School of Mining Engineering

INVESTIGATING THE INTRODUCTION OF FUEL CELL TECHNOLOGY IN UNDERGROUND MINING EQUIPMENT

Lesego Mokgethi

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2025

DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

I have familiarised myself with the University of the Witwatersrand Student Academic Misconduct Policy (SAMP). I hereby declare that the work I am submitting for assessment is my original work. I affirm that I have not plagiarised, misrepresented, or colluded with any other person or source. I have properly acknowledged, cited, and referenced all the sources that I have used in my work. I also declare that where I have used artificial intelligence (AI) tools it has only been as a means of guidance. The ideas and arguments presented in my work are my original thoughts and interpretations. I acknowledge that any academic misconduct, such as plagiarism or collusion will result in serious consequences. According to the SAMP, these consequences may include a reduced grade, a failure mark, or disciplinary action. The Faculty of Engineering and the University of the Witwatersrand have my consent to investigate any potential academic misconduct in my work. This investigation may include the use of similarity and AI detection software to check the originality of my work. I undertake to abide by the decision of any such investigation.

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19 day of March, 2025

(month) (year)

“Without commitment, you’ll never start.

But more importantly, without consistency, you’ll never finish”

Denzel Washington

ABSTRACT

Fossil fuels, which are major energy sources, have harmful effects on the environment, and their continued use contributes to global warming and climate change. Moreover, diesel combustible engines in underground mining machinery emit noise, diesel exhausts, and heat during operation, creating an unfavourable working environment. Diesel particulate matter has been classified as a human carcinogen, and occupational exposure limits have already been established in other countries and are anticipated in South Africa.

The research investigated the introduction of hydrogen fuel cell technology in underground machinery, particularly the diesel load haul dump machine, to mitigate harmful emissions during their operation and promote the use of renewable energy. The objectives of the study entailed assessing the effects of diesel exhausts in underground working environment, as well as actions taken to reduce emissions. The study also looked at the key aspects that need to be considered to support the application of fuel cell technology in mining operations, constraints affecting their adoption and status of existing regulations and policies.

The application of hydrogen fuel cell technology in the mining industry would promote the beneficiation of platinum and other minerals in South Africa, further contributing to economic development and growth. The successful implementation of hydrogen fuel cell technology would also result in a healthier working environment for underground employees and would be a step towards achieving a carbon-free environment.

The study employed a mixed-method approach. Data was collected through semi-structured interviews conducted with relevant subject matter experts within the mining industry. Measurements of the operating environment were taken, and the maintenance requirements of the current internal combustible engines and site visits to different sections of the case study mine were conducted.

Diesel fuelled machines have harmful effects on the working environment and contribute to global warming. Measures put in place to reduce effects of diesel exhausts affect productivity and are mostly human dependent such as effective use of personal protective equipment. During the design stage, key considerations

such as the environment, performance and emissions requirements must be studied. Prior to implementing fuel cell technology in underground mining equipment, sufficient testing must be done to ensure reliability and reduce repair costs. To ensure the smooth implementation of Hydrogen Fuel Cell (HFC) in underground equipment, adequate assessment of the skills and training will be required. Existing regulations and policies must be reviewed, and new policies must be introduced to support hydrogen fuel cell technology and to increase investment in the South African hydrogen economy.

With the worldview shifting towards a sustainable environment and development, all research and development that supports renewable energy is critical. Research and development to reduce capital costs of HFC technology through improved processes and large-scale production must be done.

Keywords

Greenhouse Gas Emissions; Renewable Energy; Hydrogen Economy, Fuel Cell Technology, Diesel Exhausts Emissions.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms	**Description**
AFC	Alkaline Fuel Cell
BUR	Biennial Update Report
CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
°C	Degrees Celsius
Db	Dry bulb
dB	Decibels
DEE	Diesel Exhausts Emissions
DMFC	Direct Methanol Fuel Cell
DMRE	Department of Mineral Resources and Energy
DST	Department of Science and Technology
EMS	Energy Management System
EPA	Environmental Protection Agency
FC, FCs	Fuel Cell, Fuel Cells
FCE	Fuel Cell Electric

FCEVs	Fuel Cell Electric Vehicles
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHGs	Greenhouse Gases
GHGE	Greenhouse Gas Emissions
GWP	Global Warming Potential
HEG	Homogeneous Exposure Group
HFC	Hydrogen Fuel Cell
HFCs	Hydrofluorocarbons
HySA	Hydrogen South Africa
ICEs	Internal Combustible Engines
IMC	Inter-Ministerial Committee
Kg	Kilogramme
kWh	Kilo-Watt hour
LDV	Light Duty Vehicle
LHD	Load Haul Dump
MPa	Mega Pascals
MCFC	Molten Carbonate Fuel Cell

MEA	Membrane Electrode Assembly
mg/m3	Milligrams Per Cubic Meter
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrogen dioxide
OEL	Occupational Exposure Limit
OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PFCs	Perfluorocarbons
PGMs	Platinum Group Metals
PPE	Personal Protective Equipment
PPM	Parts Per Million
RPM	Revolutions Per Minute
SAP	Systems, Applications and Products in Data Processing
SF_6	Sulphur Hexafluoride
SOFC	Solid Oxide Fuel Cell
SPOA	Special Point of Accountability
TTM	Trackless Mobile Machinery

UNFCCC	United Nations Framework Convention on Climate Change
US$	United States Dollar
UV	Utility Vehicle
Wb	Wet bulb
WRI	World Resources Institute
WBCSD	World Business Council for Sustainable Development
ZAR	South African Rand

1 INTRODUCTION

1.1 Purpose of the Research

Research into creating effective fuel cell (FC) technology for use in renewable energy is necessary to meet the demand for a cleaner, sustainable environment free of carbon emissions. Alternative renewable energy sources are being developed in response to South Africa's current energy crisis, which is impacting various businesses, particularly the mining sector. More so, climate change and its consequences also necessitate moving from internal combustible engines (ICEs) and fossil fuel energy resources to clean, renewable energy sources.

Platinum is an element used as a catalyst in fuel cells (FCs), and Figure 1.1 shows the world's Platinum Group Metals (PGMs) supply, indicating that South Africa is the largest supplier in the world followed by Russia. The potential of FC technology is demonstrated in numerous applications, including use in the home, transportation industry, portable devices, as an efficient component of energy storage systems, green hydrogen, and wastewater treatment (Olabi, et al., 2023). It is, therefore, essential to research the use of platinum FCs to increase contribution to the country's economic growth and development as outlined in the National Platinum Strategy for South Africa. The strategy aims to ensure that the South African PGM resources, which are the largest in the world, realize value addition resulting in the creation of more than one million jobs and a R8.2 trillion contribution to the country's Gross Domestic Product (GDP) by 2050 (Minerals Council South Africa, n.d.).

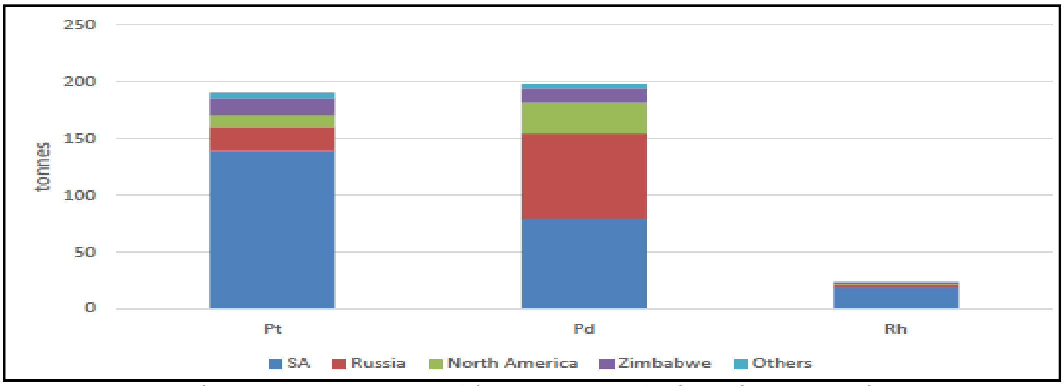

Figure 1.1: 2017 World PGMs supply (Matthey, 2018)

An increase in FC application and commercialization is also expected to facilitate the creation of local markets and the development of the required infrastructure. This is taken from the evidence in countries such as China and Europe, where the construction of hydrogen refuelling station is expedited to promote the commercialization of Fuel Cell Electric Vehicles (FCEVs), (Luo, et al., 2021). This will, in turn, facilitate local consumption, increase downstream beneficiation of platinum, and encourage industrial growth. The beneficiation of platinum through the application of FC technology in the mining industry is also expected to improve the overall environmental conditions and production efficiencies in the mining industry as FCEVs have low refueling times, are fuel efficient, and emit zero emissions during operation (Olabi, et al., 2023).

1.2 Research Background and Context

Fossil fuels are the main contributors to South Africa's energy supply. Figure 1.2 shows the South African energy mix supply by technology type. Figure 1.2 indicates that in 2020, 79% of the country's supply was from coal, 1% from diesel, which are fossil fuels, 10% from hydro power, and 5% each from nuclear and solar wind, which are renewable energy sources.

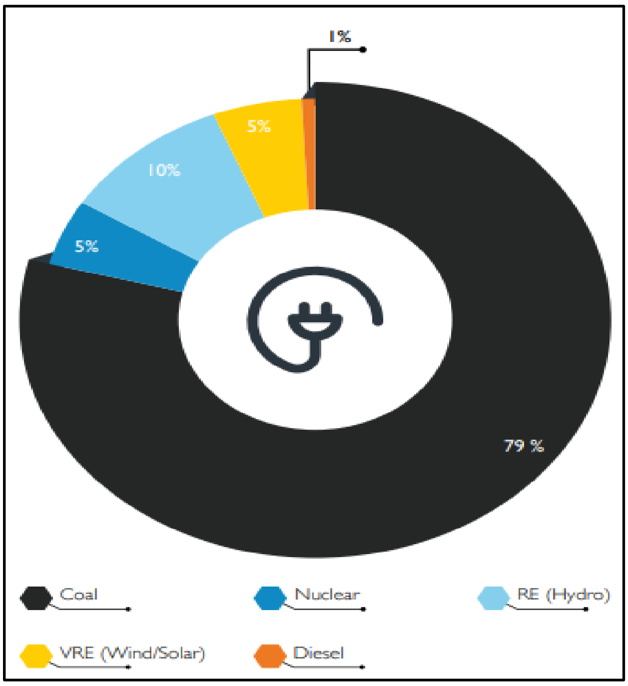

Figure 1.2: 2020 South African energy mix supply by technology type (Source: CSIR; Department of Science and Innovation, 2021a)

While fossil fuels remain the major supply of primary energy, there are issues and concerns associated with their use. Figure 1.3 shows the global monthly prices for crude oil, coal, and natural gas indices from 2020 to 2023. The figure also indicates the instability of the fossil fuel prices. The instability of the prices of fossil fuels is due to them being finite resources and as such they are associated with significant extraction and operating costs. Also, countries and regions with high supply hold significant geopolitical power, making their prices vulnerable to international conflict (Melodia and Karlson, 2022). The use of fossil fuels negatively impacts the environment, climate and health (Bertrand, 2021).

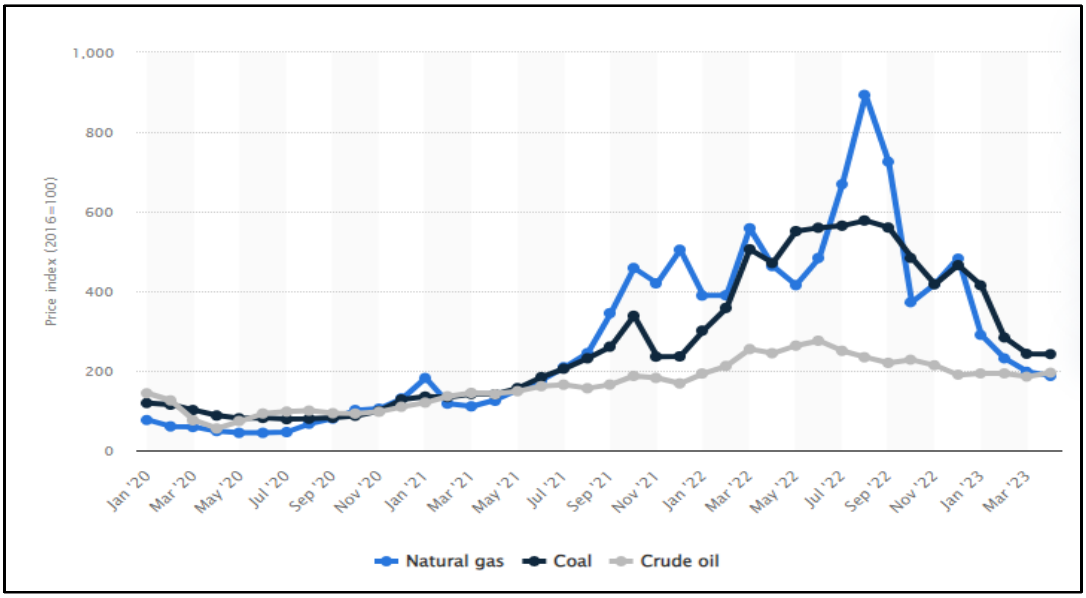

Figure 1.3: Global monthly fossil fuel price indices 2020-2023 (Statista Research Department, 2023)

According to Sharaf and Orhan (2014), FCs are considered the most promising contenders for energy conversion in the future because of the numerous benefits they possess over traditional ICEs. Compared to other propulsion technologies, hydrogen-powered FCEVs have a simple assembly, are quiet in operation due to fewer moving parts, have higher efficiencies, and only emit water and heat when operated (Olabi, et al., 2023). While there are benefits associated with the adoption of FCs, there are several factors that hinder their commercialization which needs further research and development. These factors include the inadequate existing hydrogen refueling infrastructure, economies of scale production, high capital requirements, and the reliability of FC technology (Olabi, et al., 2021).

This research aims to investigate the benefits, limitations, and opportunities associated with the application of FC technology in underground machinery, in particular the Load Haul Dump (LHD), to further reduce heat, noise, and harmful emissions.

1.3 Problem Statement

An investigation into the introduction of fuel cell technology in LHDs was conducted at Mine A.[1] Mine A is a shallow board and pillar trackless platinum mine, located on the Western Limb of the Bushveld Complex, 12km east of Rustenburg in the North West Province of South Africa. On Mine A, PGMs are mined from underground workings at a depth of 330m below surface.

Currently, internal combustible engine LHDs are used on Mine A. These LHDs are fuelled with diesel and are emitting diesel exhausts during loading and hauling of broken ore. The LHD operation, therefore, directly affects employees' overall health, particularly tip attendants and LHD operators. The use of diesel fuelled LHDs exposes workers to diesel emissions, which can cause oxidative stress, inflammation and respiratory issues (Pronk, et al., 2009). Table 1.1 shows the average fuel consumption per fleet type over a three-month period. The focus during the research was on LHDs as they represent the largest percentage of the mine’s fleet and they also contribute, on average, 70% of the total diesel consumption.

Table 1.1 Percentage of diesel consumption per fleet type (Source: Mine A, 2023)

Fleet Type	**Quantity**	**Diesel % Consumption**
LHD	27	70
Utility Vehicle (UV)	10	20
Light Duty Vehicle (LDV)	16	5
Drill Rigs	2	2,5
Bolters	2	2,5
Total	**58**	**100**

[1] Mine A is a pseudonym given to the mine that was used for the research study for confidentiality purposes.

Diesel exhausts emissions (DEE) are categorized as human carcinogens connected to heart and lung-related conditions (Maximilien, et al., 2017). Furthermore, the use of diesel engines is concerning due to the noise and heat emitted during their operation, contributing to uncomfortable and unhealthy working conditions. Due to the need to dilute the heat and fumes released, using diesel-powered engines also increases the need for and expense of ventilation. In view of the concerns relating to diesel LHDs, work has been conducted at Mine A to improve the quality of diesel used and to upgrade the engines used on LHDs.

Mine A is currently implementing Diesel Particulate Matter (DPM) filters on the LHD exhaust system to mitigate the effects of DEE. The implementation of DPM filters is increasing the operational and maintenance costs of diesel LHDs. Given the limitations of DPM filters, such as the melting of filters due to excessive heat and fire risks, it is essential to explore alternative solutions such as the application of fuel cell technology application in underground mining machinery. This will provide a viable solution to mitigate concerns associated with diesel exhaust emissions, that is their contribution to climate change through greenhouse gas (GHG) emissions and the negative effects on worker health.

1.4 Research Objectives

The aim of the study is to investigate the introduction of FC technology in underground mining machinery to reduce the exposure of employees to harmful diesel exhausts emissions, and to reduce greenhouse gas emissions into the environment. The objectives of the research are to:

- Evaluate the effects of diesel exhausts in the underground working environment and its contribution to greenhouse gas emissions.
- Assess the actions taken to minimise employees' exposure to diesel exhausts in the underground working environment.
- Identify the key aspects that need to be taken into consideration during the design and implementation of FCEV in an underground mining working environment.
- Compare the capital and maintenance costs of ICE and FCEV LHDs.

- Identify constraints affecting the implementation and commercialization of FCEV in the mining industry.
- Establish the status of existing regulations and policies to support hydrogen and fuel cell technology in South Africa.

1.5 Justification for Research

It is essential to use and investigate available technologies to improve the health and safety of mine workers and the environments they get exposed to during the operation of diesel exhaust LHDs. Research on FC technology applications as a renewable energy source is essential to counter climate change and secure a cleaner and sustainable environment, specifically in South Africa's mining industry.

The application of FC technology brings a myriad of benefits that include reduced noise and harmful emissions to workers, and this is in line with current and anticipated legislation requirements. Unlike in countries in the European Union, the Occupational Exposure Limits (OEL) for DPMs in South Africa have not yet been established, this is due to several factors limiting its control requiring careful consideration. However, efforts have been made to determine the exposure limits as South Africa shares the same health concerns associated with DPM exposure as the other countries. Thus, it is anticipated that OELs will be gazetted, and mining companies will be expected to comply (Department of Mineral Resources, n.d.). As such, the use of FC technology in underground machinery will assist to position mining companies to complying with the expected regulations.

The adoption of FC technology will also assist the mining industry to be competitive in terms of improved production efficiencies and attract investors locally and globally as they will be compliant with global GHG emissions. FCs have faster starting times due to their low operating temperatures, low refuelling times and higher operating efficiencies when compared to combustion engines (Jamal, et al., 2023). At Sibanye-Stillwater, the research is anticipated to contribute to the companies' Environmental Social Governance (ESG) Policy and commitment to promoting awareness and driving initiatives to combat the impact of global warming. (Sibanye-Stillwater, 2021).

At a national level, the application of FC technology is promoted as it provides the country with the opportunity to benefit from PGMs in alleviating socio-economic issues through value addition. The promotion of downstream beneficiation of platinum will be accomplished because of the use of platinum metal as a catalyst in the application of FC technology. The expansion of FC technology commercialization and application also offers benefits in terms of the development and growth of the necessary infrastructure.

1.6 Structure of the Research Report

The research report consists of five chapters. The overview of the chapters is outlined below:

Chapter 1 is the introduction, which covers the background of the research topic, the problem statement, the research objectives, and the justification for the research.

Chapter 2 discusses the literature review done during the research, covering fundamental aspects related to the topic. These include fuel cell and hydrogen technology, greenhouse gas emissions and their impacts on the environment, and constraints of South African mineral beneficiation.

Chapter 3 describes the research methodology applied, and the sources of the data collected during the study. It explains the approach followed with data collection and analysis, including how ethical considerations were applied. Criteria for how the research validation and reliability were considered and achieved are also discussed.

Chapter 4 presents the results and analysis of the data collected. The results are structured and discussed in accordance with the study's objectives. This chapter includes key findings and discussions.

Chapter 5 presents the conclusion reached from the research study and recommendations made based on the key findings.

2 LITERATURE REVIEW

2.1 Chapter Introduction

The literature review discusses five extensive topics, that are, the effects of diesel exhausts emissions on the underground working environment, the contribution of GHG emissions to climate change and global warming, hydrogen, and fuel cell technology as renewable energy, and the relevance of PGMs to the hydrogen and FC technology. The chapter further discusses the relevance of FC technology in South Africa and the mining industry in reducing carbon emissions which is in line with anticipated regulations and commitments as stipulated in the Paris Agreement. The chapter concludes by analysing the progress and impact that policy and legislation have had on the development of renewable energy (hydrogen fuel cell technology) in some countries, from which South Africa can learn and gain insight.

2.2 Diesel Exhausts Emissions in Underground Working Environment

Diesel engine machinery have been in use in the South African underground mining industry as far back as 1928 (Belle, 2008). The utilization of conventional diesel machinery such as LHDs and locomotives in underground mining environments leads to exposure of the mine workers to contaminated breathable air. Exposure of mine workers to DEE has been linked to an increase in cancer and cardiopulmonary diseases. Due to the confined nature of the underground mining environment, underground mine workers are likely to be exposed to diesel exhaust emissions (diesel particulate matter) than workers in any other industry (Maximilien, et al., 2017).

DPMs were classified as a class 2a probable carcinogen by the International Agency for Research on Cancer in 1989 and subsequently reclassified to class 1 definite carcinogen to humans in 2012 (Landwehr, et al., 2017) . DPM is composed of elemental carbon, organic carbon, sulphuric and ash compounds that increase health risks if inhalation of these gasses is endured long term (Jacobs, et al., 2019). Long term exposure to DPMs also has detrimental health effects on the lungs, brain, and the heart as well as a heightened risk of increased blood pressure, thrombosis and DNA damage. Mine workers with pre-existing conditions such as asthma and other respiratory conditions were found to be at a higher risk than their healthier counterparts. Studies on short term exposure to DPMs on healthy non-smoking individuals also showed negative impacts on health such as nasal and eye irritation, headaches and bronchial inflammation (Ping and Guang, 2017).

The use of diesel-powered engines is also associated with high operating costs resulting from refrigeration and ventilation systems, which must be installed to manage the heat and dilute exhaust fumes from diesel-powered engines. The ventilation needs for a specific mining operation can sometimes be influenced by the number of diesel engines operating in that vicinity, this results in an increase on the ventilation costs. Other costs such as flame-proofing the diesel equipment and fuel costs also add to the operating costs of diesel-powered machinery. In addition, to decrease the emissions produced by diesel-powered equipment, the industry has implemented engine filters and cleaner diesel fuel to minimize the emission levels (Moore, 2019).

2.2.1 Actions taken to mitigate exposure to diesel exhausts emissions

The control of diesel exhausts emissions was not thoroughly researched until the late 1980s when a link between DPMs and lung cancer was discovered and this led to US mining regulators initiating research studies towards potential controls. A variety of control methods were considered, such as low emission engines, fuel quality, proper maintenance strategy and particulate filters (Davies, 2004).

The control measures that are being considered and implemented to mitigate exposure to DEE in the mining industry ranges from substitution, engineering, administration, which includes education and training, noise demarcation zones and the use of Personal Protective Equipment (PPE). The concept of the hierarchy of controls by the Occupational Safety and Health Act (OSH Act) of 1970 is a method used for recognising and prioritising safety measures for keeping workers safe from hazards. Figure 2.1 from the National Institute for Occupational Safety and Health (NIOSH) shows the hierarchy of controls, ranked from the least effective to the most effective (NIOSH, n.d.).

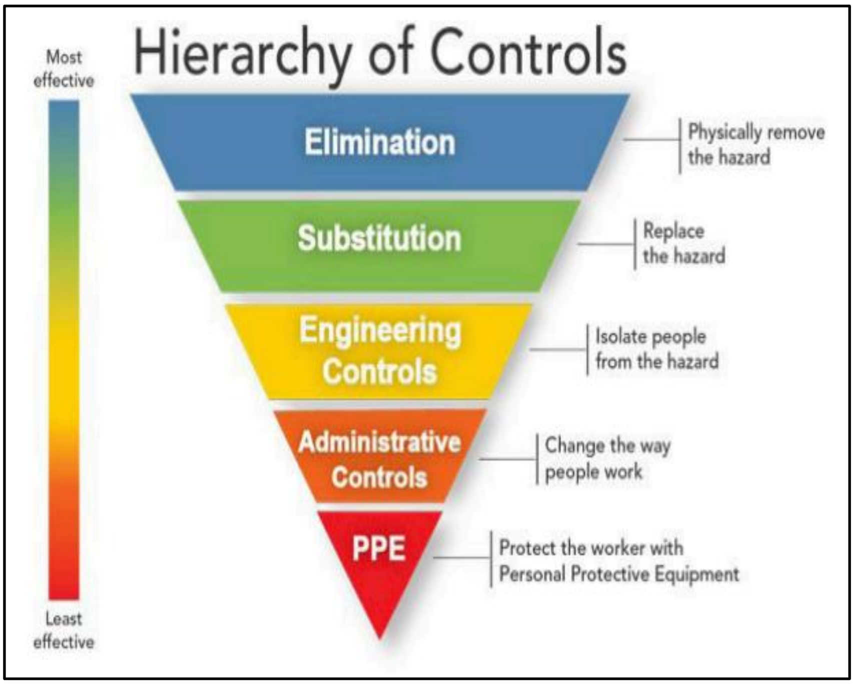

Figure 2.1: Hierarchy of controls, Source: National Institute for Occupational Safety and Health (NIOSH, n.d.)

Over the years, the technology has evolved as the diesel engine technology has evolved and the results have been improved efficiencies in lowering diesel exhaust emissions. Diesel oxidation catalytic converters have been in use over the last five decades to reduce the emissions from diesel machinery (Bugarski, et al., 2015).

The concerning health risks that DPM possess to employees requires that they be minimised, diluted or even completely removed from the underground working environment to prevent working conditions that are unhealthy for workers. Over the years, research was done to improve control technologies with specific reference to vehicles that are operational in underground working environments. Apart from filtration systems of exhaust and using engines with low emissions, minimising employees' exposure to DPM also includes possibly placing workers in environments that are ventilated. Moving towards equipment that does not require diesel to operate, providing employees with personal protective equipment, ensuring that the maintenance of engines is done efficiently (Jacobs, et al., 2019). Implementing effective controls, as shown by the hierarchy of controls model, means that the controls should prioritize engineering solutions or substitutions to remove the hazard, that is the exposure of DPMs.

Many leading mining countries have passed regulations to limit DPMs exposure in underground mines to protect mine workers. Leading countries such as Germany, Canada, the United States and Australia have implemented regulations where a standard limit per m^3 of allowable DEE has been set. Although the South African mining industry shares the global concern with regards to detrimental health effects due to diesel exhausts and DPMs exposure in the last 10 to 20 years, the levels of exposure have never been adequately quantified and as such, there are no set DPMs exposure limits (Nundlall, 2014). However, the National Institute for Occupational Safety and Health has set an exposure guideline limit of $0.16 mg/m^3$ (van Niekerk, et al., 2002).

The Mine Health and Safety Act 1996 (MHSA) makes no mention of DPMs in the regulations. However, the mine ventilation society recommends the use of a minimum of $0.1 m^3/s$ of diluting air per rated kW power of the diesel engine used in the environment. This is set to dilute the diesel exhaust gases that are emitted from the machinery (van Niekerk, et al., 2002).

Some of the actions that are taken to mitigate exposure to DEE includes, retrofitting diesel machines with new established and proven technology, by modifying an existing diesel engine to enable the injection of hydrogen into the combustion process. Hydrogen can be added to diesel fuel to help the engine burn more completely and efficiently, which lowers emissions and improves engine performance and fuel efficiency (Hydrogen on Demand Technologies, 2024). Using electrical LHDs to improve working conditions in mines and lower emissions and ventilation burdens. These electrical LHDs can be further enhanced by substituting the battery-based energy sources with hydrogen fuel cells (Funez Guerra, et al., 2019).

2.3 Greenhouse Gas Emissions

The use of diesel-powered LHDs in the mining industry does not only put workers at risk of harmful DPMs, but it also leads to an increase in GHG emissions. One of the most essential actions for a sustainable environment is GHG emission reduction because GHG emissions are closely linked to climate change, directly impacting the environment, society, ecosystems, and people's health (Karaşan, et al., 2024). Greenhouse Gases (GHGs) trap heat in the earth's atmosphere. The main GHGs occurring naturally are carbon dioxide (CO_2), methane, nitrous oxide (N_2O), and water vapor. Although these GHGs occur naturally, their atmospheric concentration is exacerbated by human activities such as thermal electricity generation by burning fossil fuels, fossil fuels used to refuel the transport mode, deforestation, and mining activities using explosives during blasting and the use of diesel in surface and underground machinery. The causes of climate change, as noted by the United Nations sources, are (United Nations, n.d.):

- Power generation for residential and commercial buildings by burning fossil fuels (coal, gas, oil), which produces CO_2 and N_2O.
- Energy production in the manufacturing industry while producing goods (e.g., steel, electronics, clothes, iron) is done mainly by burning fossil fuels.
- Cutting down forests or deforestation (i.e. forests absorb carbon dioxide and help keep emissions out of the atmosphere).
- The transportation as it operates or runs from fossil fuels.
- Food production through deforestation and clearing of land grazing and agriculture, production and use of fertilizers and manure, and the energy used for farm equipment is fuelled by fossils.
- Increased consumption of natural resources (fossil fuels) due to technological advancement and lifestyles.

Distinctively, three GHGs do not occur naturally and are exclusively human caused during industrial processes; these are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (National Grid, 2024). GHGs cause global warming and climate change, and scientists agree with this (National Grid, 2024). Humans have released higher volumes of GHGs into the atmosphere since the industrial revolution. With the knock-on effects of global warming, this amount has increased intensely over the last century. As a result, in the last 30 years, global temperatures have risen faster than ever and are currently at an all-time high (National Grid, 2024). Figure 2.2 shows the change in global greenhouse gases over time, showing the increase in GHGs over the last century.

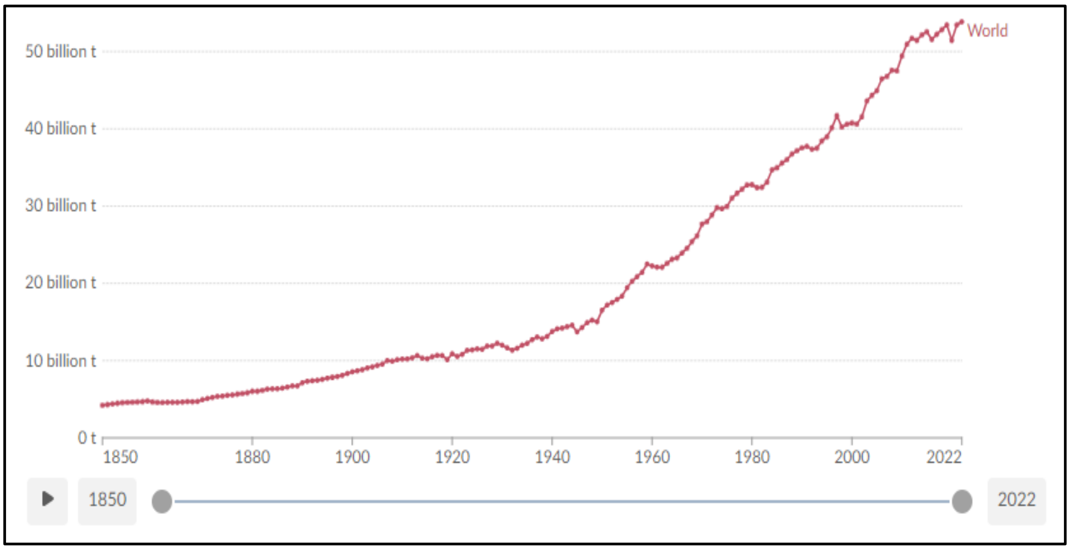

Figure 2.2: Change in global greenhouse gas emissions over time, (Source: Jones et al., 2024; Ritchie et al., 2020)

Figure 2.2 indicates that the global GHGs increased from just over 4,2 million tonnes of CO_2 equivalents in 1850 to more than 50 billion tonnes of CO_2 equivalents in 2022. Figure 2.3 shows the change in South Africa's greenhouse gas emissions over the last century. Figure 2.3 indicates a similar trend seen globally in figure 2.2 where the GHGs have increased from 2,8 million tonnes of CO_2 equivalents to over 500 million tonnes of CO_2 equivalents.

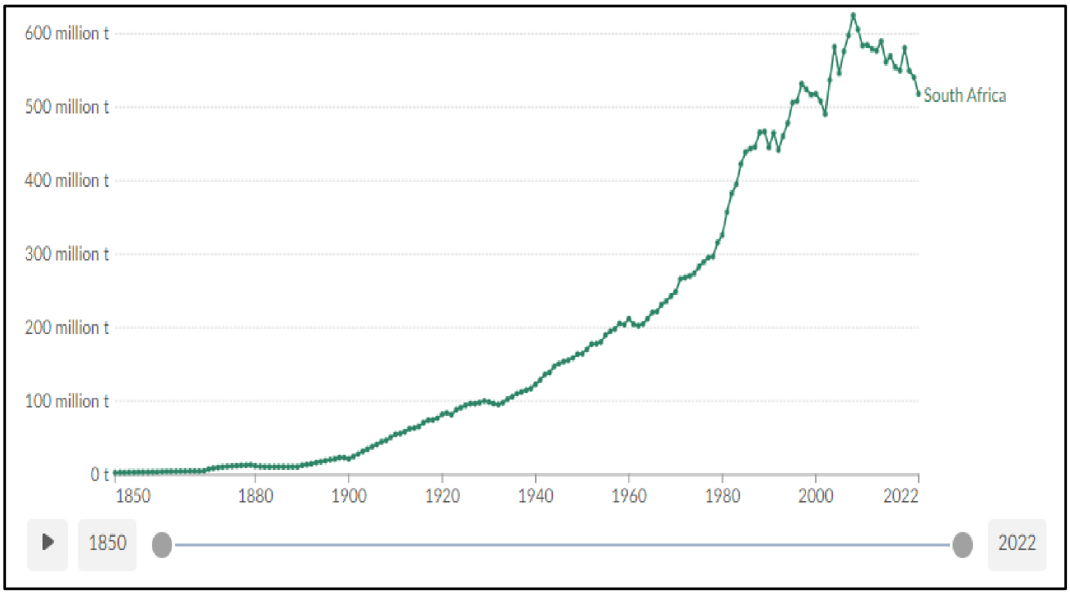

Figure 2.3: Change in South African greenhouse gas emissions over time, (Source: Jones et al., 2024; Ritchie et al., 2020)

Figure 2.2 and 2.3 shows a global increase of 11 905 times while the South African increase was 178 times between year 1850 and 2022. The increase in GHG emissions shown in figures 2.2 and 2.3 indicates that mitigation measures are required to decrease the emissions. South Africa is ranked as the 12th largest global contributor to GHG emissions (CSIR, 2021). The United Nations proposed mitigation measures for climate change, which led to the signing of the Paris Agreement by one hundred and ninety-six (196) member nations, committing to reducing greenhouse gas emissions to return global temperature to pre-industrial levels. The present objective is to maintain the rise of global warming temperature to 1.5 °C by 2050 relative to pre-industrial levels by reducing overall GHG emissions as low as possible (Rasul, et al., 2022).

All GHG emissions are measured in carbon dioxide equivalent (CO_2eq), their masses are multiplied by their potential for global warming (GWP) to convert them into CO_2eq. To give a single measure of total GHG emissions, CO_2eq tries to sum up all the warming effects of each GHG. This measurement system is implemented by the United Nations Framework Convention on Climate Change (UNFCCC). It is widely implemented and endorsed in GHG reporting and target setting by countries and institutions. GWP measures the warming effect of a gas compared to CO2; it is measured by the average of the GHG strength over the periods selected (Ritchie, et al., 2020).

The World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) developed the GHG Protocol as an international standard for corporate accounting and reporting emissions, classifying GHGs into Scopes 1, 2, and 3 based on their sources. The GHG Protocol provides accounting and reporting standards, sector guidance, calculation tools, and training for businesses, as well as for local and national governments (Greenhouse Gas Protocol, 2024). Scope 1 is the direct emissions owned or controlled by a company. In contrast, scopes 2 and 3 are indirect emissions resulting from the company's activities but do not arise from sources it owns or controls (National Grid, 2023). Figure 2.4 shows a summary of GHGs and classification into different scopes.

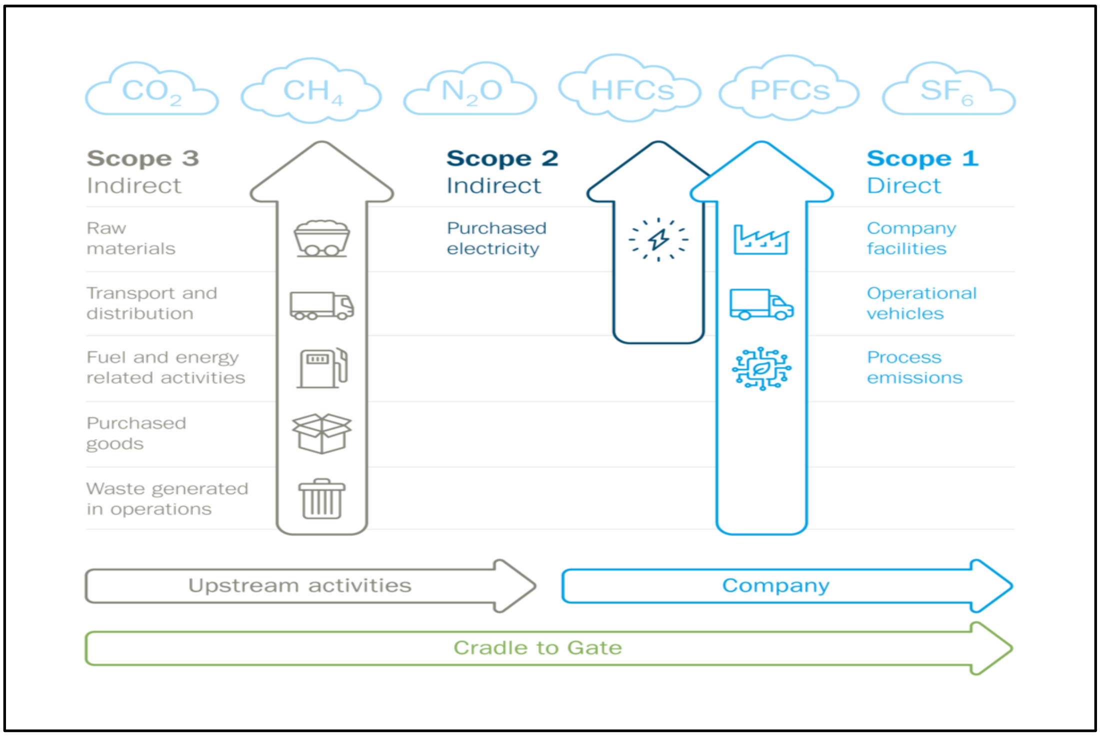

Figure 2.4: Classification of GHG emissions, (Source: (Roininen, O., 2023))

Scope 1, for example, would include fuel burning from the fleet of vehicles if they are not electrically powered. Scope 2 is emissions that a company causes indirectly; for example, it would include emissions resulting from where the energy it purchases and uses is produced. Scope 3 incorporates emissions that are not created by the company itself and are not a result of activities from assets owned or controlled by it but by those that it is indirectly responsible across its value chain; for example, it would include fuel used by employees commuting to and from workplaces. Scope 3 emissions cover all sources outside the limits of Scope 1 and 2 (National Grid, 2023).

To reduce the effects of climate change, countries are introducing initiatives and policies that aim to reduce GHG emissions, such as methane and carbon dioxide. Carbon pricing is one solution that imposes a penalty for CO_2 emissions and offers a monetary reward for reducing GHG emissions. Other solutions include investing in renewable energy sources, energy efficiency measures, and incentives for businesses to reduce emissions.

2.4 South Africa's Contribution to Greenhouse Gas Emissions

Scientific investigations have proven that many of the GHG emissions are caused by people, either directly or indirectly (anthropogenic). This suggests that the energy utilization processes, particularly that of fossil fuels, significantly contribute to atmospheric emissions. South Africa is the largest energy consumer on the continent, emitting the most greenhouse gases (Oladunni, et al., 2022). Figure 2.5 shows the energy consumption per capita, which is the average energy consumption per person each year (Ritchie and Roser, 2023).

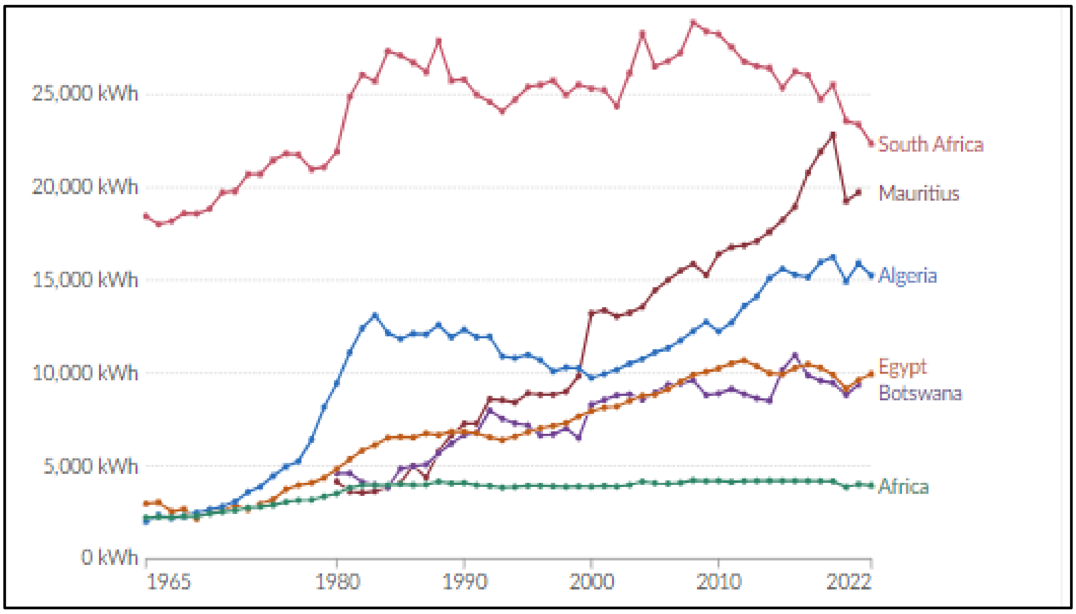

Figure 2.5: Energy consumption per capita, (Source: U.S. Energy Information Administration (2023); Energy Institute - Statistical Review of World Energy (2023); Ritchie & Roser, (2023))

Figure 5 shows that in 2022, South Africa used 22 350 kiloWatt hours (kWh) per person, whilst 3 900 kWh per person was used in Africa. Over the years, when comparing South Africa to other African countries, it has had a high energy intensity (Oladunni, et al., 2022). Figure 2.6 shows the energy intensity of South Africa and other developed African countries. Energy intensity measurement involves calculating the amount of primary energy consumed per unit of gross domestic product (GDP) in kWh per dollar. GDP is modified to account for inflation and variations in the cost of living among different countries (Ritchie and Roser, 2023). Figure 2.6 indicates that South Africa has the highest energy intensity of 1.85 kWh per dollar, followed by Seychelles and Algeria.

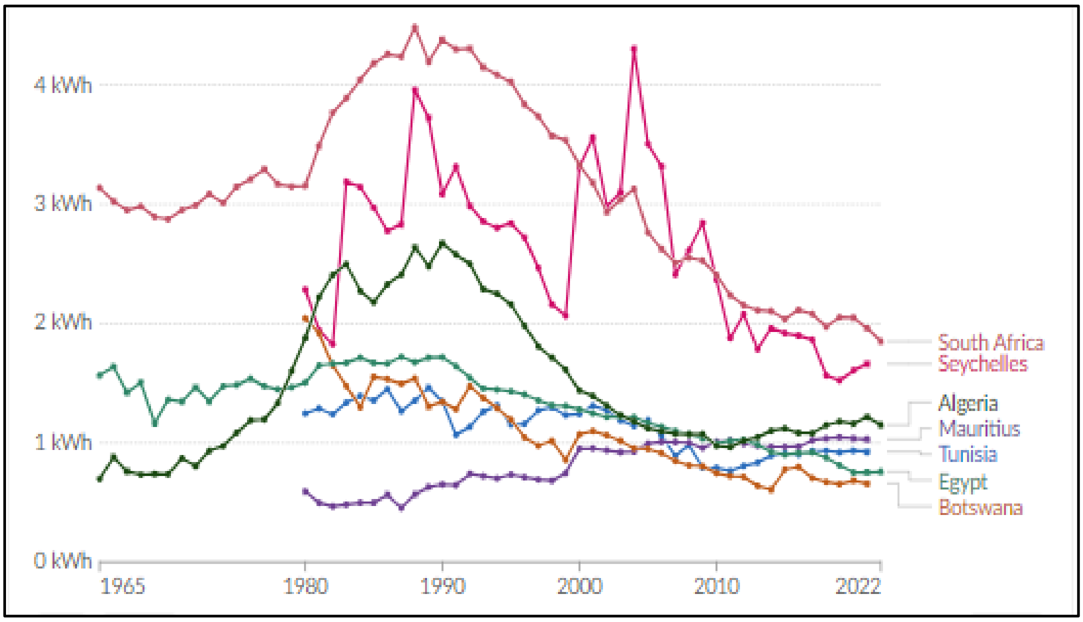

Figure 2.6: Energy intensity of South Africa and other developed African countries, (Source: U.S. Energy Information Administration, 2023; Energy Institute - Statistical Review of World Energy, 2023; Bolt and van Zanden - Maddison Project Database, 2023; Ritchie & Roser, 2023)

South Africa's Biennial Update Report (BUR) states that the energy intensity due to economic growth has led to a profile of emissions that is significantly different from that of other developing countries at a similar stage of development (Department of Enviromental Affairs, 2014). This is a result of the energy-intensive fossil-fuel-powered sector. After the energy sector, the transport industry is the second highest GHG contributor, with a share of over 23%. As South Africa is one of the largest economies in Africa, excessive consumption of fossil fuels and intolerable GHG emissions from the transport industry are a threat to our environment (Oladunni, et al., 2022).

2.5 Effects of Greenhouse Gas Emissions and Global Warming in South Africa

Figure 2.7 shows the annual surface temperature deviation for South Africa from 1951 to 2020. These are the effects of increasing GHG emissions which result in climate change. Every decade, the country warms at a rate of 0.16 °C, statistically significant at the 5% level.

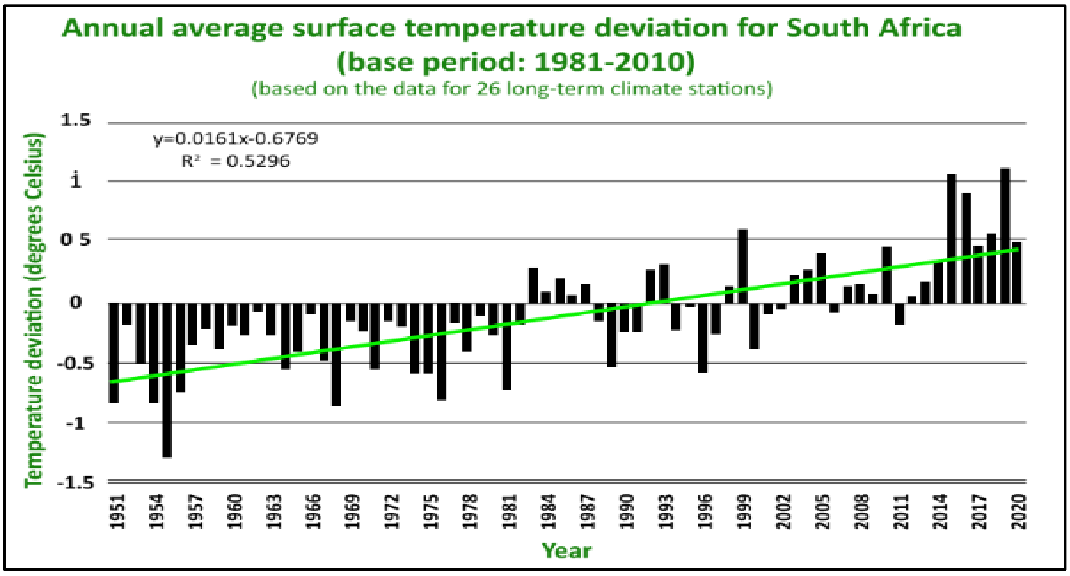

Figure 2.7: Annual average surface temperature deviation for South Africa, (Source: South African Weather Services, 2020; Department of Forestry, Fisheries, and the Environment, 2023)

Amongst the effects of climate change are extreme weather events associated with observed changes in the climate system, which continue to occur more frequently and intensely in South Africa. More so, since 2013, the country has been subject to protracted and intense drought conditions and flash floods in some areas, which have caused damage to several sectors and provinces. The following are some of the suppositions recorded due to climate change. In 2018, one of the most severe droughts ever recorded was experienced in cities like Cape Town where government was forced to impose water restrictions due to a possible day zero (a situation where water sources are depleted, and water availability cannot cater to requested needs). Another catastrophic event was the recurring droughts that affected the farmers' livelihoods, food, and water security for communities, this event resulted in crop failure and several livestock deaths in the Eastern Cape province (Department of Forestry, Fisheries and the Environment, 2023).

Human lives, sources of income such as farms, and assets were exposed when an extreme weather condition (drought), and veld fires ignited by extreme heat combined in the Knysna disaster in 2017. More than 10,000 people were displaced by the Knysna fires of 2017, which was reported to be the worst fire disaster in South African history, resulting in ZAR 3 billion cost to the South African insurance industry together with the government. (Le Maitre et al., 2019; Department of Forestry, Fisheries, and the Environment, 2023).

In April 2022, the KwaZulu-Natal coastal zone, including the greater Durban area and South Coast, received more than 300mm of rain in 24 hours. This led to calamitous flooding, with 459 people losing their lives and eighty-eight (88) people still missing by the end of May 2022 (Aylward, 2024) . Over four thousand homes were destroyed, 40,000 people were left homeless, and 45,000 people were temporarily left unemployed. The cost of infrastructure and business losses amounted to an estimated US$2 billion (University of the Witwatersrand, 2023).

More health risks, air pollution, and diseases have been experienced across the country, which indicates that more effort needs to be made to put measures that will address the impacts of climate change and reduce factors contributing to GHG emissions and global warming. To reduce this trend, there have been policy instruments such as carbon tax, which aim to reduce emissions. The carbon tax was implemented in June 2019 as a policy lever used as part of the country's strategy to minimize carbon emissions. The implementation of policy has been supported by promotion of technology; potential intervention that has been investigated which involves the application of hydrogen FC technology.

2.6 Effects of Greenhouse Gas Emissions and Global Warming in the South African Mining Industry

The mining sector's impact is significant, it contributes 4% to 7% of global greenhouse gas emissions (Henderson and Maksimainen, 2020). The industry is facing increased physical challenges due to the effects of climate change, including drought, heat, and high precipitation. The change in water levels adversely affect mining activities such as drilling, dust suppression, cooling, and extractive metallurgy processes. Increased heat and drought affect the health and safety of mine employees (Ndlovu, 2018). Therefore, it has become important that mines increase efforts towards decarbonisation (Henderson and Maksimainen, 2020).

South Africa's mining industry contributes significantly to greenhouse gas emissions and as a result faces significant challenges in reducing its carbon footprint, particularly in the context of rising electricity costs and the impending carbon tax (Votteler, 2016). The mining sector contributes 15% of the South Africa's GHG emissions (CSIR, 2021), which may be considered significant. The mining industry has relied on diesel-powered equipment and machinery for years. According to the World Health Organization, the emissions produced by diesel-powered vehicles and machinery which include CO_2, CO, NO_X, and DPM have been classified as carcinogenic to humans (Moore, 2019).

To adapt to the changing regulations, economic climates, and environmental conditions, the processes and planning in the mining industry have had to undergo transformation over the years. With the aim to reduce greenhouse gas emissions in the mining industry, there has been a shift in the energy landscape. Mining companies are leaning towards integrating battery energy storage solutions to minimise the gas emissions associated with diesel-fueled machinery and equipment. The introduction of fuel cells as an alternative to diesel-powered engines has also been investigated and is expected to assist in improving the environmental conditions in underground mines as no harmful emissions will not be emitted during operation. The South African PGM sector has been central to the development of Hydrogen and Fuel Cell technology as PGMs form part of the Polymer Electrolyte membrane electrolysis used to produce Hydrogen and as a catalyst in fuel cell technology.

The PGM mining sector has contributed to the research and development of fuel cell technology implementation in locomotives used in the mines to move away from fossil fuel-powered machinery (Anglo American, 2022). Hydrogen has emerged as a significant fuel source. As it can be produced locally, it reduces the price instabilities experienced with currently most used fossil fuels by removing the geopolitical powers. A report from McKinsey and the Hydrogen Council states that hydrogen production costs could fall by 50% by 2030 (Casey, 2020). A significant obstacle for low-carbon hydrogen is the price difference compared to hydrogen produced from fossil fuels without carbon capture. Currently, generating hydrogen from fossil fuels remains the most economical choice in many regions globally. The cost of producing hydrogen from natural gas varies between $ 0.5 US and $ 1.7 US per kilogramme (kg), depending on local gas prices. Implementing Carbon Capture, Utilization and Storage (CCUS) technologies to decrease CO_2 emissions during hydrogen production raises the levelized cost of production to approximately $ 1 US to $ 2 US per kg. The cost of generating hydrogen with renewable electricity ranges from $ 3 US to $ 8 US per kg. At the current exchange rate of $ 1 US is equal to 18.05 South African rands, that means the costs of producing hydrogen with renewable energy ranges from 54.19 ZAR to 144.51 ZAR per kg (International Energy Agency, 2021).

According to Funez et al (2019), before underground mines can apply fuel cells in their machinery, a range of operational aspects must be taken into consideration. This includes health and safety risks, regulatory issues, system fitness with mining processes, technical risks, and operational and capital costs (Funez et al., 2019). In recent years, there has been dedicated projects aimed at investigating the application of fuel cell technology in the mining industry.

In May 2022, Anglo American launched its hydrogen-powered 220t truck planned to carry a load capacity of 290t. The truck was designed similarly to a diesel-powered truck and converted to a hybrid hydrogen fuel cell. A hydrogen tank system was designed to power the haul truck and there was pipework designed to support the multiple tanks on the vessels. The truck is designed in such a way that the hydrogen enters the fuel cell from the tank and mixes with oxygen to create water, and electricity is generated to power the motors that drive the wheels (Anglo American, 2022). The most important lesson from the launch that contributed to the success of this project was the development of the infrastructure that was required to support the operation of the haul truck. The infrastructure included building a hydrogen production site, storage and a refueling complex that incorporates an electrolyzer and a solar plant (Anglo American, 2022).

The piloting of hydrogen fuel-cell technology has indicated that, the initial cost of the infrastructure required is capital intensive, but the benefits of the infrastructure are realized once the vehicles are in operation. The success of hybrid electric mobiles has led to an increase in research and development on the implementation of the hybrid concept on underground mining equipment. A hybrid LHD was successfully trialed in a Canadia underground mine and results published in 2010 showed a 12% to 64% reduction in emissions (Paraszczak, et al., 2014).

When it comes to material handling equipment, forklifts have emerged as one of the first commercial uses for fuel cells. In the United States, there are over 40,000 hydrogen-powered forklifts, with Plug Power as the leading supplier. Japan aims for a target of 10,000 by 2030, which represents a significant increase from its current count of 330, while Belgium, Canada, France, and Germany each operate fuel cell material handling equipment in the hundreds. In Chile, Walmart has revealed intentions to transform 150 battery-powered forklifts to run on fuel cell technology, utilizing green hydrogen (International Energy Agency, 2021).

On 31 March 2016, South Africa's first prototype hydrogen fuel cell forklift and refuelling station were introduced at the Impala Refineries in Springs. This was developed by Impala Platinum Holding Limited (Implats) and HySA in partnership with the Department of Science and Technology. The project highlighted the innovative metal hydride technology designed for hydrogen storage and compression on board. The metal hydride system offers considerable advantages such as enabling the forklift to function at reduced pressures of 180 bar, enhancing safety and reducing expenses. The forklift operates at reduced noise levels and allows for extended operational periods between refueling (there is sufficient fuel for two to four days before hydrogen refueling is required), which leads to enhanced productivity (University of Western Cape, 2016).

At a PGM mine in South Africa owned by Anglo American, NPROXX was completing the production of a novel new hydrogen fuel tank system that will power the biggest mine haul truck in the world. Fuel cells powered by the hydrogen tank system will offer a zero-emission for material transporting solution that is not yet available in the market yet. Following a testing at Anglo American's Mogalakwena mine, which is the world's largest open pit platinum group metals mine, the hydrogen-powered vehicle is anticipated to be used at other Anglo-American facilities worldwide. Switching from diesel to hydrogen will help the company get closer to its aim of running carbon neutral mines, as heavy trucks now consume more than 70% of the diesel used on-site. To guarantee a constant, sustainable fuel supply for the vehicle, NPROXX have provided two 6-meter tanks that can store hydrogen from the electrolysers at pressures of up to 500 bar. Anglo American and Engie are constructing a demonstration facility in South Africa, which includes a 3.5MW electrolyser for on-site hydrogen production. This facility will be capable of generating up to one tonne of hydrogen daily, which will be used to fuel the trucks (NPROXX, 2021).

2.7 Fuel Cell Technology

2.7.1 Fuel cell principle and a brief history

An FC is an electrochemical device that dynamically converts the energy from a chemical reaction between hydrogen and an oxidant into electrical energy. It operates similarly to a battery but differs in that it is designed for continuous replacement of the reactants consumed as opposed to a battery that uses the energy stored during the recharging period (Williams, 2001). The history and concept of FCs date to the early 1800s, and further development was recorded during the 1900s. Figure 2.8 provides some of the essential timelines and developments through the FC technology.

In the 1800s, British Scientists (William Nicholson and Anthony Carlisle) described the electrolysis process, which is when electricity decomposes water into hydrogen and oxygen (Ortiz-Rivera, et al., 2007). In 1839, William Robert Grove discovered that electricity could be generated by reversing water electrolysis. In 1842, William Grove produced a ‘gas voltaic battery,’ a device that combined hydrogen and oxygen to produce electricity, known as the first FC (Olabi, et al., 2021). In 1889, Charles Larger and Ludwig Mond developed the first effective FC, which produced more electricity with a longer service life than Grove’s invention. The theoretical understanding of how FCs operate was provided by Friedrich Wilhelm Ostwald in 1893. As technology and research advanced, Francis Thomas Bacon developed the first practical hydrogen-oxygen fuel cell in 1932 (Ortiz-Rivera, et al., 2007). It took another 37 years for Bacon and colleagues to develop and implement a 5kW device after several experiments in 1959. A team led by Harry Ihrig developed an FC tractor comprising 1008 fuel cells and an output of 15 kW (Ortiz-Rivera et al., 2007; Olabi et al., 2021).

Figure 2.8: Milestones in the development of FCEVs, (Source: (Luo, et al., 2021); (Sharaf & Orhan, 2014)

While fuel cell technology has seen a sequence of evolution to measure up to the performance of conventional fossil fuel systems, and extensive research is still being done to improve the performance of the technology. Hydrogen-fuel cells are getting traction due to the positive potential of being an aid to attaining a zero-carbon emission energy source. In the year 2021, approximately 40,000 fuel cell-powered vehicles were purchased globally. Moreover, the application of FC technology in commercial airplanes was observed in 2022 (Oladosu, et al., 2024).

Figure 2.9 shows the basic operating principle of an FC. The electrolyte, anode, and cathode are the primary components of a FC. Hydrogen enters and splits into ions and electrons at the anode side through a redox (reduction-oxidation) reaction as shown by figure 2.9. During this reaction, an anode loses electrons during oxidation and the cathode gains electrons during reduction. Water is a byproduct of the FC reaction. During operation, ions move from the anode to the cathode through the electrolyte, whilst electrons are lost at the anode flowing from the anode to the cathode through an external circuit and serve as the electrical current (Lucia, 2014).

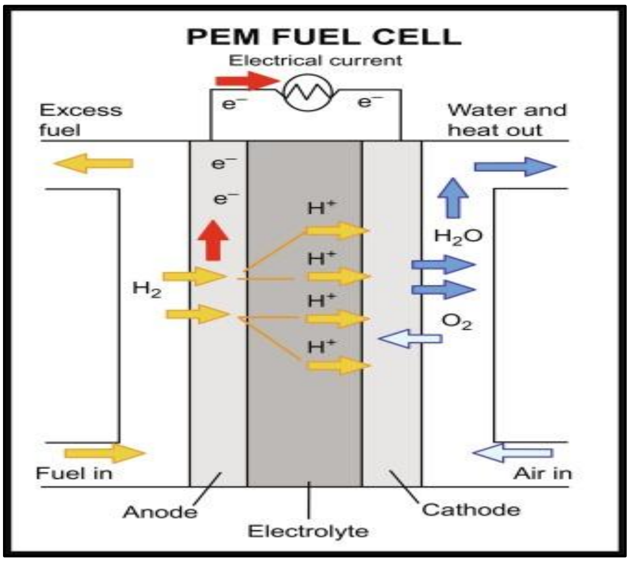

Figure 2.9: Schematic of PEMFC (Wang, et al., 2011)

The major components of a fuel cell system are the Membrane Electrode Assembly (MEA), the bipolar plates, and auxiliaries. MEA consists of the electrolyte, cathode/anode electrodes, anodic/cathodic catalysts, and gas diffusion layers. Bipolar plates are the anode/cathode current collectors with the reactant flow field; their purpose is to distribute the fuel and oxidant within the cell. Auxiliaries are required for thermal and water management, compression, and transport of gases (Alaswad, et al., 2016).

Individual fuel cells stacked one above the other make up a fuel cell stack. Fuel cell stacks are constructed in sizes ranging from a few watts up to over a megawatt (Ortiz-Rivera et al., 2007). Figure 2.10 shows the components that make up a fuel stack.

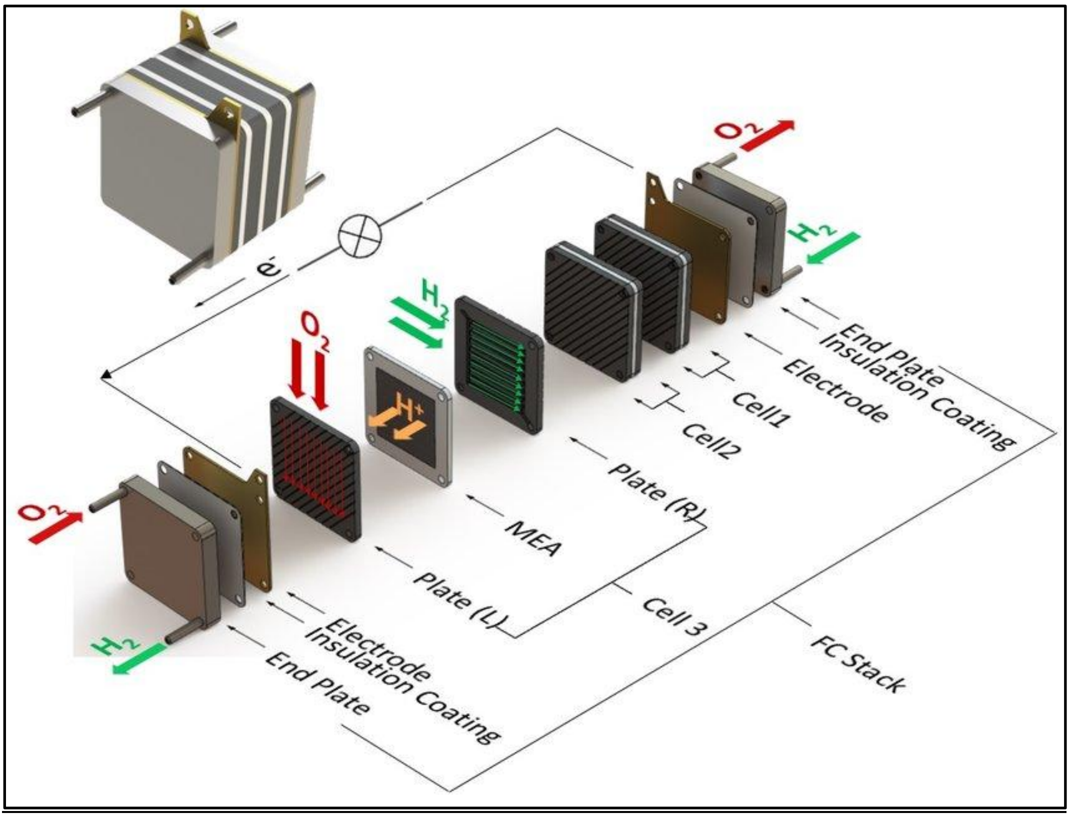

Figure 2.10: PEM fuel cell stack design (Sutharssana, et al., 2016)

The types of FC and applications are defined or categorised by the electrolyte type, operating temperature, and potential utility. Habil et al. (2022) and Ortiz-Rivera et al. (2007) described the various kinds of FCs as follows:

- Polymer Electrolyte Membrane Fuel Cell PEMFC PEMFC): ideal for applications requiring rapid startup, such as in cars, because they have a high-power density, they can quickly vary their output to meet changes in power demand and operate at relatively low temperatures (roughly 175°F, 79°C).
- Direct Methanol Fuel Cell (DMFC): similarly to PEMFCs, the electrolyte used is a polymer membrane. However, they do not need a fuel reformer because the anode catalyst extracts the hydrogen from the liquid methanol on its own. Their operating temperature ranges from 120 to 190°F (49 C to 87 C). Their short ranges make them suitable for small to medium sized applications such as powering laptops and cell phones.
- Alkaline Fuel Cells (AFC): use potassium hydroxide as the primary electrolyte and operate at 160°F (71°C). However, since they are highly

vulnerable to carbon contamination, they need only pure oxygen and hydrogen.

- Phosphoric Acid Fuel Cell (PAFC): they use liquid phosphoric acid as the electrolyte and operates at about 450°F (232°C). PAFCs are among the few FCs that are currently offered for sale commercially. These cells produce electricity at more than 40% efficiency with about 85% of the steam produced used for cogeneration. They are installed in wastewater treatment facilities, hospitals, nursing homes, hotels, office buildings, schools, landfills, and utility power plants.
- Molten Carbonate Fuel Cells (MCFC): they require carbon dioxide and oxygen to be delivered to the cathode and function at elevated temperatures, around 1,200ºF (648ºC). MCFCs ranging from 10 kW to 2 MW have been tested on diverse fuels and are mainly intended for electric utility applications.
- Solid Oxide Fuel Cells (SOFCs) function at extremely elevated temperatures (1800°F, 982ºC) using a complex, non-porous ceramic substance as the electrolyte. SOFCs are suitable for both stationary applications and auxiliary power units (APUs) used in cars to power electronics.
- Regenerative or Reversible FCs can work both as electrolysers and as FCs (Habil et al., 2022; Ortiz-Rivera et al., 2007).

Of the different types of FCs described above, the PEMFC is ideal for use in the automotive industry, and they are preferred because of their high-power density and lower working temperatures compared with other FC technologies (Samuel, et al., 2020). While this is the case, more research and development are needed to lower their costs, increase their robustness, optimise and/or improve their size, and performance (Sharaf and Orhan, 2014). According to Luo et al (2021), the typical operation costs of a PEMFC are $45 for 60 kW compared to $25 for 35 kW in ICE.

2.7.2 Application and relevance of fuel cell technology

Over the past 20 years, FCs have been used to replace internal combustion engines and provide power for stationary and portable applications. This is because burning of fossil fuels impacts the environment negatively both during the fuel's production and during combustion. Furthermore, fossil fuel resources are expected to deplete because the world's population is growing. Figure 2.11 shows the decline in fossil fuel primary energy sources. It indicates the decrease of fossil fuel supply such as coal, wood, oil, and natural gas as time progresses and the increase in other sources of energy such as solfus and nuclear. Solfus is a term used to describe an important new energy technology like solar or fusion (IIASA, 1997).

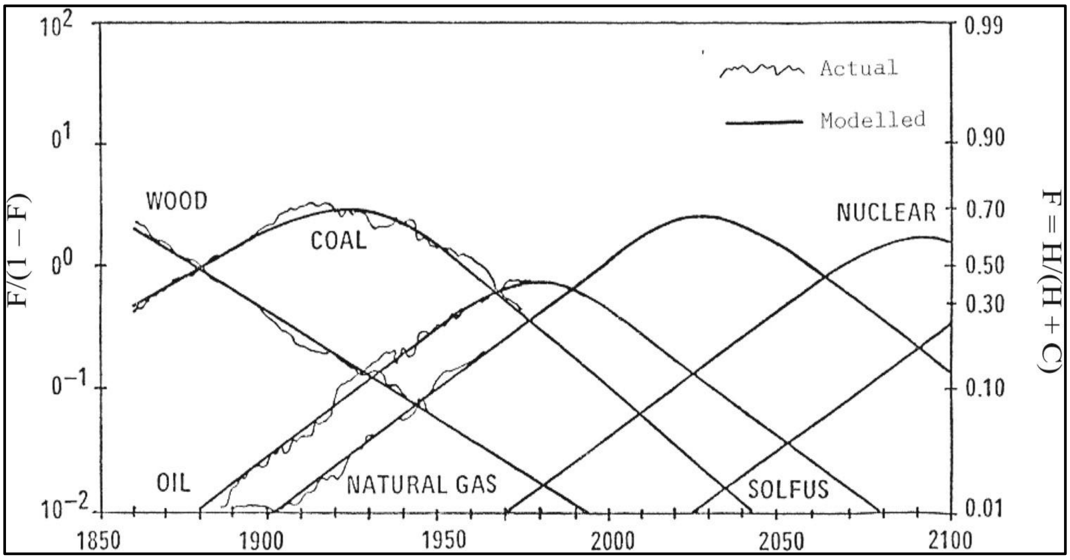

Figure 2.11: Decline in fossil fuel primary energy sources (Rosen and Koohi-Fayegh, 2016)

With the decline in the availability of fossil fuels, other alternative energy sources are being investigated. Renewable energy sources have been identified as potential sources to replace depleting of finite resources (i.e., coal, natural gas, etc.). Hydrogen fuel is amongst the sources considered due to its abundance. According to Ortiz-Rivera et al (2007), there is a need to advance the research and development of FCs, as they are the leading technology that will enable the hydrogen economy of the future, which is expected to provide clean, renewable energy.

2.7.3 Fuel cell technology benefits and limitations

FCs are rapidly becoming an innovative phase of technological advancement due to their high efficiency and low emissions (Bodkhea, et al., 2023). FCEVs have zero emissions, depending on the hydrogen production pathway. When considering fuel economy, they are more fuel efficient than ICEs. FCEVs are quiet in operation due to their assembly resulting from having few moving parts. They can quickly adapt to load changes and have lower refueling times and higher driving ranges when compared to battery and diesel operated vehicles.

While FCEVs are in the preliminary stages of development and deployment, there are specific challenges affecting their commercialisation and widespread adoption (Olabi et al., 2023). Hydrogen FCs need expensive electrolyte membranes, platinum catalysts, and complicated manufacturing procedures. The cost of platinum is also a significant obstacle to the development of FCs. The electrolyte membrane cost is substantial since hydrogen FCs must have excellent oxidation and reduction stability. According to Luo et al (2021), the cost of manufacturing a medium-sized FCEV is 50% greater than that of an ICE vehicle at the current level of technological maturity.

More so, the membrane is extremely sensitive and makes the application of FC extraordinarily complex. Hence there are ongoing studies to research and develop the reduction of platinum used on an FC stack. Figure 2.12 summarises the cost breakdown on an FC stack, showing that 41% of the total cost is spent on the catalyst used, followed by the second highest costs at 28% for bipolar plates.

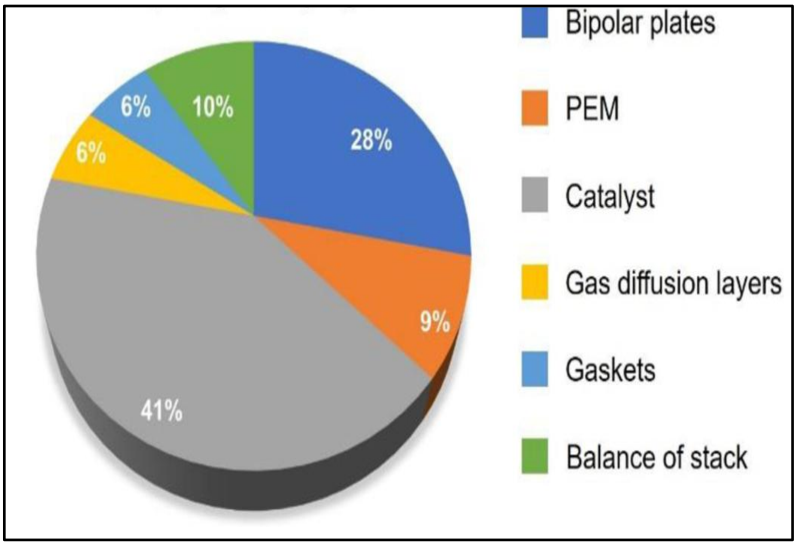

Figure 2.12: Fuel cell stack cost breakdown (Wang, 2009)

The other factor affecting widespread adoption is the reliability of FC, which is particularly important for end users' satisfaction. FCs can generate electricity with higher energy than ICEs without noise or pollutant emissions; however, additional repair costs can be incurred because 10% stack element (component composed of FCs stacked together) failure can increase costs by 60% (Luo, et al., 2021). The service life of PEMFCs is highly dependent on the degradation rate of the PEM (Luo, et al., 2021). Therefore, the repeatability and durability need to be improved. Selecting an FC membrane with a correct balance of water is crucial for the dependable operation of FCEVs since dehydration can harm the membrane, and flooding can increase corrosion and voltage instabilities (Carton and Achour, 2016).

The existing energy management system (EMS) needs significant development to support FC technology application. The purpose of an EMS is to manage various power sources that directly affect the cost of vehicle maintenance and operation and to lower hydrogen consumption. To prevent fluctuations in the FC's power and to prolong the lifespan of the auxiliary power units and electric motor, the EMS ensures that energy is effectively dispersed among the electric motor, auxiliary power units, and FC (Luo, et al., 2021).

2.8 Hydrogen Fuel Cell Technology

The main components of an LHD can be divided into the rear frame also known as the power frame and the front frame known as the load frame. The power frame includes the engine, transmission, rear axle, exhaust system, fuel tank, hydraulic oil tank and the air filter. The load frame includes the front axle, bucket, boom, transmission, hoist cylinder and stabilizer cylinder. The hydraulic system controls all the cylinder movements, the loading, hauling, dumping, brake application, and the machine's turning. The hydraulic power is determined by the payload and loading capacity of the machine. The transmission/ torque convertor is a power train system that transfers engine output power to the final drive system (wheels), and it is guided by the weight of the machine and the load required to be moved. The engine is the power pack of the machine. The engine power output is determined from the torque required to move the machine with and without load at maximum revolutions per minute (Zichen, 2021).

Figure 2.13 shows the typical hydrogen fuel cell system layout installed in an LHD.

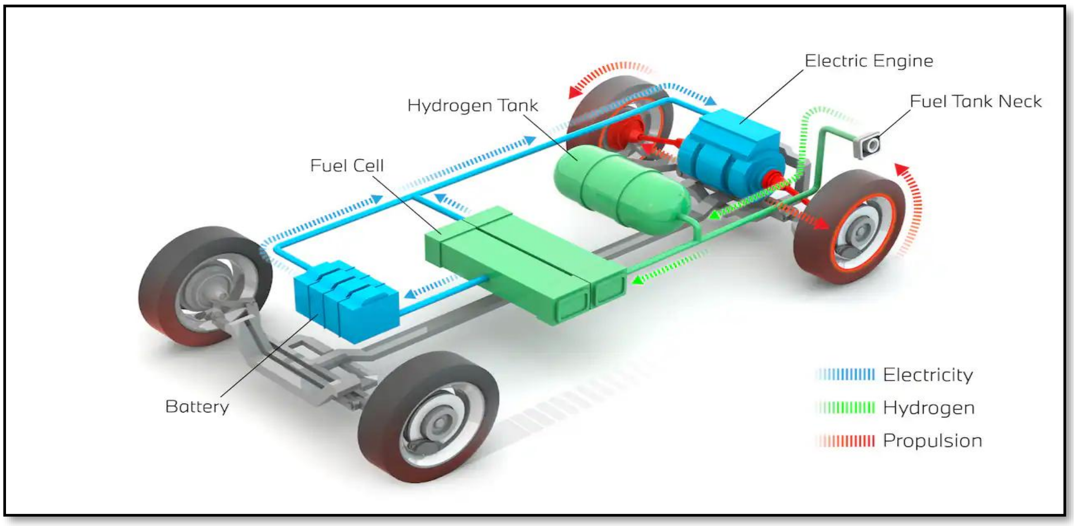

Figure 2.13: Hydrogen fuel cell system layout (Bogna, 2022)

A hydrogen fuel system works through a process called reverse electrolysis. During this process, the hydrogen from the onboard fuel tanks is combined with oxygen in the fuel cell stack to produce electricity. The electrons are removed from the hydrogen gas, which they send through the circuit to drive the motor, and together with oxygen on the other side of the circuit, forming a water vapor that can be discharged into the exhaust tailpipe. The hydrogen fuel cells generated electricity can take two paths depending on the situation, it can either directly power the electrical motor or charge the battery (lithium ion) which can store the energy for later use. The battery also captures power from the regenerative braking system of the vehicle for later use and can store excess energy from the fuel cell stack during low energy driving (Bogna, 2022).

A FCEV may be equipped with several hydrogen gas tanks. Given that hydrogen is highly flammable if not managed correctly, fuel tanks are constructed with thick walls, are pressurized, and undergo rigorous testing to guarantee safety in the event of a crash (Bogna, 2022). Figure 2.14 shows the key components of a hydrogen fuel cell electric vehicle, the low-voltage auxiliary battery supplies power to start the vehicle prior to the activation of the traction battery.

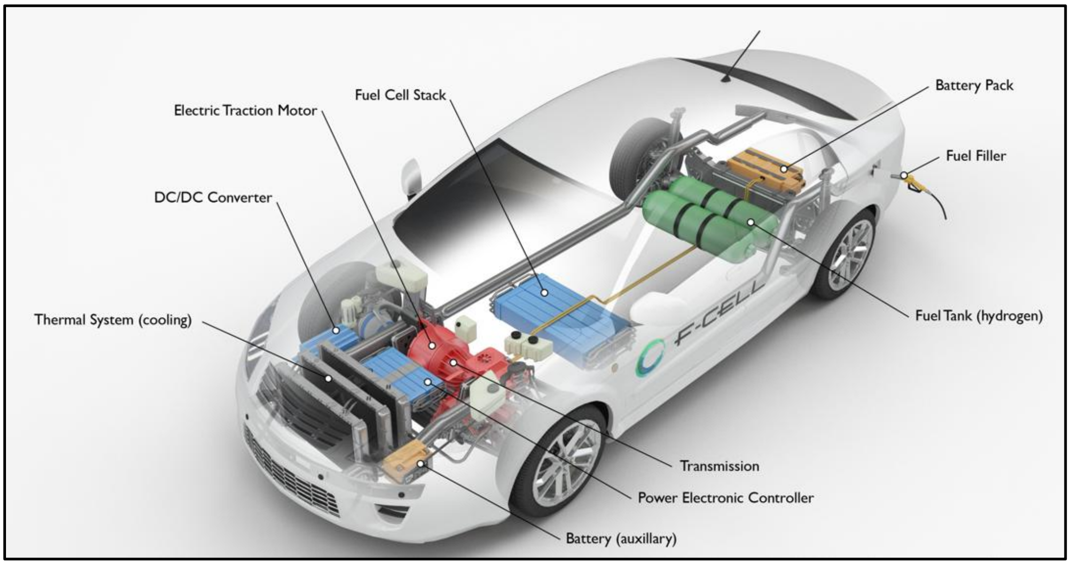

Figure 2.14: Components of a hydrogen fuel cell vehicle (Selmi, et al., 2022)

The high-voltage battery pack stores energy generated during regenerative braking and provides extra power to the electric traction motor. The fuel cell stack which is a collection of separate membrane electrodes to create high voltage required to power a vehicle, it generates electricity by utilizing hydrogen and oxygen. The hydrogen fuel tank stores hydrogen gas within the vehicle until it is required to refuel the fuel cell. A fuel filler or dispenser's nozzle connects to the vehicle's receptacle to fill the hydrogen tank. The electric traction motor harnesses energy from the fuel cell along with the traction battery pack, this motor propels the vehicle's wheels (Selmi, et al., 2022).

The DC/DC converter changes the higher-voltage DC energy from the traction battery pack into the lower-voltage DC energy required for operating vehicle accessories and charging the auxiliary battery. The thermal (cooling) system upholds an appropriate temperature range for the fuel cell, electric motor, power electronics, and all other components. The electric transmission conveys mechanical power from the electric traction motor to propel the wheels. The power electronics controller regulates the distribution of electrical power provided by the fuel cell and the traction battery, overseeing the speed of the electric traction motor and the torque it generates. An energy management system controls all the energy powers within a FCEV to ensure hydrogen reduction and power distribution (Selmi, et al., 2022).

Table 2.1 shows the costs for the hydrogen fuel cell system components. These include the battery pack, DC/DC converter, hydrogen fuel tank, electric traction motor, and fuel cell stack. The energy supplied by a FCEV, or a hydrogen fuel cell system is determined by the volume of the hydrogen storage tank, and not by the battery. Hydrogen storage onboard for FCEV of 5 -13kg is required for 483km range (Selmi, et al., 2022). As seen in Table 2.1, the hydrogen fuel tank is the most expensive item followed by the 100-kW fuel cell stack, costing about R800,000.

Table 2.1: Hydrogen fuel cell system component cost (Source: Siemens, n.d.; Hydrogen Council, n.d.; James, 2022)

	Weight (Kg)	**Total**
Battery pack (60kWh)	50	R234 000,00
DC/DC converter	118	R475 000,00
Fuel filler	0,2	R10 000,00
Electric traction motor (FCEV) (100 kW)	160	R394 000,00
Fuel cell stack (100kW)	100	R800 000,00
Compression fuel tank (hydrogen)	50	R1460 000,00
Transmission (electric)	192	R210 000,00
TOTAL	**670,2**	**R3 349 000,00**

The hydrogen fuel cell component system includes four sub systems, the air supply to supply oxygen to FCs, the hydrogen supply to stream the hydrogen coming from the tank to the FC stack. The heat and water management system to separate water and recycle the heat to the vehicle's cabin (Selmi, et al., 2022) .

2.9 Hydrogen Technology

With its minimal GHG emissions compared to other energy sources, hydrogen is the fuel of the future for supplying humanity's energy demands. Hydrogen is the simplest and most abundant element in the universe. While this is the case, hydrogen rarely occurs naturally as a gas on earth and is always combined with other elements. Therefore, it must be removed from hydrocarbons or other hydrogen-containing substances like water. Following extraction, it can be used as a fuel, in combustion processes or in FCs (Malik, et al., 2023). When comparing hydrogen to other conventional fuels, it has the second highest calorific value of 120-142MJ/kg, making it a fuel with the best energy-weight ratio (Rasul, et al., 2022). The production of hydrogen gas and its use as fuel for FCEVs have the potential to reduce global GHG emissions by 50%. This is expected to reduce the petroleum demand for ICEs by 90% or more by 2050 (Muhammed, et al., 2023). Figure 2.15 shows the operation of a hydrogen fuel cell. In an FC, hydrogen energy is converted directly into electricity with high efficiency and low power losses.

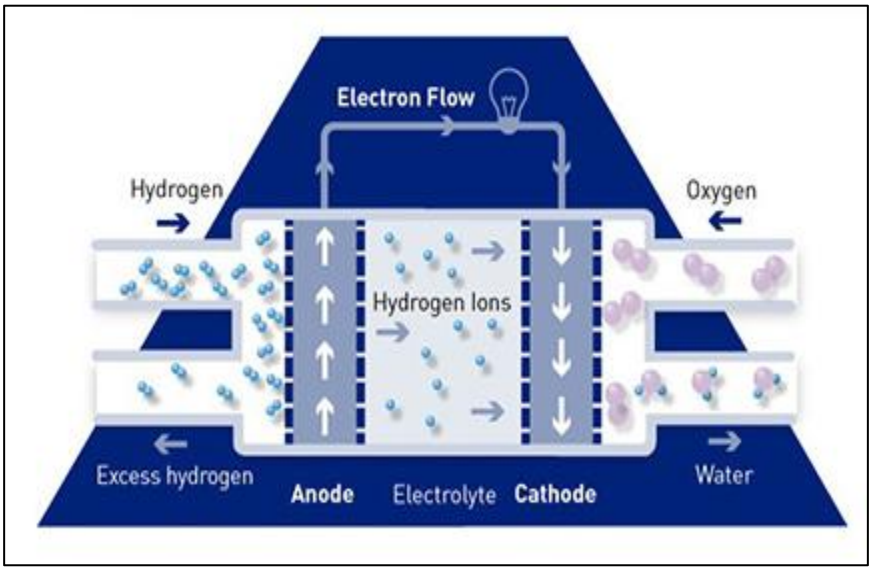

Figure 2.15: Hydrogen Fuel Cell (Anglo American, 2019)

Hydrogen is an energy carrier that moves, stores, and delivers energy yielded from other sources (Office of Energy Efficiency and Renewable Energy, n.d.). Malik *et al.* (2023) categorised the hydrogen production processes into two, that is, through renewable sources (biomass, water) or non-renewable sources (fossil fuels). The processes are summarised as:

- Electrolysis/photo-electrolysis – a process of splitting water into hydrogen and oxygen molecules.
- Biomass processes can be split into thermochemical (gasification, pyrolysis, liquefaction, feedstock combustion) and biological (dark fermentation, bio-photolysis, and photo-fermentation). Biomass gasification is a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products without combustion and
- The hydrocarbon reforming of fossil fuel processes is divided into three categories: steam reforming, partial oxidation, and auto-thermal reforming.

Producing hydrogen from the reforming of fossil fuels is still the most used in large-scale production known as grey hydrogen. Although technological advances have been made in hydrogen production through renewable sources, the cost component of it remains an area of improvement. Electrolysis is the most compatible technology that can be used to produce green hydrogen and meet the net-zero emission targets that the world is shifting toward. The production of 1kg of hydrogen currently costs 2-3 times that of fossil fuels (Zun and McLellan, 2003). Most hydrogen is consumed in refining petroleum and fertilizer industries; an insignificant part of this hydrogen gets used as fuel for transportation (Malik, et al., 2023). Various levels of CO2 emissions, infrastructure, and investment requirements depend on the type of processes and feedstock (natural gas, coal, water, and biomass) used for hydrogen production. Figure 2.16 shows the different types of hydrogen, classified according to their production process and energy source.

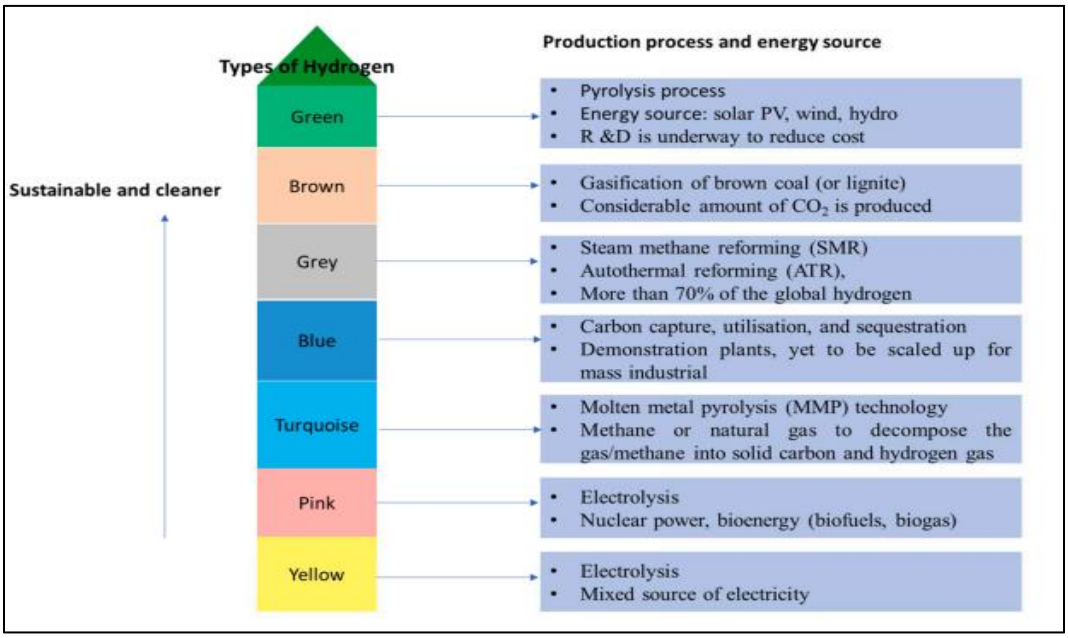

Figure 2.16: Types of hydrogen based on energy source (Rasul, et al., 2022)

2.9.1 Benefits and challenges associated with hydrogen

Hwang and Verma (2014) posited that a major obstacle to the development of hydrogen-powered FC vehicles is the lack of safe, lightweight, and energy-efficient means for onboard hydrogen storage, which needs further research and investigation. Maintaining cost control throughout the entire hydrogen production, purification, compression, and storage processes affects the profitability and marketability of hydrogen FCEVs. Luo et al. (2021) further asserted that hydrogen tanks must be as light as possible whilst fulfilling pressure limits, and this increases their manufacturing costs due to the energy-intensive compression process. Due to hydrogen's low ambient density temperature, an improved storage technique must be developed to increase its power density (Singla, et al., 2021).

Despite the known characteristics of hydrogen, which make it suitable for use as a fuel in FC technology, a lack of infrastructure for producing efficient and economical hydrogen is affecting the commercialisation of FC. When comparing the physical and chemical characteristics of hydrogen to other energy sources, it is not easy to store and transport this energy source efficiently for mass use (Rasul, et al., 2022). To fully integrate hydrogen into the world's energy supply, coordinated efforts are required to ensure appropriate and sustainable hydrogen storage to mitigate the erratic and unpredictable nature of hydrogen production. Hydrogen transportation involves the creation of safe and cost-effective transportation infrastructure, such as fuel cell vehicles, pipelines, compressed gas cylinders, and liquid hydrogen carriers, to help with availability and accessibility for end users (Muhammed, et al., 2023).

To ensure that no violent combustion or explosion occurs during leakages and collisions, measures must be put in place due to the flammable and explosive characteristics of compressed hydrogen (Calabrese, et al., 2024). Measures include storage sites with extensive safety and monitoring infrastructure, installation of fail-safe components such as valves, gas, fire and smoke detectors, and fire suppression systems (Peppas, et al., 2023). All of these are essential considerations when applying FCEVs underground, which are anticipated to further increase the costs of hydrogen technology.

There are different ways of storing and transporting hydrogen, it can be stored in a gaseous, liquid and material-based form (Calabrese, et al., 2024). The material-based form (metal hydrides) can be achieved by physically or chemically combining hydrogen with a solid material. It is done by applying heat to finely divided metal powder using a heater exchanger, and a water-heat exchange medium (Miller, et al., 2012). To fuel the system, a hydrogen source is then applied, and cool water is circulated through the heat exchanger until it is saturated by hydrogen. To release the hydrogen, a similar process is applied in reverse (Miller, et al., 2012). The process should be restricted to light metals such as Li (Lithium), Na (Sodium), Mg (Magnesium), and Al (Aluminum) to obtain a higher gravimetric density. Magnesium and its alloys are the preferred option for solid-state hydrogen as they are known to have lower cost implications and have good reversibility (Yang, et al., 2023).

One of the major benefits of metal hydrides is the broader range of its operation when compared to liquid and gaseous hydrogen storage. Moreover, metal hydrides have a high volumetric energy density, and it operates at a lower pressure in comparison to gaseous storage of hydrogen. Due to the lower operating pressure, there is greater safety, and the maintenance requirements are reduced. In addition, the overall cost of the system can be reduced by eliminating the need for components with high-pressure. A common disadvantage of metal hydrides as storage materials for hydrogen are the lengthy extraction and filling periods caused by slow kinetics and the fact that they are heavy (Klopcic, et al., 2023).

One primary benefit of compressed hydrogen is its rapid and proven reliability in terms of the refueling process because of its gaseous molecular state. Additionally, the gas is ready for consumption immediately, once it is stored. Hydrogen compression is a mature storage method; it is the most advanced and feasible hydrogen storage solution as it holds a technology readiness level (TRL) of nine and is commercially accessible. Moreover, improvements in tank materials are ongoing to reduce weight which makes it even more efficient. The main shortcomings are the low volumetric density associated with a gravimetric density that is not distinctly high. The reduced lifespan of the storage tanks because of the pressure and temperature fluctuations which cause cyclic stress and finally the heightened storage pressure. The high storage pressure poses safety risks by way of leaks, rising temperatures and explosions (Massaro, et al., 2023).

2.10 Countries' Policy in Hydrogen Fuel Cell Technology

2.10.1 Germany

Germany is one of the pioneers and leaders globally in terms of research and development and implementation of renewable energy. Germany is an ultra-modern country in Hydrogen Fuel Cell (HFC) because it has already launched its HFC economy. In 2006, a union was formed between the German government, stakeholders, and industry players to establish the National Innovation Program Hydrogen and Fuel Cell Technology (National Innovation Program). This program intended to place Germany as a technology leader in the HFC industry, to accelerate the HFC market expansion, and reinforce the trade (Azni and Khalid, 2021).

Germany's national policy on the Energy Concept has been significant in supporting HFC. Even though this policy does not have legislative effects compared to other laws in Germany, it generates a new pathway for energy in Germany. The policy serves as a guide for the government to prioritise achieving energy security while being environmentally friendly. Moreover, Germany enacted the Electric Mobility Act of 2015 to support the HFC industry and subsidies are provided for the purchase of FCEV. Furthermore, it developed the National Hydrogen Strategy in June 2020, which illustrates Germany's seriousness in developing the HFC industry. While this policy is not legislation, it permits the government to provide EUR 9 billion for developing renewable energy (Azni and Khalid, 2021).

2.10.2 The Philippians

The Philippines, a developing country, passed three legislative Acts that led to the development of the renewable energy sector. The initial law was passed when the Philippines faced an energy crisis due to a rapidly growing population in 1992. The first Act was the Electric Power Industry Reform Act of 2001 (Republic Act 9136), which led to the decentralisation of power generation and a 70% increase in power generation over the subsequent four years. The successive Act was The Biofuels Act in 2007, which was pivotal in stimulating the green hydrogen production industry as biofuels were an integral part of the energy input required to produce green hydrogen. The third Act passed mandated the Philippine state to join efforts with the international community to alleviate climate issues. The Renewable Energy Act was thus passed in 2008. To further advance its renewable energy journey, the Advanced Energy and Green Buildings Technology Curriculum Act was passed in 2019, which mandated higher education institutions to develop curricula that focus on sustainable green energy technology (Jose and Richard, 2022).

All these culminated in a consolidated Bill that aimed to establish a Philippine Energy Research and Policy Institute (PERPI) being passed into law. The aim of PERPI was for the Philippines to remain abreast and competitive with the fast-paced technology in the green energy sector. One of the most recent efforts was the establishment of the Hydrogen and Fusion Energy Committee (HFEC) and collaboration with Hydrogen Technologies Inc., a Japanese company, to focus on research and development of the use of hydrogen energy in electricity and power generation. Another collaboration with the Japanese government was through Toshiba Energy Systems and Solutions for installing a renewable energy-powered hydrogen-based autonomous energy supply system. The sole mandate of the HFEC is to research and develop hydrogen as a viable alternative clean energy source (Jose and Richard, 2022).

2.10.3 Other Countries

Countries like the United States and South Korea are also among those that have advanced themselves by incorporating hydrogen fuel cell technology into their legal frameworks (Azni and Khalid, 2021). This demonstrates the need for South Africa to review and reposition its legal framework to expedite the hydrogen fuel cell economy.

2.11 South African Perspective

FC technologies are being considered for implementation by countries with the objective of promoting decarbonised energy to move away from fossil fuel ICEs to vehicles that are powered by HFC technologies. However, Africa continues to fall short, in terms of green hydrogen and renewable energy policies. In most Southern African countries renewable energy resources are integrated into frameworks that deal with regulations and competition in the energy sector instead of being defined clearly in statutes. This in turn has influenced the investment and implementation of renewable energy ventures in a negative way (Imasiku, et al., 2021).

Although South Africa does not have a policy that solely addresses hydrogen, it has existing energy policies and strategies that govern the energy sector that can serve as a basis for introducing hydrogen. This includes the HSRM which provides an outline of the strategies for hydrogen integration in South Africa’s energy sector. There are several regulatory frameworks regulating the introduction of hydrogen as an alternative energy source and they include (Department of Science and Innovation, 2021 (a)):

- Integrated Energy Plan (2016): this plan states that in South Africa the hydrogen economy is given significant thought as an energy carrier and has potential to become a substitute energy source.
- Integrated Resource Energy Plan (2019): this plan focuses on the electricity sector and was established to provide government with a mechanism to drive the diversification of the electricity-generation mix. It promotes renewable energy and other lower carbon technologies.
- National Development Plan: focuses on infrastructure, including energy infrastructure required to diversify energy supply in South Africa.

- Green Transport Strategy – This strategy explores the potential role of HFCs on various applications in the transport sector.

In addition to the policy frameworks and strategies, there have been several initiatives to support hydrogen fuel cell technology.

2.11.1 South African Hydrogen Economy (Hydrogen Valley)

The use of fuel cells as an alternative source of energy has become one of South Africa's national priorities. The commitment towards hydrogen production, to achieve net-zero emissions by 2030, has created an opportunity for South Africa to engage in energy export at the international level. For South Africa to remain competitive amongst other energy exporters globally, the country needs to invest in a hydrogen production network in areas where there is local demand and, from there on, explore the possibility of entering the international energy export market. The Hydrogen Valley is comprised of the Mogalakwena, Johannesburg, and Durban hubs, which were strategically created by the Department of Science and Innovation in partnership with Anglo-American Bambili Energy and ENGIE. The aim of the Hydrogen Valley is to save costs through shared infrastructure investments and to improve cost competitiveness through the economies of scale production in South Africa (Department of Science and Innovation, 2021b).

South Africa contributed 2% of the hydrogen produced globally by the year 2021. With the current developments, the Hydrogen Valley is expected to position South Africa's market globally through its access to ports and solar solid irradiation (Department of Science and Innovation, 2021b). The Hydrogen Valley is expected to also ensure that a local supply chain is established, and this will allow South Africa to develop a skilled workforce to support this sector. Local application of FC technology will assist in bridging the skills gap and promoting the development of the manufacturing industry. It will also secure supply levels by establishing the required infrastructure and lower production costs through economies of scale.

Figure 2.17 shows the global platinum demand in 2022. As seen in the figure, most platinum's final application (43%) was in autocatalysts, which is supported by increasingly stringent global pollution regulations. Platinum is a powerful catalyst that transforms hydrocarbons and carbon monoxide into innocuous molecules, which is useful for light- and heavy-duty diesel engines. Platinum demand in the emerging hydrogen economy was 1% in 2022, as shown in the figure. It is used as a catalyst metal in some electrolyser technologies that create hydrogen from water and in some fuel cells that use hydrogen to generate energy for vehicles and stationary purposes (Sibanye-Stillwater, n.d.).

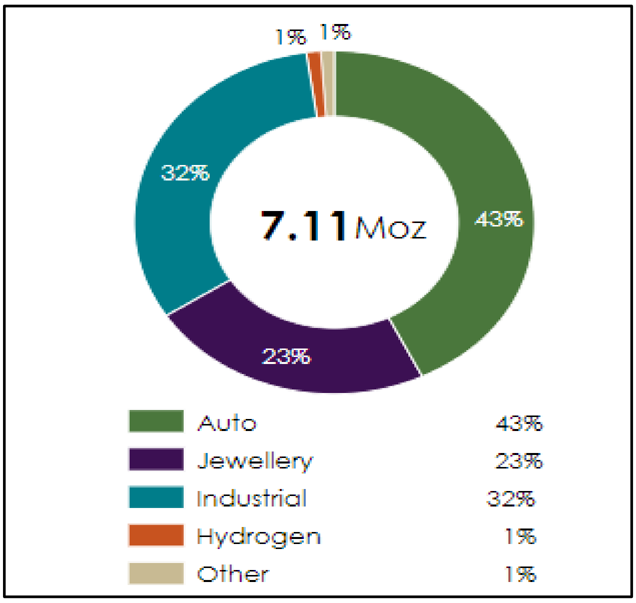

Figure 2.17: Global Platinum Demand 2022, (Source: *SFA (Oxford);* (Sibanye-Stillwater, n.d.)

In addition to the Hydrogen Valley, the Department of Science and Technology initiated Hydrogen South Africa (HySA), which the Cabinet approved in May 2007. This was a 15-year program intended to promote research, development, and innovation to support South Africa's participation in hydrogen and FC technology. HySA has established three competency centres with the aim to enable the use of platinum as a catalyst. The centres are known as "HySA Catalyst" which oversees the establishment of a platinum catalyst that can be commercialised locally and internationally. The "HySA Infrastructure" which in charge of creating labs and facilities that have the objective of generating and testing hydrogen storage materials. Finally, the third centre "HySA Systems" oversees creating by way of collaborating the output of the other two centres (Pinto and Chege, 2016).

HySA aimed to achieve a 25% share of the global hydrogen and FC technology market utilising PGMs since South Africa is a major world supplier of PGMs (Pollet, et al., 2014). In 2021, the Hydrogen Society Roadmap (HSRM) was established to serve as a national co-ordinating framework to facilitate the integration of hydrogen-related technologies. Besides the well-developed PGM sector, South Africa also has a well-established mining infrastructure and can produce many metals that are important components in various metal hydride-forming alloys such as titanium, vanadium, nickel, manganese, or rare earth. Figure 2.18 shows the available mineral deposits that the country has for the manufacturing of metal hydride alloys which are key to hydrogen storage applications (Pollet, et al., 2014).

Figure 2.18 South African mineral deposits for manufacturing of metal hydride alloys (Pollet, et al., 2014)

As stated on the South Africa Hydrogen Valley final report (2021), there are various benefits in the success of the Hydrogen Fuel Cell technology industry in the South African context, which include a reduction in the energy strain on the power grid, job creation, and a reduced carbon footprint, which translates to an environmentally sustainable energy economy (Department of Science and Innovation, 2021b). South Africa is well suited to lead the manufacturing of hydrogen fuel cell technology, as such it must use its comparative advantage and turn it into a competitive advantage through championing the commercialization and implementation of hydrogen fuel technology.

2.11.2 Gaps identified on existing policies

Some gaps need to be addressed to realize the full benefits of hydrogen economy. The International Energy Agency, which is an organization that works with different countries around the world to shape energy policies for a secure and sustainable future, makes mention of 5 pillars of policy support for the development of hydrogen economies. These five pillars can be used as a guideline to assess the adequacy of South Africa's existing policies and to support the establishment of the hydrogen economy.

The five pillars include the following (International Energy Agency, 2021):

- Establishment of targets and long-term policy signals
- Support demand creation
- Mitigation of investment risks
- Promotion of research and development, innovation, strategic projects and knowledge sharing
- Harmonization of standards to remove barriers

The introduction and implementation of clean hydrogen also comes with challenges and gaps. These include inter alia capital costs, limitation of existing infrastructure and the lack of investment. The gaps and challenges can be overcome by the introduction of policies that set standards and frameworks on the production, storage and usage of hydrogen used in FC Technologies (Imasiku, et al., 2021).

2.11.3 Hydrogen certification in South Africa

Green hydrogen is deemed to be a promising technology for the generation of energy, storage and transportation (AbouSeada and Hatem, 2022). However, standards, regulations, and certification systems that focus on the environmental characteristics of hydrogen and guarantee compliance are crucial for promoting the use of low-emission hydrogen. The criteria for the standards and regulating framework concerned with producing hydrogen can be verified by way of certification, there is no steady structure of certification across the world. As a result, without developed interoperability in regulatory systems and certification, hydrogen trade will probably be restricted to bilateral agreements, hindering the establishment of a global market. The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) has completed its methodology for assessing the GHG emissions linked to the production, conversion, and transportation of hydrogen. This document is set to be instrumental in establishing an International Standard through the International Organization for Standardization (ISO) (International Energy Agency, 2023).

2.12 Chapter Summary

Diesel engines are widely used in underground mining machinery, during their operation they emit heat, noise and noxious gases which contribute to GHG emissions. Reducing GHG emissions for a sustainable environment is essential since they affect society and ecosystems through climate change. South Africa is the largest energy consumer on the continent, resulting in it being amongst the leading GHG emitter globally, which is a great concern. Countries entered as a solution to minimise the amount of GHGs that they emitted into a Paris agreement. The Paris agreement therefore holds countries accountable for their contribution to global warming and challenges them to invest in alternative sources of energy that are clean. Implementing FC technology as a renewable energy source is one of the focus areas in many countries. Replacing fossil fuels by introducing hydrogen technology as a fuel in the industry is expected to assist in reducing GHG emissions. The implementation of FC technology will create the desired work efficiencies as fuel cells can operate at higher efficiencies than combustion engines.

In the case of South Africa, the success of the hydrogen fuel cell technology offers various benefits, including a reduction in the energy strain on the power grid, job creation, and a reduced carbon footprint, which translates to an environmentally sustainable energy economy. South Africa is well suited to lead the market given that it owns the majority of the global PGM reserves. FC systems offer benefits over traditional power systems, including low environmental impacts, high efficiency under a variety of load conditions, and modularity. These benefits and possible cost savings as a result of reduction in ventilation requirements which make FCs appealing for various uses, more especially in the mining industry. The testing of hydrogen fuel cell technology in the mining industry will be a step towards finding more engineering and substitutive controls to mitigate the effects associated with the use of diesel fuelled LHDs. The challenges and constraints affecting hydrogen fuel cell technology also requires adequate policy support that will enhance large scale production, thereby reducing the huge associated capital costs.

It is necessary to develop appropriate standards and regulations that governs the production, processing, and application of hydrogen. For South Africa to deploy enough hydrogen to meet the climate goals, there must be relevant regulations in place to keep pace with the energy markets. There must be a regulatory framework that provides a clear pathway to the zero-emissions commitments made.

3 RESEARCH METHODOLOGY

3.1 Chapter Introduction

The choice of research method is a crucial decision in the research design process since it ensures that relevant information is obtained for the study. There are different research approaches that one can employ depending on the objectives of the study; however, many interrelated decisions are made throughout the research process. This chapter focuses on the research approach adopted during the data collection and analysis; it discusses how the reliability and validation of the data collected were safeguarded during the research process. The chapter also outlines the research limitations and how they were addressed during the study. Ethical considerations that were adhered to throughout the research study are also explained in this chapter.

3.2 Research Approach and Design

Depending on the aim and nature of the research, researchers can apply any of the three research approaches: qualitative, quantitative, or mixed-method research approach (Taherdoost, 2022). Quantitative research is aimed at collecting data using measurements and analysing the data collected to find averages, trends, and relationships (Streefkerk, 2023). Quantitative research relies on quantifying specific phenomena. The advantages of conducting research using the quantitative method are that it is time efficient as it can be administered and evaluated quickly, and the findings are drawn from using large sample sizes which represent the population, and hence the results are generalized. Conversely, the disadvantage of this research method is that it fails to capture detailed and in-depth explanations (Taherdoost, 2022).

Researchers have noted that not all questions can be answered through quantitative research (Watson, 2013). The qualitative research process can be considered if there are gaps in the data collection. This method is inductive rather than deductive and involves testing ideas or hypotheses. Using this method, researchers aim to gather non-numerical data to build up concepts, assumptions, and theories. Qualitative researchers draw on their observations and understanding gained in the field to develop theories, themes, categories, and concepts (Merriam, 2002). Conducting research using the qualitative research method is advantageous because of its flexible nature. When conducting semi-structured interviews, the researcher can modify and alter the questions during the interview, this assist in checking the accuracy of the data collected. Another advantage is that it can be video-recorded or audio-recorded, which improves the data's accuracy and makes the data analysis easier (Alamri, 2019). However, the disadvantage of conducting qualitative research is that it is time-consuming, the researcher requires ample time to arrange and conduct interviews as well as gather, record and analyse the data collected (Alamri, 2019). Another disadvantage of qualitative methods is that their findings are not generalizable as their sample sizes are smaller (Taherdoost, 2022).

The mixed methods approach involves collecting and analysing both forms of data (quantitative and qualitative) in one study. Cambell and Fiske (1959) developed the concept of mixing different approaches during research. This resulted from researchers recognising that both qualitative and quantitative methods have limitations with inherent biases. Therefore, in the application of a mixed method approach, the inherent biases of each of the approaches is neutralised and sometimes even eliminated. According to Tashakkori and Teddie (1998), the mixed-method approach allows the triangulation of data sources collected using quantitative and qualitative approaches.

Particularly in this research study, a mixed method approach was adopted. According to Creswell (2003), in the mixed method approach, both forms of data are collected concurrently during the research to achieve a comprehensive understanding and analysis of the research objective, which was an investigation of FC technology in underground machinery (Creswell, 2003).

3.3 Data Collection

Qualitative and quantitative data collection methods included both primary and secondary sources during the research. The key primary data collection methods used included taking measurements, making observations and conducting interviews. Secondary data was collected through literature review focusing on four areas as depicted in figure 3.1. Figure 3.1 shows the process map of the approach followed during data collection and analysis. The process depicted by figure 3.1 is elaborated in Sections 3.3 and 3.4.

3.3.1 Quantitative study

Workplace site exposure measurements were taken during 15 underground visits, the selection method used for workplaces visited was random sampling in line with purposive method. Although the selection of the workplaces visited was random, the selection was done that all ventilations districts within Mine A were covered. Exposure factors that were considered on the physical environment created during loading operations of diesel engines, such as noise, gases and temperatures were measured. Primary measurements were taken before and during the loading of the LHD at various working sections to assess the impacts of diesel engines on the working environment.

Five visits were taken to the surface workshop on Mine A where secondary observations of the available infrastructure were made. At Mine A, all the LHDs are serviced and maintained before being sent underground for loading and hauling at the surface workshop. During these visits, relevant data was collected from the planned maintenance office. At the planned maintenance office, data on LHD specifications, production and maintenance requirements, capital costs and consumption records were collected. Historical records on previous sampling done to determine the effectiveness of controls in place to minimise employees ‘exposure to diesel emission exhausts were collected.

3.3.2 Qualitative study

Critical literature and desk review were done to understand the development of FC technology since its inception, the benefits, challenges to commercialization, and application in underground machinery. The literature review included hydrogen technology and factors affecting environmental sustainability like GHG emissions. Literature reviews were done to analyse the social and economic aspects of introducing fuel cell technology in underground equipment. Mining industry-related literature was reviewed to do a comparison between the capital and operating costs of a diesel and HFC LHDs.

The search strategy focused on journal articles, websites, reports and guidelines based on titles, keywords and abstracts aligned to the objectives of the research. Data collection during the literature review included:

- Book chapters and scholarly publications (Journals) relating to fuel cell and hydrogen technology, as experts in a particular field usually write these.
- Grey literature, such as environmental impact statements, conference proceedings, market research reports, and online documents, were used.
- Standards and publications issued by certain authorities, such as the Department of Mineral Resources and Energy (DMRE), the Department of Science and Technology (DST), etc., were also used.

Workplace site observation are important aspects of conducting qualitative research. Direct observations were made, where more than 10 specific observations were made on infrastructure requirements during the surface workshop visit. Observations made included the workshop layout, current refueling techniques, pre-inspections and maintenance schedules of the LHDs. These observations assisted in terms of getting a deeper understanding of the infrastructure requirements and changes that will be required when transitioning from diesel engines to hydrogen fuel cell technology.

Interviews were conducted with selected participants employing semi-structured questionnaires, attached as Appendix C. The interviews allowed flexibility in exploring the expert’s knowledge of hydrogen fuel cell technology's application in underground machinery. They were used to gather comprehensive and relevant information that addressed the research questions.

3.3.2.1 Participants selection for interviews

A non-probabilistic purposive sampling method was used to select participants for the interview, purposive sampling is best suited when individuals vital to answering the research question can be identified (Nikolopoulou, 2022). The purposive sampling method was used to select a correct representative in the mining industry, which are representatives that would be able to give insight on questions aligned to the aims and objectives of the study. This sampling method was chosen as experts’ opinions and knowledge were required for the research topic. Participants were identified and selected based on their experience and area of expertise in underground machinery operation and involvement in hydrogen fuel cell technology and underground equipment manufacturing. OEMs where selected to get an insight into the requirements and support required to implement FC technology in the mining industry. A total of six interviews were conducted, table 3.1 shows the profile of the participants who were interviewed during the research study. The table also shows the role that the six participants interviewed play in the mining sector and their years of experience in their roles.

Table 3.1: Profile of Participants

Identification	**Role in the Mining Sector**	**Total experience in Industry/Field**
Participant 1	Environmental and Occupational Hygiene Manager	22 years
Participant 2	Engineering Manager (mobile trackless machinery)	13 years
Participant 3	Engineering Manager (mobile trackless machinery)	17 years
Participant 4	Hydrogen and Energy Research	10 years
Participant 5	Original Equipment Manufacturer	20 years
Participant 6	Engineering Specialist (mobile trackless machinery)	20 years

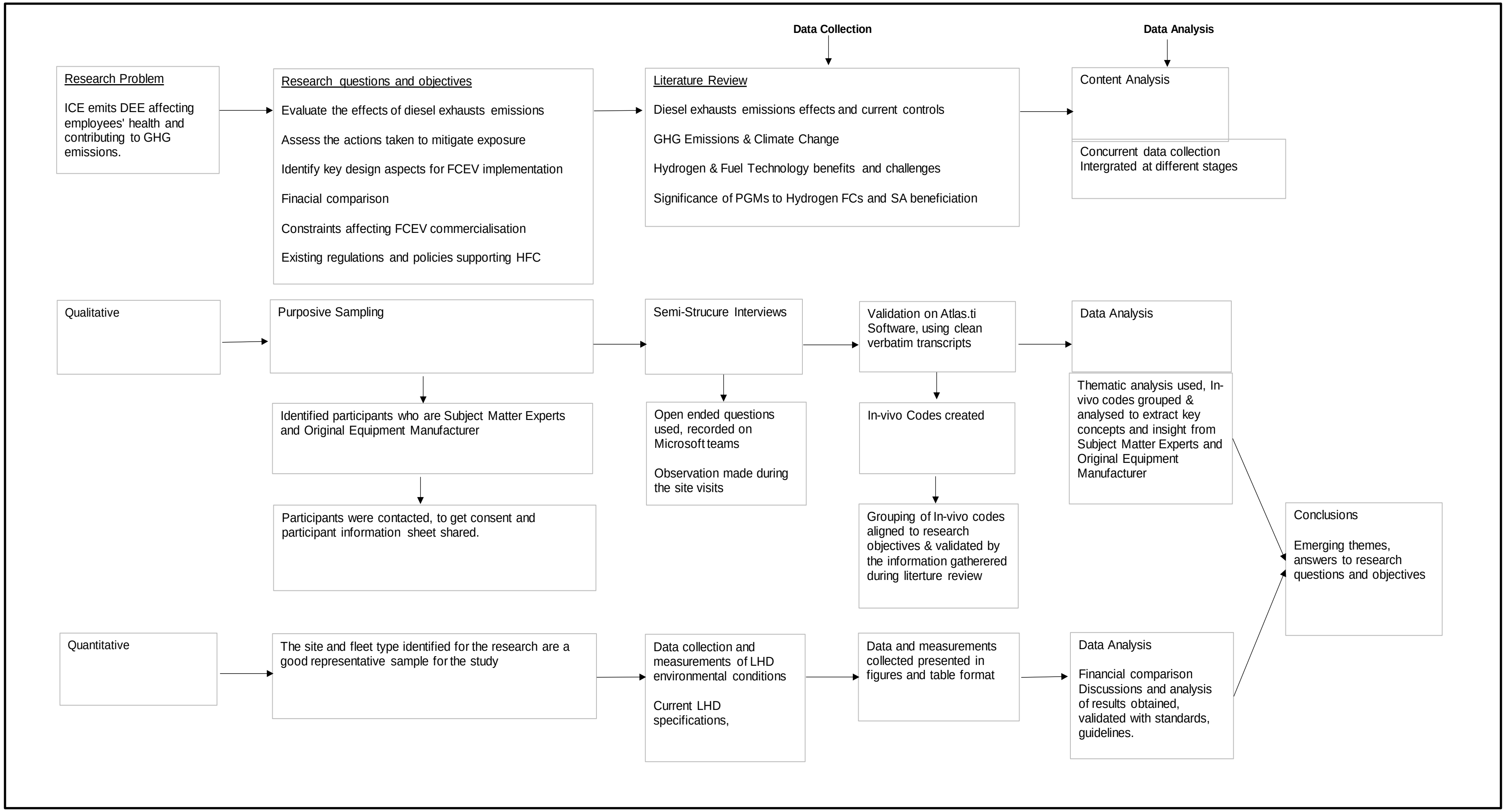

Figure 3.1 Process map for data collection and analysis

3.4 Data Analysis

The methods employed to analyse data collected is discussed under two headings below:

3.4.1 Quantitative data analysis

Quantitative data analysis focused on numerical data analysis, and it was based on the type of data format used (i.e. excel), graphical analysis, exploring relationships between variables was done. Data collected were logged using Microsoft Excel spreadsheets, where differences and commonalities were examined, and these measurements were evaluated against OEL limits. The gathered data was utilized to plot and assess the connections between the variables.

3.4.2 Qualitative data analysis

Content analysis was adopted to analyse the data collected. This is a data analysis method used to determine the presence of certain words, themes, or concepts within given qualitative data (Berelson, 1952). To analyse the text using content analysis, the text must be coded into manageable categories for analysis. Content analysis was used to extract relevant insight during the literature review. Observations made were written down and linked to the objectives of the study. During the research, the semi-structured interviews were recorded using Microsoft Teams; clean verbatim was used when transcribing the recorded interviews. Data analysis software was used whereby codes were created and grouped into emerging themes aligned to the research objectives. Coding was done using the NVivo method on the Atlas.ti software. Figure 3.2. shows the screen dump of the Atlas.ti software that was used for analysing the interviews.

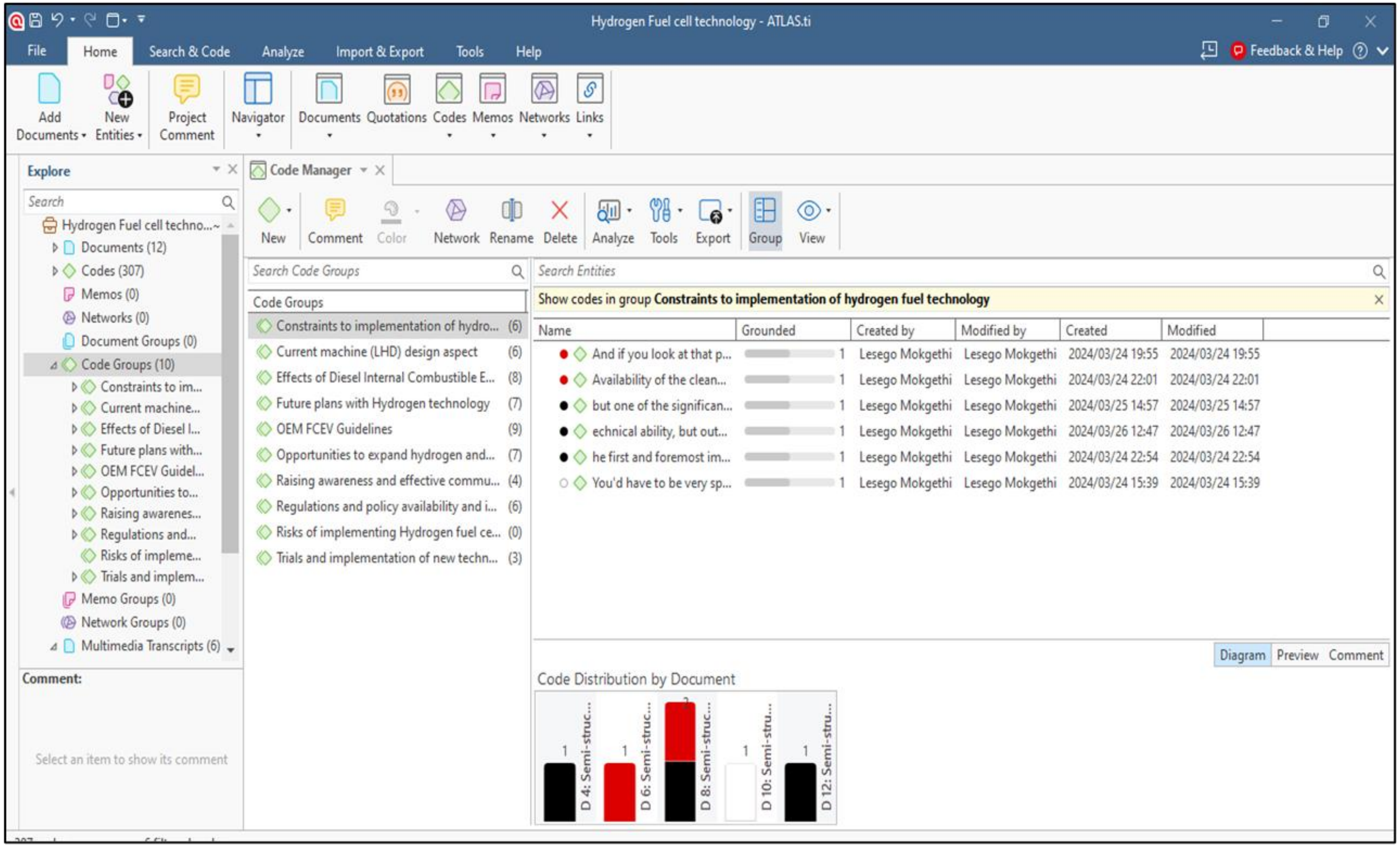

Figure 3.2: Atlas.ti screen dump showing the in-vivo codes and groups created aligned to research objectives.

3.5 Research Validity and Reliability

The accuracy and credibility of the research are important and need to be checked throughout the research study. Research reliability measures the dependability and consistency of data. According to Nicolas (2021), the information is considered to be reliable when the data collected show similar results when tested using different methods or sample groups. The purposive sample method was used to select participants during the research, triangulation was used to ensure resource validity and reliability. Participants that took part in the study are experts who are knowledgeable about the subject. The information received from participants was verified by existing literature research on fuel cell technology, and more than one subject matter expert participated in the semi-structured interviews to identify emerging themes.

All participants possess considerable experience, varying from 10 to 22 years therefore, their responses and input are reliable. To guarantee the reliability of the measurements, more consistent data was collected over a 10-day span at different strikes on various LHDs

Research validity is defined as the accuracy of the measurement, and it shows how a specific test is suitable for a particular situation. The research is valid if the results are accurate, according to the researcher's situation, explanations, and predictions (Nicolas, 2021). To remove researcher bias, open-ended questions were used in the interviews and clean verbatim extracts were preserved to reduce subjectivity. The research objectives and questions were clearly defined to ensure research validity. Data and accuracy of the recorded interviews were checked by going through the transcripts. The consistency in the answers received from different participants enabled the ability to compare the extend of stability in the findings of the research. Coding was used during data analysis to identify themes and patterns, and the validity of the coding process was ensured through consistent and coherent translation rules.

3.6 Ethical Consideration

Ethical approval for the research was obtained from the University with Protocol number EMINN/2023/100. The consent form and participant information were shared with identified participants through email requests, and these are attached in Appendix A and B respectively. Participants gave consent by accepting MS teams meeting request and sending signed participant and consent form prior to the engagements. In the report, anonymity and confidentiality of the participants was ensured by using pseudonyms, which was also applied when the transcripts were saved after the recording. The raw data collected was not shared with anyone and was kept in a password-protected laptop to ensure confidentiality. Written permission to use company data was obtained before visiting the site. All sources used during the literature reviews and research process that were accessible from the public domain were correctly referenced and accredited.

3.7 Research Limitations and Challenges

The availability of participants selected for interviews was a challenge due to the nature of their work, which resulted in several postponements. To address this challenge, more than one participant from the same field were invited to ensure that input and views from all relevant subject matter experts key to the commercialisation of hydrogen fuel cell technology were collected. Financial comparison of the FCEV LHD in the absence of a prototype onsite created limitations in terms of the full financial valuation, as some of the costs could not be quantified. However, the qualitative data collected during semi-structured interviews were used to make relevant assumptions where it was required.

3.8 Chapter Summary

The mixed method approach was adopted in the study, and it involves collecting and analysing both forms of data (quantitative and qualitative) in one study. The mixed-method approach allows the triangulation of data sources collected using quantitative and qualitative approaches. The sources of data were drawn from a wide range of sources. Data for the study was collected using observations during site visits, interviews, and literature review. Ethics clearance was obtained from the

School of Mining Engineering, and permission to use company data was obtained from the company.

4 RESULTS AND ANALYSIS

4.1 Chapter Introduction

The chapter presents the results and analysis of the collected data, which are discussed under categories aligned with the research objectives. The results cover the effects of diesel LHDs on the working conditions and actions taken to mitigate their effects. The key aspects to be considered during the design and implementation of fuel cell electric (FCE) LHDs, cost comparison between diesel and FCE LHDs and constraints to hydrogen fuel technology implementation are also presented in the chapter. The chapter also discusses the status of existing regulations and policies supporting hydrogen fuel technology in South Africa. The chapter ends with a summary of the discussion on key findings and their correlation to the literature review conducted.

4.2 Effects of Diesel Load Haul Dump on Environmental Conditions

During the visit to Mine A, data was collected to get an overview of the type and specifications of the LHDs used. Figure 4.1 shows a typical 5.5 low profile LHD used on Mine A.

Figure 4.1 Low 5.5 LHD profile (Mine A)

The main components of the diesel LHDs are the fuel system, hydraulic system, transmission and torque converter, and engine. The specifications and capacities of the main components are listed in Table 4.1.

Table 4.1: Specifications of the LHDs used on Mine A

Engine	
Type	BF6L914
Power rating	92kW at two 300rpm
Torque	430Nm at one 500rpm
Fuel consumption	220g/kWh
Engine protection	As per customer requirements
Air cleaner	Two-stage
Catalytic converter	DPM Filter
Diluter	Old system
Transmission/Torque Converter	
Three-speed forward and reverse with modulation and remote converter	
Dana T20 000 series	
Capacities	
Weight	16 000kg
Tramming capacity	5 500kg
Tipping load	254kN
Break out force	162kN
Bucket max. load	5 500kg
Hydraulic System	
System pressure	28MPa
Piston pump Flow rate	138 litres/min at two 300rpm
Hydraulic tank capacity	174 litres hydraulic level switch detection
Fuel System	
Fuel tank capacity	180 litres

From Table 4.1, it can be noted that the LHDs have a fuel tank capacity of 180 litres, which translates to 11 hours of work (at 0.9kg per litre of diesel), a hydraulic system pressure of 28 mega-Pascals (MPa), and engines with 92 kilo-Watts (kW) output. The fuel tank capacity is determined by the engine capacity, and it is designed based on the production requirements, travelling and tramming distances to allow the machine to proceed underground and out to the surface workshop without requiring refueling whilst underground.

Figures 4.2 and 4.3 show the main components of the LHD system from different views. The figures are labelled to indicate the location of the main component systems as specified in Table 4.1.

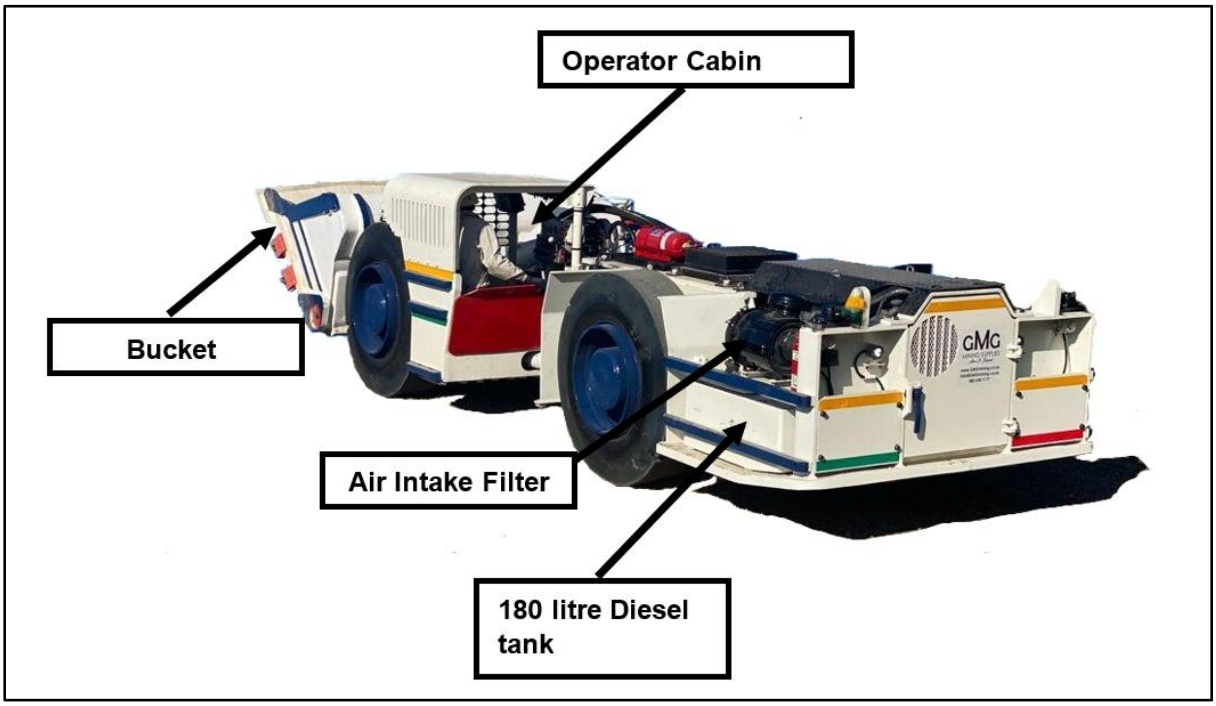

Figure 4.2: Main components of LHD system and side view, Adapted from Mine A (2024)

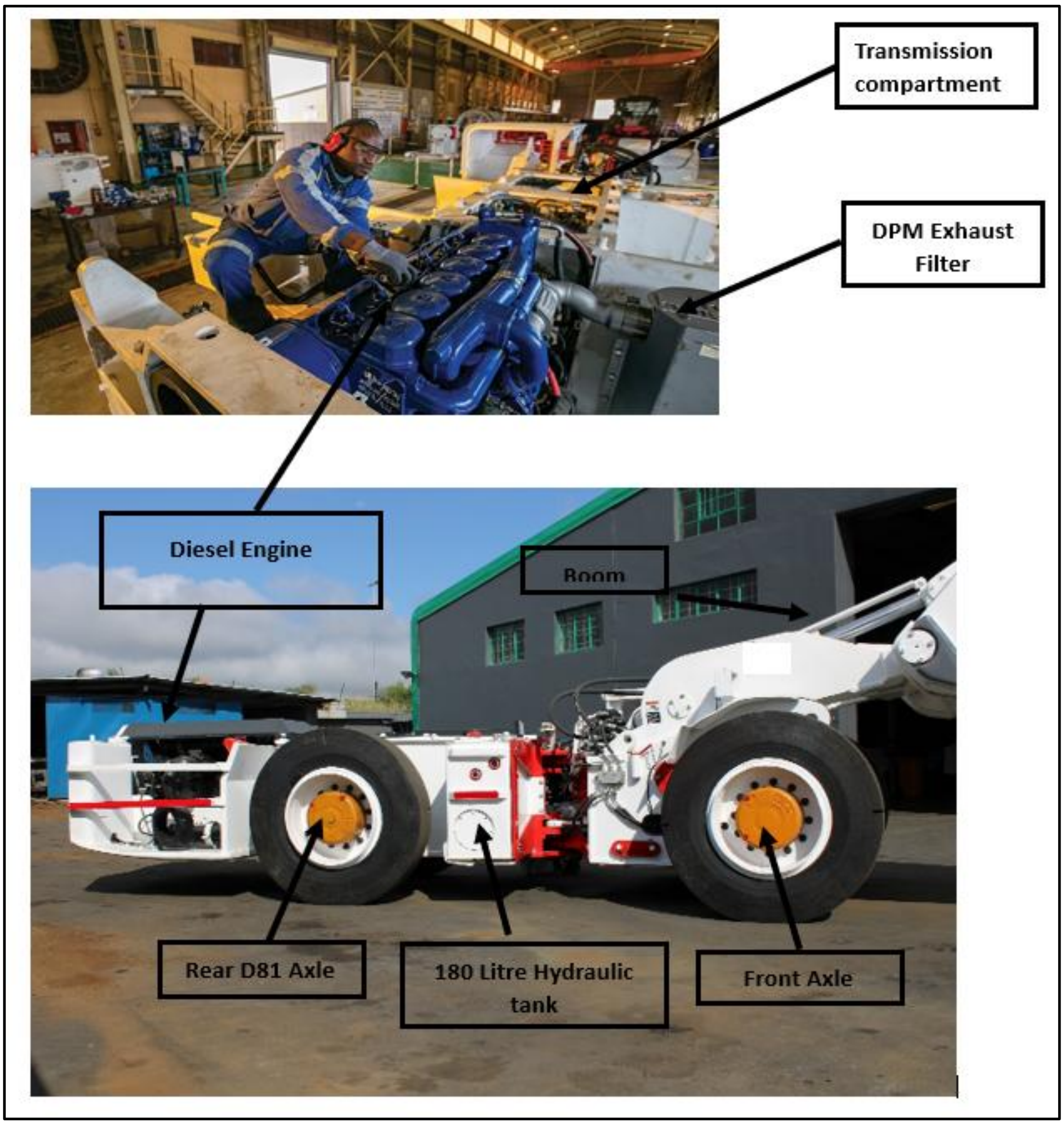

Figure 4.3: Main components of LHD system, side, and top view, Adapted from Mine A (2024)

During the underground visits, measurements were taken during loading operations to determine the immediate effects that LHDs have on the underground conditions. These measurements included temperature and heat, noise, and gases, and the release of diesel particulate matter. Table 4.2 summarises the measurements taken during underground visits whilst the LHDs (i.e., LHD 431, 293, 413, etc) were operating, one to two LHDs were loading at a time on a strike. The measurements were taken at different strike sections over a 10-day period. The environmental conditions were measured on the downstream side before the LHD started loading and during loading, the distances varied from 15m to up to 50m from the LHD. The downstream side refers to the direction of the ventilation flow in the area, which is the fresh base in this case. The distance from the LHD is controlled by the CAS level 9 installed on the LHDs, which is a collision avoidance system meant to prevent incidents and accidents.

With regards to taking measurements on the downstream side, which is a standard procedure on Mine A, it is to minimise the exposure of employees to gases and heat emitted during loading operations whilst measurements are being taken. The instruments used are checked and calibrated to ensure the environmental measurements taken in underground workplaces are accurate.

Table 4.2: Underground environmental measurements

	Prior loading	During Loading	Variance
LHD 431_ E 07 LS			
Temperature	26,5/28,1 ℃	28,5/29,1 ℃	2/1 °C
Velocity	1,4 m/s	1,4 m/s	0 m/s
Carbon Monoxide	00 ppm	7 ppm	7 ppm
Noise	74 db(A)	84 db(A)	20 db(A)
LHD 293_ E 08 LS			
Temperature	26,3/28,5 ℃	28,4/30,5 ℃	2,1/2 °C
Velocity	1,3 m/s	0,9 m/s	0,4 m/s
Carbon Monoxide	00 ppm	9 ppm	9ppm
Noise	72 db(A)	86,5 db(A)	14,5 db(A)
LHD 413_E 05 LS			
Temperature	23,1/26,5 ℃	25,6/26,2 ℃	2,5/0,3 °C
Velocity	1,2 m/s	1,0 m/s	0,2 m/s
Carbon Monoxide	00 ppm	10 ppm	10 ppm
Noise	63 db(A)	84,5 db(A)	21,5 db(A)
LHD 435_E Sinking			
Temperature	24,4/26,8 ℃	25,6/28,2 ℃	1,2/2,6 °C
Velocity	1,8 m/s	1,6 m/s	0,2 m/s
Carbon Monoxide	00 ppm	12 ppm	12 ppm
Noise	69,2 db(A)	96,5 db(A)	27,3 db(A)
LHD 411_E 11 LS			
Temperature	23,8/25,8 ℃	25,1/29,6 ℃	1,3 /3,8 °C
Velocity	1,4 m/s	1,1 m/s	0,3 m/s
Carbon Monoxide	00 ppm	9 ppm	9 ppm
Noise	69,2 db(A)	94,6 db(A)	25,4 db(A)
LHD 452_E 07 LS			
Temperature	24,1/26,1 ℃	26,8/29,3 ℃	2,7/3,2 °C
Velocity	1,4 m/s	1,2 m/s	0,2 m/s
Carbon Monoxide	00 ppm	16 ppm	16 ppm
Noise	68,3 db(A)	98,8 db(A)	30,5 db(A)
LHD 453_E 04 LS			
Temperature	23,9/25,4 ℃	25,8/28,4 ℃	1,9/3 °C
Velocity	1,2 m/s	1,0 m/s	0,2 m/s
Carbon Monoxide	00 ppm	11 ppm	11 ppm
Noise	62,2 db(A)	81,5 db(A)	19,3 db(A)
LHD 453_E 09 LS			
Temperature	24,8/26,9 ℃	27,0/29,2 ℃	2,2/2,3 °C
Velocity	1,4 m/s	1,2 m/s	0,2 m/s
Carbon Monoxide	00 ppm	17 ppm	17 ppm
Noise	60,2 db(A)	86,5 db(A)	26,3 db(A)
LHD 411_E 08 LN			
Temperature	22,4/25,4 ℃	24,2/28,2 ℃	1,8/2,8 °C
Velocity	1,1 m/s	0,8 m/s	0,3 m/s
Carbon Monoxide	00 ppm	9 ppm	9 ppm
Noise	60,0 db(A)	84,6 db(A)	24,6 db(A)
LHD 452_E 07 LS			
Temperature	24,6/25,1 ℃	26,1/28,9 ℃	1,5/3,8 °C
Velocity	1,2 m/s	0,9 m/s	0,3 m/s
Carbon Monoxide	00 ppm	11 ppm	11 ppm
Noise	68,3 db(A)	88,8 db(A)	20,5 db(A)

4.2.1 Temperature and heat

Mine A is classified as a "cool" mine where maximum allowable temperatures are less than 27.5°C wet-bulb (Wb) and less than 37.0°C dry-bulb (Db). Table 4.2 shows that the temperatures increased on average by 1.9°C Wb and by 2.5°C on Db. Due to the temperature increases shown in Table 4.2, it is recommended on Mine A that no one must be on the downstream side of the LHD during loading. According to the participants interviewed and information collected on Mine A, this supposition is made to mitigate employees' exposure to high temperatures and noxious gases. However, adherence to this rule poses challenges and constraints on production efficiencies as the number of machines loading at a time are limited. This is aligned to the findings of the qualitative study, one participant noted that, "the *number of equipment that you are using underground can be reduced, which then reduces the heat load from that aspect. However, it will have a direct impact on your production as well, because if you reduce your machines, production might be directly impacted due to that*". Although increases in temperatures were observed during measurements taken, they were still within the Wb temperature for unacclimatized employees of 27.5°C and within the legislation of 32.5°C.

More so, due to fissure water and water used for drilling, there is a high air moisture content, and Mine A has an average humidity of 81%. Although there is no mine standard regarding humidity, it has been noted that LHDs tend to overheat where humid conditions prevail. This increases the heat, which then contributes to reduced machine availability due to overheating, caused by clogged filters due to a combination of high humidity and dust in the atmosphere. This also is an indication that operators are exposed to increased heat load during loading operations which is not suitable for their health and safety.

4.2.2 Harmful gasses

Another environmental effect associated with the use of diesel engines is that they emit harmful gases that affects employees' health. As noted on Table 4.2, gases such as CO and others are emitted during LHD operation. It can be seen from Table 4.2 that, the gas detection instrument picked up an increase in CO, whereby it increased from 00ppm to an average of 12ppm. The increases in CO within the various sections were in range, slight increases were seen in sections where two LHDs were loading. This is aligned to the findings from the qualitative study, whereby a participant stated that, *"diesel engines also emit nitrous oxide or nitrogen dioxide, which is also an irritant that can cause asthma"*. Whilst another participant mentioned that "*diesel engines emit a combination of gases which are obviously harmful to* *the atmosphere".* The other study participant stated that, "*the effects of diesel emissions from exhaust systems are detrimental, if you get exceedances on those limits, they are obviously detrimental to people's health in the underground mining environment. So, your carbon monoxide, hydrocarbons, diesel particulate matter, and all the gas emissions out of your exhaust systems are not very healthy"*. CO is harmful as it reduces the ability of the blood to carry oxygen and may result in fatigue, headaches, and dizziness (OSHA, 2012) .Although the CO levels observed during measurements taken were increasing, none were measured above the OEL of 30ppm, they were all well below the threshold.

To dilute diesel exhaust fumes effectively, a factor of 0.12m^3/s/kW is applied, and 30% is added to cater for leakages on the ventilation designs of Mine A. The increased heat and gases emitted result in the need for mechanical ventilation, leading to increased operational costs. The finding is aligned to the qualitative study, whereby one participant stated that, *"the ventilation requirements increase in order to make sure that you ventilate and sort of dilute the exhaust fumes"*.

4.2.3 Noise

From Table 4.2 it can be noted that noise generated by the LHDs increased from an average of 67 decibels (dB(A)) to 88 dB(A), and in some of the areas visited where two LHDs were loading at a time and on areas with ventilation fans and/or water pumps installed, the noise levels increased to above 90 dB. One participant stated that, "*noise pollution of the diesel-powered equipment, specifically when it's underground, this equipment emit noise during their operation*". Most of the measurements taken were above the OEL of 85 dB(A) and as such employees on Mine A are issued with customised hearing protection to mitigate the risk of exposure.

Personal noise sampling using a noise dosimeter was conducted to ensure that exposures do not exceed 107 dB(A) as per DMRE 2024 milestones. These are milestones aimed at eliminating noise induced hearing loss and occupational diseases in the mining industry. These Occupational Health and Safety (OHS) milestones were collaboratively developed by stakeholders in the mining industry to speed up the progress towards achieving zero harm (Mine Health and Safety Council, 2014). Personal noise sampling is done monthly on occupations classified as being at risk of noise exposure, these occupations include rock drill operators, miner assistants, LHD, UV, drill rig and bolter operators. A minimum of 5% of the total workforce is sampled. Table 4.3 shows the personal sampling results that were collected from two LHD operators during the research study.

Table 4.3 Personal noise sampling results of LHD operators, (Source: Mine A, 2023)

Serial Number	4604821
Run Number	3
Start Time	12/20/2023 6:03:21 AM
End Time	12/20/2023 2:03:21 PM
Measurement Duration	08:00:00
Note	
Overload Duration	00:00:00
UnderRange Duration	00:08:40
Over 140 Duration	00:00:00
Motion Index	75.5 %
Octaves Enabled	No
Calibration Before Time	12/14/2023 2:09:13 PM
Calibration Before SPL	114.0 dB
Calibration After Time	1/3/2024 2:26:21 PM
Calibration Drift	0.0 dB
Dosimeter 1 Setup	ACGIH (T80, C85, Q3)
D1 Lavg	96.2 dB

Serial Number	3501559
Run Number	49
Start Time	7/20/2023 6:25:03 AM
End Time	7/20/2023 2:25:03 PM
Measurement Duration	08:00:00
Note	
Overload Duration	00:00:00
UnderRange Duration	00:11:01
Over 140 Duration	00:00:00
Motion Index	83.5 %
Octaves Enabled	No
Calibration Before Time	7/20/2023 6:12:30 AM
Calibration Before SPL	114.0 dB
Calibration After Time	7/25/2023 6:05:25 AM
Calibration Drift	0.0 dB
Dosimeter 1 Setup	Custom (T70, C85, Q3)
D1 Lavg	94.4 dB
D1 TWA 8Hrs	94.4 dB

Table 4.3 shows the parameters that are measured and checked during personal sampling. To ensure that the results are accurate, valid, and reliable, the noise dosimeters are calibrated before and after each measurement set, and the results are discarded if the calibration drift is more than 1,0 dB. The motion index tracks the movement of an employee to ensure that the badge was worn by the employee throughout the shift, and if the reading is less than 60%, the results are discarded. Octaves band can be enabled if studies are done on specific noise frequencies, and they are used when it is necessary to split the noise spectrum into narrower frequency bands. D1 Lavg is the equivalent continuous 8-hour rating level; where the shift duration is longer than 8 hours, the Time Weight Average (TWA) value is used. The noise sampling results (i.e., on Table 4.3) indicate that levels go above 85 dB (A) and reach up to 96 Db (A). The exposure levels for the two employees were not the same as the measurements were conducted at different working places. The ventilation fans and water pumps installed also contributed to the overall noise differences as well as other workplace conditions. It can be deduced from the results on table 4.2 that there is an increase in noise levels, indicating that the LHDs emit noise during their operation. It can also be seen on the results on table 4.3 that the LHD operators are exposed to noise levels above the TWA during their work shift.

4.2.4 Diesel particulate matter

The release of diesel particulate matter during the operation of the LHDs was also raised as a concern during the interviews conducted. One of the participants indicated that, *"the biggest concern [with diesel LHDs] is the diesel particulate matter, which is classified as a clause 1A human carcinogen"*. Although a national OEL has not been established in South Africa compared to other countries, such as those in the European Union, a DPM exposure control value of 0.16mg/m^3 (Total Carbon) was adopted as of 01 January 2016 (Creamer Media, 2024).

Airborne pollutant sampling is conducted in accordance with the Mandatory Code of Practice for Occupational Health Programme on Personal Exposure to Airborne Pollutants- DMRE Guideline 16/3/2/4-A1 dated 30 April 2018 issued by the Chief Inspector of Mines. The frequency of sampling is based on the previous year's 90th percentile per Homogeneous Exposure Group (HEG). Table 4.4 shows the DPM samples that were taken at Mine A monthly in the year 2023. Although 5% per annum per HEG must be sampled, additional samples were taken at Mine A to monitor and track the effects of DPMs.

Table 4.4: Mine A 2023 DPM samples, Source: Mine A, 2023

	Mine A DPM Samples 2023												
Month	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23	Nov-23	Dec-23	**Total**
Planned samples based on 5%	4	1	6	5	6	5	6	5	6	6	6	0	56
Samples taken	11	1	23	24	12	10	11	10	18	10	3	10	143
Spoiled samples	0	0	0	0	0	0	0	0	2	1	0	0	3
Samples were taken successfully	11	1	23	24	12	10	11	10	16	9	3	10	140
Additional samples taken	7	0	17	19	6	5	5	5	12	4	0	10	90

Table 4.4 shows that 56 planned samples would adhere to the 5% HEG sampling requirement; however, 143 samples were taken, with 90 additional samples taken to enable a broader investigation. Table 4.5 shows the monthly DPM personal sampling results for TMM operators, which include utility vehicles, drill rigs, roof bolters, load haul dumpers, and rock drill operators, which were taken in December 2023.

Table 4.5: DPM Sampling results (Mine A, 2023)

DPM Sampling Results				
No.	Occupation	Sample Concentration (mg/m³)	Exceedances (Yes/No) ≥ 0.16 mg/m³	Corrective control measures identified and actioned - include action number
1	Driver Utility Vehicle	0,2423	Yes	DPM Filters still being installed (Engineering had to be trained first before installation)
2	Operator Drill Rig Grade 2	0,0233	No	N/A
3	Operator Rock Drill (No Assistant)	0,3331	Yes	DPM Filters still being installed (Engineering had to be trained first before installation)
4	Faulty Pump			
5	Driver Utility Vehicle	0,0378	No	N/A
6	Faulty Pump			
7	Operator Roof Bolter	0,112	No	N/A
8	Driver Load Haul Dumper	0,459	Yes	DPM Filters still being installed (Engineering had to be trained first before installation)
9	Driver Load Haul Dumpor	0,309	Yes	DPM Filters still being installed (Engineering had to be trained first before installation)
10	Driver Load Haul Dumper	0,545	Yes	DPM Filters still being installed (Engineering had to be trained first before installation)

As shown in the Table 4.5, there were incidences where the sample concentration exceeded 0,16mg/m^3. Studies have found that both short-term and long-term exposure to high levels of diesel particulate matter can affect the health of workers negatively. The short-term exposure to high levels of DPM (above 0.16 mg/m3) can lead to health effects which include, asthma, light-headedness and nasal irritation (Ping and Guang, 2017). All sampling results are converted into an 8-hour time-weighted average for pollutant concentration, this considers the mass of the filter. The results are analyzed by a laboratory accredited by the South African National Accreditation System (SANAS), and the sampling duration is converted back to an 8-hour average for comparison with the Occupational Exposure Limit (OEL).

4.3 Actions Taken to Mitigate the Effects of Diesel Load Haul Dump

To mitigate the exposure to noise levels, gases, and dust generated during operation, the LHD operators are issued with PPE. The TMM operators are issued with customized hearing protection devices to prevent hearing loss and Filtering Face Piece 2 (FFP2) disposable dust masks. The FFP2 masks protect against dust, solid and liquid aerosols, and fumes. This control is administrative and is entirely dependent on individuals to change the way they work and comply. According to the participants interviewed, these controls are not effective as employees are often found not to be using hearing devices and dust masks. One of the concerns raised by a Participant was that "*FFP2 dust masks are used, but it's obviously not the ideal situation because it's dependent on human behaviour*". Another participant also stated that, "*PPE is ineffective, and more engineering and substitution controls should be explored to improve the health and safety of employees at the mine*". To ensure that employees comply with the requirements of PPE, Mine A also embarks on health and safety awareness campaigns.

To reduce DEE, LHDs on Mine A are fitted with air-cooled Tier 2 diesel engines. Tier 2 means that the engine is expected to perform according to the Environmental Protection Agency (EPA) Tier 2 system. Table 4.6 shows the emissions standard for tier ratings.

Table 4.6: EPA Tier 1-3 nonroad diesel engine emission standards (DieselNet, n.d.)

Engine Power	Tier	Year	CO	HC	NMHC+NOx	NOx	PM
kW < 8 (hp < 11)	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.8 (0.6)
8 ≤ kW < 19 (11 ≤ hp < 25)	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.8 (0.6)
19≤ kW < 37 (25 ≤ hp < 50)	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.8 (0.6)
	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.6 (0.45)
37 ≤ kW < 75 (50 ≤ hp < 100)	Tier 1	1998	-	-	-	9.2 (6.9)	-
	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.4 (0.3)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ≤ kW < 130 (100 ≤ hp < 175)	Tier 1	1997	-	-	-	9.2 (6.9)	-
	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.3 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ≤ kW < 225 (175 ≤ hp < 300)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ≤ kW < 450 (300 ≤ hp < 600)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ≤ kW < 560 (600 ≤ hp < 750)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ≥ 560 (hp ≥ 750)	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

† Not adopted, engines must meet Tier 2 PM standard.

This EPA regulation is a US-based guideline used to improve air quality by reducing harmful emissions from diesel engines. To reduce harmful gases in the atmosphere, there are four tiers that have been established, each building upon the previous one to make compliance more feasible. Each tier sets a specific standard for harmful emissions and imposes a limit on the emissions. The standards become more stringent as the tier level increases and progress over the years (Worldwide Power Products, n.d.).

During the interviews, one participant stated that, "*diesel particulate matter exhaust systems try to remove all of the noxious gasses, through means of retrofitting exhaust systems to the* *diesel outlet systems".* Tier 2 engines emit diesel exhaust emissions and DPMs during their operation and to mitigate exposure the engines were fitted with diesel particulate matter filters. On Mine A, two types of diesel particulate matter filters were assessed during a six-month onsite testing, the filter that is selected and fitted was based on its effectiveness in reduction of DPMs. The filters are expected to achieve a 95% plus reduction in DPMs. Figure 4.4 shows a picture of a DPM filter installed on the LHDs.

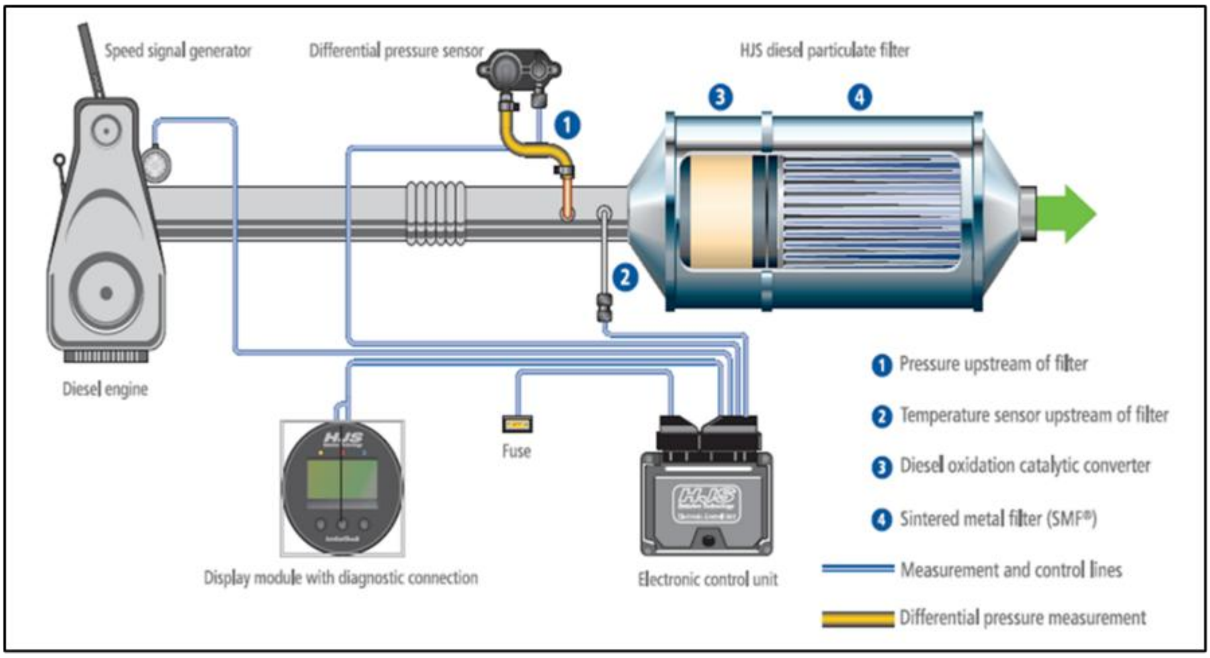

Figure 4.4: Diesel particulate matter filter, Source: Mine A, 2023

To determine the engine health status and the performance of the DPM filter, every machine undergoes opacity testing, six gas analysis (HC, O_2, CO_2, CO, NO and NO_2) and DPM measurements before and after bi-weekly service. The testing is conducted before and after filter installation and done by an independent company. The monitoring of the gases ensures that engine performance and environmental conditions are checked where the machine is operating. Opacity is a measure of the amount of light obscured by the DPM or soot in the DPM exhaust system from diesel engines, measured under normal operating conditions (DPM Exhaust Emission Testing Procedure, Mine A).

Figure 4.5 shows the results of the DPM sampling done on the fleet at Mine A before and after installation of DPM filters. Figure 4.5 shows the total percentage of carbon exceedances of LHDs before and after DPM filter installation, indicating a downward trend on both total and elemental carbon exceedances during the period when filters were installed. The filter installation plot indicates that in January 2023, 90% of the Mine A fleet were fitted with DPM filters, which were removed from April 2023 and re-installed in February 2024. After conducting further tests, analysis and applying learnings, the 10% outstanding fleet are drill rigs and bolters on which trials are conducted to find suitable filters for installation.

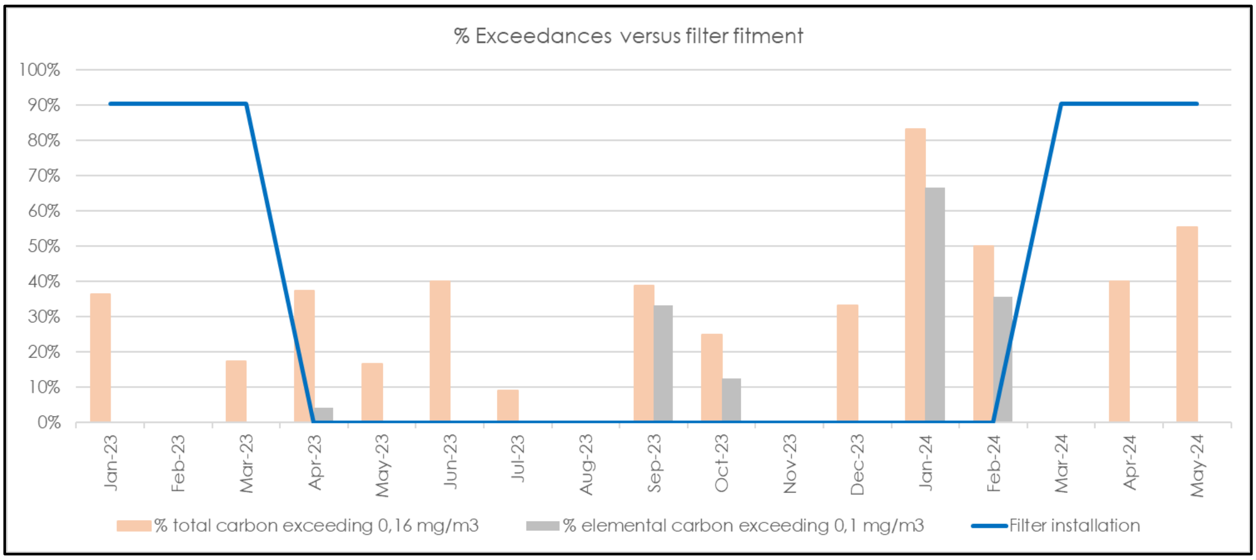

Figure 4.5: DPM sampling results of HEG, Mine A (2024)

On figure 4.5 it can be noted that there were no elemental carbon exceedances when the fleet were fitted with DPM filters up to March 2023 and after March 2024. More samples, testing, and investigations have been proposed to determine the exceedance in total carbon after filter installations as seen in April and May month of year 2024.

According to the participants interviewed the DPM filters installed on the LHDs reduce exposure but do not eliminate it. Participants also emphasised the quality of maintenance as important because it has a direct impact on the LHD engine performance. One of the participants mentioned that, "*the most important, is the maintenance of this engine. You can have all these things [DPM filter installation and monitoring], but if the engine is not maintained, you can still have the same bad results in terms of emissions [emitted]".* Another participant noted that, *"on the machines themselves, you have to ensure that your diesel engines are extremely well serviced to the OEM specifications constantly"*.

According to participants, the other action that can be taken to mitigate employees' exposure to diesel exhaust fumes is to upgrade the current Tier 2 engines to a higher tier engine, one participant mentioned that "*the first step would be to move from Tier 2 to Tier 3 engines until we can go to higher tier 4 and 5"*. According to the participant, moving to higher tier engines will reduce emissions that are emitted. However, this option would be capital-intensive and would require the engines for the whole Mine's fleet to be changed, starting with LHDs as they are the mostly used fleet on the mine.

The other options available are to include more ventilation controls within the system to dilute emissions emitted and to improve the quality of diesel used in South Africa to 5ppm same as other countries like Europe, which are already using better quality diesel. One participant stated that, "*the only way to reduce emissions is to change from an air-cooled to a water-cooled engine, however considering the fact that emission requirements and regulations are changing, and the world is moving towards cleaner emissions, air-cooled engines are not capable of giving the emission compliance that we desire. So, we will certainly have to move towards the water-cooled engines*". Transitioning to green energy and exploring electric vehicles was indicated as a potential solution to ensure the complete elimination of the release of diesel emissions.

4.4 Cost Comparison between Diesel and Fuel Cell Load Haul Dump

Table 4.7 provides capital cost comparison between a diesel and a hydrogen fuel cell LHD. The costs shown are for a hydrogen fuel cell system equivalent to the current diesel LHD size and output shown in Table 4.1. The cost of FCEVs is related to many variables primarily related to performance specifications such as travel range, top speed, and power consumption. All these aspects need to be appropriately sized throughout the design phase of an FCEV.

To calculate the capital cost of a hydrogen fuel cell electric battery LHD, the power output requirements were studied and analysed, and the market-related prices for the size of equipment required were costed. The assumption made was that the LHD sizes and output will be kept the same for the HFC LHD as the current ones on Mine A.

The cost for the hydrogen fuel cell system is R3 349 000, the type of hydrogen tank used on Table 2.1 to estimate this cost is a crypto-compressed tank. This tank can allow pressures of up to 700 bar and the tank is made of fibre reinforced composites with a lithium-ion battery as it has longer cycle times. To address or mitigate durability of the system over a lifetime of the fuel cell, a stack oversizing instead of stack replacement methods were used in determining the size of the fuel cell stack (Kleen, et al., 2023) .

Table 4.7: Capital cost comparison between HFC LHD and Diesel LHD (Source: Mine A, 2023)

Parts	Diesel LHD	Hydrogen Fuel Cell LHD
Frame	R790,000.00	R790,000.00
Diesel Engine	R280,000.00	R0.00
Hydrogen fuel cell system	R0.00	R3,349,000.00
Shut off valve	R58,000.00	R0.00
DPM Exhaust system	R285,000.00	R0.00
Filter	R15,000.00	R0.00
Torque convertor	R165,000.00	R0.00
Transmission	R185,000.00	R0.00
D81 rear and front differentials	R782,000.00	
Four traction motors		R782,000.00
Fail safe brake heads and tyres	R320,000.00	R312,000.01
Full hydraulic system	R1,484,300.00	R1,484,300.00
Bucket	R210,000.00	R210,000.00
Boom	R322,000.00	R322,000.00
Electrical system	R485,700.00	R485,700.00
Engine Management System	R280,000.00	R0.00
Energy Management System	R0.00	R280,000.00
Driver cab pack	R420,000.00	R420,000.00
Fire suppression system	R285,000.00	R285,000.00
Level 9	R355,000.00	R355,000.00
TOTAL	**R6,722,000.00**	**R8,763,000.00**

It is seen from Table 4.7 that the FCEV LHD is expected to cost 30% more on initial purchase. The calculations were based on the size and specification of the LHD used on Mine A. From the literature review findings, it was noted that FCEVs are expected to cost 50% more than ICE vehicles. It was observed that the price differences are likely to narrow down as the technology gains maturity and market share. The cost for FCEV LHD as calculated included the estimated costs of the onboard hydrogen tank. A detailed feasibility study is required to include more accurate costs for onboard hydrogen storage which would consider the details and options for hydrogen production, storage and transportation methods and be compared with costs of diesel production, storage and transportation.

Table 4.7 indicates the components that will be eliminated with the introduction of a hydrogen fuel cell system, which include the diesel engine shut off valve, DPM exhaust system, filter, torque converter, hydraulic transmission, differentials which will be replaced by electrical transmission, an engine management system which will be replaced by the hydrogen or energy management system.

Upon the transition from diesel engine LHDs to hydrogen fuel cell LHDs, there will be no need to install DPM filters as there will be no emissions during operation. The costs currently incurred for the engine management system will also be excluded as an FCEV would not need software for communication to various parts of the machine but rather an energy or hydrogen management system to control all the energy powers within a FCEV to ensure hydrogen reduction and power distribution (Mine A, 2023).

Additional components that will be added would be the water management system, during the operation of a fuel cell the production of water vapour could increase humidity underground, which could increase contribute to overheating of LHDs. From the literature review study findings, it was noted that the FCEVs have heat and water management system to separate water and recycle the heat to the vehicle's cabin, this should prevent the release of water vapour into the atmosphere and overheating effects.

On Mine A, technical support to keep the machines in a good running state is achieved through utilizing owner maintenance-based strategy in conjunction with OEMs. To calculate the monthly maintenance costs, the prices of the major components were analysed including the life expectancy of the major components measured in hours. The maintenance costs on Mine A were derived from consumables for the bi-weekly services, actual major components repair and replacements, OEM monthly technical support costs, the tyres, fuel and lubes.

There are fewer moving parts on a HFC system, therefore the maintenance required will be minimal, and more visual inspections to ensure units are in a good state will be done as well as replacements of seals and gaskets. The replacement costs will also be based on the life expectancy of the components on the HFC system. The actual replacement costs and any premature failures/damages will only be possible to estimate once a prototype is deployed, trialled and tested. The wear and tear on tyres are expected to remain the same due to the travelling distance and same underground set up. The oil consumption is expected to be less due to less moving parts, thus less leakages and less major component failures.

4.5 Key Considerations during the Design and Implementation of Fuel Cell Electric Vehicles

In addition to cost, several aspects need to be considered during the planning and design of FCEV LHDs to replace diesel LHDs in an underground mining environment. These key aspects include understanding the operating environment, the performance requirements and emission requirements based on the company's environmental goals, and applicable regulations.

The operating environment must be studied and well understood before any machine can be designed. During the qualitative study, one of the participants stated that, "*the environment where the equipment is going to operate [needs to be studied] and aspects like what is the altitude, what is the site condition, what are the temperatures, humidity".* Understanding the operating environment will allow for the correct ingress protector to be selected and used, which is important for the sensitivity and reliability of a fuel cell stack. Another participant elaborated on the importance of having the correct ingress protector stating that, "*for the harsh conditions that we have, there is a solution. There will be protection in terms of protecting it against dust, protecting it against water ingress, from shock, [and protecting] it from bumps".*

The performance parameters should be taken into consideration, and the expectation is for the current performance of diesel-powered LHDs to be matched or exceeded. The design should meet the shift duration requirements, loading and tramming requirements. During the qualitative study one participant noted that, *"it should be ensured that when you go electrically, your battery system should last for 12 hours that you require, or consider the aspect of charging the battery, whether it will be done while it is in operation, or you can have a system, where your battery can last your full shift that when the next shift starts then you can just change your battery and continue to operate ".* Another participant mentioned that, "*depending on the usage profile or what the equipment is meant for, we also consider the power and torque requirements at different speeds*".

The engine performance and reliability are important factors to be considered. The reference to the electric vehicle engine in this case is the electric vehicle power pack of the electric vehicle. According to one participant, *"one of the more important factors again is the reliability of the engine, as we know, any challenge in the engine will lead to the loss of productivity and the machine availability time"*. To ensure the reliability of the engine, testing and trials must be done in laboratories, and on the surface, including field verification to share technical inputs. This was mentioned by another participant who stated that, "[*new technology] involves a lot of* *field validation and sharing of technical inputs by gathering the information, passing it on to counterpart in the research and development field"*.

According to another participant, the duty cycle of the equipment that is the length or duration at which the equipment works at different speeds, the different power requirements and torque requirements must be understood. This is done so that a test devise can be done for the engine to be manufactured which will simulate the same duty cycle, and this is done to validate the reliability of the engine in a controlled environment. The machine's envelope size should be considered, the low profile in which the machine will be operating must be considered, and the space must be optimised to pack as much kilo-Watt power as possible. According to participant, "*OEMs [must ensure] to pack enough kilowatt hours of battery into [the] limited space [available] on a low-profile machine"*.

The emissions requirements of the area at which the machine will be operating needs to be known and incorporated into the design, and this should include all other safety requirements such as fire suppression and collision avoidance systems. The mandatory codes of practice, procedures, and regulations which the machine needs to conform to needs to be understood and incorporated during the design and planning phase. The availability and competence of skill sets required for the operation and maintenance of the FCEV need to be known, and training plans need to be made during the testing stages. One participant emphasised this during the interview by stating that, a designer should "*study the regulatory requirements in terms of not only the emissions and performance, but also the safety regulations that are there in place for mining, specifically now that the collision avoidance system and the laws that have been put forward".*

4.6 Constraints to Implementation of Hydrogen Fuel Technology

The main constraints affecting the implementation and commercialisation of FCEV in the mining industry are the availability of infrastructure to support HFC technology, high capital costs of HFC technology, availability of skill set and spares for maintenance, inadequate investment in the technology and availability of policy and legislation to support the HFC technology. These aspects are discussed below.

The availability of hydrogen infrastructure plays a big role in the implementation of HFC technology. Hydrogen is highly flammable and therefore poses risks of underground explosions. Its use in underground mining environments needs to be carefully assessed. One of the participants highlighted this risk during the interview stating that "*hydrogen is highly* *flammable and explosive"* . Storage facilities for hydrogen distribution network is one of the important factors that needs to be considered when it comes to the infrastructure development. The storage facility needs to be nearer to the mining sites; however, since the mining locations are predominantly in remote areas, finding a solution for transporting the flammable hydrogen poses a challenge. Handling systems that can counter this safety risks must be developed. Another participant stated that, *"the storage and distribution of hydrogen, which is very important for the implementation of fuel cell technology, remains a big safety concern. So that becomes very crucial".*

During the site visit, it was observed that the LHDs used by the mine are serviced and maintained in a surface workshop on a bi-weekly basis. The surface workshop consists of two diesel and oil refueling stations and is equipped with a 10t overhead crane. It is divided into four bays, which are configured in such a manner that one bay is dedicated for major component replacements and the other three bays for normal pre-checks and services. There is a fifth bay outside the workshop meant for undercarriage maintenance and inspection of machines. It was noted that the infrastructure can still be used for hydrogen fuel LHDs, however, additions would be required to accommodate the hydrogen storage facility, which is currently not available onsite.

The large capital outlay due the absence of economies of scale production, the use of platinum as an electrolyser in fuel cell technology and the cost of hydrogen production were raised as constraints. One of the participants stated that, *"insufficient involvement of business and civil society [impacts economies of scale production], because building and strengthening public-private sector partnerships and involvement of business and civil societies is very crucial, because all these technologies [including] hydrogen fuel cell technologies, depend on the endorsement and the participation of business as well as civil society for them to gain traction and for them to be implemented in huge scale"*. The role of civil society is to carry out research and publish findings that focus on offering evidence-based policy development and interventions to enhance the effectiveness and significance of hydrogen fuel cell technology.

The commercialisation of FCEV is also affected by constraints such as the lack of investment and funding due to the inadequate interaction between the private sector and the government. One participant noted that, *"for these technologies to really make their way towards commercialization, we need sufficient funding from both the public and the private sector partners".* Lack of policy support is one of the factors affecting the implementation of HFC technology. Another participant mentioned that "*the main challenges, especially when it comes to government interaction and private sector interaction, is the lack of policy coherence* *and coordination amongst the government departments"*. The lack of coherence between government departments also discourages investments, as applications and licenses must be obtained through many departments. The availability of the green hydrogen certificate and safety protocols is one of the factors affecting the hydrogen economy in South Africa. Another participant stated that, "*you need the safety protocols and the certification of hydrogen when you are trading, whether it's local trade or international trade, there has to be some safety protocols that are adhered to"* .

The availability of the skill set required for the new technology which requires careful planning, was also raised as a stumbling block. The technical ability of maintenance personnel is key to implementation of HFC technology. This is elaborated by one participant who mentioned that, "*the skills and the competence that will be required from the people that are doing the maintenance and the services on your machines [would change] if you introduced fuel cell technology, the [artisan] trades that we currently use to do the maintenance on machines like for instance, a diesel mechanic,[would change], there's going to have to be a whole revision of the competency of the people that are actually used*". Another participant mentioned that the extensive training that would be required when transitioning from diesel engines to HFC electric engines and stated that, *"when it comes to the skills and training, adopting hydrogen fuel cell will require extensive training of the operators. The handlers of distributors, everyone who is involved right from production, to storage, and distribution, the operation of equipment, including the service, maintenance, and every personnel".*

One participant highlighted the availability of spares as a constraint to FC technology implementation. It was raised that the unavailability of spares would affect the quality of maintenance, the availability and subsequently the productivity of LHDs. This is an important aspect to consider when introducing this technology. The unavailability of adequate trial sites, resulting in slow progress in terms of improvements that can be put in place to improve FCEV technology is also an issue. More so, there is inadequate awareness and information exchange in the mining industry to support existing trials and implementation of innovative technology.

4.7 Status of Existing Regulation and Policy Supporting Hydrogen Fuel Technology

The availability of regulations and policy is important to support hydrogen fuel cell technology in South Africa. According to the participants, there is no common hydrogen certification available, making it difficult for the country to trade locally and globally without safety protocols.

The lack of alignment and coherence between government departments concerning the hydrogen economy also tends to deter investors. One of the participants noted that, *“[government officials] are told that there's a lack of policy coherence and coordination amongst the government departments when it comes to advancing the hydrogen economy”.*

To address the lack of coherence that is reducing investor confidence, there is a need to have an Inter-Ministerial Committee (IMC) for coordination of point where investors will be able to get all relevant documents and applications from one point. According to one of the participants, the IMC structure was approved in February 2024 by the Cabinet, and the purpose of the structure is to ensure that government, public, and private sector efforts are coordinated. This is done in a way that makes a meaningful impact when it comes to the implementation of the hydrogen society road map for South Africa 2021.

The participant further explained that the IMC structure can be considered as a special point of accountability (SPOA), which is important to improve alignment between government departments and to ensure the implementation of the hydrogen economy. Another participant stated that, “*most countries like China, USA and Japan, have created those structures, a special point of accountability structure is where you get everything [required for applications]”*. The participant further elaborated that in the countries mentioned, it would be seamless to implement a large-scale hydrogen project as the approvals for all licenses required would be obtained at the SPOA. This is not the case in South Africa, as the approach is still segmented. As stated by one participant *“the involvement of every authority, every organization becomes of utmost importance to come up with a common agenda of moving towards the greener solutions”*.

4.8 Overall Discussion of Key Findings

Diesel combustible engines, which are fuelled by non-renewable energy sources, emit diesel exhausts, noise, and heat during their operation. These effects associated with the use of diesel engines were captured in Table 4.2, which provided a summary of underground environmental measurements. All parameters increased during LHD operation, however only the noise was measured above legislated OELs. These results align to the literature review findings by Maximilien et al (2017) where it is mentioned that the use of diesel engines is concerning due to the noise and heat emitted during their operation, contributing to uncomfortable and unhealthy working conditions.

Samples taken for monitoring of exposure levels indicated exceedances of DPMs, which pose health risks to employees, as they have been classified as human carcinogens by the World Health Organisation. According to Henderson and Maksimainen (2020), the mining sector contributes 4% to 7% of global greenhouse gas emissions therefore the continued use of diesel fuelled LHDs in the mining industry will contribute to greenhouse gas emissions and climate change.

To reduce the health and safety risks associated with diesel-powered equipment, employees are restricted from the downstream side of the LHD during operation. The recommendation to remove all employees from the downstream side can impact activities that can be performed simultaneously, thus decreasing flexibility and productivity. This links with the insight from the literature review whereby (Moore, 2019) noted that the number of diesel engines operating in a vicinity influences the ventilation needs and can increase ventilation costs. Employees are provided with PPE, such as customized hearing protection devices and dust masks. According to the literature review study, the hierarchy of controls developed by the NIOSH, PPE is one of the least effective controls as it is dependent on human behaviour which is confirmed by the observations made during the site visits and results from the interviews conducted. The other measure implemented by the mine to reduce exposure to diesel exhaust emissions is the installation of DPM filters. Whilst DPM filters installed have been effective in reducing the amount of emissions released into the atmosphere, the results from samples taken are indicating that there are still exceedances noted on total carbon.

The key considerations in the design of an FCE LHD include the understanding of the operating environmental conditions, the performance requirements, and the knowledge of the applicable legislation and emissions requirements. Whilst hydrogen-powered FCEVs are quiet in operation due to fewer moving parts, have higher efficiencies, and only emit water and heat during operation, Luo et al. (2021) noted that additional repair costs could be incurred should a stack element failure occur. Hence, a detailed analysis of the environment needs to be conducted to enable correct design parameters such as Ingress Protectors and output of the engines to be correctly quantified. One of the aspects affecting FC commercialization is the reliability of fuel cells, which is important for end-user satisfaction. Therefore, sufficient testing and trials are required prior to the implementation of FCE LHD.

Constraints to HFC implementation in the mining industry include the unavailability of skill sets required for the new technology, which in turn would require adequate training of operators, maintenance teams, and OEMs. According to Jose and Richard (2022), to overcome the skills constraints, the Philippines has passed legislation mandating higher education institutions to develop a curriculum that focuses on sustainable green energy technology. The absence of local large-scale production of HFC technology due to their high capital costs and reliability is expected to affect the availability of spares to ensure the maintenance of equipment. Hence Sharaf and Orhan (2014) have emphasized the need for more research and development to lower the costs of HFC technology and to improve their overall performance.

The availability of infrastructure to support HFC technology, that is, the storage, distribution, and transport of hydrogen, is one of the biggest challenge due to hydrogen's flammability. The literature review study from Malik et al. (2023) also stated that a lack of infrastructure for producing economical hydrogen affects the commercialization of HFC.

Inadequate investment in HFC technology and the availability of policy and legislation to support also affects the widespread implementation of HFC. Countries must focus on improving existing regulations and policies to support hydrogen fuel cell technology; success has been noted in countries like Germany and the Philippines, which are advanced in their HFC legal framework. Azni and Md Khalid (2021) have noted that the United States and South Korea are also among the countries that have advanced themselves by incorporating hydrogen fuel cell technology into their legal framework. South Africa should align their certification structure to countries in the European Union, to enable it to trade internationally. South Africa is one of the countries that has signed the Paris Agreement to show its commitment to reducing emissions and moving to renewable energy, therefore it should take steps into positioning itself as a green hydrogen producer.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The use of diesel engines in the South African mining industry continues to dominate the operations due to their reliability. More so, the country is still reliant on fossil fuels for energy generation and fuel used in many industries. Whilst this is the case, fossil fuels are finite and have unstable prices affecting production and performance of key industries. Their use is also harmful to the environment and contributes to global warming effects. Therefore, it has become necessary for the country and the mining industry to find alternative sources for energy generation to power equipment in mining operations. FCs have been identified as having the potential to replace diesel-powered machines in the mining industry.

FCs have many applications and bring with it a carbon-free environment. Hydrogen-fuelled FC technology as renewable energy has been identified as one of the solutions having the potential to reduce the amount of GHG emissions that lead to climate change globally. FC technology dates back more than 150 years ago and over the past 20 years, FCs have been used to replace internal combustion engines and provide power for stationary and portable applications. Replacing fossil fuels in the mining industry by introducing hydrogen technology as a fuel will assist in eliminating emissions of GHGs that affect the overall health and safety of the employees whilst ensuring a sustainable environment. The aim of the study was to investigate the introduction of FC technology in underground machinery to reduce exposure of harmful emissions to employees.

The research used a mixed methods approach to collect and analyse information. Literature review focusing on the research objectives was conducted. Data was also collected from site visits where measurements were taken, and observations were conducted. Interviews were also conducted with subject matter experts and original equipment manufacturers.

The use of diesel internal combustible engines emits heat and increases the temperature in the underground mining environment. During operation, diesel-powered LHDs also release noxious gasses and emit noise that is above the allowable limit of 85 dB (A). When comparing the capital costs, it was established that the hydrogen fuel cell LHD of the same size and specifications as the diesel-operated machines is more expensive. However, maintenance costs are anticipated to be less due to the absence of a diesel particulate matter filter installations and maintenance thereof. It was found that the initial capital outlay for FCEV LHD is 30% more expensive. Apart from costs, there are several factors that need to be considered during the design of HFC LHD to make it feasible to replace the diesel-powered machines. These aspects include the operating environment, performance requirements, emission requirements, and the applicable regulations.

In addition, there are various factors that are affecting the commercialisation of FC technology both in the mining industry and the country that needs to be looked at, and these include availability of skills, availability of infrastructure to support hydrogen technology and the inadequate investment. In view of the shortcomings, the study revealed that collaboration is required between private companies and the government to advance fuel cell technology. The availability of hydrogen certification will assist in the commercialization of fuel cell technology. Moreover, an IMC structure will assist in improving coherence among government departments and improve investor interest.

5.2 Limitations of Findings

The following were the shortcomings of the findings:

- The financial analysis excluded costs for the hydrogen production, transport and storage as there are many ways of producing, transporting, and storing hydrogen that needs to be fully understood.
- Financial valuation of the HFC LHD in the absence of a prototype to enable a comparison of the two systems in the operating environment, created limitations in terms of the full financial valuation as the maintenance costs could not be quantified.
- The interviewed participants possessed considerable relevant expertise in the field and provided valuable perspectives. Nonetheless, all participants highlighted the necessity of having a prototype to evaluate and measure the performance of hydrogen fuel cell technology LHD in an underground setting.

5.3 Significance of Study

The use of fossil fuelled diesel engines extensively used in the underground mining environment contributes to GHG and climate change. The use of these diesel engines emits diesel exhausts emissions during their operation which create unhealthy and harmful working environment. DPMs which are also emitted during diesel engine operation are classified as human carcinogens, and it is anticipated that emission standards for DPMs will be regulated in South Africa like countries in the European Union. The research focused on the implementation of hydrogen fuel cell technology in underground mining equipment. The successful implementation of hydrogen fuel cell technology in mining equipment will result in improved environmental conditions for all employees as the air quality will improve and the noise pollution will be reduced. Hydrogen fuel cell technology as a renewable energy source will replace the use of fossil fuels to mitigate climate change.

South Africa has resources like wind, land and the highest PGM reserves, which results in the country being well positioned to lead the green hydrogen economy globally. This would result in significant economic growth and development for the country. The implementation of hydrogen fuel cell technology in the mining industry will contribute to the widespread application to assist in creating infrastructure required to enable fuel cell technology.

5.4 Recommendations

The following recommendations are made based on key findings on the application of hydrogen fuel cell technology in the mining industry and for proposed future research work:

- One of the constraints affecting hydrogen fuel cell technology is the huge capital outlay, and so, a detailed investigation of the other applications of hydrogen that would promote large-scale production of hydrogen should be done. Applications such as implementing HFC on surface passenger transportation and for creating ammonia used as a fertilizer are options available to create the need for large scale hydrogen production. Hydrogen can be used to complement solar and wind energy by generating electricity through the electrolysis process. These applications will create economies of scale needed to support HFC or to build a case for the commercialization of hydrogen technology.
- Investigate ways of increasing investment through focus on reviewing applicable legislation that will support the implementation of HFC technology.
- Assessment of curriculum and detailed analyses on skills, training required to implement HFC technology in mining equipment should be done to better understand the impact of skills availability on HFC technology.
- Further analysis and reliability of fuel cells requires adequate testing, this will assist to determine the type of modifications required for fuel cell technology suitability in the mining industry; for example, the trial of an LHD prototype should be investigated.

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APPENDIX A. Participant Consent Form

Consent Form

Title of project: Investigating the feasibility of introducing fuel cell technology in mining equipment

Name of researcher: Lesego Mokgethi

I, ………………………………………., agree to participate in this research project. The research has been explained to me, and I understand what my participation will involve. I agree to the following:

(Please circle the relevant options below).

I agree that my participation will remain anonymous.	YES	NO
I agree that the researcher may use anonymous quotes in his / her research report.	YES	NO
I agree that the interview may be audio-recorded.	YES	NO
I agree that the information I provide may be used in an anonymized format after this project has ended, for academic purposes by other researchers, subject to their own ethics clearance being obtained.	YES	NO

…………………………………… (signature)

…………………………………… (name of participant)

…………………………………… (date)

…………………………………… (signature)

…………………………………… (name of person seeking consent)

…………………………………… (date)

APPENDIX B. Participant Information Sheet

Participant Information Sheet

Dear Sir / Madam

My name is Lesego Mokgethi, and I am a Masters student in Mining Engineering at the University of the Witwatersrand, Johannesburg. As part of my studies, I must undertake a research project, and I am investigating the application of fuel cell technology in underground machinery as clean and renewable energy to move to a carbon-free emissions environment under the supervision of Dr. Pontsho Twala. This research project aims to conduct a feasibility study on introducing a fuel cell electric battery load haul dump machine in an underground working place, to further mitigate or eliminate harmful emissions emitted during their operation.

As part of this project, I would like to invite you to take part in a semi-structured interview. This activity will involve you answering questions related to the research and will take approximately 30 minutes. With your permission, I would also like to audio record the interview using a digital device (Microsoft Teams). This recording will be stored in a password-protected laptop and only the researcher will have access to this recording. It will be deleted after 3 years.

There will be no personal costs to you if you participate in this project, you will not receive any direct benefits from participation but there are no disadvantages or penalties if you do not choose to participate or if you withdraw from the study. You may withdraw at any time or not answer any question if you do not want to. The semi-structured interview will be completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I will use a pseudonym (false name) to represent your participation in my final research report. If you experience any distress or discomfort at any point in this process, we will stop the interview or resume another time.

If you have any questions during or afterward about this research, feel free to contact me on the details listed below. This study will be written up as a research report which will be available online through the university library website. If you wish to receive a summary of this report, I will be happy to send it to you. The data collected from this research project will be stored in a password-protected laptop and will be kept for 03 years. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za

Yours sincerely,

Lesego Mokgethi, 0400972E@students.wits.ac.za

APPENDIX C. Research Instrument

Participant Interview questionnaire

Overview:

- Briefly give an overview of your current role and total years of experience in the field of work.

Effects of diesel engine LHDs and measures to mitigate:

- What are the current environmental and health effects associated with using internal combustible engine load haul dump machines in underground trackless mines?
- What work can be done to reduce the exposure of diesel exhaust fumes on employees?
- What can be done to reduce the current emission levels from underground machinery in a South African context, considering what is happening internationally?
- What exhaust emissions guidelines does your organization comply to ensure the LHD engines in South Africa are compliant?

Constraints to implementation of Hydrogen Fuel Cell Technology:

- What would you say would be the biggest challenge to implementing fuel cell technology in the South African mining industry?
- What are the infrastructure requirements to support the implementation of green energy on underground machinery, particularly in South Africa?

Key considerations during the design of FCE LHDs:

- What risks should be anticipated with introducing hydrogen fuel cell electric battery load haul dump machines in an underground operation?
- What design aspects must be considered to implement fuel cell LHDs successfully? How would maintenance, overall production, and health and safety be affected?
- What design criteria do you use to ensure the LHD engines perform optimally in the South African mining industry?

Policy and Legislation to support hydrogen fuel cell technology:

- What are the plans to increase the application of hydrogen fuel cell technology within South Africa?
- When comparing South Africa to other countries regarding the progress made with renewable energy, what learnings can be adopted?
- In terms of the policies, regulations, and guidelines available in South Africa, are there any reviews required to facilitate the implementation of hydrogen fuel cell technology?