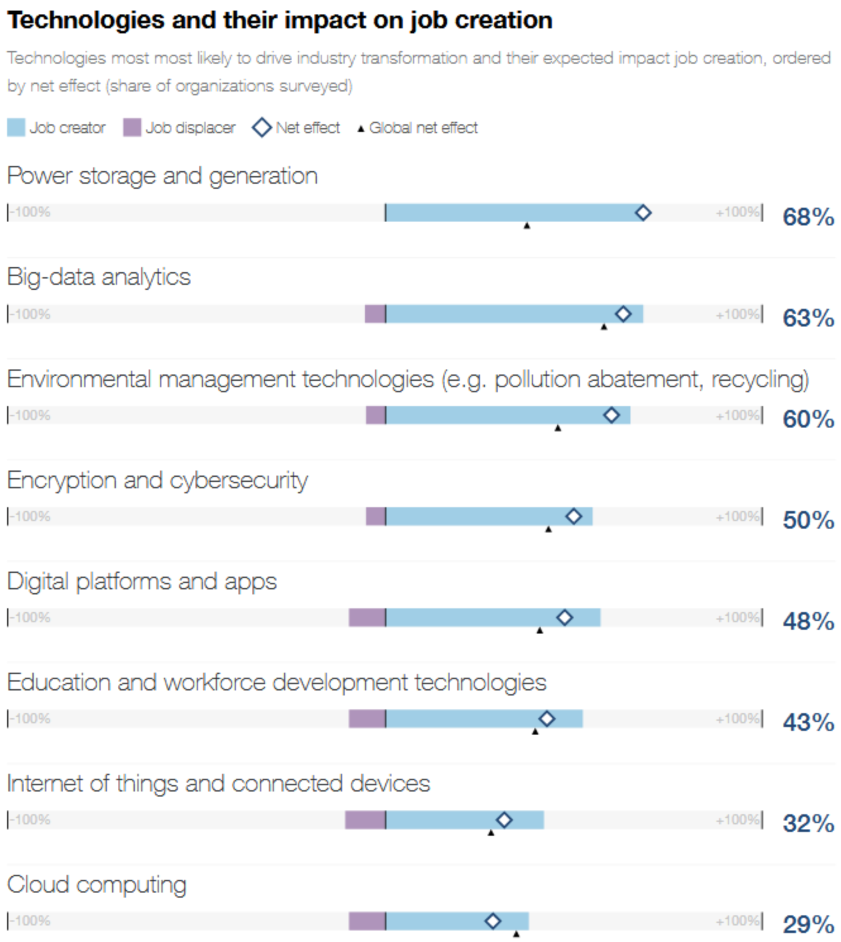

Figure 33: Power storage and generation have a significant impact on job creation in South Africa (Source: WEF, 2023)

This paints a picture of opportunities that may remain potential unless the SETA creates a clear vision of the skills that will be strategically important to the sector to take advantage of opportunities and overcome obstacles that come with the anticipated growth of power generation and storage technologies in the next 5 years. For the MQA, building bridges across the sector and with all stakeholders will be essential for developing such a vision. The following steps are important for MQA.

i. The MQA should conceptualise a compelling and strategic vision of the future the sector wants.
ii. The MQA needs to identify the type of skills that are needed to achieve this strategic vision.
iii. The MQA needs to set out a plan to develop these skills.
iv. Implementing these skills strategies requires harnessing the energy and commitment of social partners and stakeholders, as there are limits to what the MQA can achieve on its own.

The success of the vision will depend primarily on the adaptability of the skills systems developed by the SETA. Adaptability is paramount because of the risks and uncertainties associated with the green hydrogen technologies trajectory. The uncertainty is compounded by the reality that most skills will not remain the same and we are planning to a larger extent on skills that do not yet exist. The WEF has noted that 44% of core skills were projected to change in the following five years (Figure 34). The data presented in Figure 34 shows that from 2020, the percentage of core skills that changed grew from 43% to 56% in 2023. This shows the dynamism that skills have and therefore the need for the MQA to proactively adjust its skills offerings and strategies.

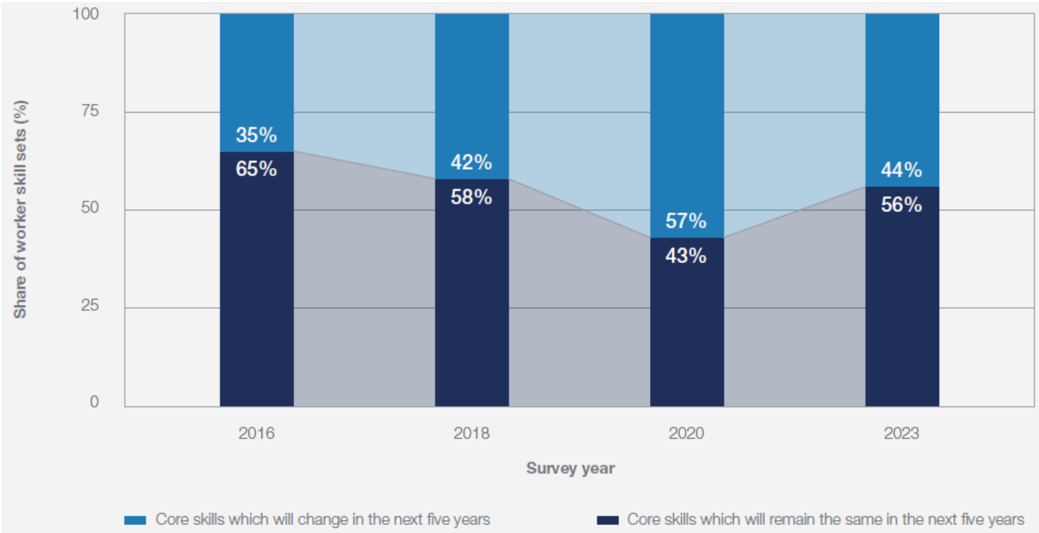

Figure 34: The percentage of core skills which will change and which will remain the same in the period until 2027 (Source: WEF, 2023)

This study is exploratory and has shed light on the key skills required for the future at a macro level for the country. In future it will be important to zoom in and forecast green hydrogen skills needs at the meso level (looking at clusters, subsectors, and value networks) and micro level (companies). In view of the dynamic environment, the MQA will need to deploy more creative initiatives and a wide range of strategies for a vision that delivers on the anticipated green hydrogen technologies. Table 16 summarises some types of learning that will be useful to ensure no one is left behind.

Table 16: Types of learning for an inclusive vision

Type of learning	Definition	Target groups
Formal training	Structured training programmes that last at least 6 months and lead to a nationally recognised qualification	Digital professionals, for hard to fill vacancies or skills at high risk of gaps
Non-formal training	Structured training in the form of courses, workshops or guided on the job training may lead to a certificate or badge recognised in the sector, or result in portable skills	Executives, MMS workforce
Informal learning	Informal learning through coaching or mentoring schemes, experiential	Executives, management, workforce

	learning, communities of practice, resource centres, learning events, or job rotation programmes	

Although this is a macro level analysis of skills needs, the vision should not lose sight of the individual learner and their specific needs, for an inclusive diverse workforce. A strategy that is recommended is the development of an Individual Leaning Account (ILA) where leaners are exposed to Massive Open Online Courses (MOOCs). This is to be done while stimulating greater cooperation between the SETA on the one hand and between employers and individuals (including unions) on the other.

The vision should balance the importance of developing the technical skills needed to alleviate current shortages as well as harnessing the potential of the emerging new green hydrogen technology. These technical skills include coding, AI, STEM/STEAM, and occupation-specific skills. Key informant interviews in this study commented on the importance of developing strong "soft" skills, such as communication skills, management skills, problem solving and critical thinking skills. Soft skills have become very important because of the increased need for collaboration among various players. Critical thinking and data-based decision making require STEAM integration at an early stage for learners. This study noted the importance of ensuring that all people develop at least basic digital skills, even if their primary role is not information and communication technology.

Most of the research participants advocated for a vision that encourages people to embrace change and pursue learning throughout life to ensure that people are adaptable and resilient in the context of change. Interviewees believed this could be facilitated by the MQA partnering with other SETAs and stakeholders to build education and skills systems that are themselves adaptable and responsive to change. This could involve advocating for education and training policy changes.

Many stressed that the vision should acknowledge the importance of starting early to build the skills and attitudes of learning. One interview said that: "…the process of developing the skills and attitudes of a lifelong learner should start very early in life, in our creches and kindergartens and continues throughout initial education and in our workplaces in adulthood. Remember I said earlier on that emphasis should be on STREAM, where 'R' for reading should be emphasised to develop a culture of continuous learning"

For many, this means ensuring that all children get a good start in schooling and complete compulsory education. In this context, delegates mentioned the importance of modernising curricula to ensure that people develop the skills and attitudes needed to support further learning, promote innovation, engage in entrepreneurship as well to develop the skills and attitudes needed to support change, including energy transition as the sector adopts green hydrogen. The importance of investing in teachers and infrastructure was also noted as key informants emphasised the need to focus on train the trainer model.

Echoing a recurring theme throughout the study, several participants noted the need to promote awareness of the importance of TVET and raise its stature in society. Several commented that TVET was too often seen as a second choice and that the sector needs to redouble their efforts to overcome this stigma. Several interviewees lamented the MMS giving more priority on sector specific qualifications such that after the leaners exit university or the TVET they can be employed directly but must undergo months of additional training. This underscores the need for a broad vision to build coherence in the qualifications offered by TVET and the industry.

The other recurring theme echoed by research informants was the need for a vision that promoted collaboration and coordination across the whole sector and with social partners and other stakeholders, including other SETAs in developing green hydrogen technologies skills. It was noted by most interviewees that building a highly skilled workforce requires engagement with employers, labour unions and other key stakeholders. Some made mention of specific mechanisms that were implemented to facilitate dialogue and collaboration, such as skills councils, regional skills bodies and skills forums. Some respondents noted the important role that skills strategies may play in helping the sector to foster an actionable vision with input from across sectors well as from wider stakeholder network.

The MOU signed by MQA, CHIETA and TETA is a typical example of meaningful collaboration to advance Green Hydrogen Centre of Specialisation (CoS) to offer hybrid training programmes focusing on continuous professional development, with specialised courses aimed at upskilling, and reskilling people for the green hydrogen and derivatives industries. This initiative could benefit from insights by the WEF which found in a recent study that human machine interaction will accelerate in the next years to 2027.

In executing the collaborative vision, it is important to integrate digital technologies as the MMS is modernising to improve on safety and efficiency. For the green hydrogen technologies to achieve the desired scale, there will be integration of digital technologies. For that reason, the learning interventions will need to be digital centric. A study by the WEF shows that a significant number of tasks will be automated in the next 5 years and that the percentage of those that will require less human, and more machine role will keep increasing. Several tasks, ranging from the simple to the complex, form reasoning and decision making to coordinating, developing, managing and advising, performing complex and technical activities, communication and interaction, to information and data processing, there will be more machine involvement. The vision of the skills of the future needs to be centred on this reality (Figures 35 & 36).

Figure 35: The growing role of machines in tasks calls for learning and training that recognises the growing human-machine collaboration (Source: WEF, 2023)

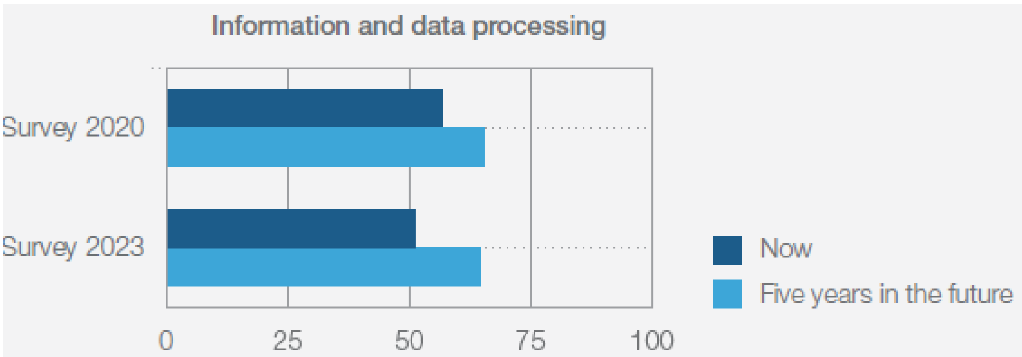

Figure 36: Information and data processing tasks will be executed more with the aid of machines by 2027 (Source: WEF, 2023)

4.6.2. Creating learning and career pathways that lead to new green hydrogen technologies opportunities

Education and training programmes, industry partnerships, and public policy and funding

Key interview informants noted the many factors that highlight the need for improving learning and career pathways to new opportunities. This was underscored by the need for the sector to overcome the challenge and risk that comes with preparing youth for professions that do not even exist today. Interviewees differed on the approach going forward, some pessimistic while others more optimistic. One pessimistic informant believed that learners should only be trained for skills in renewable energy such as wind and solar for upstream value chain where the jobs are currently available and growing. This contrasts another informant who mentioned the importance of visualising learning and careers as a freeway with on- and off-ramps instead of as ladders to underscore the increasing regularity of transitions and importance of efficiently facilitating them to ensure people stay employed or find new or better jobs. This was echoed at an Energy and Mining Skills Forum in Mpumalanga where this was seen as very relevant as the province transitions from coal to alternative energy sources.

Figure 37 is a matrix of skills development based on the sector's exposure to need for green hydrogen technologies in the near future on the vertical axis, and on the horizontal axis is the compatibility or transferability of current skills. Based on these dimensions, for example, the NEETs will be around ZERO as they are not in any sector and they have no skills compatible with green hydrogen (Quadrant A), this may require assessing and providing initial skilling (assess and act). In the next quadrant B, these are people with highly complementary skills, but their sub-sector may not be highly exposed to green hydrogen technologies. This may include services incidental to mining. The strategy requires transformative initiatives as the employees may need to move to other sectors, ensuring the sending sectors are not left with skills gaps (transform and optimise). Upskilling and cross skilling are important strategies in the quadrant. In quadrant C, these are highly compatible skills in sectors highly likely to integrate green hydrogen. An electrician or chemical engineer in the PMG mining sector would be likely to be in this category, some employees in the coal sub-sector would fall in quadrant C if they had skills compatible with green hydrogen technologies. People working in renewable energy are typically in this quadrant. Their strategy involves augmenting skills and building a hybrid of skills by multiskilling.

In quadrant D, these are people who have fewer compatible skills but in sectors highly likely to be in the green hydrogen space soon. Examples are those in the quadrant are CLAS sub-sector. The cement sub-sector for example is anticipated to take advantage of the green hydrogen to decarbonise this hard-to-abate subsector. It is proposed that the strategy involves the replacement of the current skills and develop hydrogen specific skills (replace and hydrogenise) through re-skilling. Figure 38 shows the skills development strategies for the different quadrants.

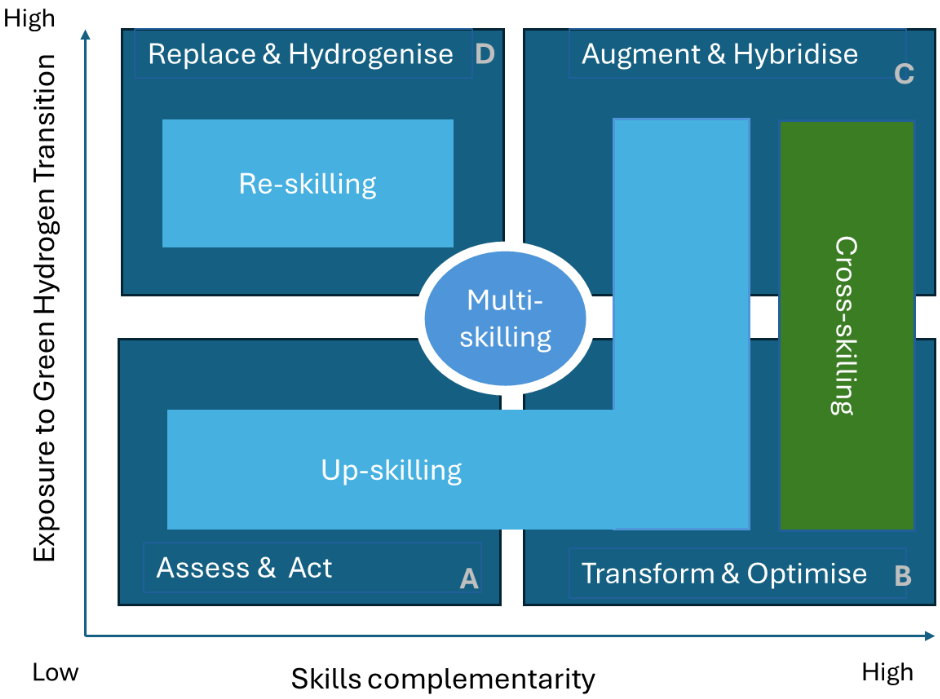

Figure 37: Exposure to green hydrogen transition, skills compatibility and skilling strategies

Workshop participants from TVETs expressed the need to recognise that too many young people have bad experiences in school, with damaging impacts on their school performance and completion, as well as on their motivation to learn in adulthood. For some, curricula that emphasise the memorisation of factual knowledge was a key problem. One presenter from the mining industry argued for the introduction of competency-based curricula, informed by a strong understanding of the sector's labour market needs. This will be important for targeting NEETs and school-going segments who are in the low end of quadrant A in Figure 37. The pathways envisioned by the MQA should pay attention to the NEETs, school-going and the disadvantaged youths and women in the townships where digital technologies may be lagging. To achieve this, collaboration with MMS actors operating in these areas will be important when deploying initiatives.

Most forum participants mentioned the importance of investing in teacher training and infrastructure to ensure all students have access to technologies such as robotics, AI, etc which they will use in workplaces. This was seen as valuable not only for strengthening the link between education and the world of work, but also for strengthening school completion in the face of a new generation of learners who are so much glued to their digital gadgets which shifts their ability to focus. The need to ensure that youth had early exposure to technology to stimulate their interest in both the technology and learning was highlighted.

This research found that most of the green hydrogen jobs will require at least metric level of education, so are occupations in the MMS. This implies that effective pathways to post-senior education are seen as critical given that higher levels of education are increasingly required for most of the perceived green hydrogen jobs.

Targeted funding of green hydrogen was proposed by some participants: “Offer more learning or study financial aid that will be more specific to studies on green hydrogen technologies”. Key informants also identified several key supports including access and tailored career advice, accessible and high-quality skills and labour market information; access to work-based learning and/or internships; and access to industry recognised credentials. Once again, the importance of elevating the status of TVET to promote greater participation was echoed to attract pathways for lower-level qualifications to be absorbed in the new economy. Figure 38 shows that mining industry employees are required to have higher qualification than most South African have.

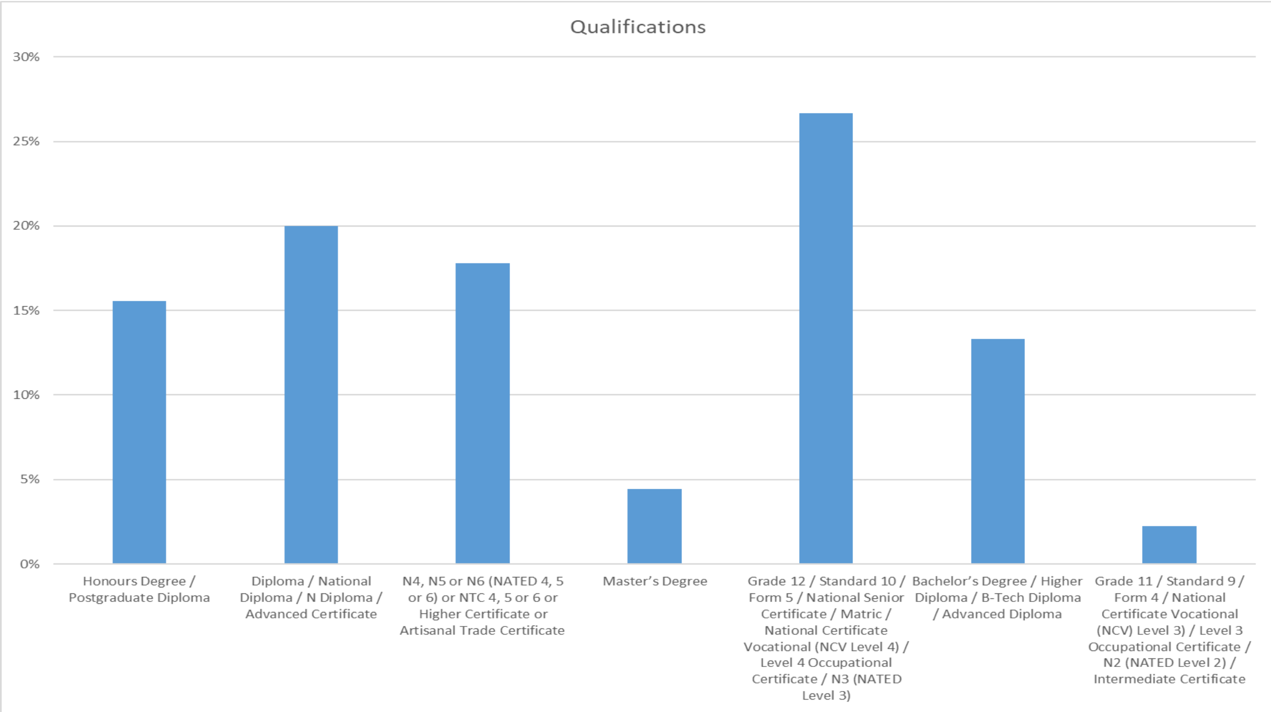

Figure 38: The level of qualifications of survey participants shows that the industry individuals with grade 11 or higher.

An interviewee mentioned that: "The MQA could develop training programmes focused on hydrogen production, storage, and safety by partnering with industry leaders for workshops, internships, and mentorships."

The study finds that the anticipated green hydrogen technologies trajectory will increase the need to upskill or reskill in adulthood for most current and future employees. It is anticipated that in the next years to 2027, the following will be important as shown in Figure 39. The Figure shows a breakdown of the average training strategy for a representative group of 100 employees, calculated based on the training strategies reported by organizations surveyed by the WEF (2023).

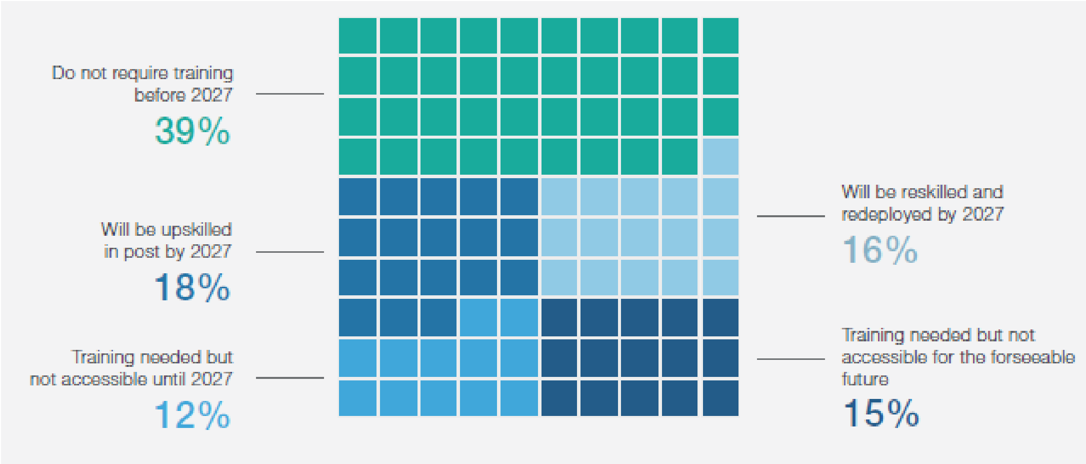

Figure 39: The distribution of the global workforce and their skills development needs (Source: WEF, 2023)

The most concerning image painted by Figure 40 is the fact that some people need training but will not be accessible until 2027 (12%), training needed but not accessible for the foreseeable future (15%) and some will be reskilled and redeployed by 2027 (16%), while some will be upskilled in post (18%). The implication of this finding is that the MQA will need to have a diverse set of strategies to reach out to these different categories of people. These global trends are shaping developments in South Africa.

A wide range of measures could be integrated to encourage and support adult learning. The MQA could develop strong career and learning guidance systems because they are critical in supporting and informing learning. To focus on relevant skills for green hydrogen, it will be important to craft short-term training programmes delivered in partnership with employers to help adults quickly acquire the skills needed to return to work or find better green jobs. Interviewees noted the importance of flexible provision to meet the needs of learners, as well as measures to better align the training offer with emerging green hydrogen technologies labour market needs. Industry partnerships are important for delivering internship programmes between universities and companies for students to gain practical experience in the green hydrogen sector. Further, joint research ventures involving mining sector companies, research institutions and the MQA to develop new technologies and improve existing processes are necessary. The partnership involving the MQA, CHIETA, and TETA to develop the green hydrogen centre of specialisation is a great starting point. The private sector and additional stakeholders could be included in the collaboration, for example the Mandela Mining Precinct and Impact Catalyst.

This is where flexibility should be embedded in education and training policy, such that it becomes important for skills development systems to recognise and certify skills no matter where and when acquired to facilitate learning pathways and career mobility. Participants also mentioned other measures to support worker pathways, including skills plans, entrepreneurship programmes, training leaves, and increased discretionary grants to companies that develop green hydrogen technologies people' skills. In this regard, individual learning accounts (ILA) can be an important tool for motivating learning but should be also noted that ILA need to be complemented with strong guidance and quality assurance systems to ensure their success. One interviewee mentioned these strategies: "Offer incentives and training for research and pilot projects in green hydrogen on the skills needed. Update mining certifications to include hydrogen-related skills. Set up regional training centres for easy access to green hydrogen education."

The importance of social dialogue and partnerships was also seen as important for strengthening learning and career pathways since employers and labour, education and training providers and other stakeholders are well positioned to help learners to make informed decisions. The MQA will need to actively participate in Energy and Mining Forums such as the one in Mpumalanga where stakeholders discuss skills needs. Further, establishment of a green hydrogen sectoral skills council with industry representation may help to draft recommendations on skills needs and support curricular reform. Skills Pacts could also be useful for the MQA rather going it alone in green hydrogen technologies skills development. This can bring together social partners, public employment services, and other industrial stakeholders in common purpose to support people to develop skills that are most needed in the labour market. On the job training is anticipated to grow over the coming five years as shown by 81.2% of companies. According to the WEF (2023) only 22.4% of companies anticipate hiring more significantly permanent staff, which means the MQA needs to focus on portable skills (Figure 40).

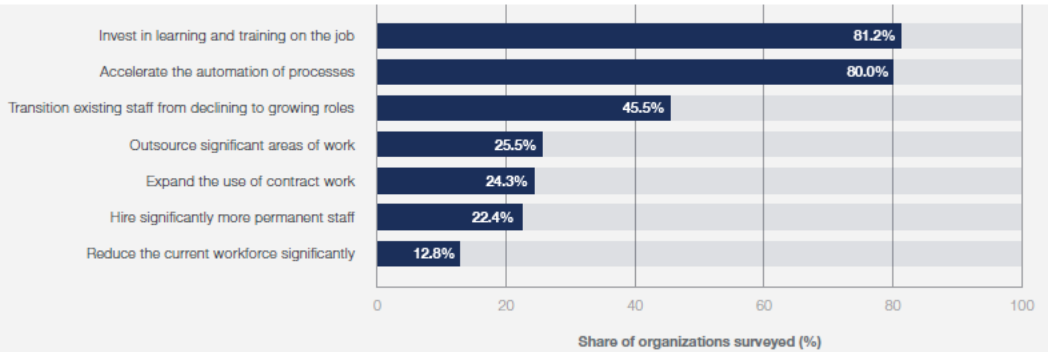

Figure 40: Share of organisations and their planned strategies

In developing these pathways, the MQA will need to create a Skills Pact as it cannot achieve the desired outcomes alone.

The Skills Pact

The skills pact will be a collaborative agreement between various stakeholders, including MQA and other green hydrogen interested SETAs, industry, education and training providers, and trade unions. The primary goal of the Skills Pact is to address skills gaps and shortages in the MMS or in regions such as in Mpumalanga due to energy transition impacts of coal scaling down, or Northern Cape where renewable energy could be scaling up, or the Green Hydrogen Valley, where the core of green hydrogen technologies is expected to flourish. The Skills Pact thrives by promoting cooperation and coordination among stakeholders (Table 17).

Table 17: How the Skills Pact works for the MQA

Action	**Description**
Identifying stakeholders	Mapping of stakeholders that may contribute to jointly developing skills.
Identifying of skills gaps	Stakeholders come together to identify the specific skills gaps and shortages in the sector or region
Developing a skills plan	Based on the identified skills gaps, stakeholders develop a comprehensive skills plan that outlines the necessary skills development initiatives.
Committing and taking responsibilities	Each stakeholder commits to specific responsibilities and actions to support the skills development initiatives outlined in the plan.

Implementing and monitoring	Stakeholders work together to implement the skills development initiatives, and progress is regularly monitored and evaluated.
Reviewing and adjusting	The Skills Pact is regularly reviewed, and adjustments are made as needed to ensure that the skills development initiatives remain relevant and effective.

The Skills Pact could generate several benefits including improved collaboration and coordination among stakeholders, enhanced skills development and training programmes, better alignment of education and training with industry needs, increased competitiveness and productivity in the sector or region, and improved employment opportunities and social mobility for individuals.

The focus of the Skills Pact

According to the WEF (2023) some skills are anticipated to dominate the job market, and most companies are focusing on them. Figure 41 shows the distribution of companies responding to the Future of Jobs survey. The highest priority for skills training from 2023 to 2027 is analytical thinking, which is set to account for 10% of training initiatives, on average. The second priority for workforce development is to promote creative thinking, which will be the subject of 8% of upskilling initiatives. The highest priority for skills training from 2023 to 2027 is analytical thinking, which is set to account for 10% of training initiatives, on average. The second priority for workforce development is to promote creative thinking, which will be the subject of 8% of upskilling initiatives (WEF, 2023).

It is recommended that the Skills Pact focus on sector-specific skills development through delivering hydrogen specific workshops to develop skills on emerging green hydrogen technologies and safety measures. They also jointly work towards certification programme development for technicians and engineers specialising in hydrogen systems.

Figure 41 paints a clearer picture of the key focus areas in terms of skills development and the strategies necessary to achieve that. The figure shows that analytical thinking, creative thinking, AI and Big Data analytics have the highest focus in reskilling up to 2027.

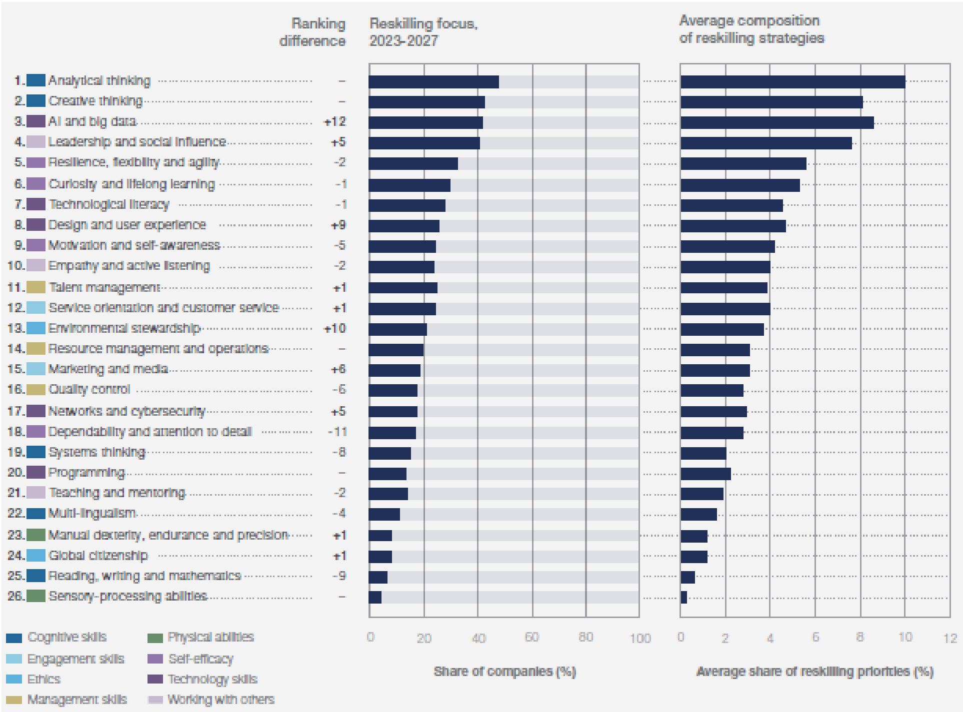

Figure 41: The focus of skills and strategies developed for the period to 2027 (Source: WEF, 2023)

4.6.3. Enabling everyone to develop the green hydrogen skills

The green hydrogen technologies present a huge inclusion risk emanating from the challenge of a labour market mainly made up of jobs for highly skilled workers and, at the same time, a very low-skilled population. At the Energy and Mining Skills Forum in Mpumalanga, it was unanimously echoed that the province had a serious challenge of finding highly skilled people as education levels were low. The forum emphasised the need to do a better job of engaging NEETs recognising the high level of NEETs in South Africa. These are people of working age who are not in education, employment or training. The Green Hydrogen Valley initiative estimates that at least 380,000 jobs will be created in the green hydrogen economy by 2050, with at least 20,000 jobs created by 2030 and about 15,000 to 30,000 jobs created annually from 2030 to 2040. There is therefore a need to prepare NEETs to fill shortage occupations.

The MQA could partner with other stakeholders, including community service organisations to reach out to NEETs where they live. Other policy reforms could also help in this regard, for example the introduction of paid training leave for part-time workers, has been found to greatly improve their take up by women. By partnering with schools, the MQA could leverage the role of school and teachers to support inclusion and success in learning for all and rekindle the interest in leaners to consider a career in mining and in the green hydrogen technologies. Other countries are now considering other reforms to combat inequality like lowering the starting age in school, shortening school holidays, making specialist support available to pupils with autism, and providing financial support to buy supplies for children from disadvantaged families. The MQA could play an important role in supporting the finding in this study that green hydrogen may need to play an important role in addressing some of the country's pressing challenges such as inequality. This could involve the importance of reaching out to the most vulnerable groups and providing them with support, guidance and orientation. This should be done in a coordinated, centralised way. Interview participants stressed the importance of making learning pathways flexible to equip everyone with the skills needed to meet the major societal challenges.

Evidence from research underscores the need to address inequality in career choices, noting that opportunity gaps open early in life, compound in childhood and persist into adulthood (Lee & Saygin, 2023). This is typically true as evidence suggests that students from disadvantaged schools often do not have access to the same resources as those from advantaged schools, precluding them from choosing educational paths that will lead to the jobs they aspire to. There is need to close this misalignment between educational paths and aspirations for disadvantaged students to develop the skills for success in future labour markets and societies. Encouraging gender diversity in green hydrogen technologies should be a priority. An interviewee from the Women in Green Hydrogen believed that there were far too limited opportunities for women in green hydrogen and called for increased efforts to create conducive conditions for women. The participant noted that even the participation of women in mining was still facing huge obstacles as women did not have equal opportunities and working conditions still skewed in favour of men. She highlighted reports of sexual harassment and discrimination being rife.

These findings have huge implications for MQA training efforts. In addition to technical skills, there is increasing need to develop skills for managing growing stress and managing other dynamics in the workplace to diversify the workforce. This should be supported by conditions for further lifelong and lifewide learning to tackle the significant transformations taking place in the South African economy and societies.

Several research participants emphasised the importance of overcoming aspirational and motivational gaps. In this context, some mentioned the need to ensure that girls as well as boys are aspiring to develop STEM skills and that they have access to opportunities that allow them to act on these aspirations. Many commented on the need to reach out to youth NEETs and re-engage them in learning or work. The importance of tailoring education policies to the needs of different learners was discussed at length. For example, some participants spoke of adapting school curricula to the needs of different learners. The importance of early warning systems to identify pupils in danger of falling out of school and targeting them with additional support was also given as a good practice. There could be need for providing extra advice and support to parents and students from disadvantaged backgrounds, such as subsidies and co-financing for books, materials, meals and transportation. This, as was mentioned, needs the educators to be also trained through train the trainer initiatives.

TVETs were seen as an important means for engaging and supporting school completion among disadvantaged populations. Some argued that TVET provides a good pathway to jobs for disadvantaged populations as it offers a more tangible learning experience and direct exposure to the world of work. Along similar lines, some participants highlighted importance of initiatives to provide career guidance from very early grades, to motivate disadvantaged students to remain in school. There is a need to strengthen access to learning among unemployed or inactive adults. MQA could create conditions that promote work-based learning for these groups, including internships and apprenticeships. Research participants mentioned the need to strengthen active labour market policies, including by providing improved outreach through public employment services, the provision of free and equal access to employment, training and self-employment programmes, as well as providing employment opportunities in emerging green hydrogen technologies.

The importance of investing in the integration of new entrants to green hydrogen technologies by supporting the recognition of previous qualifications, degrees and skills, as well as access to further education and training was also noted. This is important as currently there are no green hydrogen qualifications or degrees except for isolated modules in other programmes.

Several interviewees underscored the importance of promoting digital learning, not only to support the development of digital skills among disadvantaged populations but also to reach those who might otherwise lack access to learning opportunities, such as those living in rural or under-serviced provinces. Key informants were of the view that it is important to integrate social partners. The MQA could leverage business and community service organisations as important agents to engage disadvantaged populations and encourage and support their return to education, training or work.

The three pillars of inclusive education and training

This study finds that inclusive education and training should be based on call to action to rethink the continuum of education, training and the workplace and this should be constructed across three pillars: digitalisation of education, credentialing and a reimagined future encompassing sustainability in its broadest sense. Rather than starting with educating people and finding roles for them, there is a need to be intentional about early career guidance and encouraging more learners to be in STREAM. Table 18 shows the need to transition from education, training and workplace to workplace, education and training that allows pathways that interconnect, from workplace back to education or training during early education to expose learners to the realities of the workplace.

Table 18: The three pillars of an inclusive workplace, education, and training

Pillar	Traditional Dichotomy View	Future Seamless View	Implications for MQA
Digitalisation	**Supply side:** discourse has been dominated by education and training providers, using artefacts such as qualifications, curriculum and examinations. **Demand side:** discourse dominated by employers and employees, with their own narrative and artefacts, such as occupation, workplace organisation, work-based learning, competency-based assessment and more.	**Unlimited potential** of connecting learning spaces and making accessible the codification of knowledge, skills and competencies in the form of learning outcomes with a global conjoining effect. **In connecting** learning spaces and sharing a common language, the world of work and the world of education and training are becoming more seamless, even more so as the credentials designed and issued on either side of this continuum are increasingly commonly interpreted. Conditions: curbing risks and ensuring digital tools are accessible.	Integrate digital learning in all workplaces, education and training initiatives

Pillar	Traditional Dichotomy View	Future Seamless View	Implications for MQA
Credentialling	Essential proxy for society regarding the value and status of learning Conditions: may deepen inequality unless globally agreed upon principles foreground education and lifelong learning as a public good and internet access as a human right. In South Africa, short courses and certificates of competencies issues in universities have no way of relating them to the NQF, obscuring the importance of lifelong (and lifetime) learning.	An emerging fourth generation of qualifications framework encompassing the Continuum through new types of credentials such as micro-credentials, badges and learning portfolios ecosystem recognises the diversity of learning spaces, the variety of learning outcomes and the difficulty of fitting all learning outcomes into a formal qualification while not excluding the possibilities of stacking those learning outcomes into a qualification. Ecosystem supported by ecosystem is supported by digital technology, such as credentialing platforms, interoperability technology, artificial intelligence and other technologies. It also requires rethinking the quality assurance systems,	Ensure there is alignment among the various skills, including those gathered from lifelong and lifewide learning. Specifically ensure the learning from TVETs is recognised so that learners do not find themselves with qualifications that are not needed in the marketplace.

Pillar	Traditional Dichotomy View	Future Seamless View	Implications for MQA
		which heavily rely on key institutions and actors, such as qualification and accreditation authorities, assessors, and verifiers. Examples: the US-based Credential Engine offering transparency and visibility of credentialling ecosystem; European Qualifications Framework, Europass, and the European Digital Credentials for Learning.	
Sustainability	The discourse is focused on siloed pursuant of sustainability from a planet, people and profit perspectives.	Digitalisation provides the pathway to fully realise lifelong learning by connecting the world of work with the world of education and training • Enhance international cooperation and solidarity for strengthening the	Focus on collaborations and integrate sustainability thinking because green hydrogen is driven from a sustainability perspective more than the short-term economic gains

Pillar	Traditional Dichotomy View	Future Seamless View	Implications for MQA
		human rights framework regarding lifelong learning. • Develop international resources for learner credentials, data protection and security and, more broadly, enhance digital credentialing to promote open access to quality digital learning and credentialing.	

From a sustainability perspective, education and training institutions need to tighten links with their local communities and establish themselves as anchor institutions. This helps them to work closely with other local institutions enabling schools and institutes to better understand and provide for the learning needs of their communities. This is important for the learners to create meaning as the multiple layers of uncertainty around the future of work and the planet suggest that there is a risk of traveling the journey alone leaving learners and communities behind.

The pathways that we create will need to be flexible like a freeway, and not rigid like a ladder. This calls for a lot of flexibility to prepare a workforce that is agile because of the level of uncertainty confronting our world in the future. In developing these pathways, the MQA will need to think in terms of creating education that supports the creation of long-term economic well-being for individuals, their families, and their communities, taking a broad view that looks at the world of formal, waged work and goes well beyond.

4.6.4. Summarised process model of skills development pathways for green hydrogen technologies

Figure 42 shows the important processes for delivering on sustainable green hydrogen technologies and skills development pathways in the MMS. For the MQA this calls for a clear vision of what the SETA wants for the sector. This study offers an important ingredient for refining this vision, together with stakeholders.

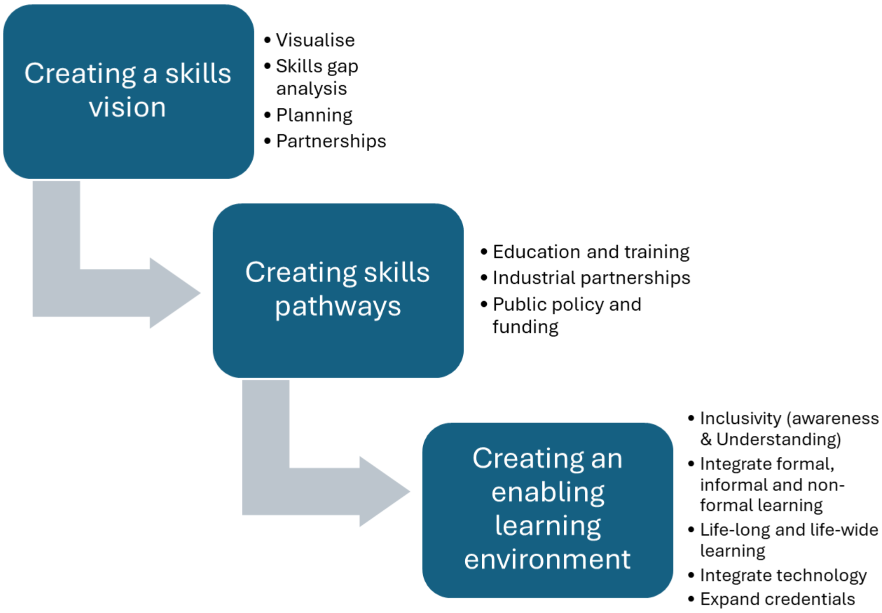

Figure 42: Green hydrogen technologies skills development process model (Source: Authors)

When the vision is clear, the MQA will need to follow the pathways proposed in this study focused on fostering education and training, through primary, secondary schools, universities, and technical and vocational education and training (TVETs). Education and training will provide degree programmes and research initiatives, while vocational training provides technical courses, learnerships and apprenticeships with an emphasis on hand-on green hydrogen technology experience. This is achieved in partnerships with other stakeholders to deliver internship programmes and joint research ventures. Partnerships could help in designing and delivering sector-specific green hydrogen technologies training. Examples include hydrogen specific workshops, and certification programmes for technicians and engineers and other important trades and occupations outlined in this study. Lobbying government and the private sector to accelerate funding for training programmes will be important. The government could offer tax incentives as part of policy initiatives where tax deductions are given for companies that invest in employee training related to renewable energy and green hydrogen technologies in particular. Further government participation includes developing policy frameworks that encourage safety standards requiring professionals to in the field to undergo specific training and certification. This is enhanced through policies to foster research and development in green hydrogen technologies.

To ensure no one is left behind, the MQA needs to create an environment that enables learning for everyone, including NEETs. This involves offering digital opportunities for remote learning, yet sensitive to the plight of the township and rural communities where a significant part of the MMS business occurs.

4.7. Summary of key findings and insights

The key findings from the study are outlined below, and these are presented to respond to the objectives of the study.

Objective 1: To identify the green hydrogen technologies implemented in the MMS

Finding 1: The green hydrogen technologies are conceptualised as a value network rather than a value chain.

Green hydrogen technologies are more clearly understood when viewed as a value network rather than a value chain. A value chain perspective focuses on the main actors such as suppliers of renewable energy, electrolysers, fuel cell and water (upstream), production, transportation, and storage (midstream), and consumption (downstream). However, such a narrow perspective overlooks the important role that other services provide. For example, the role of support from skills development providers, education, training, funding, and regulators which are important in developing a stable network. From a network perspective, this study finds that the MMS does not develop green hydrogen technologies in a vacuum. The sector needs to build on successes in other sectors.

Finding 2: Although a limited range of technologies are being implemented in the country, the study finds several green hydrogen technologies have potential in the future. When asked which green hydrogen technologies are likely to be implemented in the MMS: 40% said none, showing a low level of preparedness for the sector. A significant number showed that fuel cell electric vehicles (16%) and hydrogen powered machinery (16%) are likely to be implemented. Some technologies identified are electrolysers (alkaline and proton exchange membranes), stationary fuel cells, hydrogen storage solutions (compressed, liquid), hydrogen blending technologies, hydrogen powered machinery (drill rigs), and hydrogen transportation solutions. As many as 40% of respondents did not yet anticipate green hydrogen adoption in the near future.

Finding 3: Compiling data from major investments in renewable energy in the sector, the study finds that there is over 1426 MW of investment in renewable energy capacity. This shows that although there is low preparedness in green hydrogen specific technologies, renewable energy investment is already underway (confirming the 13% of participants who outlined anticipation or already using renewable energy). CLAS, PGM mining, gold mining and coal mining leading renewables

Finding 4: Considering some of the current uses of green hydrogen in the MMS the following were identified:

- Transport 24%, power had the highest with (56%). Other applications include heat (22%) and industrial (18%) demonstrating the versatility of green hydrogen.
- The MQA could use these applications to advocate for green hydrogen in the MMS.

Objective 2: To establish the factors impeding the implementation of green hydrogen technologies in the MMS.

Finding 5: The level of awareness and understanding of green hydrogen technologies, and therefore preparedness in the MMS in South Africa is very low.
The MMS mirrors the overall lack of awareness and understanding of green hydrogen technologies as a significant percentage of participants reported they were not sure of several questions asked during the survey. This was despite the survey participants having at least Grade 11 and the majority having degrees. A significant number has 6 years or more in the MMS. This lack of awareness makes it difficult to adopt green hydrogen technologies in these early stages of take-off.

Finding 6: South Africa has made significant strides in developing a legislative framework to drive green hydrogen, but lack of coordination of efforts and perspectives was found to be a crucial blocker. For example, the Presidential Climate Commission (PCC) sees climate change as a huge threat to water security, yet the green energy initiatives are not showing evidence of that realisation. There is need for increased coordination. On the legislative front, however, the findings are that there is still a lack of standards not only in South Africa but globally, making trade of green hydrogen difficult.

Finding 7: Fewer projects globally have reached Final Investment Decision (FID) and in South Africa green hydrogen technologies are at embryonic stage

Although there is growing interest in green hydrogen technologies, very few projects are past the "investment valley of death". In other words, final investment decisions (FIDs) are not happening at the anticipated pace. Several projects are either under pilot or planning phase. This is causing the MMS to be hesitant in developing green hydrogen plans beyond pilots.

Finding 8: South Africa's MMS has huge potential to ride on the abundance of renewable resources in wind and solar to lead the green hydrogen technologies drive, but it needs to overcome several barriers to achieve that. Regulatory uncertainty was identified as a major challenge to implementation of green hydrogen, with about 40% agreeing to that. Other factors identified from interviews included:

- Water scarcity
- Competition from other energy technologies
- Unreliability of electrolysers
- High price of green hydrogen (US$6/kg) when compared to, for example, grey hydrogen (US$1/kg)
- In addition to high upfront costs, green hydrogen has faced scalability issues.

Objective 3: To determine the nature of skills demand related to green hydrogen technologies in the MMS.

Finding 9: Green hydrogen technologies have potential for accelerating economic growth, and creation of jobs.

Green hydrogen technologies are anticipated to grow the economy, contribute to GDP and create 20 000 jobs per year by 2030, 30 000 jobs per year by 2040 and a total of 380 000 jobs by 2050. This is a significant contribution to the economy. Further, green hydrogen is important for the decarbonisation of the MMS, which has implications for skills development trajectory which will be driven by sustainability.

Finding 10: Currently there are no green hydrogen skills gaps, yet the risks of future shortages and mismatches are apparent.

Although there are no skills gaps now in the MMS, the future is at risk of skills mismatches unless coordinated efforts are done to ensure supply and demand for competences and skills are harmonised. This is crucial because, at the moment, qualifications, training programmes and anticipated green hydrogen skills needs are not synchronised. The top 5 technical skills at high risk of future mismatches as shown by respondents are as - material science (56%), renewable energy systems (53%), electrochemical engineering (42%), energy storage and grid (38%) and process control and automation (33%). There is a need to target renewable energy urgently as the sector is already implementing such technologies especially in the Northern Cape.

Finding 11: Several competences and skills are anticipated to be lacking in future.

The study finds that technical skills are at the highest risk of shortages in the future. Several competences were identified as important for the future of green hydrogen technologies: understanding hydrogen properties had the highest percentage of respondents with about 47%, testing, calibrating and maintaining hydrogen equipment (38%), knowledge of power electronics (36%), and fuel cells (29%). MQA interventions could be targeted at these opportunities to avoid mismatches in future. However, the other skillsets, such as business management skills and soft skills are becoming increasingly important. The soft skills identified include critical thinking, problem solving and communication. There is anticipated growth in demand for soft skills such as adaptability (44%), communication and stakeholder engagement (42%), problem solving and analytical thinking (40%), collaboration and teamwork (36%). Only 7% were not sure and 1% said none of these skills would be important in green energy technologies. This shows a high level of confidence for the respondents in terms of skills. This is not surprising as the green hydrogen technologies require a lot more collaboration, critical thinking and negotiation skills. For example, this study notes the need to negotiate with utilities actors for water or electricity wheeling. As such the green hydrogen managers need to be a lot more versatile.

Finding 12: There are several emerging skills that are essential for the green hydrogen technologies.

The study demonstrated the importance of looking at emerging skills such as artificial intelligence and machine learning (58%), digitalisation and internet of things (47%), policy and regulatory frameworks (47%), cybersecurity (40%), and sustainability and lifecycle assessment (31%). These are universally applicable skills for the MMS. The importance of developing a broad set of skills was therefore, strongly stressed; not just technical skills, but also general cognitive and meta cognitive skills such as problem solving and critical thinking, as well as transversal skills such as communication and teamwork skills. Therefore, the green hydrogen workforce is anticipated to be an agile workforce (flexible and adaptable), hard workforce (professional and dexterous), cognitive workforce (intelligent and analytical), emotional intelligent workforce: (self-aware and empathetic), and digital workforce competence (digital literate and digital interactive). This is the workforce that the MQA should thrive to create in "Mining Future Skills".

Objective 4: To determine the nature of skills supply in relation to green hydrogen technologies in the MMS.

Finding 13: Mismatch between certification needed and what higher education institutes are prepared to offer.

There is projected mismatch between certification needed for the hydrogen economy and qualifications/programmes in South African universities and vocational colleges. A total of 68 certifications is needed for the hydrogen economy whereas only 47 qualifications/programmes are available in South African higher education institutes. Gaps are mainly witnessed in Engineering Bachelors and Diploma.

Finding 14: The need for increasing digital technologies in training, education and the workplace it is becoming more apparent.

The study finds that by 2027; more companies will digitise and automate more roles. This is compounded by the finding that 44% of core skills are projected to change in the following five years. As core skills change and roles digitise, there is need to closely monitor the trends and focus on reskilling, upskilling and cross skilling. In the context of green hydrogen technologies, there is need to consider the different subsectors and their likelihood to transition to green hydrogen. PGM mining, and CLAS, for example, are likely to transition faster to green hydrogen due to the role of PGMs in the green hydrogen technologies. Meanwhile the CLAS subsector is one of the hardest to abate subsectors which are anticipated to benefit from green hydrogen technologies. Already, these subsectors have taken a lead in renewable energy adoption. The mineral sands subsector's proximity to coastal areas also provides access to seawater which could be useful for the technology. There is need to assess transferable skills and find ways to redeploy them. Organisations are beginning to innovate their business models, for example asking themselves if they are into coal mining or energy provision. The study finds coal mining to have more transferable skills into green hydrogen than other subsectors. However, the study finds there are challenges of anticipating skills needs in a time of profound change. Interview and workshop participants noted the need to make better use of the same technologies that are helping to drive change, such as AI, to help assess what these changes mean for future skills needs.

Finding 15: Workplace, education and training pathways are not keeping pace with industry and global trends.

On the job training is anticipated to grow over the coming five years with 81.2% of companies interviewed by WEF (2023) anticipating growth. The same study found that only 22.4% of companies anticipate hiring more significantly permanent staff, and 45.5% anticipated transitioning their workforce from declining roles to more growing roles. This has important implications as it means the MQA needs to focus on developing portable skills, and on the job training. New pathways of joining the workforce are needed where education choices and training should start with what the industry wants and not educating people and fit them into jobs. The MQA should pay attention to the dynamism in the sector, for example, the finding that companies anticipate hiring fewer permanent staff is aligned to the current restructuring happening in the MMS. It is important to perhaps keep a workforce training accounts and develop platforms for matching skills, training and jobs.

Finding 16: TVETS will play a crucial role, and so will Universities of Technology and other learning institutions.

This study finds that the demand for artisans and technicians will increase as the production of green hydrogen technologies gathers momentum. Therefore, there is need to build capacity of TVET colleges to offer National Certificate (Vocational) (NC[V]), NATED and Occupational Qualifications that are relevant and effective. A focus on engineering (chemical, electrical and civil) will be important in providing foundational knowledge and skills necessary to support the green hydrogen technologies development in the MMS in South Africa. Training at TVET colleges should be targeted at developing the three important capabilities that cut across different roles and qualifications which are to gain understanding of hydrogen properties, identify and manage hydrogen hazardous areas (safety and risk), and read and interpret technical drawings with hydrogen equipment. This is important at a time when the green hydrogen ecosystem is in the process of developing standards and guidelines to ensure uniformity. Currently, the challenge is that these standards and guidelines are not yet fully developed. TVETs are seen to provide an important pathway to work, and one which could be particularly useful for those preferring a more practical learning experience as well as for youth from many disadvantaged groups (including NEETs). The skills developed in TVET were also seen as critical in addressing skills shortages. However, a widely held concern was that too few youths today aspire to enrol in TVETs. Many spoke of the need to elevate the status of TVET in our societies. The need for training the TVET trainers was also highlighted.

Objective 5: To benchmark South African MMS with global best practices and level of development of green hydrogen technologies.

Finding 17: South Africa has made significant strides in developing a legislative environment at the back of renewable energy and PGM endowments, and the MMS has joined other global MMSs in advancing green hydrogen technologies.

In Europe, some sites conducted successful trials using a hydrogen-fuel blend with bio-derived components like meat and bone meal and glycerine to produce bio-based green hydrogen. In North America, a cement company has been actively involved in green hydrogen initiatives to incorporate hydrogen as a fuel in cement production processes to further decarbonize their operations across locations. An Australian mining company has begun testing hydrogen and ammonia fuel systems in mining locomotives, to decarbonize rail fleet. They are exploring various configurations and plan to roll out hydrogen-powered locomotives across their mining operations by 2030 as part of a broader carbon neutrality target. South African MMS companies have not yet introduced green hydrogen trials in the CLAS sub-sector where other countries are making inroads. Like other regions, the sector has made significant progress in renewable energy deployment, which is important for green hydrogen. However, in the PGMs, a mining company has partnered government, financial institutions, and other energy actors to develop a fuel cell powered haul truck.

This puts South Africa in good stead to be among leaders in green hydrogen technologies. Regarding opportunities, South Africa is endowed with renewable energy and the PGMs which are sources of competitive and comparative advantage globally. This provides the MMS in South Africa with a huge opportunity to benefit from green hydrogen's potential to decarbonise an otherwise hard to abate sector. Other countries, such as the UK, are making efforts to integrate green hydrogen in cement production. As in other countries, South Africa faces challenges such as huge upfront costs, lack of financing, lack of a market, high cost of electrolyser, and water scarcity, which may require desalination (an expensive process). The other renewable energy sources are currently having competitive cost advantages. This requires significant investment in research to drive down these costs.

Objective 6: To propose strategies for the MQA to deliver on green hydrogen technologies in the MMS in South Africa

Finding 18: The MQA could utilise skilling, upskilling, re skilling, cross skilling and multiskilling in line with different sub-sectors' likelihood of adopting green hydrogen technologies and the employee's skills transferability to green hydrogen technologies

Utilising a four-quadrant framework (figure 36), the study identified initial skill development for people who have not yet exposed to any skills, reskilling, upskilling, cross-skilling and multi-skilling for different quadrants depending on whether the people have complimentary skills or none. People with complimentary skills may require cross-skilling and upskilling. It is important for the MQA to address existing and anticipated migration of skills from declining sectors like coal mining and to emerging green hydrogen technologies in other sectors. The MQA will need to develop a clear vision for the sector, pathways for education and training, and an enabling environment for learning where no one is left behind. Collaborations and partnerships are important for driving green hydrogen technologies because by nature the technologies are interlinked, with several suppliers, producers, and consumers.

Towards a skills-based green hydrogen technologies network development framework for the MMS

The study finds that the skills development process will be gradual, yet the MQA and other stakeholders need to pay attention to the small changes that will keep unfolding. Building on the Actor Network Theory, the study argues that the socio-technology network building process will follow five stages and at each stage the MQA will need to adjust its skills development strategies, as illustrated in Figure 43.

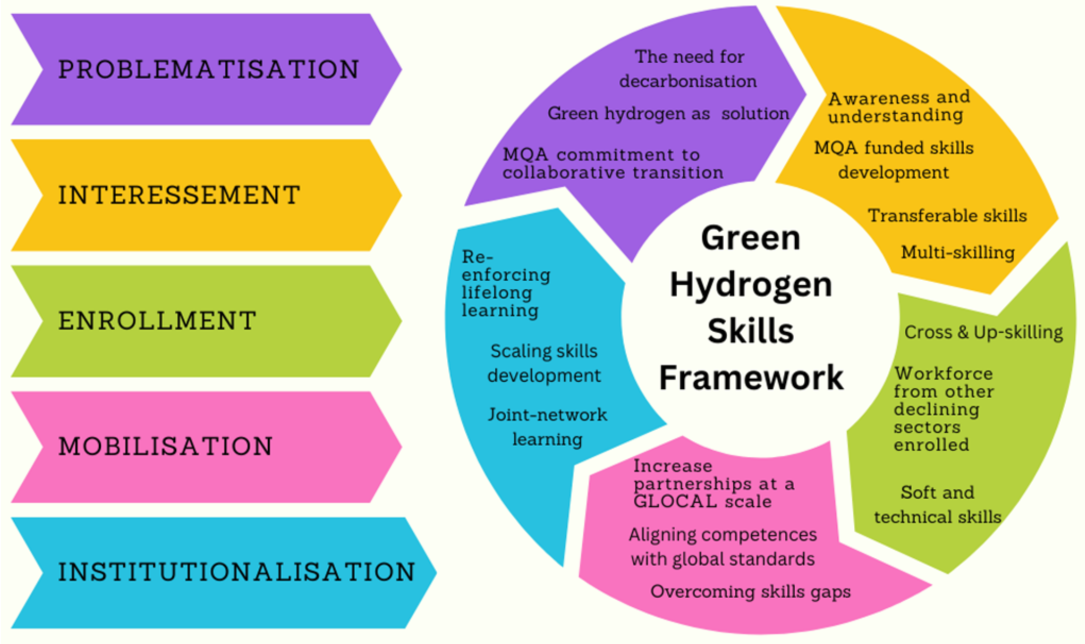

Figure 43: The Green Hydrogen Skills Framework

The first phase will be the *problematisation period*. Currently, the MMS seems to appreciate the urgent need for decarbonisation as reflected by the increased investment in renewable energy, particularly wind and solar. However, what seems to be the missing link is the argument that green energy is the only viable solution to sustainable decarbonisation. Raising these arguments and requires the MQA and other stakeholders to increase investment in research, innovation and development to reduce the cost of green hydrogen and to build a business case for the resource to gain the 'best solution' tag.

The following phase is *interessement* where the focus is on building interest. This phase is important for generating interest in the industry for green hydrogen as a solution by building awareness and understanding. From a skills development standpoint, this entails focusing on technical, business management and soft skills. This is important to develop the required skills for collaboration and negotiation needed with multiple stakeholders. Skills development is important for the industry as well as the MQA personnel to understand green hydrogen technologies. Gaining interest in green hydrogen is important for recruiting current and future workforce to work in the resource, which is expected to generate about 380,000 jobs by 2050.

The time to begin generating interest and building that future is now in line with the MQA idea of Mining Future Skills.

The *enrolment phase* entails enrolling stakeholders, including partners and learners. The MQA will need to ensure that the stakeholders cover the entire hydrogen value network, including TVETs and other learning institutions. In doing so, the focus will be on ensuring inclusivity where women and the previously marginalised are included. As some skills will be coming from other sectors, cross skilling and upskilling will be important. This study shows that much of the training is currently on chemical engineering and very little targeted on green hydrogen. This means the alignment of qualifications alongside the need to encourage lifelong learning will be important. Digital skills development will gain increased demand and therefore the MQA will need to proactively invest in train the trainer initiatives targeted at green hydrogen technologies. An idea echoed during the Energy and Mining Skills Forum was the lack of skills on the part of the trainers from TVETs and Universities. This training, including machine learning and AI, should be integrated in the trainers and MQA staff to be able to understand big data analytics.

The *mobilisation phase* is when the green hydrogen technologies generate participation from GLOCAL (Global and Local) collaborators. The MQA needs to integrate global partners so that the development of green hydrogen technologies skills is in line with global standards and practices. Currently the world does not have established standards but as they emerge, MQA and stakeholders need to embrace the emerging reality of a transitioning MMS. Although currently there are no skills gaps related to green hydrogen technologies, it is anticipated that by the time the technologies mobilise, there could be some skills mismatches. The strategy should begin to prepare now and build some social safety nets for the workforce from other industries, sectors and that could be declining.

The final phase is *institutionalisation* which refers to a stage when green hydrogen is taken for granted. This is when it becomes a norm for the MMS to use or integrate green hydrogen technologies in the energy mix for decarbonisation. This requires legitimating green hydrogen for the sector. Thus, it is important to ensure development of a complete workforce which is agile workforce, hard workforce, emotional intelligent workforce, digital workforce, soft workforce. To achieve this the MQA will need to develop a compelling vision, develop skills development pathways and ensure it creates an enabling environment for everyone to learn and contribute to the green hydrogen technologies space.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

South Africa is well-placed to emerge as a key player in the global green hydrogen economy. With its abundant renewable energy resources and PGMs important for green hydrogen technologies, proactive policy initiatives, and strong international partnerships, the country has the potential to lead the world in clean hydrogen production. However, to realize this potential, South Africa must overcome significant challenges related to low levels of awareness, infrastructure, regulation, and the just transition from coal, high upfront costs and competition faced from green hydrogen alternative energy technologies. If these hurdles can be addressed, South Africa's green hydrogen sector could become a cornerstone of its economic future, contributing to both national development, job creation and global climate goals. The MQA has an important task of developing the needed skills demand emanating from this new technology. These are technical as well as soft skills. This will be important considering that the current level of preparedness of universities and vocational institutes to offer training is far behind the expected increase in demand as we approach 2030 and beyond. Although the country has not faced green hydrogen skills shortages, there are risks of shortages soon when the technologies gather momentum.

Benchmarking against other countries has shown that South Africa in good stead to be lead in the green hydrogen technologies as the country has made significant strides in renewable energy deployment and haul truck piloting, institutional frameworks development, and the MMS has shown leadership in the establishment of the Green Hydrogen Valley in the country. There is therefore need for partnerships and collaboration with other SETAs and the private sector locally and globally to ensure the sector is ready for the anticipated growth of the technologies.

5.2 Recommendations

The following recommendations are based on the key objectives and main findings of the study and are presented according to the SMART framework, which ensures that the recommendations are Specific, Measurable, Achievable, Relevant, and Time-bound.

Recommendation 1: Develop a green hydrogen workforce development plan

The is a need for MQA to develop a green hydrogen workforce development plan. The plan should be anchored on a solid vision for the sector's skills direction and aim to develop a workforce with the necessary skills to support the adoption of green hydrogen technologies important in the MMS. This study has identified the skills which will be important to take the sector forward. Although the study found that there are currently no skills shortages, the risk for future skills shortages is quite high and the sector will need to proactively prepare for the anticipated acceleration of the green hydrogen technologies, expected to generate 20 000 jobs per year by 2030 and 30 000 jobs per year by 2040 and a total of 380 000 jobs in total by 2050. This is approximately 80% of the current employment levels of the entire mining sector. The workforce development plan should utilise these estimates to inform skills development. This study has identified the green hydrogen technologies important in the MMS. MQA could build on these technologies to develop the needed skills. The following steps are important for MQA to develop a compelling vision.

i. The SETA should conceptualise a compelling and strategic green hydrogen technologies vision of the future the sector wants.
ii. The SETA should identify the type of skills that are needed to achieve this strategic vision (this study has identified them).
iii. The SETA needs to set out a plan to develop these skills.
iv. Implementing these skills strategies requires harnessing the energy and commitment of social partners and stakeholders, as there are limits to what the SETA can achieve on its own.

Activity	**Develop a *Mining Future Skills Development Programme* at three levels – basic, fundamentals and practice** **Lobby DHET to fill the gap of 21 qualifications missing in SA** **Develop a green hydrogen workforce development plan, including:** - **national and regional committee** - **a monitoring and evaluation framework** - **a learner and employed platform**
Timeline	1 to 2 years

Recommendation 2: Develop a green hydrogen technologies awareness and understanding campaign

This study found a very low level of awareness and understanding of green hydrogen technologies in the MMS. The MQA could create an awareness campaign to educate stakeholders about the basics, benefits and opportunities of green hydrogen technologies in the MMS. The challenges that are faced in the green hydrogen technologies implementation are important for stakeholders to know. Specifically, the campaign should focus on *problematising* the challenges that green hydrogen technologies seek to address which are summed as the energy trilemma of energy security, access, and sustainability. Second is for the campaign to *raise interest* for more sector and stakeholder participation which is a crucial condition necessary to build critical mass for the technologies to be economically viable. The sector needs to understand the benefits, such as employment creation and associated structural transformation, industrial diversification and economic growth, and assisting to decarbonise and meet their green targets. Additionally, for PGM mining sub-sector this generates alternative uses that sustains the sector. This helps to *enrol* more stakeholders to actively participate in building the green hydrogen technologies network. Over time, the campaigns will need to focus on mobilising participation of other sectors within the country and beyond to support the network to grow and finally *stabilise,* and for green hydrogen to become seen as the *institutionalised* energy resource to decarbonise the MMS which is one of the hard-to-abate sectors.

Activity	**Develop a green hydrogen awareness campaign in the MMS, include roadshows, digital newsletters, digital media, school hydrogen competitions**
Timeline	Annually

Recommendation 3: Create learning and career pathways that lead to new green hydrogen technologies opportunities

Key informants noted the many factors that highlight the need for improving learning and career pathways to new opportunities. This is underscored by the need for the sector to overcome the challenge and risk that comes with preparing youth for professions that do not yet exist and balancing that with opportunities that are envisioned in a fully hydrogenised MMS. This study has developed a matrix of four quadrants based on the sub sectors exposure to green hydrogen technologies and the compatibility or transferability of skills that employees already have or miss (Figure 37: *Exposure to green hydrogen transition, skills compatibility and skilling strategies*. We recommend that career pathways be based on that matrix. For example, the cement, mineral sands, PGMs mining, and gold mining sub-sectors are hard to abate and therefore more likely to lead the green hydrogen transition. The coal mining subsector is at high risk of scaling down as the economy decarbonises. Pathways need to take cognisance of these details in order to introduce specific interventions.

Recommendation 4: Create a framework to enable everyone to develop the green hydrogen skills needed in the future

The MQA is recommended to create a framework to enable the development of green hydrogen technologies skills for the future. This should be done by integrating formal learning, informal learning, and non-formal training to allow everyone to learn. The importance of investing in the integration of new entrants to green hydrogen technologies by supporting the recognition of previous qualifications, degrees and skills, as well as access to further education and training was also noted. This is important as there are no green hydrogen qualifications or degrees except for isolated modules in other programmes. Going forward, it is important to align the current qualifications and identify additional training that recognises current capabilities and competencies. The other challenge relates to the low value accorded to TVET qualifications. There is need for concerted efforts to collaborate with industry, stakeholders, and communities to build confidence to avoid a situation where TVETs do not have the required learner supply base. This due to no one wanting to take up courses or as graduates have no jobs due to being perceived to be unready for the job market. The framework should aim at capitalising on the NEETs. Such a framework should be inclusive to carter for women, the disabled and other marginalised groups.

Activity	**Create learning and career pathways that lead to new green hydrogen technologies and opportunities (lifelong and lifetime learning)** - **formal, informal and non-formal education and training, gamification** - **introduce games for basic, senior and young employees, integrated VR** - **Roadshows to recruit learners, train the trainer initiatives**
Timeline	2 to 3 years

Recommendation 5: Develop sector-led green hydrogen standards for the MMS

It is recommended that the MQA collaborate with industry stakeholders to develop standards for green hydrogen technologies in the MMS. This study found that the lack of standards and clear policies was a major challenge for the development of the green hydrogen technologies in the country and in the MMS. It is recommended that the MQA takes a leading role in advocating for sector-led green hydrogen standards for the MMS. This is achievable through partnering with the South African Bureau of Standards (SABS) and industry experts to align the standards with international best practices.

Activity	**Sector-led green hydrogen standards for the MMS should be established. Engage stakeholders, unions, mining companies, OEMs, academics through virtual and provincial roadshows**
Timeline	Once-off by 2028

Recommendation 6: Develop a GLOCAL collaboration strategy and enrol international and local partners for green hydrogen

A GLOCAL collaboration strategy is centred on global collaborations that have local impacts. Such a strategy also focuses on collaborations with local actors including but not limited to SETAs. A typically example of a local partnerships is the MoU that the MQA, TETA and CHIETA formed recently to establish the Green Hydrogen Centre of Specialisation (CoS) at CSIR. However, the MQA could leverage the existence of the CoS to partner with international organizations and research institutions to leverage expertise and best practices in green hydrogen technologies. International collaborations and partnerships allow MQA to attend international conferences, engage with industry associations, and participate in global research initiatives. Collaborations should focus on the entire value network as it is important to build a comprehensive green hydrogen ecosystem in South Africa and globally for the MMS to thrive in these technologies. This study finds that the sector will not achieve green hydrogen transformation unless it collaborates with other sectors, including EWSETA, and merSETA. Green hydrogen technologies require usage of significant amounts of renewable energy, water and land, which makes the active participation of local governments important.

Activity	**Develop a GLOCAL collaboration strategy and enrol international and local partners for green hydrogen** **Develop a green hydrogen skills pact with local partners, leverage partner research to enrich initiatives** **Develop a green skills committee, leverage partner support to enrich initiative** **Develop a green hydrogen skills forum with local partners, leverage partner footprint to enrich initiative**
Timeline	Once off, by Q4 2028

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