A study of the transition from diesel trucks to electric trucks in the mining sector in South Africa

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ABSTRACT

Diesel is the primary energy source for many mining applications. Still, it has significant drawbacks, including high operating costs, air pollution, and greenhouse gas emissions, all of which pose risks to human health and the environment. Mining companies should consider alternative energy solutions to address these environmental concerns, such as battery electric trucks. These technologies could offer several benefits, including lower operating costs, reduced emissions, and improved worker health and safety. This study aimed to explore replacing diesel trucks with battery electric trucks in the underground mining sector in South Africa to help these companies meet decarbonisation and emission goals. By transitioning to battery electric trucks, the mining sector reduces its carbon footprint and enhances its sustainability and social responsibility, aligning with the global efforts to combat climate change. It is important to note that transitioning to clean energy technologies can be costly and will require government support through regulations, grants, and collaboration with other stakeholders such as original equipment manufacturers. This study's uniqueness lies in its approach to gathering both qualitative and quantitative data involved in transitioning from diesel trucks. The study investigated the use of trucks in underground mining, more specifically the environmental impact of diesel trucks compared to battery electric trucks, the economic viability of adopting battery electric trucks, as well as the barriers to the adoption of electric trucks. The analysis was based on data collected from secondary sources. The main findings showed that the use of electric trucks in underground mining is better for the environment; furthermore cost parity of battery electric trucks could be achieved in the next three to five years and to encourage the adoption of this new technology, the government has a key role to play.

KEYWORDS

decarbonisation, environmental impact, battery electric trucks, total cost of ownership, mining, diesel

DECLARATION

I, Carina Pather, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in the field of Energy Leadership at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Carina Pather

Name Signature

Signed at ……Johannesburg………

On the ……25………… day of ……June……………… 2025

DEDICATION

This research is dedicated to all the visionaries and pioneers in the fields of sustainable technology and environmental stewardship, whose relentless pursuit of innovation continues to inspire positive change.

I would also like to dedicate this work to my daughter, Talia Pather, whose unwavering support, encouragement, and patience have been invaluable throughout this journey. To my mentors and colleagues, thank you for your guidance and wisdom.

Finally, this research is dedicated to the future generations, with the hope that this work contributes, in some small way, to a cleaner and more sustainable world.

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BET	Battery electric truck
CBAM	Carbon Border Adjustment Mechanism
DEE	Diesel Exhaust Emissions
DPM	Diesel Particulate Matter
EU	European Union
GDP	Gross Domestic Product
GWP	Global Warming Potential
ICE	Internal Combustion Engine
ICET	Internal Combustion Engine Truck
ICSV	Innovation for Cleaner Safer Vehicles
IEA	International Energy Agency
IRENA	The International Renewable Energy Agency
NDC	Nationally Determined Contributions
SA	South Africa
TCO	Total Cost of Ownership
UN	United Nations

CHAPTER 1. INTRODUCTION

1.1 Purpose of the study

This mixed methods study intends to explore the potential impact of battery electric trucks (BETs) on lowering emissions in South Africa's mining sector. Trucks play a critical role in both open-cast and underground mining. In open-cast mining, trucks are primarily used to transport materials from the mines for further processing and for quarrying activities. In underground mining, trucks are used for tunnelling, stemming, and hauling the ore to the surface for further processing. Both types of mining processes use trucks to transport the processed materials to the end user.

For purposes of this study, the use of trucks in underground mines and only at the site of the mine will be considered. Transportation to the end user does not form part of the study.

Diesel-powered vehicles in underground mines are a major source of toxic emissions, including carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter, which require extensive ventilation to mitigate (Laamanen et al., 2022). To achieve economic improvement, the mining sector needs a balance between economic activity and environmental concerns (Laamanen et al., 2022).

In recent years, electric vehicles have been adopted widely due to their lower carbon footprint and environmental impact (Yu & Sun, 2024). The use of BETs results in high productivity, improved preventative maintenance, lower underground emissions, and reduced planned and unplanned maintenance compared to their diesel counterparts (Moreau et al., 2020).

The Greenhouse Gas Protocol defines the scope of GHG emissions: Scope 1 incorporates direct GHG emissions, Scope 2 covers GHG emissions from the generation of purchased electricity, and Scope 3 includes indirect GHG emissions (Lyu et al., 2023).

Scope 1 emissions from electric trucks is zero as these trucks do not have a tailpipe (Wolfram et al., 2021). Scope 2 emissions can be reduced by using solar, wind or hydropower to generate electricity and charge BETs (Howarth & Jacobson, 2021).

The focus historically has always been on Scope 1 and 2; however, in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), Scope 3 emissions were for the first time also considered. Scope 3 emissions are value chain emissions not directly associated with the owner of BETs (Lyu et al., 2023). Therefore, looking at the whole value chain of BETs from production to disposal is becoming increasingly important.

In July 2021, The European Commission proposed a regulation for a Carbon Border Adjustment Mechanism (CBAM), along with other broader adjustments in support of a 55% decrease in carbon emissions by 2030 in the European Union (EU) (Sartor et al., 2022). The purpose of CBAM is to prevent carbon leakage for energy-intensive industries and applies to the cement, iron and steel, aluminium, fertiliser, and electricity sectors by imposing an import duty on carbon-intensive products into the EU (Sartor et al., 2022). Carbon leakage is defined as "*the shift of carbon emissions from a region with emission constraints to an unregulated region*" (Wei et al., 2020). Hence, regions with lower carbon emission constraints relative to the EU will be charged an import levy for goods exported to the EU of which SA is one.

The regulation came into force on 1 October 2023, with the first three years being a transition period where only reporting obligations will apply. The obligations under CBAM for importers will come into force on 1 January 2026 on a phased approach for reduced emissions reaching the 55% target in 2030 and zero percent by 2034 as shown in Figure 1 (Bond et.al., 2023).

Year	Reduction factor for free allowances[8]
2026	97.5%
2027	95%
2028	90%
2029	77.5%
2030	51.5%
2031	39%
2032	26.5%
2033	14%
2034	0%

Figure 1 Phased emissions reduction for CBAM

Source: www.whitecase.com

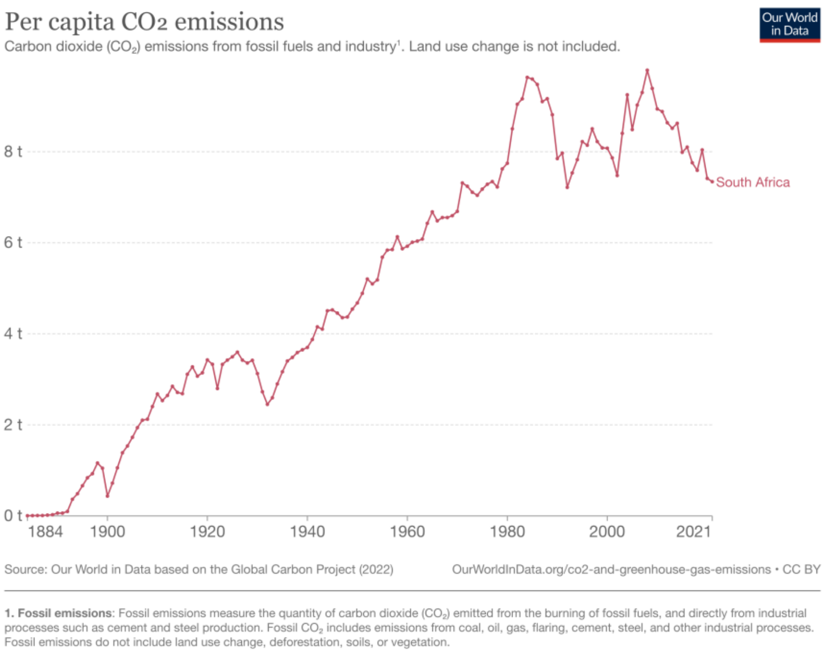
According to Trading Economics' website, SA is the EU's biggest trading partner in Africa, with primary exports being mining goods, machinery, and transport equipment. Imports from SA were US$26.97 billion in 2022 with precious stones, metals, coins and pearls being the biggest category at US$5,16 billion (Trading Economics, 2023). Considering the imposition of CBAM, South African mining companies should be motivated to reduce emissions to remain competitive in the EU and avoid additional import duties. Having financial implications because of CBAM may incentivise the mining companies more aggressively towards achieving their reduced emissions goals.

This study will aim to investigate the environmental benefits of transitioning to BETs, assess the economic viability of these options, and consider the availability of infrastructure such as charging stations and other factors that could hinder the adoption of these technologies.

Within the context of a largely resourced-based economy, the mining industry is a significant contributor to the economic and social welfare of SA. SA's mining sector contribution to Gross Domestic Product (GDP) has more than doubled in the past five years (Domela et al., 2023).

Mining activities serve as the socioeconomic bedrock for many communities, providing critical economic support and employment. The mining sector plays a crucial role in responsible corporate citizenship by adopting sustainable practices and actively working to reduce greenhouse gas emissions (Husnah & Fahlevi, 2023). A significant portion of these emissions originates from diesel trucks, which account for more than 50% of the total emissions from mining operations (Rajesh K Ahluwalia et al., 2023). Globally, trucks used in mining are responsible for 68 million tonnes of CO_2 emissions annually, and as a result, decarbonising these large trucks has become a key focus for mining companies (Rajesh K Ahluwalia et al., 2023).

SA relies extensively on coal-fired power plants to generate electricity, as shown in Figure 2. As a result, , mining activities contribute significantly to emissions due to the energy-intensive nature of the equipment, machinery, and blast furnaces utilised.



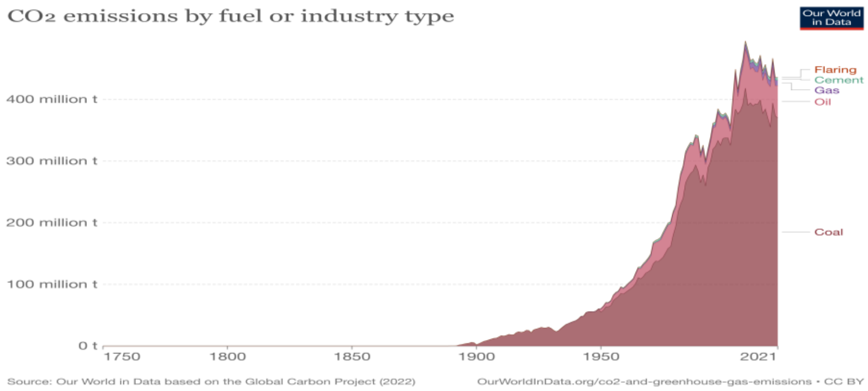


Figure 2 Emissions in South Africa

Source: www.ourworldindata.org

Hydrogen fuel cell technology is a promising technology for reducing CO_2 emissions of heavy-duty diesel trucks (Rajesh K Ahluwalia et al., 2023). Similarly, with developments in battery technology since 2016, the new generation of BETs is also proving to be beneficial to reduce emissions of heavy-duty diesel trucks (Halim et al., 2022).

Figure 3 Representation of electrification

Source: 4 Sight Consulting. (n.d.). *test*. 4 Sight Holdings. https://4sight.cloud/the-benefits-of-electric-mine-simulation

The study's conceptual model is represented in Figure 3 (4 Sight Consulting. (n.d.). *test*. 4 Sight Holdings. https://4sight.cloud/the-benefits-of-electric-mine-simulation). Renewable sources charge BETs to lower emissions.

1.2 Context of the study

The objective of this study is to reduce transport emissions in South African mining companies by examining alternate technology to diesel-powered internal combustion engines (ICEs), complete a techno-economic comparison of this technology, and understand what the barriers to the adoption are.

Mineral resource exploration is a crucial factor for governments and industries as the government relies on revenue from resource development (Singh et al., 2024). SA is one of Africa's largest economies and is endowed with some of the world's largest natural resources of gold, platinum group metals, chrome ore, manganese ore, and also the first, second, and third largest resources of titanium, zirconium, and vanadium (Dramani et al., 2022).

The process of extracting these natural resources from the ground is referred to as mining. Mining has been an essential part of human activity for thousands of years, and has helped improve security and quality of life in building today's industrial society. Typical mining activities include breaking, excavation, hauling, transportation, and mineral processing to reduce the size of large rocks so that the mineral content can be upgraded and beneficiated. Mining activity is rapidly increasing due to urbanisation (Banerjee & Raval, 2022).

There are two types of mining methods: underground mines where minerals are mined from the ore body beneath the surface and accessed through sinking shaft, and surface mining where soil and rock overking or hosing an orebody is removed to access the mineral resource (Xue et al., 2022). SA has a mix of underground and surface mines.

Undeniably, mining provides jobs, grows the economy, and improves the livelihoods of communities; however, if done irresponsibly could cause permanent and irreparable damage to the environment (Mabey et al., 2020).

Mining is one of the most energy-intensive industries globally and plays a crucial role in providing raw materials for beneficiation processes in other sectors of the economy. Many mining operations, especially those in remote areas, rely on fossil fuels such as diesel, coal, and heavy oil as their primary energy sources (Igogo et al., 2021).

For purposes of this study, the focus will be on diesel as a fuel source for the trucks used in mines. Venter (2022), states that "roughly 80% of emissions from one of SA's largest mining companies Anglo American, comes from diesel use with mine trucks, in turn, responsible for most of its emissions". Venter further states that each of these trucks uses 900 000 litres of diesel per annum, highlighting a significant opportunity for Anglo American to decarbonise.

One of the options to decarbonise transport in the mining sector is battery-powered trucks; however, the long charging time could be a deterrent (Bołoz, 2021). For this reason, companies like Sandvik, Epiroc, and Komatsu have been investing in technology to address the long charging time of mine trucks weighing between 30 to 40 tonnes as the estimated time to charge these trucks is currently approximately 120 minutes (Bołoz, 2021). Hanely, 2022, in his article "Designwerk unveils megawatt charging systems for electric trucks", states that the Swiss Company Designwerk is investing in technology to design a charging system that can charge trucks six times faster than a 350kW fast charger.

The upfront capital costs of renewable energy sources to charge the BETs, such as solar, wind, or hydropower, often represent the largest portion of the total expenditure (Taibi et al., 2020). In SA, the electricity crisis and the high cost of electricity from Eskom have compelled mining companies to invest in solar and wind plants. As a result, a significant portion of this capital expenditure has already been accounted for. Reducing renewable energy costs over the years have narrowed this gap (Taibi et al., 2020).

The use of BETs in underground mining operations can offer significant advantages in creating a safer and cleaner work environment. Diesel-powered vehicles in underground mines require extensive ventilation systems to mitigate the harmful emissions and heat generated by their engines, which can account for up to 50% of a mine’s total electrical energy costs (Habibi et al., 2023).

The transition to battery-powered trucks can help address these environmental concerns by eliminating the need for such intensive ventilation and reducing miners’ exposure to pollutants (Gonen, 2021). The effectiveness of BETs in underground mining is dependent on several key factors, including the specific requirements of the mine, its geographic location, and the availability of a reliable power source for charging the batteries (Rafi et al., 2020).

Metals perform a myriad of functions and are important for a low-carbon economy for energy generation and zero-emission transport. Although metals are important for the de-carbonising of the economy, their extraction is very carbon-intensive (Bloodworth et al., 2019).

Modern economies are reliant on fossil fuels for economic development, social inclusion, and maintaining a good quality of life. Achieving climate-related objectives aligned with the Paris Agreement requires a substantial reduction in the use of fossil fuels (Cahen-Fourot et al., 2021).

Diesel engines are widely used in mining due to their high-power output. Diesel is used by: a) mine haul trucks to transport metals mined to the surface, and b) to power machinery used for tunnelling which speeds up the digging time (Korshunov et al., 2021).

Diesel prices in SA are variable and steadily rising (Ngwaku et al., 2022). In mining, diesel accounts for approximately 46% of the operational cost (Ngwaku et al., 2022). According to data released by the South Africa Petroleum Association, between 2019 and June 2022, the cost of diesel rose by 40% (Ngwaku et al., 2022). South African mining companies are faced with two challenges beyond their control in terms of costs: commodity prices which are internationally set and uncontrollable diesel prices (Ngwaku et al., 2022).

Different types of trucks are used in mining for various types of processes. The processes are broken into two phases as illustrated in Figure 3: the mining operation where minerals are explored and the hauling stage where minerals are transported for further processing (Aguirre-Jofré et al., 2021).

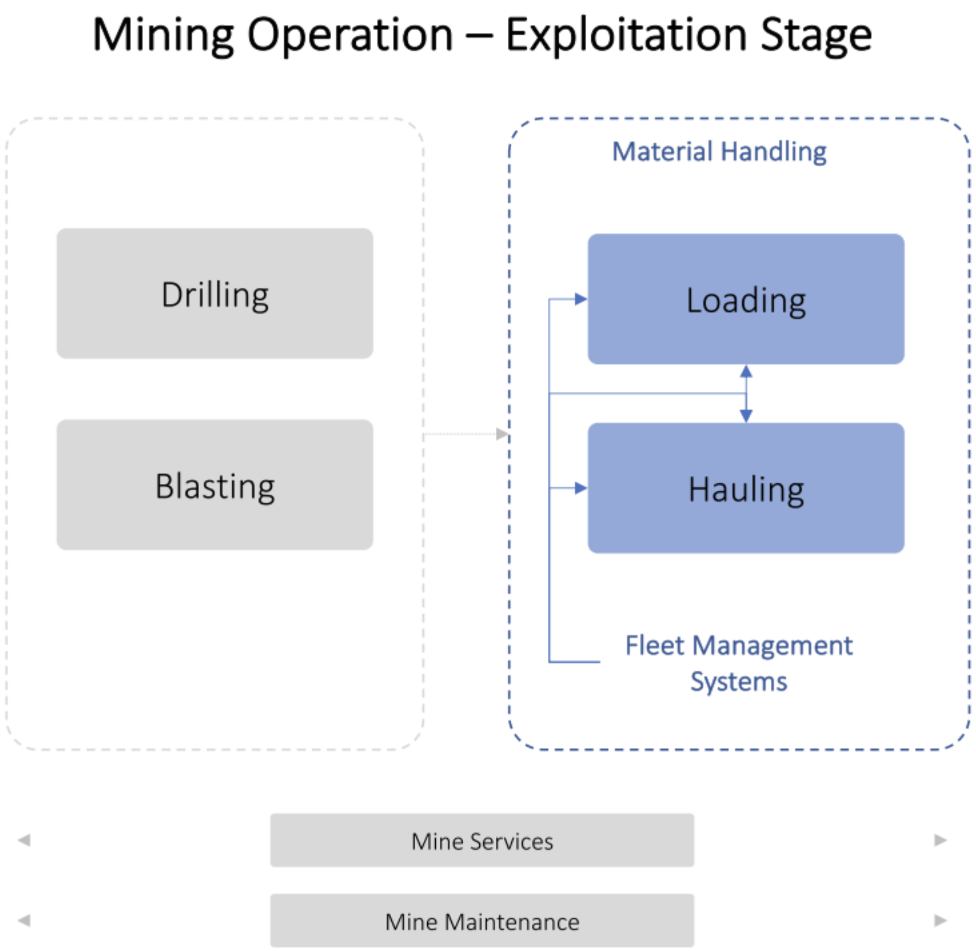


Figure 3 Phases of mining

Source: Aguirre-Jofré et. al (2021)

During the drill and blast mining phase, stemming trucks are used. Stemming trucks are used to backfill holes in a mine site to reduce the effect of the blast on the surface. This process is necessary so the rock underground can be broken into smaller prices and transported to the surface for waste disposal or stockpiled for further processing.

Underground mining operations present unique challenges and requirements when it comes to the transportation of materials and resources, given the confined spaces, varying terrain, and need for efficient and safe hauling solutions. One of the primary types of vehicles used for hauling in underground mines is mine haul trucks, which are specifically designed to handle the demands of these environments (Hejase & Ozguner, 2022).

During the hauling process, the largest heavy-duty trucks are used to transport heavy minerals such as ore, coal, and copper for further processing. Trucks used during this process can range from 40 to 100 tonnes and travel a long distance. These trucks are internal combustion engine trucks (ICETs) fuelled by diesel, and the fuel consumed depends on the distance travelled and speed due to the heavy load (Hejase & Ozguner, 2022).

Diesel-fuelled ICE trucks contribute significantly to environmental degradation. They are one of the primary sources of emissions of harmful pollutants, including black carbon, a particulate matter that is particularly damaging to both human health and the environment (Makarova et al., 2023).

For this study, the emphasis will be on the 42-tonne payload capacity which is classified as medium to heavy-duty as shown in Figure 4, and will be confined to movement at the mine and not on any public roads.

Figure 4 42-tonne payload capacity truck

Source: https://www.epiroc.com/en-sk/products/loaders-and-trucks/electric-trucks/minetruck-mt42-battery

Diesel exhaust emissions (DEE) is an output of using these high-powered vehicles and pollute the air around them which can also be referred to as diesel particulate matter (DPM). DPM consists of polycyclic aromatic hydrocarbons which are harmful to humans, particularly in confined spaces such as underground mines (Arregocés et al., 2023).

There are many options to de-carbonise mining as shown in Figure 5 (Delevingne et al., 2020). As the sector increasingly comes under pressure from governments, investors, financial institutions, and environmental lobby groups, the leadership of this sector needs to act.

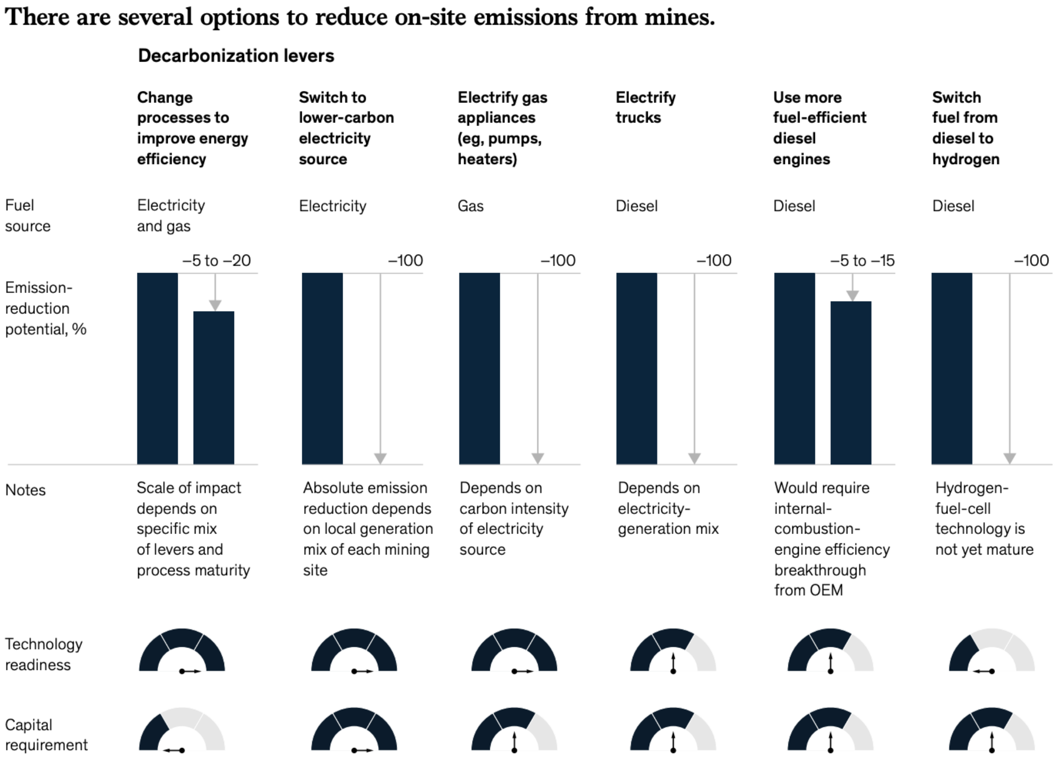


Figure 5 Options to reduce on-site emissions

Source: Delevingne et al. (2020)

To provide greater context and depth to the topic, a collaboration between original equipment manufacturers (OEMs) and mining companies led to the formation of the Innovation for Cleaner Safer Vehicles (ICSV) initiative in 2018, with the sole aim of decarbonising transportation in mining. The ICSV identified BETs as an option to replace diesel fuel (Leonida, 2020). The finding by the ICSV has also been backed up by the McKinsey study as illustrated above.

The high number of battery-operated electric truck demos was the largest change on display at MINE Expo 2021, which was hosted at the Las Vegas Convention Centre. This was due to the increased awareness in the mining industry to limit the use of diesel-fuelled trucks and accomplish their sustainable goals (Fiscor, 2021).

BETs are becoming increasingly popular due to improvements in technology such as increased energy density and faster charging times, low emissions, and relatively low operating costs (Albatayneh et al., 2023). OEMs of mining equipment have followed the automotive sector and have begun manufacturing heavy-duty mining equipment powered by batteries.

Battery-driven machines are already in operation around the world, Epiroc's Schoomtram ST7, 8-tonne payloader has already clocked 80,000 hours at Nexa Resources mine in Brazil. The Swedish-owned mining company, LKAB, plans to use Epiroc's BETs at its mine expansion. A year after Epiroc launched its battery electric mining equipment such as its 42-tonne mine truck MT42 and various battery-powered drilling rigs, orders started flowing in from different countries for this equipment (Boudreault, 2019).

Not be outdone by Epiroc, a 240-tonne haul truck fitted with a 1.4 MWh prototype battery system has been developed by Fortescue, a green energy company, and Liebherr, a heavy equipment manufacturer. The truck with a 30-minute charging time was delivered to be tested in a mine in Australia in 2023. The power systems weigh 15 tonnes and are made up of eight sub-packs and 36 modules, all individually cooled with their battery management system (Lewis, 2023).

FCETs have a longer range and can be fuelled more rapidly, making them more suited for heavy-duty transport. However, the high cost of production and limited fuelling infrastructure makes the adoption of this technology challenging (Albatayneh et al., 2023).

In May 2022, Anglo American, a global mining company, launched the world's first 300-tonne haul truck powered by hydrogen fuel cells. It was a collaborative effort with Engie, a leading energy provider. The programme is part of Anglo American's FutureSmart mining sustainability programme. The pilot involved the conversion of a haul truck to run on hydrogen at its Mogalakwena operation in SA. The modification included replacing diesel tanks with hydrogen tanks and replacing the engine with hydrogen fuel cells, a 3.5MW Alkaline electrolyser, and a 1.2MWhr battery pack. The green hydrogen will be provided by solar power generation at the mine (Leonida, 2020).

The development by Fortescue and Anglo American, while still needing to be tested in mining conditions, is demonstrative that technology for BETs and FCETs is progressing and being considered for rollout in heavy-duty industry. However, remote mine locations with challenges to electricity sources could make the rollout difficult.

This research investigates whether BETs can be used in underground mines in SA to assist the mining industry with its decarbonisation goals so metals can be mined in a sustainable way and, therefore, reduce the carbon footprint associated with the metal supply.

1.3 Research problem

The widespread use of diesel trucks in underground mining in SA contributes to environmental degradation and operational inefficiencies. Little research has been done in SA to explore the environmental and economic viability of transitioning to BETs. However, due to global pressure on the OEMs to transition from diesel trucks, there has been some recent developments. This study aimed to evaluate the potential environmental benefits, assess cost parity benefits, and identify the barriers to the adoption of BETs in underground mining.

Research questions

The following research questions frame this study:

1. What is the environmental impact of using medium and heavy-duty BETs, and how does it compare to diesel? The specific trucks considered will be 40-tonne trucks used for stemming and hauling in underground mines at the mining site only.
2. How do medium and heavy-duty BETs compare to diesel trucks in terms of the total cost of ownership?
3. What are the barriers to the adoption of medium and heavy-duty BETs in mining?

1.4 Significance of the study

Electrification of mines is moving up the agenda of the mining sector as is evident by several initiatives by the International Council on Mining and Metals. The increasing emphasis on electrification reflects the broader pressure by investors, governments, and society on the mining sector to adopt more sustainable mining practices.

One of the highest input costs for mining is the extraction and processing of metals. This function is generally powered by diesel or electrical grid power. The use of diesel in underground mining creates an additional cost of ventilating the environment to make it safe for workers. Operating diesel-powered equipment for transport in the long term is not economically sustainable. Influencing factors such as fluctuating pump prices results in high transport and increased operating costs when the diesel price increases (Mulenga et al., 2023).

Positive economic development has been linked to increased use of energy, and with increasing urbanisation, energy demand is expected to increase globally by 1.4% per annum leaving experts concerned about energy security and the impact on the environment (Nel et al., 2019).

Approximately 30% of SA’s energy supply is to the mining industry, and with the announcement by the country’s president that the licence exemption cap set on self or distributed-generation plants has been raised from 1MW to 100MW, many mining companies have registered their own self-generating solar plants totalling 5.1GW (Botha, 2022). The generation capacity of these plants ranges from 38MW to 100MW, with many of them being solar plants. Pan Africa Resources is already producing 10MW of renewable energy, Goldfields is expected to add 50MW, Anglo Platinum is expected to add between 75MW to 100MW plant, and Harmony is expected to add 38MW (Botha, 2022).

In 2022 alone, Nersa registered 295MW of projects for mining companies (Botha, 2022). Solar plants can provide a reliable and sustainable power source for battery charging.

BETs are being increasingly considered in SA's underground mining sector to enhance sustainability, reduce emissions, and improve operational efficiency. These vehicles offer significant advantages over traditional diesel-powered trucks including lower greenhouse gas emissions, reduced ventilation requirements, and decreased operational costs. Some of the key developments in SA include:

- Sandvik's TH665B truck: In September 2022, Sandvik unveiled the TH665B, a 65-tonne capacity BETs, at Electra Mining Africa in Johannesburg. This model is noted as the world's largest-capacity BET for underground mining, designed to boost productivity and sustainability in bulk mining operations (Bulbulia, 2022).
- Fermel's Battery electric range: South African Manufacturer Fermel (Pty) Ltd has developed a range of battery electric vehicles tailored for underground mines. Its offerings include personnel carriers and low profile shuttles, emphasising zero-emissions solutions suitable for mining operations (Fermel (Pty) Ltd, n.d.).
- Epiroc's zero-emission equipment: Epiroc has expanded its battery electric and zero-emission underground fleet including loaders, mine trucks, and drilling rigs. These advancements help to create a healthier working environment and reduce the environmental footprint of mining operations Epiroc (n.d.).

The use of battery-powered trucks in mining processes offers several advantages, including reduced emissions and improved efficiency, as well as potentially lower long-term cost benefits compared to diesel-powered vehicles. However, the study sought to determine whether these technologies are currently viable and practical for use in mining, considering factors such as the availability and cost of infrastructure for charging, the range and power of the vehicles, and the overall cost-effectiveness of switching to these alternative technologies.

Overall, the study aims to provide insights into the potential benefits and challenges of adopting battery-powered trucks in mining, and to inform decision-making around the transition to more sustainable and environmentally friendly transportation options.

1.5 Delimitations of the study

The study sought to evaluate the effectiveness of the substitution of BETs for diesel-powered trucks from the unique perspective of being more environmentally friendly.

The delimitations of the study are:

a) The study is limited to underground mining companies in SA that use diesel as a fuel source; however, due to alternate technology being nascent in SA, data from other countries will be used from which South African mining companies can benefit.
b) The study excludes the following:
    a. Trucks used outside the mines.
    b. Skills required to operate BETs.
    c. Opinions of communities in which the mine operates.

1.6 Definition of terms

Table 1 Definition of key terms

Term	Definition
Decarbonisation	Reduction in carbon intensity of the whole economy by reducing CO_2 emissions and greenhouse gases into the atmosphere (Trencher et al., 2022).
Energy transition	The current push for a transition from the reliance on conventional energy sources to "cleaner" energy sources (Halawa, 2024).
Mining	The process of extracting and processing precious minerals and metals from the ground (Maus et al., 2022).
Mine haul truck (medium and heavy-duty truck)	Trucks of various capacities with the largest weighing 600 tonnes and carrying loads from <75 tonnes to >200 tonnes (Thompson et al., 2019).
Renewable energy	The International Energy Agency defines renewable energy as "energy derived from natural processes that are replenished at a faster rate than they are consumed" (Harjanne & Korhonen, 2019).
Battery electric trucks (BETs)	BETs are trucks that run solely on electricity and store the energy in a battery pack in the vehicle which is generally recharged through plug-in and do not produce emissions (Mao et al., 2021b).

1.7 Assumptions

The following research assumptions were made:

a) The data collected will be sufficient.

b) The data is truthful and accurate.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter explores battery technology for medium and heavy-duty trucks to replace diesel-powered trucks for their environmental benefits, the total cost of ownership of the technology and how it compares to diesel, and the barriers to entry for South African mines to adopt this new technology. In this way, the researcher provided answers to the following three questions that framed the study:

1. What is the environmental impact of using medium and heavy-duty BETs in mining trucks and how does it compare to diesel?
2. How do medium and heavy-duty BETs compare to diesel trucks in terms of the total cost of ownership?
3. What are the barriers to the adoption of medium and heavy BETs in mining?

2.2 Definition of topic

To thoroughly address the questions at hand, it is essential to begin by establishing a comprehensive understanding of the broader context in which the research takes place, both globally and within SA. This section aims to provide an in-depth overview of decarbonisation efforts, with a specific emphasis on the trucks used in mining operations. Additionally, it will explore technological advancements aimed at reducing emissions in this sector, with a particular focus on BETs. Lastly, the section will assess the costs associated with adopting and implementing BETs within the mining industry, equipping decision-makers with the necessary information to make informed choices regarding this emerging technology.

The importance of decarbonisation has evolved over the years. The use of fossil fuel that is harmful to health has been known for years, but it was only in the mid-1980s that a more serious problem emerged, which was the enormous amounts of CO_2 released into the air causing global warming and responsible for climate change (Smil, 2019). Smil (2019) goes on to note the various United Nations (UN) conferences since 1992 which attempted to tackle this problem. Smil (2019) notes that the 5th IPCC report on the influence of human activities on climate change was worrying.

Strategies and pathways to decarbonisation post the COVID-19 pandemic represent one of the most thought-provoking topics in energy and climate change which calls on countries to limit the global rise in temperature to 1.5°C (Beccarello & Di Foggia, 2023). Many organisations and businesses have set defined climate goal targets, with the EU setting certain policies in the Green Deal which will be instrumental in reducing net greenhouse gas emissions by 55% in 2030 (Beccarello & Di Foggia, 2023).

The International Energy Agency (IEA) goes on to say that the momentum for clean energy is recent and has yet to translate into a major change in energy supply. Most countries have been strengthening their support for clean energy post the Paris Agreement of 2015 (IEA, 2023). The IEA also notes that materials, production and components in clean energy supply are markedly different to those needed for fossil fuels.

To reduce the impact of ICE, several initiatives have been launched globally. The UN has initiated the Paris Agreement and the Kyoto Protocol aimed at reducing GHG and CO_2 in the atmosphere (Söderberg et al., 2023). In the EU, regulation (EU) 2019/1242 sets CO_2 emission performance standards for medium and heavy-duty trucks and in the United States, the Clean Air Act can be used to regulate clean air emissions (Söderberg et al., 2023).

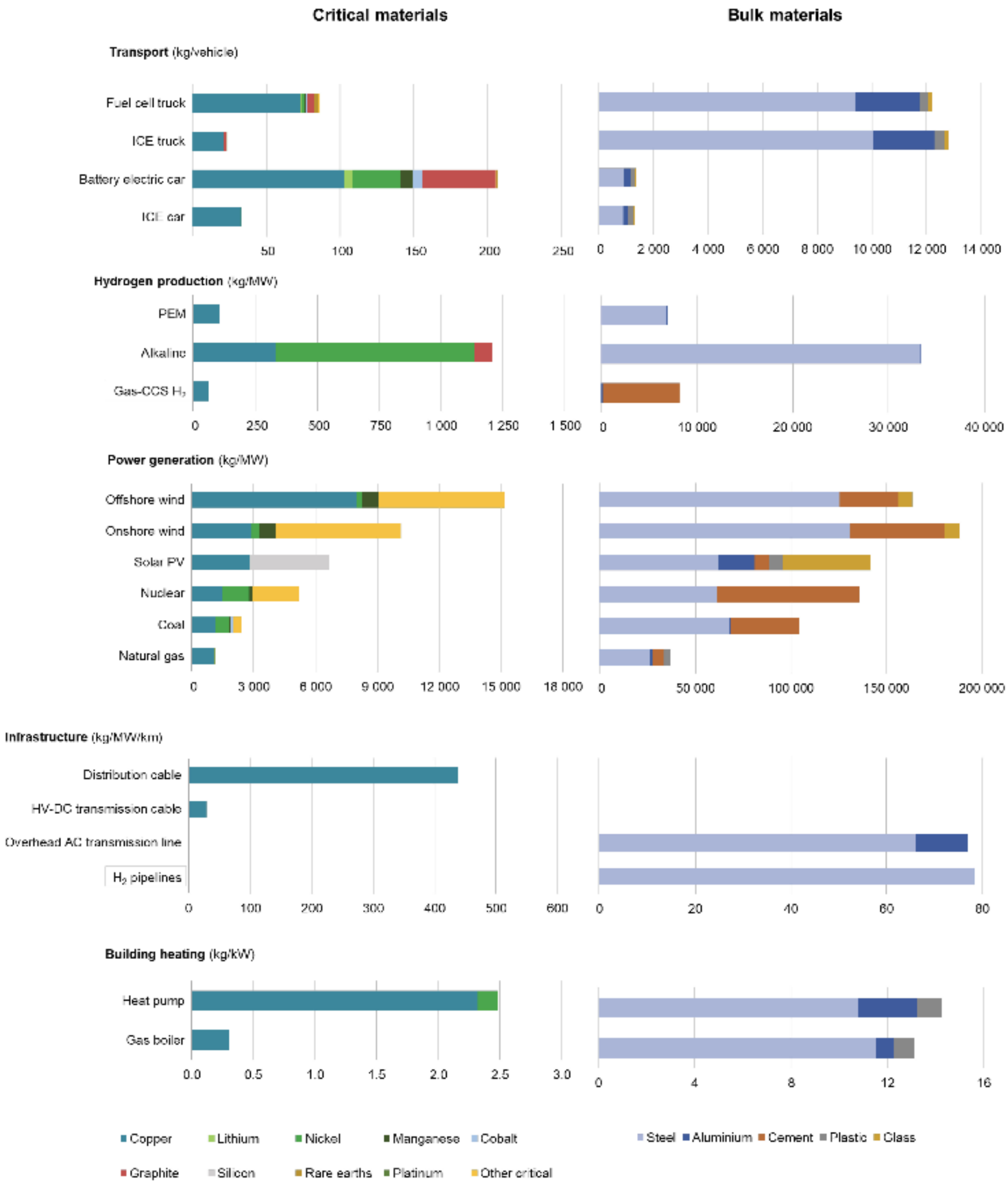


Figure 6 Critical minerals needed for clean energy technology

Source: www.iea.org

Figure 6 shows that the transition to clean energy relies significantly on a wide range of metals and critical minerals, such as lithium, cobalt, nickel, copper, and rare earth elements. These materials are essential for manufacturing batteries, electric vehicles, solar panels, wind turbines, and other clean energy technologies. As demand for these minerals increases, the mining sector faces the challenge of scaling up production while simultaneously reducing its carbon footprint.

Globally, more than 90% of the world's transport is powered by fuel derived from oil. However, the consumption of this type of fuel is deemed to be problematic due to the cost and the generated greenhouse gas emissions or air pollutants (Perez & Perez, 2022).

Using data from a study done in 2020 by the IEA, Figure 7 shows that medium- and heavy-duty trucks are a significantly high emitter of CO_2.

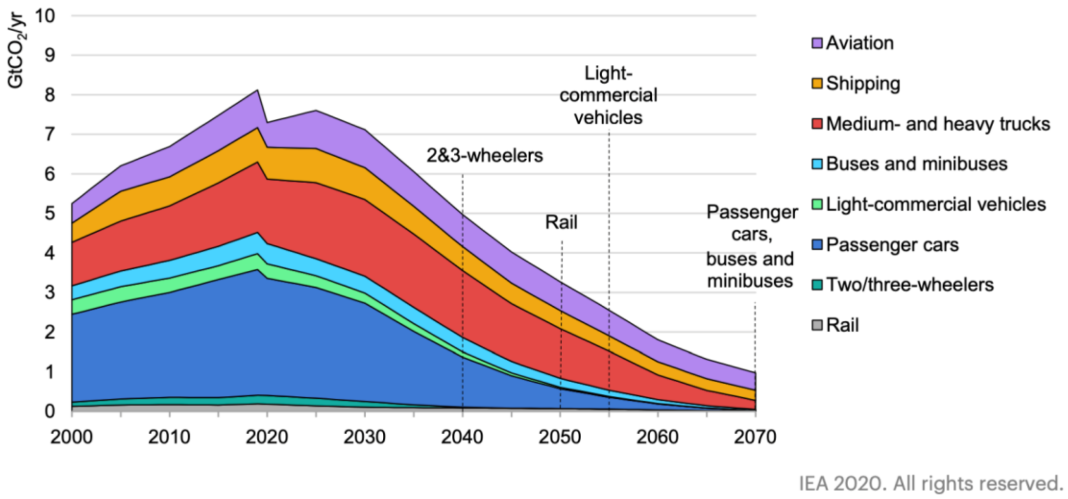


Figure 7 Global emission per transport mode in 2020

Source: www.ourworldindata.org

Figure 8 shows emissions per sector in SA, with emissions from oil being the second highest after coal. The transport sector in SA depends on petroleum fuels, diesel, and petrol for all of its energy needs (Ntuli et al., 2024).

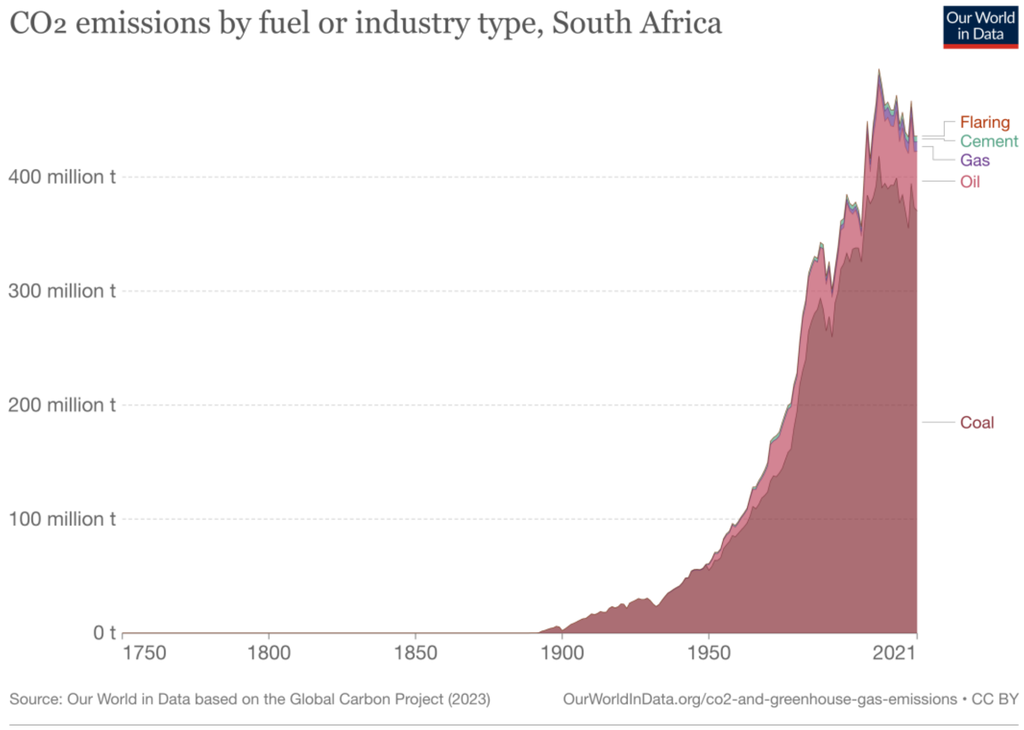


Figure 8 Emissions in South Africa

Firoozi et al. (2024) state that the mining industry stands at a pivotal junction where operational excellence is not only defined by production and profictability but also its commitment to environmental sustainability and safety.

Source: www.ourworldindata.org

The Department of Energy releases annual statistics on fuel sales by volume in litres, which shows that diesel is the highest-selling fuel by volume in SA.

2022	JANUARY TO DECEMBER SA FUEL SALES VOLUME / CONSUMPTION				
VOLUME IN LITRES					
Product name	Q1-January to March	Q2 - April to June	Q3 - July to September	Q4 - October to December	Grand Total
Diesel (All grades)	3 231 738 750	3 133 180 422	3 243 821 404	3 108 585 743	12 717 326 319
Petrol (All grades)	2 341 864 168	2 236 069 851	2 215 985 646	2 390 950 250	9 184 869 916
Jet Fuel	348 615 167	337 004 668	366 946 268	425 583 749	1 478 149 853
Paraffin	305 535 945	299 681 865	300 792 072	271 889 750	1 177 899 632
Furnace Oil	146 344 818	144 652 082	138 673 744	164 369 521	594 040 165
LPG	90 989 584	86 753 233	68 725 142	76 921 377	323 389 336
Aviation Gasoline	1 495 073	1 236 517	902 118	1 062 723	4 696 431
Grand Total	6 466 583 506	6 238 578 638	6 335 846 394	6 439 363 113	25 480 371 651

Figure 9 Fuel sales in South Africa

Source: www.energy.gov.za

With ever-increasing diesel prices, as shown in Figure 11, alternate fuel sources could be viable. The United States Department of Energy released a report in March 2022 that states that, “Zero-emission vehicles can reach a total driving cost of parity with conventional diesel vehicles by 2035.” (Ledna et al., 2022).

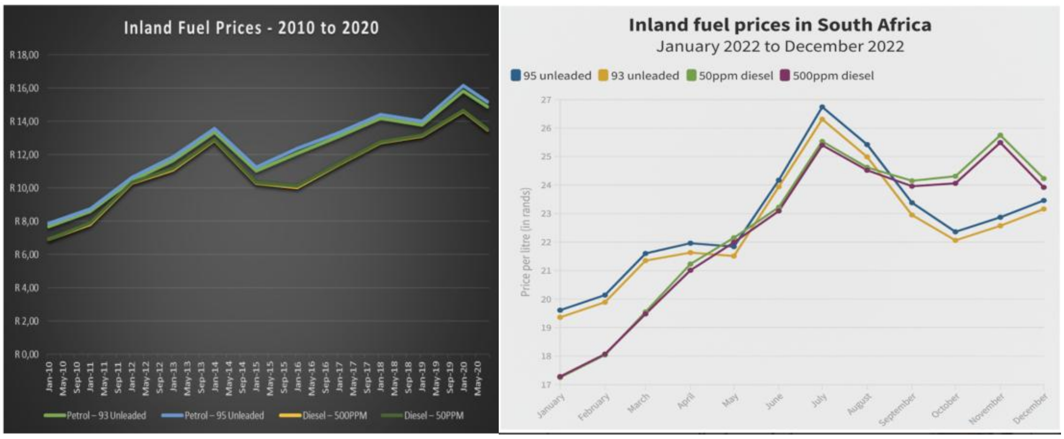


Figure 10 Change in fuel price in South Africa

Source: www.broadband.co.za (2022)

Ledna et al. (2022) identified BETs and FCETs as two technologies for medium and heavy-duty trucks that could be viable in terms of costs and offer an alternative to decarbonisation.

According to Liimatainen et al (2019), development of battery technology is making battery electric heavy-duty trucks technically and commercially viable, and several manufacturers have introduced BETs. Concerning the total cost of ownership (TCO), Burnham et al. (2021) state that due to recent and ongoing developments in battery technology, the upfront premium price paid to purchase BETs can be recovered over the life of the vehicle, taking into account lower operating and maintenance costs.

Leading mining companies such as Vale, Anglo American and Newmont are exploring are exploring renewable energy and fuel switching products to reduce their scope 1 and scope 2 emissions (Tokac et. al., 2025).

The electric mining truck market is in its early stage, but more and more OEMs are increasingly electrifying their products and mining companies have shown a willingness to adopt this technology. According to a research report by IDTechEx, an independent research house on emerging technologies, a more potent incentive for adoption is the TCO savings which will drive adoption more than regulation (Jaswani & Jeff, 2023).

The report further argues that the savings for underground mines is more than surface mines as underground mines will have reduced ventilation costs and heat, and noise and emissions by diesel trucks are a bigger concern underground than on the surface (Jaswani & Jeff, 2023).

Reduced diesel consumption will help South African mining companies meet their decarbonisation targets. Transitioning to BETs offers a viable path to attain this goal. However, like with any new technology, there are challenges. Conducting this research will help mining companies make well-informed decisions in their consideration of this technology. This research will provide valuable insights on how to improve emissions through cost-effective solutions. In addition, it will help identify potential limitations and challenges associated with the transition to electric trucks.

2.2.1 Recent developments in the heavy-duty BET sector

The heavy-duty battery electric truck (BET) sector has experienced significant advancements, driven by technological innovations, increased production, and strategic partnerships.

a) Technological innovations and production

Major manufacturers have introduced advanced BET models with enhanced range and efficiency. For instance, Mercedes-Benz Truck unveiled the eActros 600, a long haul electric truck with a range of 500km, aiming to replace diesel trucks in the segment over time (Mercedes, n.d.). Similarly, Volvo's heavy-duty electric truck demonstrated superior range and energy efficiency in independent tests, using 50% less energy than its diesel counterpart with a range of 600km (Lind, 2024).

b) Market growth and adoption

The global market for electric trucks is expanding. In 2023, sales of electric trucks increased by 35% compared to 2022, surpassing electric buses for the first time, with around 54,000 units sold. China led the market, accounting for 70% of global sales (IEA, n.d.).

c) Strategic partnerships and investments

Companies are forming strategic partnerships to accelerate BET adoption. Fortescue Metals Group entered a $4.06 billion deal with Liebherr to convert two-thirds of its mining fleet to zero-emissions battery technology, including 360 autonomous BETs (Slater, 2024). Additionally, Chinese start-up Windrose plans to establish a US assembly plant in Georgia to deliver semi-trucks to American customers starting in 2025, directly challenging Tesla in its home market (Yan, Z., Krolicki, K., 2024).

d) Challenges and considerations

Despite progress, challenges remain. The lack of public charging infrastructure is a significant barrier for companies considering electric trucks. Scania, for example, is establishing its own charging installation company to address this issue, but broader societal and governmental support is needed. Scania believes on-site renewable energy generation such as wind or solar will assist with grid capacity for charging stations and gives Shoprite as an example of a company that has achieved this success (Scania, n.d.).

2.3 Environmental impact of diesel-fuelled trucks compared to

electric trucks

2.3.1 Environmental impact of diesel trucks

The Kyoto Protocol is considered a milestone in climate change as it was the first agreement signed that included binding targets to reduce greenhouse gas emissions (Anderhofstadt & Spinler, 2019).

Khubana et al. (2022) elaborate further on the definition of environmental impact, by defining it as a variable affecting shared value that an organisation can implement to mitigate the negative effect on natural resources in a way that creates benefits for communities and the organisation. This includes engaging in the economic use of natural resources, environmentally friendly packaging, pollution control, and nature conservation through recycling, waste reduction, and water preservation, i.e. in a sustainable manner.

Singh et al. (2019) add that the most important definition of "sustainable development" was put forward to the UN (1983) by the Brundtland Commission, which was to "meet the needs of the present and future generations without compromising the ability of future generations". Das et al. (2019) add that policy and regime coherence is extremely important to achieve the goals of the Paris Agreement and requires support from the international trade system. The IEA, World Energy Council, World Economic Forum, and a large number of major energy corporations are consistent in their views that the global energy and economic system are shifting from one that relies largely on fossil fuel-based energy, to one that is more reliant on low-carbon sustainable energy generation and consumption (Sovacool & Griffiths, 2020). Mobility is a key enabler of economic development (Orbelyan, 2024).

Nabi et al. (2022) stated that diesel is widely used in industrial sectors such as transportation, mining, and construction due to its high-power output, ease of accessibility, proven technology, and portability in spite of known greenhouse gas emissions. They add that policies and regulations are in place by many countries to stimulate the development of vehicle technologies for a transition from diesel-based transportation to low-carbon fuel alternatives to reduce greenhouse gas emissions (Nabi et al., 2022). In addition, Cheng et al. (2020) state that emissions from medium and heavy-duty diesel trucks pose a threat to the environment and human health. Cheng et al. (2020) note that harmful pollutants such as nitrogen oxide (NO_x) and DPM released from ICEs like diesel engines are extremely detrimental to air quality and human health. Balboa-Espinoza et al. (2023) state that the DPM has been classified as human carcinogenic by the International Agency for Research on Cancer due to many miners developing lung cancer especially in underground mines where diesel equipment is used.

Due to the inability to obtain fine-grained activity data of emissions per type of medium and heavy-duty diesel trucks, the existing emission inventory treats all these diesel trucks as one inventory irrespective of tonnage and technical standard of the vehicles (Cheng et al., 2020).

According to SA’s Just Energy Transition Investment Plan (JET_IP), SA’s transport sector is the third-highest emission sector (57 Mt of CO_2 per annum or 10,8% of National GHG emissions). It therefore remains an important focus for emissions reduction interventions to comply with the country’s Nationally Determined Contributions (NDC) targets (Climate Commission, 2022).

The operation of modern underground mining equipment relies heavily on ICE equipment. For this reason, health and safety policies and mine regulations all over the world have specified fresh air flow to dilute diesel pollution (Gren et al., 2022). Diesel-powered equipment is versatile, has a big range, offers unlimited range ability when well maintained, and has a low capital cost and quick refuelling. Many mines have opted to comply with legislation around air quality instead of transitioning to an alternate fuel for decades (Kotyla et al., 2024).

The International Council of Mining and Metals (ICCM) is an organisation comprising mining companies around the globe as its members. It was formed after mining chief executive officers came together to explore how mines can contribute to sustainable development and reduce their environmental impact (ICCM, 2023). In keeping with this purpose, the ICCM launched the ICSV Initiative. The initiative brings together the members, OEMs, and technology suppliers to address the challenge of emissions in mines caused by ICEs (ICCM, 2023).

Health effects of diesel exhaust exposure in underground mines is receiving much attention. Some of these health issues include:

Respiratory issues: Exposure to diesel exhaust can lead to respiratory problems such as irritation of the eyes and nose, headaches, nausea, and exacerbation of asthma. Chronic exposure may result in more severe respiratory conditions.

Carcinogenic risks: The International Agency for Research on Cancer (IARC) has classified diesel exhaust as a Group 1 carcinogen, indicating sufficient evidence of carcinogenicity in humans. Epidemiological studies have shown an increased risk of lung cancer among miners exposed to diesel exhaust.

MINE SAFETY AND HEALTH ADMINISTRATION

Cardiovascular effects: Diesel exhaust exposure has been linked to cardiovascular issues, including increased blood pressure and a higher risk of heart disease. The particulate matter in diesel exhaust can contribute to systemic inflammation, affecting cardiovascular health.

DMIRS

Neurological impacts: Some studies suggest that exposure to diesel exhaust may have neurotoxic effects, potentially leading to cognitive impairments and other neurological issues.

DMIRS (Landwehr et. al., 2019).2.3.2 Environmental impact of BETs

Emissions are expected to grow despite large improvements in energy efficiency due to increasing demand. This reiterates the growing need for electrification of the transport industry (Liimatainen et al., 2019). Breuer et al. (2021) noted that the primary goal of the energy transition in the context of transport was to reduce greenhouse gas emissions. According to Breuer et al. (2021), the CO_2 emission factor for BETs drops to zero due to the absence of exhaust emissions.

BETs propel themselves using electricity and do not require the use of an ICE. “They both convert the chemical energy stored in active materials into electrical energy within the electrochemical cells” (Cunanan et al., 2021). Batteries have the active material stored within the system which provides energy until it needs to be recharged (Cunanan et al., 2021).

The competitiveness of BETs against their diesel counterpart has been the focus of research since the early 2010s. However, BETs have not been a viable option to replace heavy-duty diesel trucks because of the high energy requirements and low energy intensity of batteries (Liimatainen et al., 2019). However, Samet et al. (2024), states that there has been increasing development in technology for batteries and charging infrastructure for heavy duty trucks, charging technology development has elevated to 1MW and beyond to enable fast charging technology.

According to Kurien and Srivastava (2020), electricity generation in developing countries such as India and SA is dependent on fossil fuel-based thermal power plants, and the introduction of electric trucks will shift the threat of emission from the operation stage to the energy generation stage. CO_2 emissions for BETs can be completely removed only if the electricity generation is derived from renewable sources (de las Nieves Camacho et al., 2022).

2.4 Proposition 1

The use of diesel in mining has been associated with various health and environmental issues, including air pollution, greenhouse gas emissions, and respiratory diseases among miners. In recent years, there has been a growing push towards using cleaner fuels in the mining sector.

According to the literature review, mining companies have an obligation to cut back on their use of diesel-powered medium and heavy-duty trucks for the following reasons:

- To contribute to South African NDC targets.

- The technology for electric trucks exists, placing the responsibility on mining companies to investigate this alternative.
- As mining companies operate in communities, they are responsible for protecting the communities and the environment around them.

According to the emerging literature, it is proposed that battery-powered trucks are better alternatives to diesel-powered trucks for reducing emissions, protecting the environment, and protecting human health.

2.5 How do medium and heavy-duty BETs compare to diesel trucks in terms of TCO?

Ghorbani et al. (2023) note that mining equipment is expensive and depending on the terrain and the location, maintaining this equipment can be difficult. They add that the need for underground mining is increasing as surface stocks of minerals get depleted, further adding to the complexity of equipment needed.

Eros (2020) states that the mining industry historically took a very conservative approach to the adoption of new technology in its business. However, the many advantages of electric power combined with the desire of many mines to reduce emissions are driving the attention of miners to this technology (Eros, 2020). The ICSV is demonstrative of the commitment of the mining organisations.

Lebeau et al. (2019) define the TCO as “a purchasing tool and philosophy which is aimed at understanding the true cost of buying goods or services from a particular supplier”. Borlaug et al. (2021) further elaborate that the commercial nature of heavy-duty transportation means that the economic profitability of vehicle operation is a major consideration for operators who purchase these vehicles, unlike the light-duty sector where other factors such as comfort, brand, and styling also take precedence.

According to Ahluwalia et al. (2023), performance, range, durability, and cost are the main criterion considerations for comparing BETs and diesel-powered trucks. Patyk et al. (2021) elaborate that the selection of mining systems including vehicles should be based on a thorough technological and economic analysis that factors in mining conditions. Various performance and durability criteria of trucks at mines include: a) the truck must be operational and running for a specific time, b) the truck should be able to be maintained and serviced, and c) the truck should be able to handle the transport routes in terms of distance with a load (Patyk et al., 2021). Economic factors include costs of purchase and ongoing running and maintenance costs (Patyk et al., 2021).

2.5.1 Battery electric trucks

Economics in mining companies is one of the main factors driving the adoption of new technology. This means that the demand for BETs could see higher adoption once cost parity is reached with its diesel counterpart. Furthermore, manufacturing capacity, and charging infrastructure need to commensurately increase to support the use of BETs (Ledna et al., 2022).

In analysing the TCO factors such as initial purchase cost, fuel cost, maintenance and repair costs, and residual value are taken into account (Muratori et al., 2021).

Lyu et al. (2023) define initial purchase cost as the upfront cost to purchase a piece of equipment which is considered a short-term cost, while maintenance cost is defined as a long-term cyclical cost to ensure that the piece of equipment performs optimally. Ziółkowski et al. (2022) define fuel cost as the energy cost of using a piece of equipment for its functional purpose. Cerquitelli et al. (2020) define residual value as the estimated value of a vehicle at disposal based on the degradation as well as the remaining life estimate of the vehicle.

The TCO is the main aspect studied when comparing alternate fuel sources. It looks at all the costs incurred during the lifecycle of the vehicle providing an additional tool for buyers to make a decision (Tanco et al., 2019). Zhou (2024) further adds that over time electric trucks demonstrate lower operating costs and superior environmental benefits relative to their diesel counterparts.

According to Hovi et al. (2019), the main reason for the small number of adoption of heavy-duty BETs is the prohibitively high purchase price compared to ICETs and technological and operational limitations and uncertainties such as short driving ranges, operational stability, and resale value. Hovi et al. (2019) note that important factors for the adoption of BETs are societal and environmental effects as well as strategic consideration of the organisation's sustainability goals.

In their study of medium and heavy-duty trucks in China, Mao et al. (2021b) found that the base estimate cost for BETs is higher than diesel trucks, which is largely due to the differences in upfront initial purchase costs of the two vehicles. Furthermore, the BETs may require expensive battery replacement costs during their lifetime use. However, the BET benefits from the lower fuel cost during the lifetime of ownership, which offsets the higher initial purchase cost (Mao et al., 2021b).

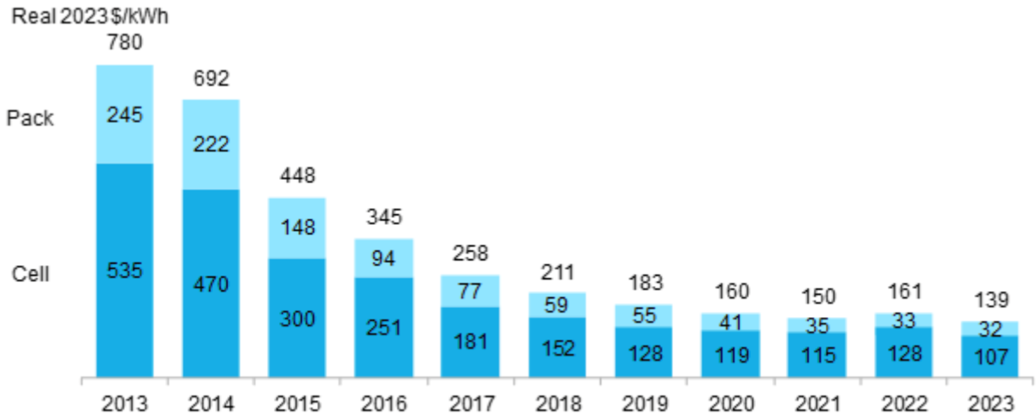


Figure 11 Cost of lithium-ion batteries

Source: Bloomberg New Energy Finance

As illustrated in Figure 12, according to Catsaros (2023) the cost of lithium-ion batteries has decreased significantly since 2013 due to improvements in technology and economies of scale achieved from $780/kWh to $139/kWh.

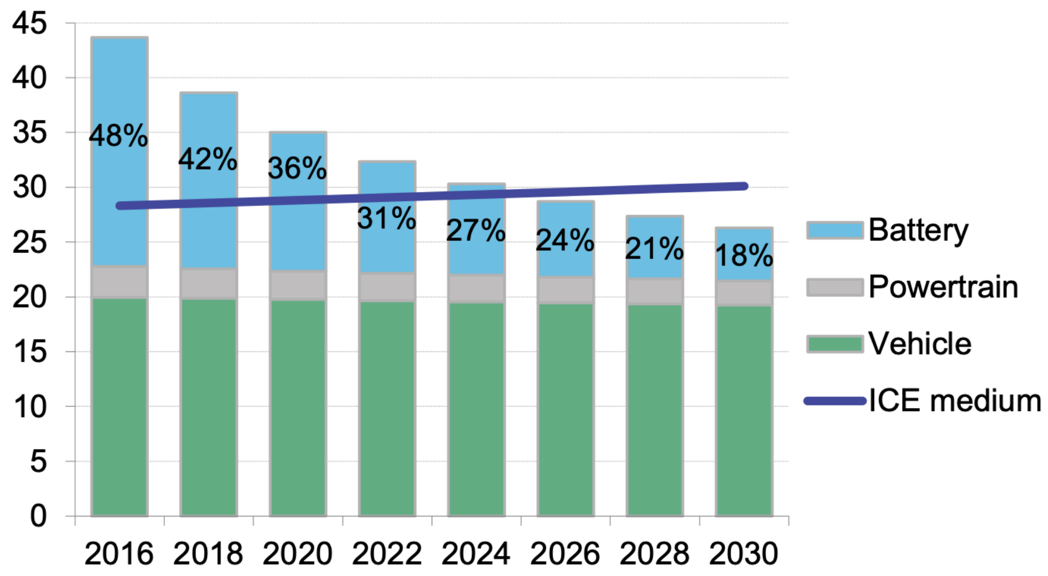


Figure 12 Breakdown of elements of BETs

Source: Bloomberg New Energy Finance

As shown in Figure 13, battery pack cost reductions substantively drives down the upfront cost of BETs as the cost of cell production reduces and economies of scale are achieved (Kaur et al. 2024).

According to Tanco et al. (2019), battery prices are forecasted to fall due to competition and improved production processes. Berckmans et al. (2017) support this view in their projections of the cost of lithium-ion batteries for electric vehicles by 2030. In a more recent study done in 2024 by Bloomberg New Energy Finance (BNEF), the cost of BETs is projected to be even lower than initially anticipated.

By 2030, the initial cost of a diesel truck is projected to be $153,000, while the cost of its BET equivalent is expected to be $146,000. By 2040, this cost disparity becomes even more pronounced, with diesel trucks anticipated to cost $157,000, compared to just $127,000 for BETs. The primary factor driving this growing cost advantage for BETs is the declining price of battery packs, making electric trucks increasingly affordable and economically competitive with internal combustion ICETs, as illustrated in Figure 14 (BNEF, 2024).

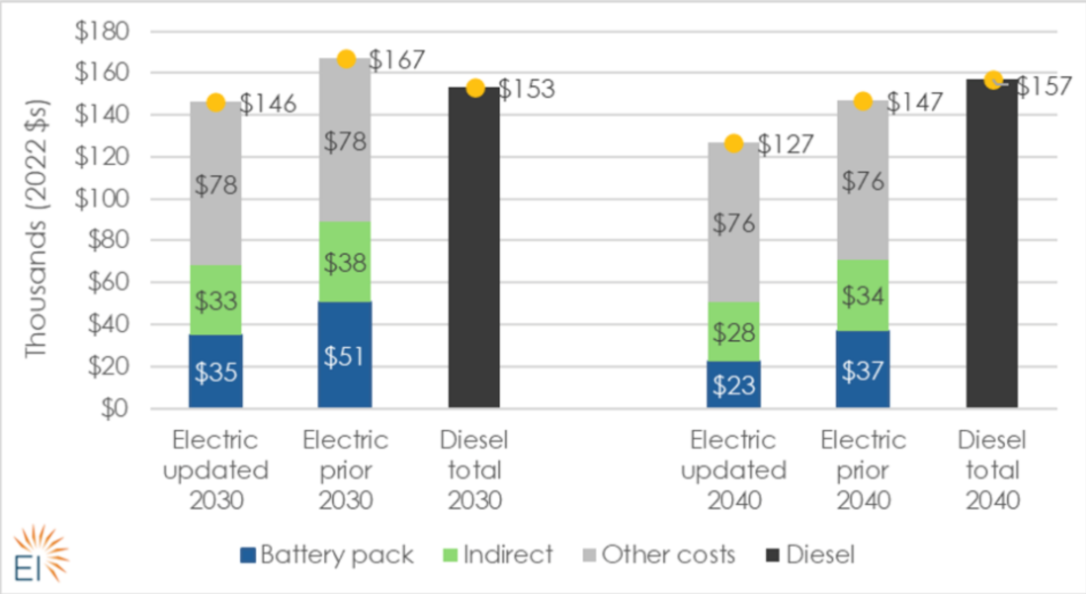


Figure 13 Class 8 short haul cost comparison

Source: BNEF, 2024 (https://about.bnef.com/electric-vehicle-outlook/)

Zhou et al. (2017) used Autonomie, a vehicle simulation software design system to simulate energy consumption for ICETs and BETs. A class 6 (20-tonne) BET and diesel truck were used in the simulation with the geographic scope being Toronto, Canada. The materials for both trucks were the same with only the fuel type being different, an 80kWh battery pack for the BET and a diesel tank for the ICE. Under the same driving conditions, the study found that the fuel consumption of the diesel truck was higher with a load, while the efficiency of the electric motor was relatively constant with or without a load.

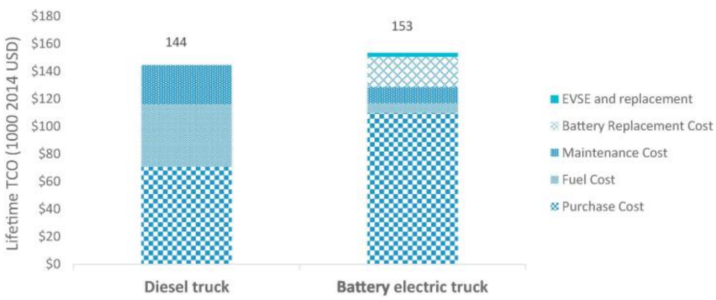


Figure 14 Total cost of ownership elements

Source: Zhou et al. (2017)

The results of the study show that the TCO of diesel trucks is lower than that of BETs due to the high upfront cost as shown in Figure 15; however, Zhou et al. (2017) note that TCO is sensitive to any emission costs that can be passed on, especially for diesel trucks brought on by government policy.

2.6 Elements of the TCO

2.6.1 Fuel prices

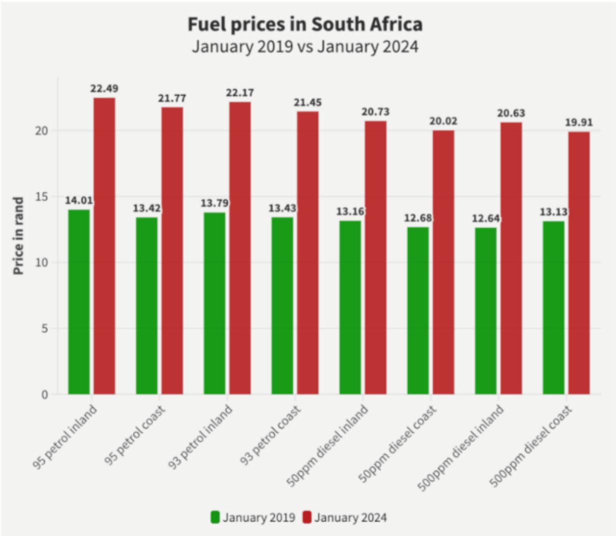


Figure 15 Historical price of diesel in South Africa

Source: Labuschagne (2019) (https://mybroadband.co.za/news/motoring/521345-south-africans-paying-up-to-r678-more-for-petrol-than-five-years-ago.html)

The above images are demonstrative of the astronomical increase in the prices of diesel since 2019, excluding inflationary pressures. The price of diesel is linked to the international oil price and the currency exchange rate between the South African Rand (ZAR) and United States Dollar (USD). SA has very little refining capacity, hence the trajectory depicted above is likely to continue. Fuel costs associated with ICETs are expected to increase year-on-year. Rout et al. (2022) noted that ICETs is a mature technology that will not use less fuel going forward as manufacturers are looking to phase out this technology. Fuel costs for ICETs will therefore only increase in the future. Although fuel usage is also a function of payload, this will be ignored for purposes of this study as payloads in mines for various activities differ quite substantially.

2.6.2 Initial purchase cost and running costs

Rout et al. (2022) state that the automotive market lacks a broad inventory of BETs compared to ICETs. For this reason, the initial purchase cost of BETs is higher compared to that of ICETs. For BETs, ongoing running costs could be the lithium-ion battery cost and electric motor (Rout et al., 2022). In terms of batteries, Casals et al. (2019) note that manufacturers can offer a ten-year warranty for BETs, while batteries for ICETs are required to be replaced often.

Table 2 illustrates the initial cost and trend in the United States and Europe (Sharpe & Basma, 2022). In terms of cost and for purposes of the study, the equivalent of a 40-tonne truck is listed below. Since there are no truck manufacturers in SA, the prices provided will need to be converted to ZAR using the prevailing exchange rate. This conversion is necessary to accurately reflect the local cost of diesel trucks and BETs in the South African market.

Table 2 Initial purchase cost in the United States

Region	Truck class	Technology	Technical specification in 2020	Driving range	Retail price 2018-2020	Retail price 2025
US	Class 8 tractor truck	BET	2,200kWh	750 miles (1 207kms)	$816, 000	$423,000
US	Diesel	ICE	Engine 317kW	-	$165,000	$175,000
Europe	Class 5 long haul tractor truck	BET	Battery 1187Wh	800kms	€417,300	€145,300 (2030)
Europe	Class 5 long haul tractor truck	Diesel	Engine 350kW	-	€105,500	€115, 300 (2030)

Source: Sharpe & Basma (2022)

Mao et al. (2021a) lists the equivalent cost in China as follows:

Table 3 Initial purchase cost in China

Truck class	Technology	Technical specification in 2020	Driving range	Retail price 2018-2020	Retail price 2030
Dump truck	BET	275kWh	300kms	475,221 CNY	336,515 CNY
Dump truck	FCET	280kWh	600kms	577,709 CNY	361,754 CNY
Dump truck	Diesel	Not provided	-	330,000 CNY	446,263 CNY

Source: Mao et al. (2021a)

In all regions, the initial purchase cost of the ICET was significantly lower.

2.6.3 Financial cost and deterrents

Due to the high initial cost of purchase, incentives could be offered to entice customers to buy zero-emission trucks. There are no incentives currently in SA due to the limited availability of this technology. The United Kingdom government has implemented measures to encourage the adoption of electric vehicles. Pickett et al. (2021) highlight some of these measures as:

- Imposing targets on manufacturers for zero-emission vehicles from 2024 onwards.
- Alongside the transport decarbonisation plan, a 2035 delivery plan for zero-emission vehicles was published.
- More charging stations have been built with grants for charge points at home (Pickett et al., 2021).

2.7 Proposition 2

According to the literature review, the TCO for vehicles can vary based on factors such as fuel costs, electricity rates, maintenance expenses, and available government incentives. ICETs currently have an advantage due to their mature technology and predictable maintenance costs. However, with evolving regulations and increased governmental pressure to eliminate tailpipe emissions, manufacturers are being pushed to develop cleaner technologies. As a result, end users, including mining companies, will increasingly be compelled to adopt BETs to comply with these stricter emissions standards and achieve sustainability goals.

Emerging literature suggests that, at present, the TCO for ICETs is significantly lower. However, with advancements in technology, economies of scale, and increasing government support, the TCO for BETs is expected to reach parity with, and eventually fall below, that of ICETs in the next decade.

2.8 What are the barriers to the adoption of BETs?

Many factors affect the rate of adoption including an innovation's characteristics, economic and sociological factors, the organisation itself, and its need for change (Stratopoulos & Wang, 2022). Using the normal distribution model, Stratopoulos & Wang (2022) identified five major categories of adopters.

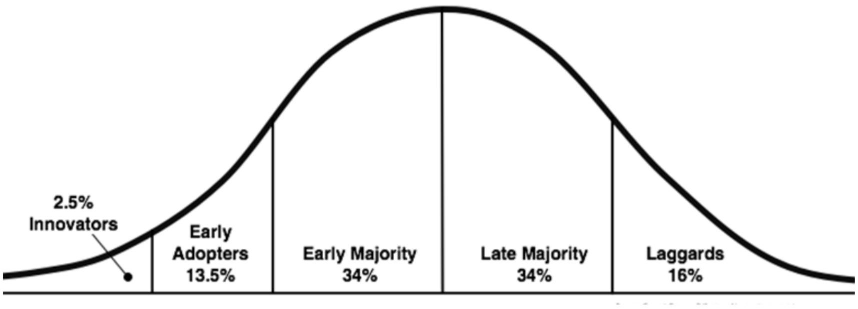


Figure 16 Technology adoption curve

Source: Stratopoulos & Wang (2022)

Figure 17 depicts the categories of adopters, with early adopters most likely being leaders in their field. The early majority are opinion leaders and deliberate in adopting new innovation, need to see evidence, but are not necessarily leaders. The late majority are sceptical about change and wait until their peers have adopted the technology. The laggards, bound by tradition and very conservative, tend to decide after they have seen the success of new technology (Stratopoulos & Wang, 2022).

According to Vimal et al. (2023) , technology is developing at a fast rate, in which many new types of technology have an ample range of applications. The COVID-19 pandemic has highlighted the need for countries to build back plans so that they can react quickly to changes in the current situation and changes in production and consumption to ensure a sustainable future. Sustainable production is about maximising resources and decoupling financial stability from environmental degradation (Mathivathanan et al., 2021). Tanco et al. (2019) state that drivers and barriers exist intrinsically with any new technology with the latter overwhelming the former. Qasim and Csiszar (2021) add that the high initial price, limited range, and charging time are some barriers to the adoption of BETs.

2.8.1 Battery technology and efficiency

Robust design and reliability are important requirements for the automotive system, including the power-supply system. Furthermore, car manufacturers are required to design their products for high recycling efficiency. The European Directive on end-of-life vehicles aims at increasing the recyclability of waste vehicles and avoiding pollution (Song et al., 2023).

Astaneh et al. (2020) state that off-road vehicles such as trucks used in mining operate under different driving cycles compared to on-road vehicles. Some of these differences are low operating speeds, stationary conditions, and high torque and power demand. For this reason, large battery power packs are needed which adds to the overall weight of the truck limiting the load these trucks can carry.

Nykvist and Olsson (2021) add that the low gravimetric-specific energy of batteries is typically a limiting factor, making battery technology more suitable for lighter vehicles than for heavy-duty ones. Mavlonov et al. (2023) add that the wide adoption of electric vehicles is a result of drivers' range anxiety, comparably longer charge time, and high cost. Buberger et al. (2022) state that with improvement in technology using fast charging methods, range anxiety can be reduced.

2.8.2 Infrastructure readiness

According to Sadek et al. (2020), the wide uptake of BETs is hindered by the high manufacturing cost, limited truck variety, and insufficient supporting infrastructure. The optimal setting of charging infrastructure is key to the uptake of BETs and reduces the anxiety of potential users (Sadek et al., 2020).

Limited battery range, long charging times, and limited charging infrastructure are some of the reasons for the low adoption of EVs in Africa (Ayetor et al., 2023). Another important factor is that nearly 600 million people living in Africa do not have access to electricity (Senyagwa, 2022). Any introduction to this type of technology will first need to be socialised with a large part of the population to dispel myths about its reliance (IEA, 2022).

According to the IEA 2022 report, only China has a meaningful deployment of electric trucks due to strong government support. Truck manufacturers have developed new ranges with more than 170 available outside of China. However, the longer range and high-power charges of heavy-duty trucks will often require grid upgrades. As a result, early planning and investments are crucial to minimise the strain on the grid and provide a suitable network for this stage of heavy-duty electrification (IEA, 2022).

Tongwane and Moeletsi (2021) state that SA's current power-supply constraints are not conducive to the adoption of electric trucks and will further strain on the power supply. Currently, with more than 70% of the grid being dependent on coal supply, charging BETs in SA produces more carbon emissions 23% higher than when petrol or diesel is used (Singh et al., 2019). Avoided emissions can be further increased if batteries are charged using renewable energy sources (Tongwane & Moeletsi, 2021). Charging BETs would require about 10-20 GW of additional power between 2030 and 2045 (Ahjum et al., 2018). This may demand that future electricity generation in SA must be more than 60% renewable for electric vehicles to be environmentally friendly (Singh et al., 2019).

Mining companies are increasingly employing renewable energy for their operations. In 2015, there were 600MW of renewable energy in mines across the world. By the end of 2019, there were nearly 5GW of installed renewable energy projects across the world (Kirk & Cannon, 2020). The same trajectory is occurring in South African mines, which bodes well for BETs used in the mines.

2.8.3 Supply chain

Zhang et al. (2020) define supply chain as "the management of relationships in the network of organisations from end customers to original suppliers, using key cross-functional business processes to create value for customers and other stakeholders". Steinweg (2011) breaks down the EV supply chain into phases: a) the extraction of raw materials, b) second production which includes cell production and battery production, and c) vehicle assembly.

The move to electric vehicles to decarbonise the transport sector requires increased natural resources. The expected rapid increase in batteries could result in resource challenges and supply chain risks (Baars et al., 2021). Metals used in the manufacture of batteries include lithium, cobalt, copper, graphite, manganese, and rare earths. Many of these critical elements are produced as by-products of mining other metals, meaning their supply depends on the ongoing extraction of those primary metals. If mining for these primary metals decreases, the supply of these critical elements becomes uncertain, potentially requiring the development of new mines. Additionally, mineral exploration and the mining process have long lead times, often spanning several years, which can further exacerbate supply constraints (Jowitt & McNulty, 2021).

The ethics of the mineral supply chain is also important. “Conflict mineral” debate about how minerals are sourced now encompasses a broad range of factors such as child labour, corruption, environmental degradation, and green transition from fossil fuels. Automotive companies are increasingly mindful of how the minerals they use are sourced to protect their brand reputation. This growing awareness reflects a commitment to ethical and sustainable sourcing practices, ensuring that their supply chains are free from environmental harm and human rights violations (Deberdt & Le Billon, 2021).

2.8.4 Lack of government support and policy

According to Qasim and Csiszar (2021), lack of support from the government is one of the major factors limiting the increased adoption of BETs.

In its 2021 report on policies to promote electric vehicle deployment, the IEA noted that significant fiscal incentives spurred the adoption of electric duty light vehicles which underpinned the scale-up in EVs and battery manufacturing. These were designed to close the gap between the cost of ICE and EVs (IEA, 2021).

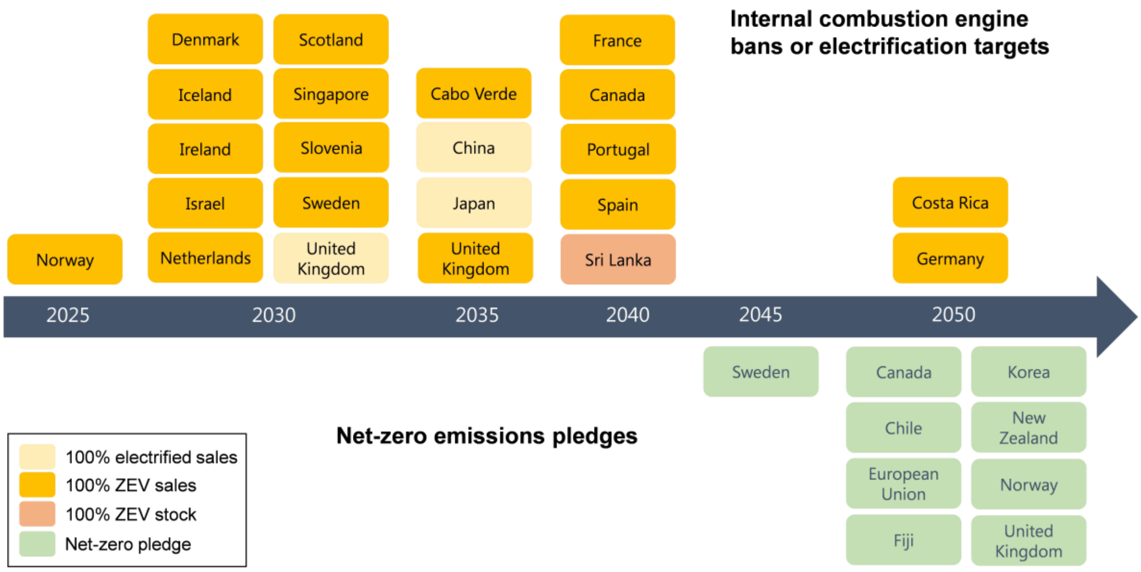


Figure 17 Net-zero pledges

(IEA, 2021)

Figure 18 shows the countries that have signed up for net-zero and electrified sales until 2050. This shift has been facilitated by government incentives aimed at encouraging the adoption of EVs. According to the IEA, China has implemented the New Electric Vehicle Subsidy, while the EU supports EV uptake through initiatives like the Green Deal and the EU Sustainable and Smart Mobility Strategy. Although the United States has a less aggressive approach compared to the EU and China, it still offers incentives, such as low-carbon fuel standards and tax credits, which are supported by relevant policies (IEA, 2021). The IEA further notes that heavy-duty EVs have seen a lower adoption than light-duty EVs due to higher energy demand, large battery capacity, and limited range of vehicles.

To ensure that the pledges to net-zero are achieved, many countries are now focusing on the heavy-duty segment which is expected to surge over the next 10 years. China is the leader in this segment with current subsidies reaching as much as 50% of the initial cost, Japan has a hydrogen strategy to decarbonise this segment, India is targeting the electrification of buses, EU member states are using the commercial incentive of up to EUR 50 000 for this segment, and Switzerland has policies for the adoption of FCETs (IEA, 2021).

Addressing climate change through the transport sector involves the participation of government and non-governmental sectors (Odiyo et al., 2022). In SA, The Department of Transport released the Green Transport Strategy and Implementation Plan in 2018 intending to promote transport that reduces emissions while supporting the contribution of the transport sector to the social and economic development of the country (Odiyo et al., 2022). In May 2021, the Department of Trade and Industry released a green paper on the advancement of new electric vehicles for comment. The automotive industry provided extensive comments with the hope the paper would be gazetted but it has not yet been (Naamsa, 2023).

In its report on The New Energy Vehicle Transitional Roadmap, The National Association of Automobile Manufacturers of South Africa (Naamsa) noted that a supportive regulatory framework, additional incentives to address the price differential of EVs and ICE to stimulate sales, additional incentives to manufacture EVs, and rolling out public charging infrastructure is required (Naamsa, 2023).

2.9 Proposition 3

According to the literature review, the main barriers to entry for electric vehicles include limited range, insufficient charging infrastructure, high costs, supply chain constraints, and a lack of policy support.

Despite these barriers, emerging literature suggests that ongoing technological advancements, increased government support, and greater investments will gradually address these challenges. As a result, the adoption of BETs is expected to rise over time, leading to significant environmental benefits.

2.10 Conclusion of literature review

This chapter offers a comprehensive overview of the literature on several key topics: the environmental impact of ICEs and BETs; the TCO for these vehicles; and the barriers to adopting this technology. The primary objective is to explore how reducing diesel consumption in the mining sector in SA can contribute to cost-effectively lowering greenhouse gas emissions. Despite various definitions of environmental impact in the literature, the ultimate goal remains the same: Singh et al. (2019) add that the most important definition of "sustainable development" was put forward to the UN (1983) by the Brundtland Commission which was to "*meet the needs of the present and future generations without compromising the ability of future generations*".

Reducing diesel consumption is a critical goal for mining companies due to its significant greenhouse gas emissions and adverse effects on human health. This reduction is a crucial component of their decarbonisation strategy, helping to mitigate climate change and improve overall environmental and public health. A technological solution in this sector is BETs as there are no emissions from their exhaust tailpipe (Bhardwaj & Mostofi, 2022). This technological solution, however, comes at a cost to mining companies. For this reason, it is important to unpack the TCO. The TCO has been widely employed to study and compare the economy of these vehicles comprehensively and transparently to enable rational decisions by customers (Z. Liu et al., 2021). The TCO represents the cost of ownership during the period of the product, and considers factors such as initial purchase price, performance, and operating costs (Z. Liu et al., 2021).

Technological innovation enables mining companies to cut costs and reduce their environmental impact. However, alongside technological advancements, there are barriers to adoption in a sector that is both regulated and conservative. Effective policy is therefore crucial, as is demonstrating to stakeholders that adopting new technologies will ultimately benefit the organisation (Ediriweera & Wiewiora, 2021).

The three main research propositions are summarised below:

2.10.1 Proposition 1

The use of diesel in mining has been linked to significant health and environmental issues, including air pollution, greenhouse gas emissions, and respiratory diseases among miners. In response, there has been a growing movement toward adopting cleaner fuels in the mining sector. It is proposed that battery-powered trucks are better alternatives to diesel trucks for reducing emissions, protecting the environment, and protecting human health.

2.10.2 Proposition 2

While the total cost of ownership can vary based on factors such as fuel, electricity, maintenance expenses, and government incentives, ICETs currently have an advantage due to their mature technology and predictable maintenance costs. However, as policies evolve and governments increasingly pressure manufacturers to eliminate tailpipe emissions, end users – including mining companies – will be compelled to adopt cleaner technologies. It is proposed that currently the TCO of ICETs is much lower; however, with improving technology, economies of scale, and government support the total cost of BETs will reach parity and ultimately be lower than ICETs.

2.10.3 Proposition 3

The main barriers to entry for adopting electric trucks are a limited range of available models, inadequate charging infrastructure, evolving battery technology, high costs, and insufficient policy support.

Despite these barriers, it is proposed with ongoing technological advancements, increased government support, and investments these challenges will be gradually addressed, and the adoption of BETs will increase over time which will be beneficial to the environment.

Table 4 Consistency table: Research questions and propositions

RQ #	State Research Question	Prop	State Proposition or Hypothesis
1	What is the environmental impact of using medium and heavy-duty BETs and how does it compare to diesel?	1	It is proposed that battery-powered trucks are better alternatives to diesel trucks for reducing emissions, protecting the environment, and protecting human health.
2	How do medium and heavy-duty BETs compare to diesel trucks in terms of the total cost of ownership?	2	It is proposed that currently the total cost of ownership of ICETs is much lower, however with improving technology, economies of scale, and government support, the total cost of BETs will reach parity and ultimately be lower than ICETs in future.
3	What are the barriers to the adoption of medium and heavy BETs in mining?	3	Despite these barriers it is proposed with ongoing technological advancements, increased government support, and investments these challenges will be gradually addressed and the adoption of BETs will increase over time which will be beneficial to the environment.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Research approach

This research paper seeks to assess and clearly define the environmental impact of diesel usage in mining operations, with a particular focus on trucks. Given the capital-intensive nature of the mining sector and its susceptibility to fluctuating diesel and commodity prices, controlling costs is essential. Therefore, adopting new technologies, such as BETs, must not only contribute to reducing the environmental footprint but also prove to be economically feasible for long-term sustainability.

Secondary data will be collected from publications that will seek to explore the environmental impact and challenges associated with diesel usage, including its effects on emissions and air quality, which will form the foundation for a qualitative analysis.

On the other hand, a quantitative approach, specifically a techno-economic analysis, is essential to evaluate the economic viability of transitioning to this technology. This analysis will consider factors such as the initial investment cost, operational expenses, maintenance requirements, and potential savings from reduced fuel consumption.

By combining qualitative and quantitative approaches, the mixed methods study can provide a robust and evidence-based assessment of potential benefits and challenges associated with reduced diesel usage in the mining industry.

According to Islam and Aldaihani (2022), research methodology is rapidly changing to adapt to the questions being asked; a pragmatist approach is needed and the research questions need to be addressed accordingly. Adu et al. (2022) define mixed methods research as “a type of research in which the researcher or team of researchers combine elements of quantitative and qualitative research approaches for the broad purpose of breadth and depth of understanding and collaboration”. Adu et al. (2022) add that when used in combination in one study, the two approaches provide multiple perspectives in one study.

Aschbrenner et al. (2022) state that by integrating qualitative and quantitative data within pilot feasibility studies, the researcher can harness the potential of mixed methods for developing a comprehensive understanding of the subject matter.

In choosing a mixed methods approach, the study's underlying questions will be thoroughly addressed, with the qualitative and quantitative approaches complementing each other. This combination allows for a more comprehensive understanding of the issues, ensuring that both the environmental and barriers to adoption combined with the economic aspects are effectively analysed.

From an environmental perspective, the primary target audience will be mine workers who are directly exposed to the harmful effects of diesel emissions. Their health and safety are significantly impacted by air quality issues related to extended diesel exposure. Improving air quality in mining operations is essential to safeguarding their well-being and enhancing overall workplace safety.

For the discussion on barriers to adoption and the techno-economic analysis, the target audience will include mining companies, OEMs, and government agencies. These stakeholders are crucial in decision-making, policy development, and implementation of new technologies, ensuring that the transition to cleaner alternatives is both feasible and economically viable.

3.2 Research design

According to Leavy (2022), research design "are procedures for collecting, analysing, interpreting, and reporting data in research studies". There are different design models for research and these models have distinct names and procedures associated with them. The four types of mixed methods research design are: triangulation design, embedded design, explanatory design, and exploratory design (Leavy, 2022).

For purposes of this study, the triangulation design will be adopted. This design will be used as the data is different but will complement each other to provide more meaningful answers to the research questions. According to Adu et al.

(2022) and Creswell and Piano Clark (2011), this design is often employed when researchers aim to use qualitative data to expand upon or validate quantitative data. In this approach, both types of data are collected simultaneously, in a single phase, allowing for a comprehensive understanding of the research topic by integrating different perspectives. Noble and Heale (2019) add that the triangulation design method is used to increase credibility and validity of the research findings.

There are variants to the triangulation model which are: the convergent model, the data transformation model, the validating quantitative model, and the multi-level model. The first two models differ in how the data is merged either during analysis or interpretation, the third model is used to enhance finding from a survey, and the fourth is used to investigate different levels of analysis (Adu et al., 2022; Creswell & Plano Clark, 2011). For this study, the convergent model will be used.

With the convergent model, the researcher collects qualitative and quantitative data separately on the same phenomenon and the results are converged during the interpretation as illustrated in Figure 19 (Sick & Bröring, 2022). The notion of convergence presents itself as significant empirical phenomenon with an increasing relevance when it comes to new technology (Sick & Bröring, 2022).

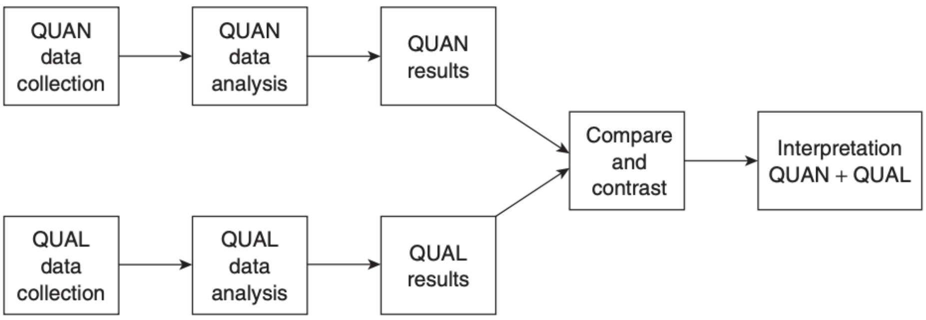


Figure 18 Convergent model

Source: Creswell & Piano Clark (2011) and Sharma et al. (2023)

Despite the advantages of triangulation, there are challenges in using this method. Chen et al. (2023) identify some of these as using only the strengths and neutralising the weaknesses of qualitative and quantitative methods.

In this study, qualitative data will be collected using Google Scholar from academic journals, government publications, and industry reports. These sources are valuable for both their wealth of statistical and qualitative data as well as their credibility and reliability. The timeframe for data collection will span from 2019 to 2024. Objectivity will be ensured by following steps:

- Multiple sources will be used to confirm accuracy.
- Confirmed bias will be avoided by not selecting sources that only support the propositions.
- Understanding the context in which the research was taking place.
- Peer-reviewed articles will be used.

These data sets will be integrated during the interpretation of results to assess whether transitioning from ICETs to BETs is beneficial for the environment. Additionally, the analysis will evaluate the associated costs to mining companies and identify the barriers to adopting this technology. This comprehensive approach will provide insights into both the environmental and economic implications of such a transition, helping to make informed decisions about future investments in cleaner mining technologies.

3.3 Data collection methods

Mwita (2022) describes secondary data as data that has already been collected by other people and is available for researchers to use in their study. For this study, secondary data both quantitative and qualitative, will be used. SA aims to reduce emissions from its road transport sector; however, studies focusing on reducing energy consumption and related emissions have been sparse (Ntuli et al., 2024). However, mining is an extractive industry that operates globally. Therefore, qualitative data collected from other regions with similar mining conditions to those in SA like China can be relevant and applicable. This approach allows for leveraging insights from international experiences to understand the potential environmental benefits and challenges associated with adopting BETs in the South African mining context.

Furthermore, the use of secondary data covering the period 2019 to 2024 enables the researcher to examine trends and patterns. While battery technology has not been employed in mines in SA, it has been in pilot use in other parts of the world with available data indicating reduced emissions due to BETs' tailpipes having zero emissions. Interviewing or having focused groups for South African mines to collect data on the environmental impact of BETs may not yield sufficient data to draw a conclusion for the purposes of this study, given the lack of implementation.

TCO requires a comprehensive understanding of initial capital expenditure, maintenance and operational expenses, and fuel costs. Secondary data on the costs, performance, and associated expenses of BETs is readily available, offering valuable insights. This data includes information on battery range and performance, enabling mining companies to assess the feasibility and rate of adoption of BETs. Additionally, secondary data facilitates direct comparisons between BETs and ICETs, allowing for a more informed evaluation of the potential benefits and challenges associated with transitioning to cleaner technology.

3.4 Population and sample

This section covers the population and sample.

3.4.1 Population

Secondary data will be collected from journal articles, government databases, OEMs of trucks and batteries, and publications by the IEA and The International Renewable Energy Agency (IRENA). The data collected from these sources will be used to answer the research questions and will be cross-checked against multiple sources to ensure consistency and accuracy. The objective is to enhance confidence in the research findings and provide robust answers to the research questions. The target population will be senior executives in the South African mining sector, who are key decision-makers in the decision to transition to BETs. By focusing on this group, the research aims to deliver insights that are directly relevant to those responsible for evaluating the financial, operational, and environmental implications of adopting this technology. These findings will help inform strategic decisions that align with sustainability goals and operational efficiency.

3.4.2 Sample and sampling method

According to Rahman (2023), when a small group is selected that is representative of the whole, it is known as a sample method. Non-random sampling is a method where a sample is not based on the probability on which a unit can enter the sample but on other considerations such as expertise, intention, and experience of the sampler. One type of non-random sampling is purposive sampling. The main goal of purposive sampling is to focus on particular characteristics of a population that will enable the researcher to answer the questions (Rahman, 2023).

Purposive sampling will ensure secondary data that is suitable for the qualitative approach on the environmental impact of diesel trucks and BETs and the rate of adoption of this technology in mines.

Purposive sampling will ensure that secondary data is selected on the TCO to form the basis of the quantitative approach to determine the economic viability of BETs and fuel cell trucks in mines.

3.5 The research instrument

In the context of secondary data, the research instrument refers to the tools or methods used to gather the data. For purposes of secondary data collection, the research instruments could be: a review of literature on the environmental impact of mining, a review of policies encouraging the use of alternate technology in mines, and publications relating to standard international best practices of environmental protection for mines (Agboola et al., 2020).

The major benefit of secondary data is economy, the fact that someone else has collected it makes it cost-effective for the user. The second benefit is the breadth of data available across a population and geography, and the third is that data collected and published is often collected by experts and professionals and may not be available through small data collection projects. The inherent disadvantage of secondary data is that it is not collected by the researcher, so the data may not answer the research questions. Another disadvantage is the researcher did not plan and execute the research so it may not be apparent how the data was collected (Chawla, 2020).

3.6 Procedure for data collection

Collecting secondary data is a process of collecting data that has already been collected and analysed by others. Data saturation will be achieved when no new themes, insights, or data emerge from the data collected. To ensure proximity to the target audience and prevent data corruption, the following will be followed:

- Secondary data will be cross-checked.
- Personal assumptions and preconceptions will be set aside.
- An Artificial Intelligence tool will be used for coding the qualitative data.
- A structured data analysis process will be followed.

In terms of the data collection process, the following process will be followed:

- Identify relevant data sources, including government databases, academic journals, corporate publications, industry reports, and online repositories.
- Confirm that the researcher can have access to the data and comply with permissions.
- Evaluate the data quality to ensure it answers the research questions.
- Data cleaning to ensure any inconsistencies and errors are removed. This is necessary to ensure the validity of the results.
- Analyse the data to ensure the questions are answered and the results can be interpreted.

3.7 Data analysis and interpretation

The primary means of analysing the data will be thematic analysis for research questions one and three which will have a qualitative approach. Wæraas (2022) describes thematic analysis as “identifying and describing both implicit and explicit ideas within the data, that is themes”. Codes are then typically developed to identify the themes and then linked to raw data for analysis. Such analysis may consist of comparing code frequencies, identifying code occurrence, and graphically displaying relationships between the codes (Wæraas, 2022). Braun and Clark (2021) have categorised thematic analysis into three broad approaches: a) coding reliability, b) reflective thematic analysis, and c) codebook analysis. Coding reliability is characterised by the ideas or topics that capture the frequency of ideas as expressed by the data on an explicit level. This assumes the objective facts are in the data as uncovered by the researcher. The benefit of this approach is the data can be gathered easily; however, the data is on an explicit level which would make a more in-depth analysis difficult (Ayre & McCaffery, 2022).

The reflective analysis presents analysis as themes. The quality of reflective analysis relies on the researcher to identify and construct themes from the data. Codebook thematic analysis lies in coding reliability and reflective analysis. In this analysis, themes are generated and charted into a framework; however, this framework does not determine reliability or accuracy as it would for content analysis, rather the framework exists to further develop themes (Ayre & McCaffery, 2022).

Karolemeas et al. (2021) add that a methodical thematic analysis will be used to contextualise the data in accordance with some of the techniques and systematic and analytical principles. The themes are specified in the literature review, so the thematic analysis will be more of a theory-driven analysis and not a primary data-driven analysis where themes are more spontaneous (Karolemeas et al., 2021).

The following process will be used to analyse the qualitative data:

- Identify the secondary data that provides relevance and insights into answering the research questions.
- Sort the data into code groups.
- Sort the code groups into themes.
- Review the themes.
- Refine the themes.
- Interpret the data and discuss the findings.

(Braun & Clarke, 2021).

Research question two, which will have a quantitative approach, will be analysed using descriptive statistics analysis. Croucher and Cronn-Mills (2021) define descriptive statistics as a “numerical procedure or graphical technique used to organise and describe the characteristics or factors of a given sample”. The form of descriptive statistics that is used to describe the variable in a sample is dependent on the level of measurement. The level of measurement is nominal, i.e. the level of measurement is divided into broad categories, ordinal; i.e. the level of measurement is hierarchically ordered categories and lastly continuous; i.e., data is measured using infinite scales and the increments of measurements are in equal distance (Croucher & Cronn-Mills, 2021).

The following process will be used to analyse the quantitative data:

- The data will be separated into categories, i.e. ICEs and BETs.
- The variables from these two board categories such as initial cost and operating cost will form the basis of a frequency table and measure of central tendency.
- Visualise the nominal data into bar graphs and pie charts.
- Interpret and discuss the findings (Ali, 2021).

3.8 Limitations of the study

- The study will rely on secondary data to answer the questions which may not be as in-depth as needed.
- The triangulation of the data may lead to one research approach dominating the study.
- The population may not address nuances or specific variables of the research questions relevant to the South African mining sector.

3.9 Validity and reliability (quant) OR trustworthiness (qual)

Assessing environmental major development projects requires an advanced level of environmental secondary data that may not be readily available from primary data (El Sayed & Salah, 2023). This research adopts a mixed methods approach related to methodology. The following sections refer to validity and reliability in this context.

3.9.1 External validity (generalisability) OR transferability

External validity is a key criterion in quantitative research. It determines if one can draw general conclusions from the data and model used and whether the results can be generalised (Findley et al., 2021). External validity is threatened if the sample population is not wide enough and if there is bias, and as a result the study cannot be generalisable (Findley et al., 2021). Environmental validity can be a problem where there are different geographies and the result is generalisable (Johnston et al., 2021). The TCO could be a problem in this study if there is no data available for SA; however, the TCO will be indicative for a conclusion to be drawn on the cost of ICEs relative to BETs. In qualitative research, external validity is concerned with whether the results are transferable to a wider audience or have a theoretical generalisability (Maxwell, 2021). In terms of the environmental impact of ICEs relative to electric trucks and barriers to the rate of adoption, it is possible for transferability to a wider audience as the phenomenon will be relevant to mines in different countries due to the following:

- Global similarities in underground mining practices as there are similar environmental challenges such as pollution and greenhouse gas emissions in other countries.
- Mining operations in other countries use similar underground diesel-powered trucks which can be compared to the ones used in SA.
- The barriers to adoption such as limited range and battery costs will be relevant for South African mines.
- The challenge will be with government and policy support as these are different for other countries.

3.9.2 Internal validity OR Credibility

In quantitative research, validity has been long accepted. In qualitative research, validity has been more contentious with different terms produced and used (Brennen, 2021). In the quantitative approach, the ultimate question is if valid conclusions can be drawn from the data to answer the questions. To this extent, it is about logic between the data and the theory (Brennen, 2021). In qualitative research, the key question in the context of validity is authenticity. ”Will the lived experience of the people be captured in the text so that the research correctly captures them?” (Hemming et al., 2021). The study will be valid and credible as data will be sourced from credible data sources.

3.9.3 Reliability OR dependability

In quantitative research, reliability refers to the extent to which a variable or set of variables is consistent in what it is intended to measure. Failure to answer questions or have more than one answer to a question indicates a lack of reliability (Coleman, 2022). In qualitative research, reliability refers to consistency, which means that another person should be able to come to the same conclusion (Coleman, 2022). A typical question asked is “did we accurately capture the investigation?” (Coleman, 2022). In selecting the secondary data sources, every effort will be made to source data from academic journals, publications by experts, and credible organisations to ensure the data is reliable and dependable. The study will be reliable and credible.

3.9.4 Objectivity OR confirmability

Conformability in qualitative research is the neutrality or degree of findings that are consistent and can be repeated. Detailed notes must be kept to ensure the findings are adequately recorded (Kakar et al., 2023). Quantitative research rests on the principle of objectivity and completely removes the researcher from the object of the study; the data speaks for itself with no self-involvement from the researcher (Kakar et al., 2023). Confirmability will be maximised in the study in terms of the environmental impact of diesel in underground mines. Governments in other jurisdictions from the literature review appear to be ahead of the South African government in creating an enabling environment for the adoption of electric trucks, so it may be difficult to compare this and be conformable to the South African government.

To ensure objectivity, the data used in this study will focus specifically on trucks that are suitable for employment in South African underground mines. By using data on vehicles with similar specifications, capacity, and operational requirements, the study ensures that the analysis is directly relevant to the South African context. This approach will minimise bias, providing a representation of the potential benefits and challenges of transitioning to BETs in South African underground mining operations.

By narrowing the scope to trucks with comparable capabilities, the study maintains objectivity and avoids generalising findings that may not apply to the local industry. This enhances the validity of the research, ensuring that the results are practical and applicable to decision-makers in the mining sector.

3.10 Ethical considerations

Secondary data analysis involves investigations where data collected for a previous study is analysed either by the same researcher or a different researcher (Facca et al., 2020). For research involving quantitative data, this has become commonplace as it is time-saving and cost-effective; however, ethical dilemmas arise in the use of qualitative data (Facca et al., 2020). With qualitative data, in some instances, people can offer personal information while developing a rapport with the researcher which can be re-used, creating an ethical dilemma (Facca et al., 2020).

For this study, secondary data will include sources from published sources, databases, archives, and publicly available datasets. To ensure ethical considerations, the following will be observed:

- Even though the data may be publicly available, individual identities will be kept anonymous.
- Consent and permission: if using the data requires consent and permissions, the necessary consent and permission will be obtained.
- In terms of data ownership, journals, and publications used, the proper credit will be given to the owner of the data.
- The data will be accurately used to protect the integrity of the data.
- The data will be processed and reported transparently.
- The data will be presented in a non-biased way so that the research questions are objectively answered.

Consistency table

Table 5 Consistency table: Research questions, propositions, data collection, and data analysis

RQ #	State research question or objective	Prop / hyp #	State proposition or hypothesis	Data collection detail	Data analysis method
1	What is the environmental impact of using medium and heavy-duty BETs and how does it compare to diesel?	1	It is proposed that battery-powered trucks are better alternatives to diesel trucks for reducing emissions, protecting the environment, and protecting human health.	Secondary data	Thematic analysis
2	How do medium and heavy-duty BETs compare to diesel trucks in terms of the total cost of ownership?	1	It is proposed that currently the total cost of ownership of ICETs are much lower, however with improving technology, economies of scale and government support, the total cost of BETs will reach parity and ultimately be lower than ICETs in future.	Secondary data	Descriptive analysis

RQ #	State research question or objective	Prop / hyp #	State proposition or hypothesis	Data collection detail	Data analysis method
3	What are the barriers to the adoption of medium and heavy BETs in mining?	1	Despite these barriers, it is proposed with ongoing technological advancements, increased government support, and investments these challenges will be gradually addressed, and the adoption of BETs will increase over time which will be beneficial to the environment.	Secondary data	Thematic analysis

CHAPTER 4. PRESENTATION OF FINDINGS

4.1 Introduction

The mining sector is confronted with an evolving energy market and regulation, which is putting pressure on the industry to adopt sustainable mining practices (Balboa-Espinoza et al., 2023). Climate change occurs because of global warming caused by greenhouse gases released into the atmosphere at an alarming rate. Controlling greenhouse gas emissions is critically important for the mining sector as anthropogenic greenhouse gases are emitted directly during actual mining and activities and indirectly by energy-intensive activities associated with mining equipment, ore transport, and the processing industry (L.-y. Liu et al., 2021).

A total of 50 journal articles were reviewed to answer questions one and three. Question two data was collected from scholarly peer-reviewed articles by the International Council of Clean Transportation, OEM websites, IRENA, and IEA publications. The articles were reviewed over six months ending in September 2024. The findings for questions one and three were extracted from the articles, demonstrating emerging themes expressed by the various authors. This thematic approach allowed the researcher to connect the data analysis to answer the research questions. For question two, data was used from the International Council of Clean Transportation, OEM websites, IRENA, and IEA publications accessed through their websites.

The following three research questions guided the data analysis:

RQ1. What is the environmental impact of using medium and heavy-duty diesel-powered trucks and how does it compare to BETs?

RQ2. How do diesel-powered medium and heavy-duty trucks compare to BETs in terms of total cost of ownership?

RQ3. What are the barriers to adopting BETs in underground mining in South Africa?

4.2 Presentation of secondary data

Google Scholar, University of the Witwatersrand's library, the IEA, and IRENA publications were used to source data for questions 1 and 3.

For question 2, OEM's websites, International Council of Clean Transportation, IRENA, IEA, and OEM websites were used to source data. All publications were not older than five years.

4.3 Thematic analysis of data

4.3.1 Generation of codes

The initial data analysis process involved establishing a series of primary codes driven by research questions. A subscription software tool Atlasti was used to generate the codes. The codes were then categorised into themes for questions 1 and 3. Table 6 shows the primary codes generated for these questions.

Table 6 Primary codes

Environmental impact of diesel trucks (RQ1)

Diesel-powered equipment generates significant heat.
After two hours of operation underground the temperature increased.
Pollution of the atmosphere at mines was due to engine emissions.
Dust blew off the truck's body causing pollution.
The heat from diesel trucks requires sufficient ventilation.
The heat caused strain on mine workers.
HDVs are the main contributors to Nox emissions.
Black carbon from diesel engines affects the climate.
Tailpipe emission causes premature death.
Diesel engines affect air quality due to CO_2 emissions.
HDVs are lower in volume but emit more CO_2 than passenger cars.
Diesel exhaust carries DPM.
Soot a component of DPM poses a health risk.
Carbon emissions at mines is caused by explosives and diesel trucks.
Exposure to NO_2 can result in adverse respiratory effects.
Changes in temperature and emissions from trucks affect worker exposure.
Carbon emission of the diesel scraper is the result of diesel consumption.
During the mining process, emissions result from diesel consumption.
The operation of vehicles in mining contributes to pollution.
Extensive ventilation is needed underground to ensure worker safety.
IPCC is concerned about emissions from diesel consumption.
Health issues due to heat exposure cause loss of worker days.
The heat from diesel combustion increases the temperature underground.
Diesel combustion highly affects the ozone layer.
Mine workers have an increased risk of lung cancer from diesel exposure.
Diesel exhaust is classified as "carcinogenic" by WHO.
Air pollutants such as DPM and Nox affect the crop.
The mining industry is "dirty" due to diesel consumption.
Back carbon from diesel consumption is a threat to the Arctic.
Ventilation is complex underground due to tailpipe emissions.
Diesel emissions account for 50% of heat underground.
The mining fleet is one of the main GHG emitters.
Mining transportation can account for almost 50% of emissions of open-cast mines.
Mineral and hauling processes contribute to truck emissions at mines.
Medium and heavy-duty trucks are the main GHG emitters.

Environmental impact of BETs (RQ1)

Ventilation costs can be as much as 50% less if BETs are used in underground mining.
In terms of the overall lifecycle of raw materials, diesel trucks use 2% and BETs use 12%.
Electricity generation affects emissions of BETs.
In terms of lifecycle, electricity generation is key to BETs being effective in reducing emissions.
Zero tailpipe emissions.
Emissions from BETs depend on the technology used for electricity generation.
The source of energy generation is key for BETs.

Barriers to adoption of BETs (RQ3)

Interruption of the BET supply chain during COVID-19.
Commodity price downturn for batteries.
Mining sector volatility.
Lack of charging infrastructure.
Integration of BETs into the production value chain.
Manufacturers adapting to new production paradigm.
Examining the need for transition.
Regulation such as regional green deal in the EU.
Legislation for mining emissions.
Increasing demand for BET minerals.
Co-ordinate sustainable production.
Ethical supply chain.
Negotiating tax breaks.
Policy co-ordination and implementation.
Building relationships with communities for decision-making.
Accuracy of information being fed into the supply chain for mining truck emissions.
Targets for mining sector reduction emissions.
Energy savings interventions in mining.
Energy efficiency targets.
Durability of BETs.
Battery technology limitations.
Performance of batteries under mining conditions.
Maintenance and after-service costs.
Strict safety and environmental standards in mines.
The durability of BETs in the mines.
Perceived competitiveness of BETs.
OEMs keeping up with demand.
Accessibility as mines are in remote areas.
Import duties on BETs.
Absence of finance for BETs.
The mining sector performing badly in terms of energy efficiency.
Energy demand reduction in mining.
Diesel intensity use.
Energy variability in mining.
The highest energy intensity in mines is diesel.
High diesel dependence in mining for various processes.
Slow adoption of BET technology.
Lack of political will.
Lack of incentives to promote uptake of BETs.
No pilot test cases.
Lack of charging infrastructure.
Transport emissions is a problem.
Upfront capital costs.
Number of trips done versus charging time.
Equipment is costly.
Social factors that BETs require more skill to drive.
Carbon intensity of electricity grid in SA.
Infrastructure requirements underground at the mine.
Battery technology limitations for range.
SA is far from demand markets for BETs.
Will ICE and BET technology support each other?
Current transport fleet requirements and how many can be replaced by BETs.
Availability of renewable energy for charging.
Renewable energy for solar or wind plan need large land area.
Absence of suppliers in country.
Changes in technology which makes the decision hard for companies to adopt.

4.4 Presentation of findings pertaining to research question one

This section discusses the findings of the environmental impact of diesel vehicles and how they compare to BETs based on the data reviewed. The data is not necessarily centred on the South African mining industry, but the mining industry in general, including surface and underground mining. Recent data not older than five years was not available for the South African mining industry.

The open coding for question one identified 175 codes. The thematic analysis emerged by eliminating duplicate codes and grouping similar codes as shown in Figure 20.

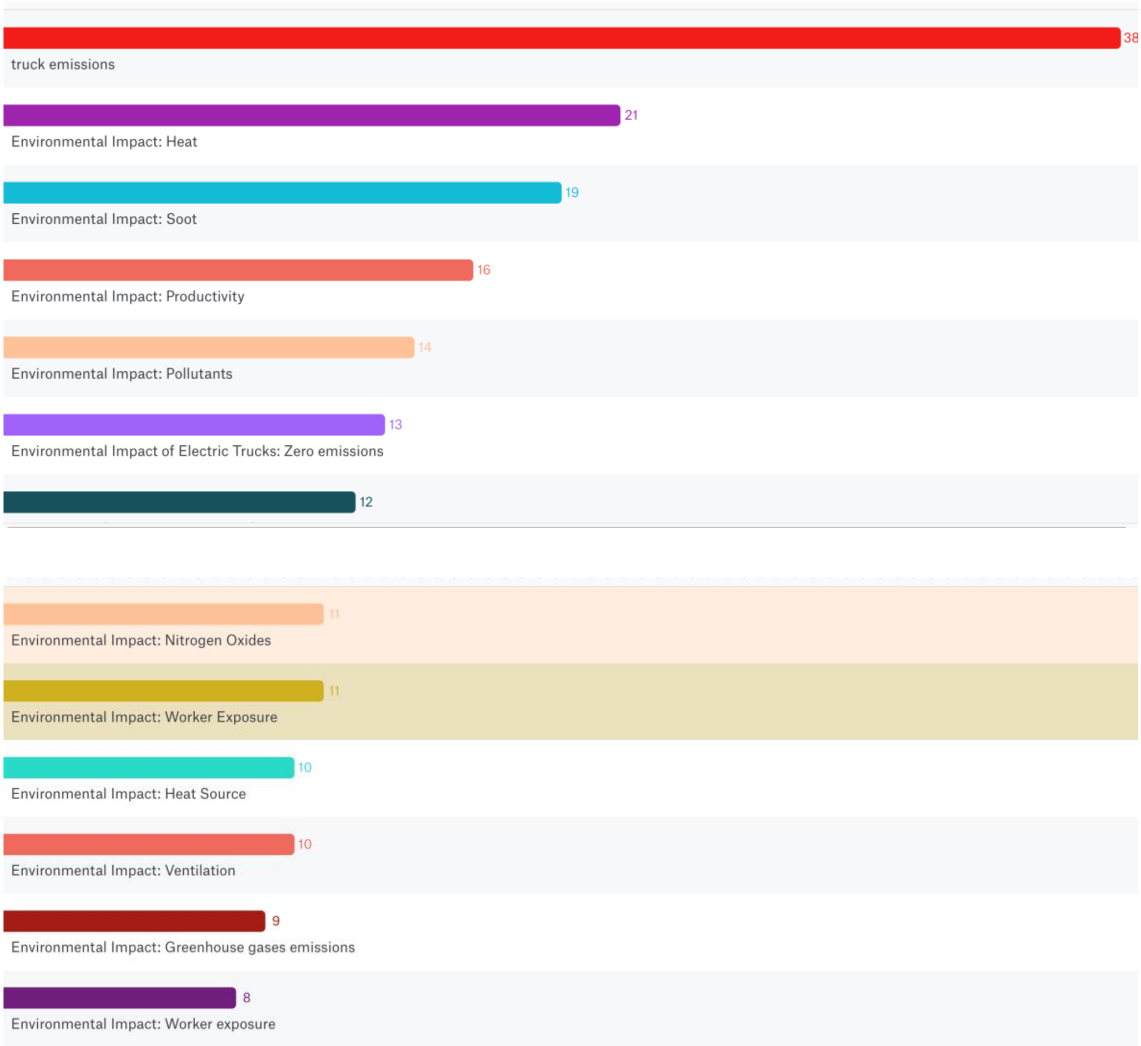


Figure 19 Codes from Atlasti (www.atlasti.com)

In grouping similar codes, the following themes emerged for diesel-powered trucks:

- Truck emissions
- Environmental impact with sub-themes of:
  - heat
  - ventilation
  - pollutants
  - worker health

In grouping codes for BETs, the following themes emerged:

- Zero emissions
- Charging infrastructure
- Manufacturing of BETs

4.4.1 Truck emissions

According to Kuzmin et al. (2020), the pollution of the atmosphere at mines is a direct result of emissions from diesel equipment. This was confirmed by several publications reviewed. Jin et al. (2021) added that “HDVs are the main contributor to exhaust emissions and health effects, accounting for 86% of on-road diesel nitrogen oxides (NO_x) emissions”. In addition, Jin et al. (2021) stated, “Besides the impact on air quality and public health, black carbon from diesel engine exhaust severely affects the climate as the particles produce significant near-term climate warming”.

The data showed that diesel trucks in mining operations were significant contributors to emissions in mining.

Balboa-Espinoza et al. (2023) noted that, “During the process of mine production, the operation of mechanical equipment consumed a considerable amount of fossil fuels, necessitating the calculation of carbon emissions resulting from fuel combustion”. Furthermore, “Stratospheric Ozone Depletion (SOD) refers to the decline of ozone (O_3) concentrations in the earth’s stratosphere. Diesel combustion highly impacts SOD, contributing to 93.7% of the entire life cycle's impact for the diesel truck" (Balboa-Espinoza et al., 2023).

Makarova et al. (2023) noted, "The mining industry has one of the most negative impacts on the environment due to the potential health hazards and impact on the growth of various diseases of fine particles in the exhaust gases of diesel and gasoline engines. Diesel emissions make a significant contribution to overall black carbon concentrations in the Arctic" (Makarova et al., 2023).

"The mining transportation fleet is one of the primary sources of on-site GHG emissions of the mining industry" (Yu et al., 2024), and "The mining transportation fleet can account for up to 30% of on-site GHG emissions or up to 80% if the mine is without refinery facilities" (Yu et al., 2024).

Mining encompasses a wide range of processes, each requiring different types of machinery, and diesel-powered equipment is widely used across various stages of these operations. From extraction and drilling to material transport and site maintenance, diesel engines power vehicles such as haul trucks, loaders, and excavators, which are essential to the efficiency and productivity of mining activities (Skrzypkowski et al., 2022). Diesel equipment plays a key role in:

- Drilling and blasting: Diesel-powered drills are commonly used for boring holes for underground and surface mining explosives.

Figure 20 Drilling and blasting trucks

Source: https://miningforschools.co.za/lets-explore/coal/the-coal-mining-life-cycle

- Loading and hauling: Heavy-duty trucks, typically powered by diesel, transport large volumes of mined material from extraction sites to processing facilities.

Figure 21 Loading and hauling trucks

Source: https://www.groffengineering.com/what-is-underground-mining/

- Tunnelling and excavation: Diesel-powered machinery is used to accelerate the excavation process in underground mines, reducing digging time.

Figure 22 Tunnelling and exaction trucks

Source: https://www.nsenergybusiness.com/projects/mponeng-gold-mine/

“It is reported that mineral loading and hauling operations account for 41.4% of total energy consumption and contribute 37.1% of GHG emissions during coal mineral processing. Therefore, decarbonising the transportation system is critical for the decarbonisation of the whole mining production process” (Yu et al., 2024). Feng et al. (2022) stated that, “Apart from the energy consumption, the greenhouse gas (GHG) emission, measured by the carbon dioxide equivalent, the contribution of mineral loading and hauling operations reaches 50.5%, 53.1% respectively”.

The data shows that the use of diesel trucks in mining produces emissions can harm the environment.

4.4.2 Environmental impact factors

4.4.2.1 Heat

The data showed that heat generated by trucks in the mining industry can be significant, especially in operations where heavy-duty trucks are used in confined spaces.

Kuzmin et al. (2020) state that, “diesel-powered equipment generates significant heat underground. After engines had operated for two hours, the temperature increased by almost 2°C. The sources of heat have a significant impact on ventilation requirements, refrigeration demand, and productivity” (Kuzmin et al., 2020).

The data also showed that heat can have a significant impact on mine workers.

“The sources of heat have a significant impact on ventilation requirements, refrigeration demand, and productivity” (Kuzmin et al., 2020). Balboa-Espinoza (2023) noted that, “Health issues due to heat illnesses have been shown to cause loss of work days and a decrease in mine productivity”.

Swift et al. (2023) stated that, “There are several sources of heat in underground mines with diesel transport being one of them”.

“Auto compression, strata, and electrical and diesel equipment are sources of heat in a mine; diesel equipment is also an emissions source and can account for more than 50% of the heat” (Swift et al., 2023).

In mining operations, trucks are often subject to demanding conditions and terrain both in surface mining and underground mining, and so are required to work much harder to generate heat.

4.4.2.2 Ventilation

The findings showed that the usage of diesel trucks causes mining businesses to place an increasing emphasis on ventilation.

“To improve the underground air quality and maintain reasonable temperatures, extensive ventilation systems are used to move emissions and heat to the surface, but research shows health risks remain” (Balboa-Espinoza et al., 2023).

“Goldcorp has recently announced plans to operate its Borden Lake mine with only electric mining vehicles, meaning it will be the world’s first electric mine. Goldcorp predicts a reduction of 5,000 tonnes of CO_2 per year and 50% less ventilation needs compared to a baseline diesel underground fleet” (Meshginqalam et al., 2024).

“With heat in underground mines, the ventilation and refrigeration systems that maintain a safe working environment can be complex and costly as mines grow in size and depth” (Swift et al., 2023).

4.4.2.3 Pollutants

The findings showed that diesel trucks used in mining can emit various pollutants which can have environmental and health impacts on surrounding areas and workers.

“Diesel exhaust from the tailpipe carries both particulate and gaseous emissions, specifically soot, unburned hydrocarbons, and NO_x. Soot is a component of DPM, the characteristic black smoke visible in exhaust” (Jin et al., 2021).

Balboa-Espinoza et al. (2023) state that, “Exposure to NO_x can result in adverse respiratory effects such as pulmonary inflammation or exacerbation of asthma”.

“Although HDDTs account for only 3% of the vehicle population in China, they emit 74% of NO_x and 52.4% of particulate matter (PM)” (Cheng et al., 2022).

4.4.2.4 Worker health and productivity

The data showed that worker exposure to truck emissions in mining environments is a concern due to potential health risks and loss of productivity.

“Transportation tailpipe emissions resulted in 385,000 premature deaths and $1 trillion of health damages globally in 2015” (Jin et al., 2021).

“Soot particles pose a health risk because they are small enough to become trapped in the lungs when inhaled” (Balboa-Espinoza et al., 2023).

“Exposure to NO_x can result in adverse respiratory effects such as pulmonary inflammation or exacerbation of asthma” (Balboa-Espinoza et al., 2023).

“Research has shown that mine workers have an increased risk of lung cancer death that correlates to increasing exposure to diesel exhaust” (Meshginqalam et al., 2024).

“Diesel exhaust was classified as Group 1 “carcinogenic to humans” in 2012 by the World Health Organization” (Meshginqalam et al., 2024).

“Air pollutants, such as fine particulate matter (PM2.5) and nitrogen oxides (NO_x), are major risks that affect human health, crop yields, and environments worldwide” (Huang et al., 2022).

“Breathing clean air is healthy to the human body, mainly for brain and nervous system function, hence ventilation in underground mines is a requirement by law and must be a high priority” (Morla et al., 2021).

4.5 Environmental impact of BETs

4.5.1 Zero emissions

The data showed that BETs have significantly reduced emissions compared to diesel-powered trucks, but they are not completely emission-free. While the tailpipe does not produce any emissions during operation, emissions may be generated indirectly during their lifecycle.

“There are zero direct emissions from the electric trucks” (Balboa-Espinoza et al., 2023).

“To reduce carbon emissions from transport, the United Kingdom has set a ban on the sale of new internal combustion engines from 2035” (Xia et al., 2022).

“Vigorously promoting electric vehicles is an effective path to reducing GHG emissions and energy consumption” (García et al., 2023).

“BETs emit higher carbon in the production phase, but their carbon emissions throughout the life cycle are lower than diesel-powered trucks” (Xia et al., 2022).

4.5.2 Charging infrastructure

The emission associated with BETs depends on the source of electricity used to charge the trucks.

“In reviewing the effect of electric mobility on air pollutants, GHG emissions, and human health emphasised that the benefits of EVs for reducing GHG emissions depend, among other factors, on the source of energy generation” (Balboa-Espinoza et al., 2023).

“Considering the whole life cycle, GHG emissions associated with electricity generation showed the greatest contribution to the life cycle of the electric truck, corresponding to 87% of the total impact” (Shishir Bhardwaj & Hamid Mostofi, 2022).

“Electricity generation matrix has been shown to affect the emissions from EVs” (Shishir Bhardwaj & Hamid Mostofi, 2022).

4.5.3 Manufacturing of BETs

According to the data evaluation, the key minerals required in the manufacture of BETs are much greater than in diesel-powered trucks.

"Considering the raw material supply of each truck and its impact on global warming potential (GWP), the results show that the EV has 33% more emission of CO_2 eq. than the diesel vehicle" (Shishir Bhardwaj & Hamid Mostofi, 2022).

"In terms of the overall life cycle, raw materials only contribute 2% for the diesel truck, while for the electric truck they contribute 12% of the entire life cycle" (Bloodworth et al., 2019).

"Although BETs do not directly generate emissions, they transfer emissions through electricity production. Carbon emissions of BETs from raw material procurement, battery production, recycling, and disposal cannot be ignored"(Xia et al., 2022).

4.6 Conclusion for research question one

The use of diesel-powered trucks in both surface and underground mining has a range of environmental and health concerns including air pollution, greenhouse gas emissions, respiratory diseases among miners, and loss of productivity.

Pollutants such as DPM, NO_x, soot, and carbon monoxide are released by diesel vehicles. These pollutants are hazardous to miners and surrounding communities as they expose them to contaminated air.

Tailpipe emissions produce heat, which necessitates substantial ventilation systems, particularly in underground mines, to decrease the temperature. Ventilation is critical for the health of miners working near diesel-powered trucks as they are at risk of exposure to DEE which contain harmful substances known to cause respiratory diseases, cardiovascular problems, and other health issues.

Tailpipe emissions are zero in BETs, minimising the impact of greenhouse gases on the environment; however, the charging infrastructure and the manufacturing process may not necessarily result in overall lower emissions than diesel trucks as anticipated.

4.7 Presentation of findings pertaining to research question two

The section presents the findings on research question two, the TCO when transitioning from internal combustion trucks to BETs. According to Burnham et al. (2021), to accurately compare the cost of two vehicles, the TCO should consist of all costs related to purchasing the vehicles and the cost of operating them. Gunawan and Monaghan (2022) add that TCO includes the initial capital cost of the vehicle, fuel, insurance, maintenance, and resale value. As environmental regulations become increasingly stringent and the potential for cost savings in areas such as ventilation, fuel, and consumables grows, mining companies have an increasing economic incentive to consider alternatives to traditional diesel-powered trucks (Huang, 2022).

One of the key factors in determining the TCO is the initial upfront capital cost of the truck. Studies have shown that BETs have a higher initial upfront capital cost (Kim et al., 2021). However, the operating and maintenance costs of BETs are typically lower since they have fewer moving parts and do not require fuel, oil changes, or other maintenance associated with diesel-powered trucks (Kim et al., 2021).

4.7.1 Initial capital cost

The initial capital cost is the cost of purchasing the truck. Class 8 trucks in the United States and class 5 trucks in Europe are equivalent to the haul trucks used in underground mines in SA. Basma et al. (2023) state that the battery pack makes up 60% of the cost of BETs. BUSCH (2023), however, adds that battery packs are falling faster than initially anticipated and BETs will reach their diesel counterparts in terms of cost parity sooner than initially anticipated. The challenges remain in terms of supply chain issues with battery pack manufacturing and delivery (BUSCH, 2023).

4.7.1.1 Initial capital cost in China

Table 7 Cost in China

Factors	Diesel	BET
		
Vehicle model	CA4256P2K15T1E5A80	HN4253H36C8BEV
Manufacturer	FAW	Geely
Gross weight	48,800 kg	48,870 kg
Engine power	276kW	Rated: 250 kW Maximum: 360 kW
Engine torque	2,060 N·m	Rated: 1,600 N·m Maximum: 2,800 N·m
Engine displacement	11.6L	-
Energy storage	Diesel tank, 600 L	Battery, 282 kWh
Certified range	1,500 km	170 km on single charge
Price	¥300,000	With battery pack: ¥806,000 Without battery pack: ¥436,000

Source: Niu & Zhu (2024)

4.7.1.2 Initial capital cost in Europe

The websites of European OEMs such as Volvo, Mercedes, and Epiroc were visited to scout for ICE and BET pricing. These OEMs do not readily make their pricing public. It is often customised according to its customers' needs such as configuration, optional features, regional market conditions, and bulk purchase agreements. Table 8 was extracted from the website of the ECG Association, a common platform to support the finished vehicle logistics sector in Europe.

Table 8 Cost in Europe

COST	ICE HDT 80 000 kms	BET HDT 80 000 kms	Comments
Purchase cost	€116,230	€272,800	Initial capital cost.
Subsidy	0	€125,256	Some countries, such as Germany, offer 80% of the difference in cost as an incentive. The incentive shown is 45% as stated on the website with no country specified.
Net cost	€116,230	€147,554	

Source: www.ecgassociation.eu (accessed July 2024)

4.7.1.3 Initial capital cost in the United States

Figure 24 represents the initial capital cost of various technologies in the United States (Ledna et al., 2022). The advanced pricing scenario reflects improvements in the pricing of battery packs as economies of scale are achieved (Ledna et al., 2022). The graph shows BETs having a significantly higher cost, similar to other regions in the world.

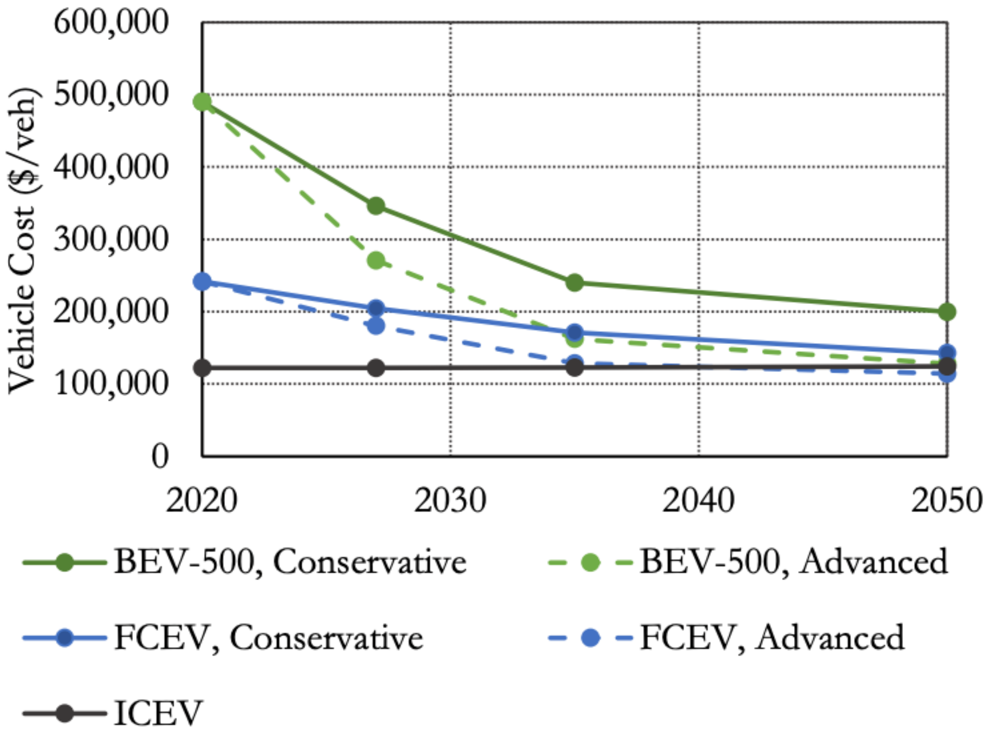


Figure 23 Initial capital cost of different technologies

Source: Ledna et al. (2022)

4.7.2 Maintenance cost

Internal combustion trucks are complex, requiring highly skilled mechanics and high maintenance costs for diesel-based engines. This is in addition to the high cost of replacing tyres on these trucks (Leonida, 2024). BETs are one of the technologies that can be used to replace ICETs as they not only help to accomplish decarbonisation goals but also have fewer mechanical systems and control logic than conventional ICETs requiring more straightforward maintenance costs. Nevertheless, the battery size, energy density, battery swapping, and charging are other challenges experienced with this technology (Leonida, 2024).

Mao et al. (2021b) note that there is a 33% cost reduction in the maintenance cost of BETs relative to ICE counterparts. However, there could be an increasing cost in terms of tyres, as BET tyres are subject to greater torque and friction as they accelerate from the start (Mao et al., 2021b). For the purpose of this study, the tyre duration will be ignored in calculating TCO as the data could not be found.

Table 9 Maintenance cost

Region	**ICE**	**BET**	**Source**
China	0.325 CNY/km	0.218CNY/km	(Mao et al., 2021b)
Europe	Starts at €14,800 in YR1 and increases to €74,000 in YR5	Starts at €4,4440 in YR1 and increases to €22,200 in YR5	https://www.ecgassociation.eu/wp-content/uploads/ECG-Business-Intelligence-22.04-Cost-of-going-electric.pdf
US	$0.152 per mile	$0.098 per mile	(Ledna et al., 2022)

It is apparent from the data that the maintenance cost of BETs is significantly lower than ICETs.

4.7.3 Energy cost

The South African mining industry depends heavily on diesel to power the trucks and for machinery used in the mining processes. Mines are often located in remote areas and have diesel stored on site, which aligns with local diesel storage regulations (Geldenhuys et al., 2023).

BETs are powered by electric energy stored in batteries. The batteries are charged by the BET plugging into the electric grid. The electric grid is powered by renewable energy sources such as solar or wind to reduce carbon emissions (Baral et al., 2021). For this study, the cost of energy will be examined in SA as data is easily available.

4.7.4 Cost of diesel

The price of diesel globally is affected by crude oil prices which fluctuate daily and by local country levies and taxes. Table 10 is an extract from mining companies in SA. It was extracted from the ESG datasheet which listed companies on the Johannesburg Stock Exchange need to comply with. The 2022-year data was used. It is imperative not to draw a comparison among the mining companies selected as each one has different production metrics and ways of work. The point to note was the high diesel usage and the cost thereof.

Table 10 Cost of diesel at South African mines

Name of company	**Diesel usage litres (000)**	**Scope 1 emissions which is mainly diesel (CO_2e tonnes)**	**Cost of diesel as of 24 July 2024 price (R20.52 / l 500ppm)**	**Source**
Exxaro	83 226	225 000	R1 707m	https://www.exxaro.com/investor-centre/esg/exxaro-2022-esg-databook
Harmony Gold	60 030	161 081	R1 231m	https://www.har.co.za/22/download/HAR-ESG22.pdf
Northam Platinum	16 230	50 096	R333m	https://www.northam.co.za/sustainability/sustainability-report-archive
Tharisa Minerals	42 000	135 077	R862m	https://www.tharisa.com/esg-data.php
Impala	40 252	527 000	R826m	https://www.implats.co.za/pdf/annual-reports/annual-integrated-report/2023/ESG-spreads.pdf

4.7.5 Cost of electricity

The Minerals Council of South Africa media statement in January 2024 reads as follows, “The latest 18.65% and 12.74% tariff increases mean the mining industry’s electricity costs will increase by R13.5 billion, or 33.7%, to R53.5 billion by the end of 2024. Over the four years between 2021 and 2024, electricity tariffs would have increased by 46%. Since 2008, the price of electricity for the mining industry has increased eightfold while consumer prices, as measured using the consumer price index (CPI), have only doubled" (www.mineralshttps://www.mineralscouncil.org.za/component/jdownloads). For this reason, mining companies have begun procuring renewable energy through agreements with Independent Power Producers (IPPs). This strategy offers a dual benefit for the mining sector in SA: it not only reduces harmful emissions but also achieves significant energy cost savings.

The specific costs at which mines have finalised their wind and solar projects with IPPs are not made public. However, the tariffs from South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) are publicly available. These tariffs provide a useful reference for understanding the general cost trends in renewable energy. The average prices from each bid window of the REIPPPP offer insight into the cost of renewable energy technologies, such as wind and solar, giving a benchmark that can help demonstrate the potential financial feasibility of these projects for mining companies.

By comparing these average bid prices with traditional energy costs, stakeholders in the mining sector can better assess the economic viability of renewable energy projects, especially when considering energy-intensive operations. According to the first quarter report for 31 March 2024 released by the IPP office, the average cost of renewable power for bid window 5 was R0,54 kWh (https://www.ipp-projects.co.za/Publications).

Using this energy rate on a simple calculation of charging a 300 kWh BET assuming 90% charging efficiency, the energy cost per truck is as follows:

- 300 kWh / 90% = 333 kWh
- Using an average rate of R0,54c kWh

  Total Cost = Energy Required × Electricity Tariff

  *333 kWh * R0,54 = R179,82*

4.7.6 Insurance cost

The National Association of Insurance Commissioners states that insuring an electric car can cost as much as 20% more than an internal combustion car. The reasons given for the discrepancy in premiums are:

- Scarcity of repair shops and skills.
- Long lead times in getting parts as electric cars are currently low volume so no spare parts are kept on site.
- The higher initial cost of electric cars (https://content.naic.org/insurance-topics/electric-vehicle-insurance-rates)

All the above factors will apply to BETs and with no data available for insurance on BETs in mines, the TCO calculation will assume a 20% increase in insurance premiums for BETs over ICETs.

For the study, the discount rate of 10% which applies to the private sector will be used and the residual value will be ignored as there is no data for residual value on BETs used in mines.

4.7.7 Ventilation cost

One of the biggest challenges of underground mining is ventilation, dealing with heat emitted from mining practices using diesel trucks and from virgin rock. Since electric trucks produce far less heat and no emissions, they reduce the demand on ventilation systems, leading to significant cost savings in cooling and air filtration (Ayres da Silva et al., 2023). Ventilation is critical for the health and safety of the workers (Jacobs et al., 2022). The typical ventilation system per unit cost is as follows:

Table 11 Ventilation cost

Description	Cost per unit
Ventilation door / regulator	R24 000
45kW fan	R110 000
500kW cooling fan	R520 000
Total	R654 000

Source: Jacobs et al. (2022)

Ventilation systems are estimated to cost between 40-50% of a mine's energy cost (Ayres da Silva et al., 2023). Electric mining vehicles have zero tailpipe emissions and so emit less heat, which means that ventilation costs decrease (Meshginqalam et al., 2024).

Transitioning from diesel-powered trucks to BETs in underground mining operations can lead to significant reductions in ventilation costs. Diesel engines emit exhaust gases and particulate matter, necessitating extensive ventilation to maintain air quality and ensure worker safety. BETs, on the other hand, produce no exhaust emissions, thereby reducing the need for ventilation by 40-50% leading to substantial cost savings and improved energy efficiency within the mine (Batt Mobile Equipment, 2023).

Similarly, a study conducted by IGO Limited, Perenti, and ABB on the Cosmos Nickel Project found that converting to an all-electric underground fleet would enable a significant reduction in cooling and ventilation demands compared to the existing diesel fleet. This reduction in ventilation requirements helps offset the additional power needed by the proposed BET fleet, resulting in an overall decrease in energy consumption (IM Mining, 2024).

While the exact percentage reduction in ventilation costs can vary depending on specific mine conditions and the extent of diesel equipment replacement, these studies suggest that replacing diesel trucks with BETs can lead to ventilation cost reductions ranging from approximately 40%-50%.

4.8 TCO calculations (Base Case)

The following assumptions were used to generate the results:

- The current fleet is assumed to be 20 trucks with 50% replaced by BETs.
- The mileage of the BETs and ICETs is the same, 70,000 km per year and only used at the mine for haulage of rock to the surface and not on the road.
- The 2023 was the base for an average diesel price of R20,09 per litre for 500 ppm.
- The diesel efficiency of ICETs is 40ℓ per 100km.
- The BET will only charge at the mine, with an average cost of R0,54 kWh as per the fifth bid window price for renewable energy.
- The infrastructure cost of the solar or wind plant has been ignored as mines in SA have already planned and financed this. The cost of charging infrastructure has also been ignored as this is a once-off capital cost.
- Insurance for BETs is 20% higher compared to ICE.
- Ventilation costs have been estimated as exact saving data could not be found. SA has some of the world's deepest underground gold and PGM mines (Mvile, et.al, 2024). This results in significantly high ventilation costs due to the depth. For this reason, energy cost for ICETs was increased by a further 40% to cater for ventilation costs.
- The average CPI for 2023 was 6,5%.

The maintenance cost of BETs was 33% cheaper than ICETs with an annual increase of 20% year-on- year for ICE and 5% for BETs as per the guidance provided by the United Kingdom study.

- Insurance premiums was 20% higher for BETs.
- The price of BETs and ICETs was based on the cost in Europe.

- The capital cost of ICETs increased by 20% in YR1 and thereafter by 10% year-on-year. The 20% was based on data from the Bureau of Transport statistics (https://www.bts.gov/data/data-spotlight/increase-transportation-consumer-price-index-accounts-nearly-27-year-over-year) which was on average 20% in 2022.
- The capital cost of BETs decreased by 5% year-on-year over the 10-year period based on data from https://energyinnovation.org/wp-content/uploads/2024/02/Fast-Falling-Battery-Prices-Boost-Economic-Benefits-Expected-from-Heavy-Duty-Vehicle which shows the price of battery packs decreasing $85 per kWh in 2030 to $59 per kWh in 2040.
- The EUR/ZAR exchange rate of R19,50 was used.
- Import duty for vehicles into SA is 30% and VAT is 15% which was added to the capital cost of both ICE and BET as these are imported and not manufactured in SA.
- The lifespan of the trucks was 10 years as the battery pack on a BET can last between five to 15 years depending on factors such as battery chemistry, usage patterns, charging practices, and environmental conditions. Proper management and maintenance can help maximise the lifespan and efficiency of the battery pack (Berntsson & Petkovski, 2023).

Table 12 Capital cost of BETs in SA

Calculator to estimate cost of a BET in the local SA market		
Calculation:		
BET CAPEX = Capital cost + import duty + VAT		
Variable	**Inputs**	**Guide**
BET retail capital cost (in original international currency, without	272 800	As per prices from the Europe
Original currency	EUR	EUR
Exchange rate (ZAR)	R19,50	As at 24 July 2024
BET capital cost (Rands), without SA taxes	**5 319 600**	Cost in Rands
Import duties for vehicles (%)	12%	Preferential agreement with the EU https://naamsa.net/tax-revenue/
Ad valorem excise duty	0%	0% for trucks
VAT	15%	Standard VAT rate is 15% in SA
BET capital cost (Rands), with SA taxes	**6 755 892**	Total cost including importy duty and VAT

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool/)

Table 12 and Table 13 illustrates the cost of a class 5 truck, equivalent to a 40-tonne mine haul truck used in underground mining operations, presented in ZAR. The conversion from foreign currency is based on the current exchange rate and applicable import duties for SA have been factored in. This pricing breakdown can help mining companies in SA to better assess the financial impact of acquiring new BETs and compare them to the costs of traditional ICETs.

Table 13 Capital cost of ICETs in SA

Calculator to estimate cost of a ICE in the local SA market		
Calculation:		
ICE CAPEX = Capital cost + import duty + VAT		
Variable	**Inputs**	**Guide**
ICE retail capital cost (in original international currency, without	116 230	As per prices from the Europe
Original currency	EUR	EUR
Exchange rate (ZAR)	R19,50	As at 24 July 2024
ICE capital cost (Rands), without SA taxes	2 266 485	Cost in Rands
Import duties for vehicles (%)	12%	Preferential agreement with the EU https://naamsa.net/tax-revenue/
Ad valorem excise duty	0%	0% for trucks
VAT	15%	Standard VAT rate is 15% in SA
ICE capital cost (Rands), with SA taxes	**2 878 436**	Total cost including importy duty and VAT

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

A data comparison shows that BETs have a significantly higher initial capital cost if it was to be imported into SA.

Table 14 Total cost of ownership outputs for ICETs based on assumptions for 10 years

Baseline		**Incr**	**Variable**	**Type**	**Unit**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
						1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vehicle type 1				**Lifespan >**	**10**	**km p.a. >**	**100 000**	**Vehicles >**	**20**						
Heavy Truck (>12t) Diesel			0	Vehicles >	10										
Results per vehicle															
2 878 436	ZAR		Capital cost	Cumulative	ZAR	2 878 436	3 454 123	3 799 536	4 179 489	4 597 438	5 057 182	5 057 182	5 057 182	5 057 182	5 057 182
2,02	R/km	21%	Maintenance cost	Annual	ZAR	202 000	222 200	244 420	268 862	295 748	325 323	357 855	393 641	433 005	476 305
			Maintenance cost	Cumulative	ZAR	202 000	424 200	668 620	937 482	1 233 230	1 558 553	1 916 409	2 310 049	2 743 054	3 219 360
10 000	R/month	7%	Insurance cost	Annual	ZAR	120 000	116 182	112 485	108 906	105 441	102 086	98 838	95 693	92 648	89 700
			Insurance cost	Cumulative	ZAR	120 000	236 182	348 667	457 573	563 014	665 100	763 938	859 630	952 279	1 041 979
40	lit/100km		Energy use	Annual	Litres	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000
20,09	R/lit	7%	Energy price	Annual	R/lit	21,50	20,91	20,34	19,79	19,25	18,72	18,21	17,71	17,23	16,76
			Energy cost	Annual	ZAR	859 852	836 401	813 591	791 402	769 818	748 823	728 401	708 535	689 211	670 415
			Energy cost	Cumulative	ZAR	859 852	1 696 253	2 509 844	3 301 246	4 071 064	4 819 887	5 548 287	6 256 822	6 946 034	7 616 448
			Total cost of ownership	**Cumulative**	**ZAR**	**4 060 288**	**5 235 071**	**6 405 567**	**7 574 737**	**8 745 744**	**9 921 976**	**11 107 069**	**12 304 938**	**13 519 803**	**14 756 223**
Sum of results across all vehicles of this type															
			Maintenance cost	Cumulative	ZAR	2 020 000	4 242 000	6 686 200	9 374 820	12 332 302	15 585 532	19 164 085	23 100 494	27 430 543	32 193 598
			Insurance cost	Cumulative	ZAR	1 200 000	2 361 818	3 486 669	4 575 730	5 630 139	6 650 998	7 639 375	8 596 304	9 522 785	10 419 788
			Energy cost	Cumulative	ZAR	8 598 520	16 962 535	25 098 440	33 012 457	40 710 638	48 198 868	55 482 873	62 568 224	69 460 338	76 164 485
			Total cost of ownership	**Cumulative**	**ZAR**	**40 602 880**	**52 350 713**	**64 055 670**	**75 747 367**	**87 457 438**	**99 219 757**	**111 070 693**	**123 049 382**	**135 198 026**	**147 562 230**

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

The TCO of 10 diesel trucks increasing from R40,602,880 in Year 1 to R147,582,230 in Year 10 is significant at 263% and highlights the impact of rising capital, fuel, and maintenance costs. This year-on-year escalation in TCO is consistent with market trends, where diesel vehicle operating costs have surged due to increasing fuel prices, and maintenance demands for ageing fleets. Additional regulatory compliance costs for emissions have been ignored in these calculations. Including ventilation costs, the TCO for 10 diesel trucks increases from R44,042,288 in Year 1 to R178,028,024 in Year 10.

Table 15 Total cost of ownership outputs for BETs based on assumptions for 10 years

Heavy Truck (>12t) Electricity			0	Vehicles >	10	Public charging >		0%							
Results per vehicle															
6 775 892	ZAR		Capital cost	Cumulative	ZAR	6 775 892	6 437 097	6 115 243	5 809 480	5 519 006	5 408 626	5 300 454	5 194 445	5 090 556	5 090 556
0,67	R/km	5%	Maintenance cost	Annual	ZAR	67 000	70 350	73 868	77 561	81 439	85 511	89 786	94 276	98 990	103 939
			Maintenance cost	Cumulative	ZAR	67 000	137 350	211 218	288 778	370 217	455 728	545 515	639 790	738 780	842 719
16 000	R/month	7%	Insurance cost	Annual	ZAR	192 000	185 891	179 976	174 250	168 705	163 337	158 140	153 109	148 237	143 520
			Insurance cost	Cumulative	ZAR	192 000	377 891	557 867	732 117	900 822	1 064 160	1 222 300	1 375 409	1 523 646	1 667 166
540	Wh/km		Energy use	Annual	kWh	54 000	54 000	54 000	54 000	54 000	54 000	54 000	54 000	54 000	54 000
0,54		7%	Energy price (fleet)	Annual	R/kWh	0,54	0,53	0,51	0,50	0,48	0,47	0,46	0,44	0,43	0,42
0,00		7%	Energy price (public)	Annual	R/kWh	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			Energy cost	Annual	ZAR	29 160	28 365	27 591	26 839	26 107	25 395	24 702	24 028	23 373	22 736
			Energy cost	Cumulative	ZAR	29 160	57 525	85 116	111 955	138 061	163 456	188 158	212 186	235 560	258 295
			Total cost of ownership	**Cumulative**	**ZAR**	**7 064 052**	**7 348 658**	**7 630 092**	**7 908 742**	**8 184 993**	**8 459 236**	**8 731 865**	**9 003 277**	**9 273 877**	**9 544 072**
Sum of results across all vehicles of this type															
			Maintenance cost	Cumulative	ZAR	670 000	1 373 500	2 112 175	2 887 784	3 702 173	4 557 282	5 455 146	6 397 903	7 387 798	8 427 188
			Insurance cost	Cumulative	ZAR	1 920 000	3 778 909	5 578 671	7 321 168	9 008 222	10 641 596	12 223 000	13 754 087	15 236 457	16 671 660
			Energy cost	Cumulative	ZAR	291 600	575 247	851 159	1 119 545	1 380 612	1 634 559	1 881 580	2 121 864	2 355 595	2 582 952
			Total cost of ownership	**Cumulative**	**ZAR**	**70 640 520**	**73 486 576**	**76 300 925**	**79 087 417**	**81 849 927**	**84 592 357**	**87 318 646**	**90 032 774**	**92 738 770**	**95 440 720**

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

The TCO of 10 BETs increases from R70,640,520 in Year 1 to R95,440,720 in Year 10 (a 35% increase) reflecting the impact of several positive market developments, including decreases in battery pack costs, lower maintenance demands, and reduced charging expenses due to declining cost of renewable energy over the past decade.

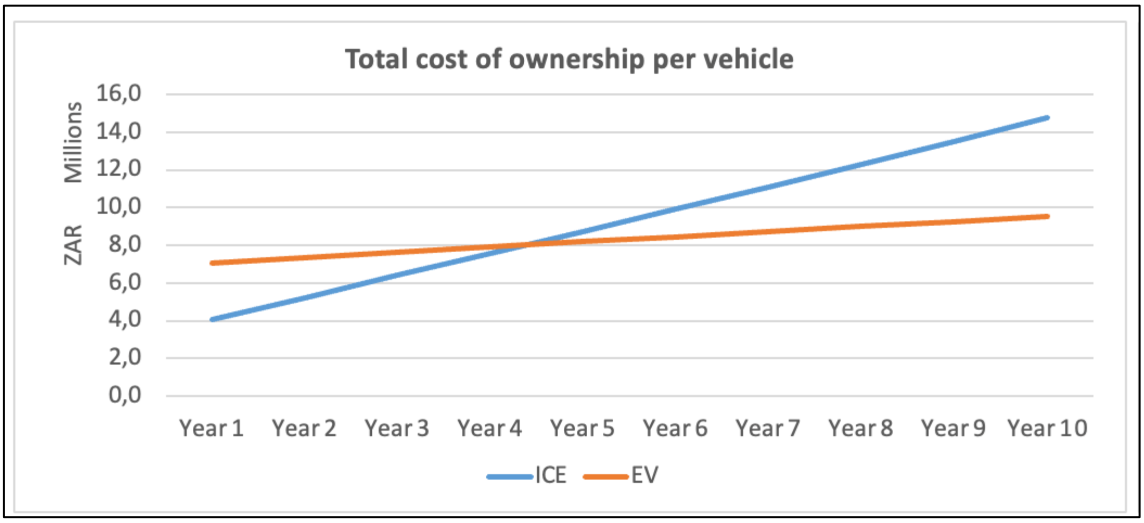


Figure 24 Time taken to reach cost parity

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

BETs have a significantly higher capital cost than ICE; however, based on the assumptions, the data shows that cost parity will be reached in Year 4 and thereafter BETs will have a lower TCO than ICETs.

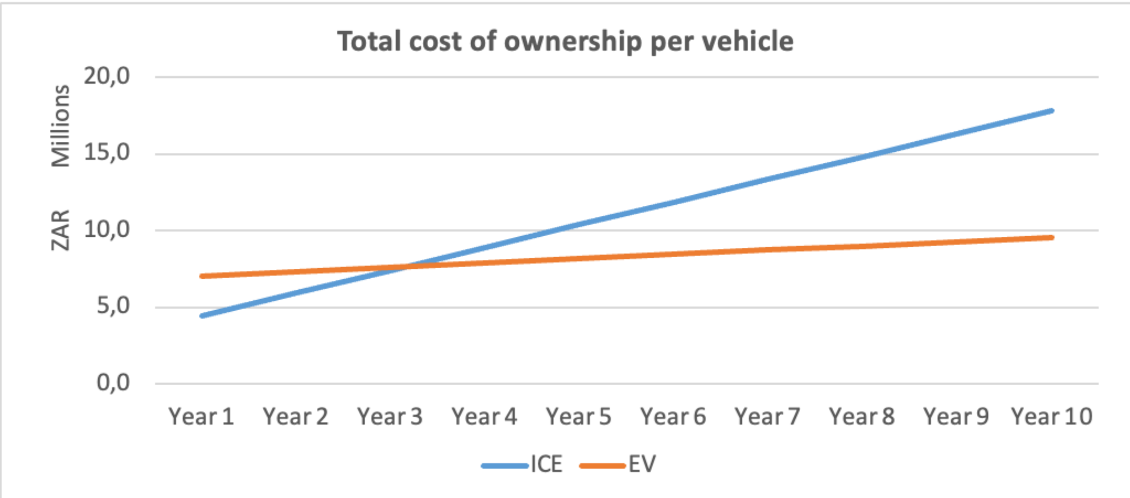


Figure 25 Time taken to reach cost parity including ventilation cost

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool

Switching from ICETs to BETs can drastically reduce the need for ventilation as BETs produce no harmful emissions. This means less energy is needed to cool deep South African underground mines, resulting in cost parity being reached in three years for BETs.

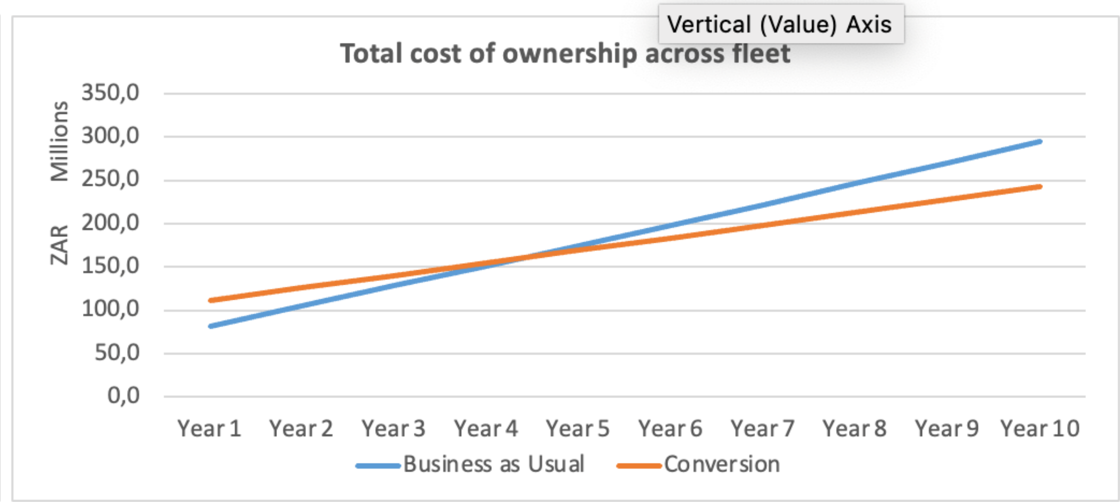


Figure 26 Time taken to reach cost parity for 50% of the fleet replaced with BETs

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

The data shows that by replacing the fleet with 50% BETs (10 trucks), cost parity will be reached between years 4 and 5. Thereafter, the TCO of the fleet will be lower than continuing to operate the entire fleet with ICETs.

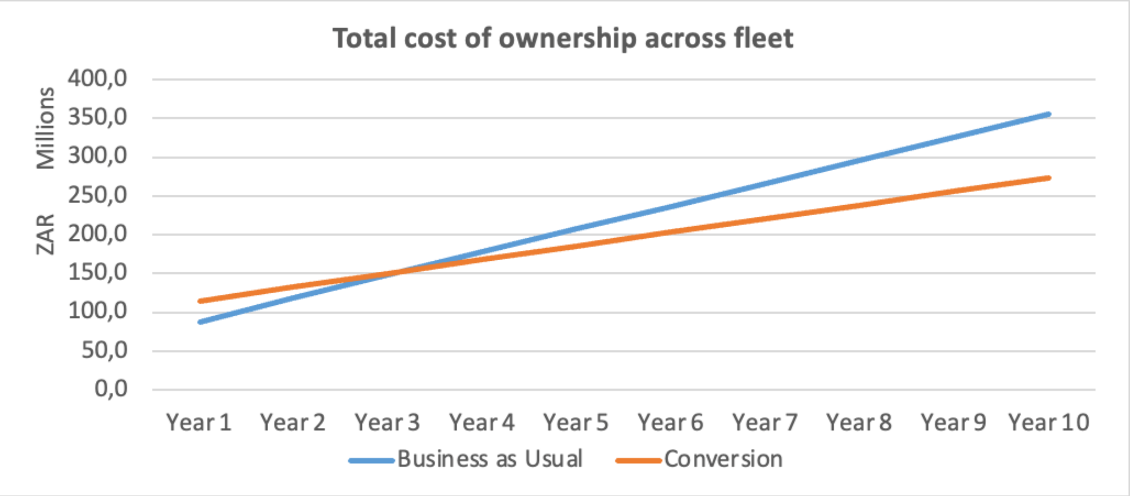


Figure 27 Time taken to reach cost parity for 50% of the fleet replaced with BETs including ventilation cost

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

Including ventilation cost, time taken to reach cost parity by replacing 50% of the fleet with BETs reduces to between two and three years.

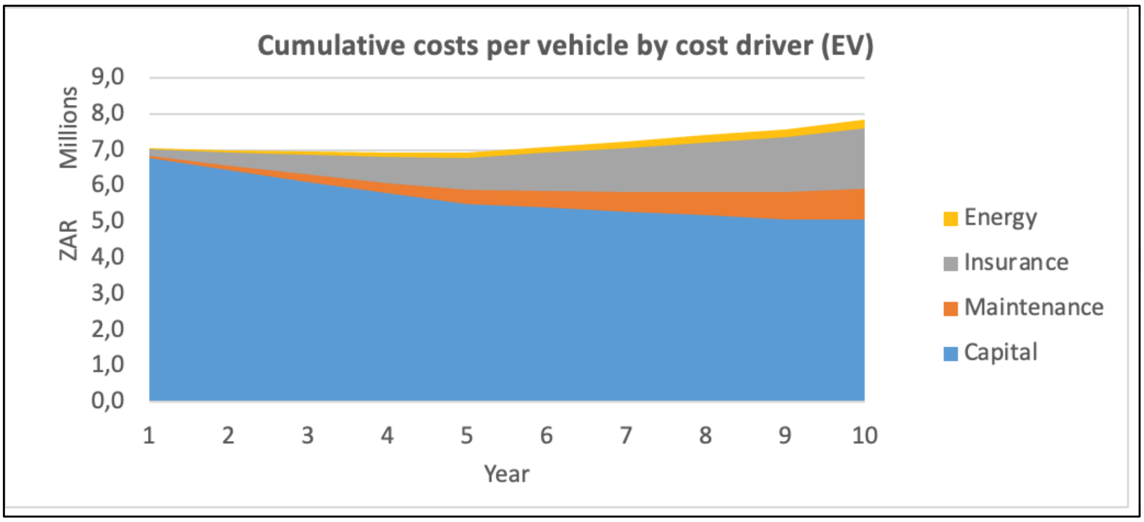


Figure 28 Cumulative cost by cost per driver for BET

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

Figure 29 shows that the cost driver for BETs over 10 years is the capital cost followed by insurance.

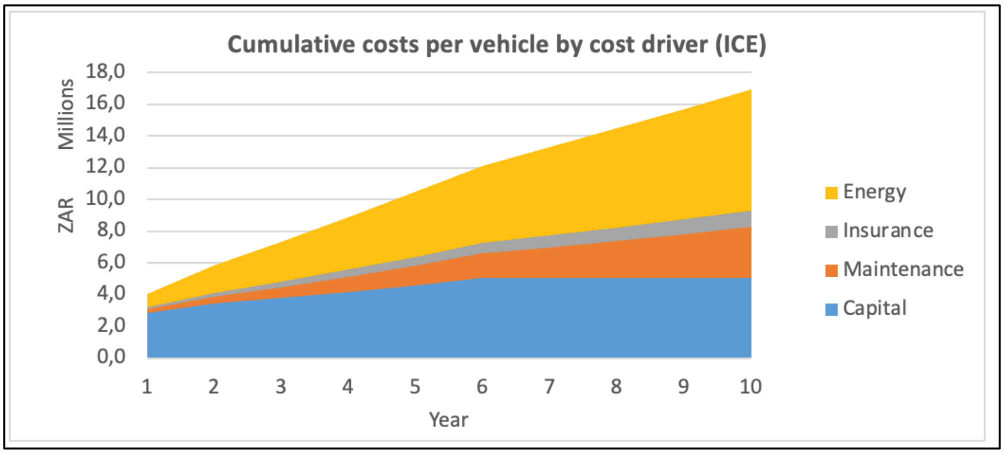


Figure 29 Cumulative cost by cost per driver for ICETs

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

Figure 30 shows the cost per driver for ICETs is the cost of energy with the rising cost of diesel.

4.9 TCO calculations – Sensitivity Analysis on key TCO variables

The following assumptions were stressed to further understand the impact of switching:

- BETs are imported into SA which results in foreign exchange risk for importers. ZAR/EUR was stressed by 20% from EUR/ZAR19,50 to EUR/ZAR23,40.
- Oil prices increase by 15% due to geopolitical events following the change in administration in the United States.
- The batteries are charged at the mine using owned renewable energy resources, hence a change in the Eskom tariff will not affect the cost of electricity. However factors such as increased capital cost, relacing solar

panels, and maintenance can increase the tariff over time. The tariff was increased by 20% from R0.54 kWh to R0.65 kWh.

- Although battery packs are decreasing, supply chain issues could result in higher prices. Hence, BETs increased by 20%.

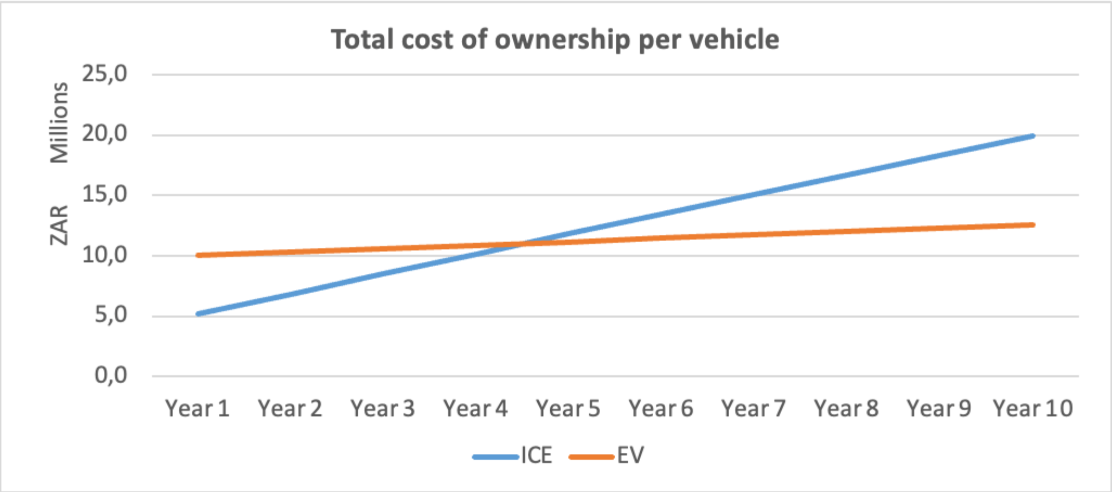


Figure 30 TCO per vehicle

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

Under the stressed case, BETs' cost parity is delayed from two to three years to four to five years with the biggest influencing factors being the exchange rate and the cost of battery packs.

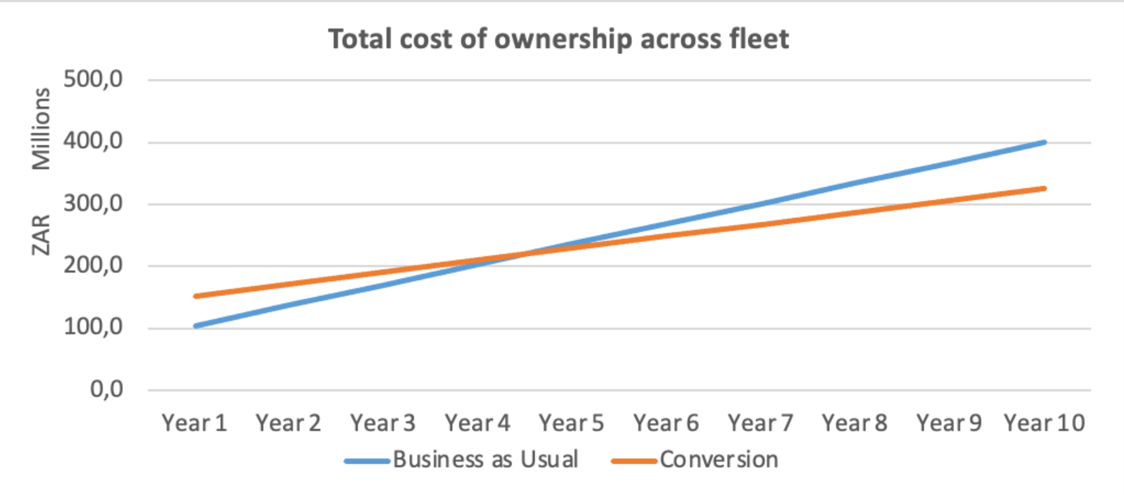


Figure 31 TCO across fleet

Source: TCO calculator (https://www.cityenergy.org.za/total-cost-of-ownership-comparison-of-evs-and-ice-vehicles-in-south-africa-tool)

The delay in cost parity for replacing 50% of a mine's fleet with BETs by two years, despite the narrowing gap in TCO between ICE vehicles and BETs, underscores the complex financial dynamics facing South African mines. Specifically, it highlights how exchange rate fluctuations and supply chain issues affect the adoption of BETs in mining operations. South African mines are particularly vulnerable to currency fluctuation since both ICE and BETs are fully imported.

With respect to supply chain issues, the South African market is small relative to other markets, and battery supply presents challenges. Furthermore, battery mineral supply is exposed to geopolitical risks as these resources are in unstable political regions such as cobalt in the Democratic Republic of the Congo.

4.10 Conclusion for research question two

Evaluating the TCO for ICETs versus BETs involves a comprehensive analysis of various factors. Data indicates that BETs incur significantly higher upfront costs due to the battery pack. Furthermore, the rising cost of electricity in SA supplied by Eskom is a crucial factor to consider when purchasing BETs. However, many mining companies have begun constructing their wind and solar plants, which has led to a decrease in the cost of renewable energy in SA with each successive bid window.

Furthermore, the cost of diesel has experienced a significant increase over the past few years. Given the limited refining capacity in SA, it is unlikely that diesel prices will decline substantially any time soon. Consequently, the energy costs associated with diesel trucks remain high, rendering it the most uncompetitive element in the TCO analysis. This is further exacerbated when considering the significant ventilation cost of systems required by mining regulation in SA for deep underground mines.

The data projections show in the next few years that cost parity will be reached between BETs and ICETs. This coupled with the environmental benefits makes the adoption of BETs quite compelling. However, it remains a significant upfront capital cost.

4.11 Presentation of findings pertaining to research question three

4.11.1 Thematic analysis of data

To transition to clean energy, an unprecedented amount of new clean energy capacity needs to be deployed at a rapid rate. Understanding and categorising the barriers hindering progress is necessary to accelerate clean energy. By clearly understanding these challenges, stakeholders across the industry can align their efforts more effectively, target solutions more precisely, and drive meaningful advancements in clean energy (Emodi et al., 2022).

The following categories of barriers to adoption were identified in the study of fleet operators exploring electric truck options (Sugihara et al., 2023). These barriers are widespread and multifaceted.

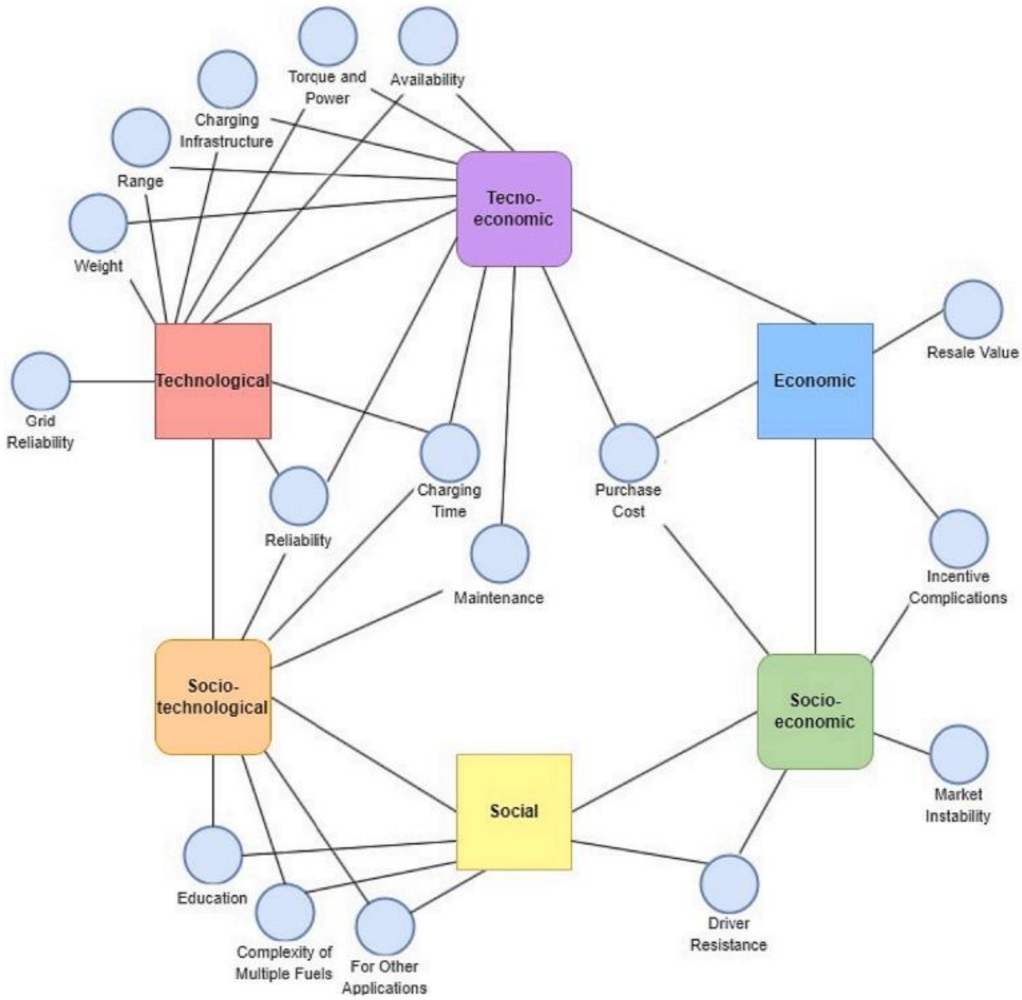


Figure 32 Barriers to adoption

Source: Sugihara et al. (2023)

For this study, the primary codes identified were grouped into themes by Atlasti and are illustrated below.

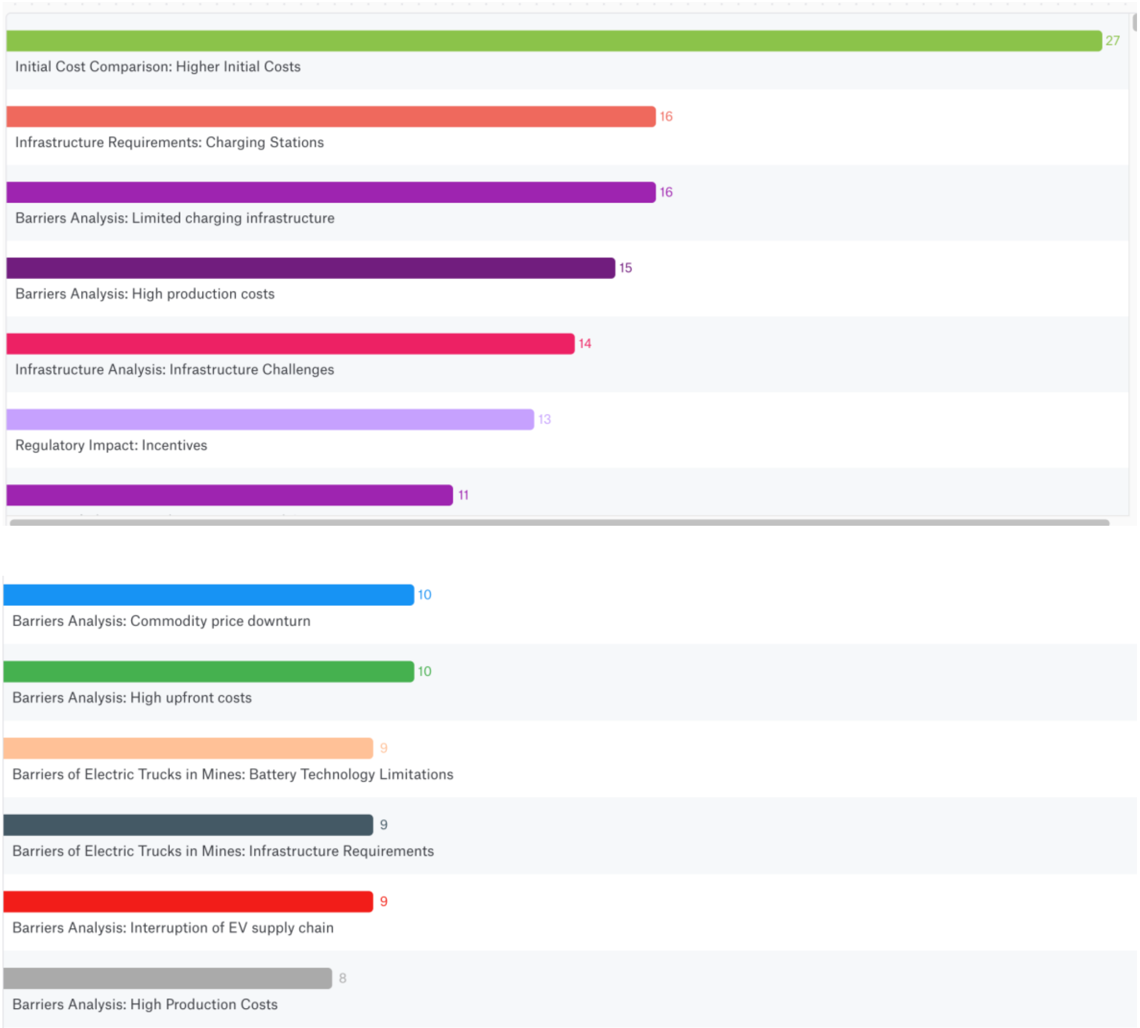


Figure 33 Primary categories for barriers to adoption

Source: Atlasti (www.atlasti.com)

In grouping similar codes, the following themes emerged:

- Economic barriers
- Infrastructure challenges
- Technology limitations
- Regulatory and policy issues

4.11.1.1 Economic barriers

Economic barriers are impediments of the flow of money to the organisation.

Economic barriers focus on the financial aspects of the adoption of BETs. The high upfront purchase price and the cost of the battery pack are major financial barriers despite the long-term cost savings (Sugihara et al., 2023).

Themes identified: high upfront capital costs, cost of EV batteries, and economic incentives.

"*High acquisition costs were the primary reason they were not considering electric trucks" (Sugihara et al., 2023).*

"Consumers and organisations may not identify savings as attractive due to the high upfront costs" (Ruoso & Ribeiro, 2022).

"The most concerning barrier is the high purchase price" (Tanco et al., 2023).

"The incremental upfront costs in BETs is simply the extra cost of the battery pack" (Rajagopal et al., 2024).

"Notably due to technology cost reductions from improvement in the batteries, both battery electric and fuel cell vehicles could witness significant cost reductions between 2023 and 2040" (Burke et al., 2023).

"Developed and developing countries have recently focused on making BET sales more attractive through tax incentives and government subsidies (Wangsa et al., 2023).

"One of the main barriers pointed out in the study was a lack of incentive policies to promote EVs in Brazil" (Ruoso & Ribeiro, 2022).

4.11.1.2 Infrastructure challenges

Infrastructure challenges relate to the physical infrastructure needed to support BET adoption (Tanco et al., 2023).

The themes identified include lack of charging stations, operational cost, and maintenance cost.

“To optimise the use of electric trucks, the number of electric charging stations has to increase”(Tanco et al., 2023).

“BETs can be charged through plug-in chargers but there are still challenges associated such as heavy battery packs and the time taken to charge” (Ruoso & Ribeiro, 2022).

“Positioning charging infrastructure at the optimal geographic location to ensure maximum utilisation is a challenge (Speth et al., 2022).

“In mines, the vehicles and infrastructure are owned and operated by the same company, the usage is known in advance making infrastructure investment easier” (Meshginqalam et al., 2024).

“BETs are said to have a lower maintenance cost than diesel trucks” (Burke et al., 2023).

“The technology in BETs requires highly skilled labour for maintenance” (Fenton & Kailas, 2021).

4.11.1.3 Technology barriers

Technological barriers focus on the perceived and real constraints of battery electric technology. Charging time and battery performance are seen to be the biggest technology hurdles (Ntombela et al., 2023).

“One of the main barriers to adoption is operational reliability of driving range and battery capabilities coupled with lost downtime” (Konstantinou & Gkritza, 2023).

“Most concerning barriers are low incentives, charging infrastructure, and driving range” (Ruoso & Ribeiro, 2022).

“From a technological perspective, driving range and charging time are the biggest barriers to electric vehicle adoption” (Müller, 2024)

4.11.1.4 Regulatory barriers

"The slow adoption of electric vehicles in SA is due to a lack of political will and the absence of incentives" (Ruoso & Ribeiro, 2022). "Barriers to adopting electric vehicles in SA require policy changes, regulatory framework and skill set" (Ruoso & Ribeiro, 2022).

"The SA government has recognised the importance of developing its mining equipment industry and to do so would require a master plan to provide the right framework for policy action" (Andreoni & Torreggiani, 2020).

Cloete (2020) states the need for a SADC-wide just mining transition, vision, and pathway.

"There should be tax breaks for mining and manufacturers fostering an appropriate policy environment for change to BETs" (Cloete, 2020).

"The post-COVID era must compel governments to question their dependence on fossil fuels and the heavy cost burden of importing fuel thereby creating incentives to reduce reliance on fossil fuels by switching to electric vehicles" (Cloete, 2020).

4.12 Conclusion for research question three

The adoption of BETs in mining face several barriers. Understanding these challenges is crucial for stakeholders to decide to adopt this technology in their organisation. Addressing these barriers requires a multifaceted approach and requires the involvement of the government, automotive manufacturers, and mining companies (Ruoso & Ribeiro, 2022).

CHAPTER 5. DISCUSSION OF THE RESULTS

5.1 Introduction

This chapter discusses the findings, explanation, and interpretation of the results presented in Chapter 4 for the three research questions. The discussion of the results for each question is structured to present each finding, followed by an analysis of each finding in the context of the literature review.

5.2 Discussion of research proposition one 1: BETs are better for the environment than ICETs

This section describes and discusses the findings in relation to the literature review about proposition one, which states that BETs are better for the environment and human health than ICETs as they emit zero tailpipe emissions.

5.2.1 Emissions and environmental impact of ICETs

Diesel-powered trucks are a common sight in mining operations where their proven technology and high-power output make them well-suited to manoeuvring in confined spaces, especially in underground mines. However, the emissions produced by these trucks can pose significant environmental and health concerns for workers in the environment.

5.2.1.1 Evidence in the data

Secondary data reviewed indicates that ICETs emit a complex nature of DPM, nitrogen oxide, carbon monoxide, and hydrocarbons. These emissions contribute significantly to reduced air quality and increased exposure to harmful substances over time, causing respiratory problems for miners.

The combustion process of the ICETs causes these emissions. As diesel fuel burns, it releases fine particulate matter and gases that degrade air quality and contribute to environmental concerns such as global warming. In underground mining operations where ventilation is limited and expensive to maintain, the accumulation of these emissions poses an even greater health risk.

In addition, factors influence and constrain worker productivity, particularly due to their working environment.

Table 16 Worker production factors

Ventilation	ICETs emit harmful gases and extensive underground ventilation systems are required to maintain air quality. Workers may need to pause productivity to maintain effective ventilation and air quality.
Heat	Diesel trucks generate significant heat underground which can lead to unsafe working conditions after prolonged periods of time. Without effective ventilation, workers can become exhausted and less productive.
Health impact of workers	Diesel emissions are associated with respiratory issues such as bronchitis or long-term lung damage. This can reduce worker productivity and increase absenteeism over time. Poor air quality in underground mines affects workers' ability to perform optimally, particularly over longer shifts.

5.2.1.2 Comparison to the literature

The definition of environmental impact was initially proposed in Chapter 2 as "to mitigate the negative effect on natural resources in a way that creates benefits for communities and the organisation" (Khubana et al., 2022). By focusing on mitigating the negative effect on natural resources, organisations and communities will realise long-term benefits on air quality, health, and long-term economic stability.

Cheng et al. (2020) and Balboa-Espinoza et al. (2023) both state that air emissions from diesel trucks are harmful to human health. DPM has been classified as carcinogenic by the IARC.

a) Truck emissions

The secondary data reviewed showed that diesel trucks emitted significant gases that were harmful to the environment. In underground mining, this problem is exacerbated by the fact that the emissions are accumulated in confined spaces. Support for this is found in Geldenhuys et al. (2023) which states that diesel machinery such as haul trucks and drill rigs emit harmful gases, which are not only cause for concern from an environmental standpoint but also from a human health perspective, especially due to confined underground mining spaces. Katta et al. (2020) add that cleaner production in mining aims to improve the efficient use of energy, reduce environmental impact, and develop optimum GHG mitigation solutions. However, the high variability in mining operations has made the application of alternate technology challenging, resulting in the industry falling behind in climate change expectations of society.

b) Environmental impact

The emissions from diesel trucks include DPM, NO_x, and sulphur dioxide, which degrade air quality underground. This results in mining companies having to invest significantly in ventilation systems for the workers' safety and to meet regulatory pressures. DPM poses severe health risks. Diesel trucks also produce significant amounts of heat which adds to the already high underground temperatures. Cooling systems are needed to ensure worker safety and continued productivity to prevent worker heat stress. This is also congruent with Kotyla et al. (2024) who argue that the negative impact of NO_x on human health cannot be underestimated and that continuous research and development of technology to predict NO_x emissions and reduce them are crucial to improving mining safety. Swift et al. (2023) stated that health issues due to heat illnesses have been shown to cause loss of days and productivity in mines.

From a review of the literature and the findings, it is evident that diesel-powered trucks have been an essential part of underground mining operations for decades due to their efficiency and reliability. However, their environmental impact, especially in terms of emissions and worker health, has led to growing concerns. The high cost of ventilation to manage diesel emissions, coupled with increasing regulatory pressures, is pressurising the mining industry to explore alternatives such as BETs. The transition away from diesel will not only help companies meet decarbonisation goals but also improve workplace safety.

5.2.2 Emissions and environmental impact of BETs

BETs are increasingly being considered as an alternate technology in underground mines. This technology offers lower emissions and reduced environmental impact on its surroundings due to zero tailpipe emissions and reduced heat generation.

5.2.2.1 Evidence in the data

The secondary data reviewed indicates that BETs produce zero tailpipe emissions and generate less heat, which could mitigate the worker productivity factors of ICETs, especially in underground mines where ventilation is of paramount importance.

The charging infrastructure of BETs is a critical component of their successful deployment. Underground mines present a unique challenge as space is limited among all the other equipment needed. Careful consideration in planning for charging stations is needed, which could limit the number to be installed and may delay the charging time of the BETs.

The manufacturing of BETs is more energy-intensive than ICETs, primarily due to the mining of critical minerals such as lithium, cobalt, and nickel for battery production. These processes contribute to the overall carbon footprint of BETs. In addition, if the charging infrastructure relies on non-renewable sources, the reduction of emissions, particularly Scope 3 through the value chain, is limited. Furthermore, BET use in mining is nascent; hence, the market for recycling batteries is limited. In evaluating reduced emissions from BETs, the entire value chain must be considered to ensure a comprehensive assessment of emissions.

5.2.2.2 Comparison with the literature

In Chapter 2, Breuer et al. (2021)stated that the emissions factor for BETs drops to zero due to the absence of tailpipe emissions. This was aligned with the data reviewed.

Although the BETs have no tailpipe emission, the charging infrastructure and the source of electricity it uses contribute to Scope 2 emissions if it is not renewable energy. The South African mining industry is powered by Eskom, which generates electricity from the burning of coal (Akinbami et al., 2021). Although the REIPPPP has been successful in diversifying the energy mix in SA, baseload power is still generated by Eskom (Akinbami et al., 2021). However, Nkambule et al. (2023) argue that the mining sector in SA is committed to exploring alternative renewable sources of energy to move away from high Eskom tariffs, unstable supply, and its own commitment to its net-zero targets.

The data shows that the manufacturing of BETs is a carbon-intensive process. This is consistent with Iyer et al. (2023) who note that there is a big emphasis on reducing GHG emissions from ICETs by moving to BETs; however, these efforts ignore the high energy intensity of producing the batteries needed for BETs. Gao et al. (2023) further state that when looking at the lifecycle of BETs, the battery production stage – particularly the material preparation stage – is the main contributor to lifecycle carbon emissions.

The environmental impact of BETs spans their entire lifecycle. The findings show that the operational impact of BETs is positive for the environment due to zero tailpipe emissions; however, the emission from BETs depends on the energy mix used for charging infrastructure and the manufacturing impact.

While the initial production of BETs has a high environmental cost due to battery production, they offer significant environmental benefits during operation, particularly if charged by renewable energy which is consistent with the literature.

5.2.3 Conclusion for proposition one

The research proposition based on the literature review in Chapter 2 is as follows:

It is proposed that BETs are better alternatives to diesel-powered trucks for reducing emissions, protecting the environment, and human health. However, when considering the entire lifecycle of BETs, the environmental advantage becomes more complex. The carbon intensity of manufacturing, the resource extraction for batteries, and end-of-life issues must be factored into the assessment. Overall, BETs represent a promising solution, but a holistic approach that includes greener production methods, cleaner energy grids, and effective recycling is essential to fully realise their environmental and health benefits.

5.3 Discussion of proposition two – total cost of ownership of ICE and BETs

TCO encompasses all the costs associated with purchasing, operating, and maintaining an asset over its lifetime. To compare BET and ICETs, all these cost components must be accurately compared to provide a clear understanding of which technology offers more economic viability and sustainability in the long term.

5.3.1 Evidence in the data

a) Initial capital cost

Secondary data reviewed showed that the initial capital cost of BETs relative to ICETs was significantly higher. The primary factor contributing to the cost disparity was the battery pack, which made up approximately 60% of the cost of BETs. This high expense is due to the complex value chain of battery production and the small-scale production of battery packs for medium and heavy-duty mining trucks.

The data showed that China was cheaper than Europe and United States in terms of initial capital cost.

b) Maintenance costs

The data reviewed indicated that maintenance costs for BETs was lower than that of ICETs. The cost advantage is primarily due to the simpler design of BETs relative to ICETs. BETs have fewer moving parts and eliminate parts such as the engine, transmission, and exhaust systems. As a result, BETs have fewer servicing intervals and lower wear and tear. Additionally, BETs benefit from reduced expenditure as oil filters, spark plugs, and exhaust systems do not have to be replaced. However, the cost of replacing a battery pack could be significant as it makes up approximately 60% of the cost of the BET.

c) Energy costs

The energy cost for SA was considered. The data indicates that diesel and Eskom-supplied electricity costs have risen sharply in SA. Mining companies have responded by investing in solar and wind projects to maintain a stable electricity supply and lower the cost of electricity. The move to renewable energy provides a sustainable and cost-effective solution compared to the increasing cost of traditional energy sources such as diesel and grid electricity.

The data shows that the energy cost of ICETs will continue to rise due to the country's vulnerability to the USD/ZAR exchange rate and the international oil price which both influence the cost of diesel. However, the energy cost of BETs is expected to remain competitive as renewable energy costs have been declining in SA over recent years as is evidenced in the latest REIPPPP average pricing.

d) Insurance costs

The data reviewed showed that insurance costs for BETs are higher than that of ICETs. This is primarily due to the technology being relatively new and the high cost of battery packs, which make up a significant portion of the truck's overall value. As a result, insurance premiums for BETs are higher to cover potential risks associated with the expensive components and the limited track record of the technology in the mining sector.

e) Ventilation costs

The data for ventilation costs was reviewed to give the researcher an idea of potential cost savings by using BETs in underground mines. Despite the higher initial capital costs for BETs, the substantial reduction in ventilation and operational costs can lead to cost parity within a relatively short time.

5.3.2 Evidence in the literature

As introduced in Chapter 2, TCO refers to “a purchasing tool and philosophy which is aimed at understanding the true cost of buying goods or services from a particular supplier.” (Lebeau et al., 2019). Ahluwalia et al. (2023) add that performance, range, durability, and cost are some of the main factors to consider when purchasing trucks. According to Magnino et al. (2024), TCO is the prevailing methodology to assess the economic benefits of different decarbonisation pathways of heavy-duty trucks.

a) Initial cost of capital

The data showed that the initial capital cost of BETs was as much as 60% higher than that of diesel-powered trucks. The findings state that China has the lowest cost of BETs relative to Europe and the United States. This is consistent with the view of Kaur et al. (2024b), Rajagopal et al. (2024), and Burke et al. (2024) who maintained that TCO of BETs is much higher than ICETs mainly due to the cost of the battery pack. Therefore, the data is consistent with the literature.

b) Maintenance cost

The data showed that the maintenance cost of BETs was lower than that of ICETs due to the reduced complexity of the engines. Electric trucks use regenerative braking, meaning less stress on the braking systems and improved battery technology, leading to extended use. Wang et al. (2022) argue that currently BETs are as much as 20% lower than ICE, which is not marginally different.

However, this could drop over time as technology improves. Bhardwaj and Mostofi (2022) support the views of Wang et al. (2022) and add that the battery will not need to be replaced in the first five years of the life of the BET, reducing maintenance costs. The data, therefore, is consistent with the literature.

c) Energy cost

In SA, both electricity and diesel costs have risen significantly over recent years, increasing the operational expenses for mining companies using ICETs. Due to the increasing cost of both electricity and diesel, energy expenses for operating diesel trucks have risen disproportionately in SA especially since the refining capacity in the country is almost non-existent. Pram et al. (2022), Rangel et al. (2023), and Alao and Popoola (2024) agree that cost of diesel has increased substantially in SA. Therefore, the data is supported by the literature that the energy cost of ICE has increased over time.

Concerning BETs’ energy costs, Uhunamure and Shale (2021), Nyoni and Phiri (2020), and Kruger et al. (2021) state that the cost of renewable energy has decreased with every bid window round. The data is supported by the literature that mines with wind and solar plants used to charge the BETs will benefit from the lower cost of electricity.

d) Insurance costs

There is very little literature on insurance costs for BETs other than to state that it is higher relative to ICE due to the cost of the high battery pack. According to the National Association of Insurance Commissioners (NAIC) website, the insurance cost for electric vehicles including trucks is higher due to the following factors:

- Scarcity of trained repairers
- Costly repairs due to new technology
- Battery fires
- High cost of replacing the battery pack

(2024, www.naic.org)

The NAIC notes that insurance costs have decreased over time from and average difference of $14 000 in 2013 to $1 810 per vehicle in 2019 (2024, www.naic.org).

5.4 Conclusion for proposition two

The research proposition based on the literature review in Chapter 2 is as follows:

It is proposed that currently, the TCO of ICETs is much lower; however, with improving technology, economies of scale, and government support, the total cost of ownership for BETs will reach parity and will be lower than ICETs. The findings and the literature show that at present, the TCO of ICETs is lower than BETs. However, as diesel costs rise and remain exposed to oil price volatility and environmental regulations along with growing maintenance expenses for ICE vehicles, electric trucks eventually reach cost parity. In the mining sector, the decision to transition to BETs often hinges on a longer-term perspective. Although BETs offer lower operating and maintenance costs over time, conservative financial directors may hesitate to make this shift, particularly given the high initial costs and rather nascent long-term value in mining applications.

5.5 Discussion of proposition three – barriers to adoption of BETs

Barriers to adoption refer to challenges or obstacles that prevent organisations from embracing new technologies or products. These barriers could be diverse and widespread.

5.5.1 Economic barriers

The data shows that economic barriers are high for BETs. The high initial capital cost proved to be the main barrier of adoption. The technology promises long-term savings; however, the 30% to 40% higher upfront remains a barrier.

Despite numerous governmental commitments to achieving net-zero emissions, there has been a lack of financial incentives to reduce the high upfront costs of adopting low-emission technologies such as BETs. This gap hinders widespread adoption, as many organisations are reluctant to invest in these technologies without sufficient subsidies or incentives. Incentivising the transition to BETs through tax credits, grants, or subsidies could play a crucial role in supporting corporate shifts toward cleaner alternatives.

5.5.2 Infrastructure challenges

The lack of charging stations is one of the most common infrastructure challenges as shown in the data. For this study, truck traffic is limited to the mine site. The trucks' principal function will be to transport mineral deposits from underground to the surface for further processing. If the mine adopts BETs, there will be sufficient charging infrastructure over time, but at the start of adoption it may be difficult to determine how many charging stations are required to provide optimal charging time and minimal truck downtime.

Another significant barrier to the adoption as identified in the data is that the requirement for highly skilled repair facilities capable of handling potential breakdowns. Access to service and maintenance shops is considerably more straightforward for internal ICETs, as mining companies have established long-standing relationships with OEMs. In contrast, the availability of repair shops and spare parts for BETs presents challenges that are unlikely to be resolved until economies of scale are achieved in the electric truck market.

5.5.3 Technology barriers

ICETs are more energy-dense because they are fuelled by diesel, which possesses a higher energy density than batteries. As a result, BETs require a longer charging time. The data indicates that charging time and driving range are among the most significant barriers to the adoption of BETs. In mining operations, the cost of downtime due to charging is substantial, as it means that trucks are unavailable for work, leading to a loss of production time and increasing overall production costs. In addition, these trucks must be able to cover the required mileage for the day and meet the demands of the work assigned to their drivers, which proves to be a barrier to the transition to electric vehicles in this sector.

5.5.4 Regulatory barriers

The data showed that South African government has no incentives to motivate its citizens to adopt electric vehicle technology. Reducing emissions in the mining sector will assist the government in achieving its net-zero commitments to the Paris Agreement, however mining companies should be incentivised to do so and have clear policy direction.

The data showed that there was no training and development of skilled people to operate and repair BETs or even electric passenger cars. This is a barrier to adoption as without skilled staff, companies may face challenges in ensuring the operational reliability and longevity of their BETs, ultimately impacting the overall transition to electrification in the mining sector.

5.6 Evidence in the literature

Chapter 2 introduced barriers to adoption based on the innovation’s characteristics and economic and sociological factors (Stratopoulos & Wang, 2022). The data showed that these factors influence the rate of adoption.

5.6.1 Economic barriers

Economic barriers such as high capital costs of BETs proved to be a major barrier to adoption. Qasim and Csaba (2021), Tanco et al. (2023), and Amante García and Canals Casals (2024) agree that the initial upfront cost of BETs remain high and can negatively impact the decision to transition to BETs. Mohammadi et al. (2023) argue that there is an emphasis on reducing transport emissions by transitioning to electric vehicles. However, the incentives necessary to support this shift are often insufficient, making the decision to adopt electric vehicles challenging for the average consumer. The data aligns with the literature.

5.6.2 Infrastructure challenges

After studying data from 30 different countries, Mohammadi et al. (2023) noted that charging infrastructure plays a key role in electric vehicle adoption. This was further supported by Mohamed et al. (2020)and Mahdavian et al. (2021) who noted that charging infrastructure is a barrier to adoption; however, this could be mitigated by battery swapping stations which will also reduce charging time.

Sopha et al. (2020) note that electric vehicle production and operation requires a specific skill set and human resources needs to ensure this skills set is developed. Iosifidou (2024) adds that talent integration and workforce upskilling for all EV-related projects is a challenge. Gautam and Bolia (2024) add that work must be done to identify skills gap in transitioning to electric vehicles so the organisation knows what additional skills to employ. The data lays the upskilling of employees at the hands of the government, while the literature review places the responsibility on the organisation transitioning.

5.6.3 Technology barriers

Technological barriers are the functional limitations of an electric truck (Bae et al., 2022). Sugihara et al. (2023) note that shorter driving range and reduced payload capacity are some of the technological barriers. Adu-Gyamfi et al. (2024) argue that battery range has improved over time; however, the introduction of battery swapping will solve the scepticism associated with range and charging time.

5.6.4 Regulatory barriers

Tura et al. (2019) define regulatory barriers as external barriers to the transition to BETs. These barriers could include a lack of standardisation, lack of policy, tax breaks, subsidies, and economic support (Chidambaram et al., 2023). Rizos and Urban (2024) maintain these views, but add battery circularity as a policy measure to control the disposal of batteries. China is the leading country in terms of electric vehicle adoption due to the government strategically supporting emerging industries by issuing a series of supportive policies (Wu et al., 2021). The data is congruent with the literature that regulatory support is crucial and a major barrier to the adoption of BETs if not provided.

5.7 Conclusion for proposition three

The research proposition based on the literature review in Chapter 2 is as follows:

It is proposed that despite the barriers to adoption, with ongoing government support and investment, technological advancements and infrastructure readiness, the adoption of BETs will gradually increase over time which will be beneficial to the environment. The data and the literature show that many barriers to the adoption of BETs exist in mines in SA. The primary barrier to transitioning to electric vehicles in SA is the lack of government support in the form of incentives, tax breaks, and a clear policy direction. While the South African government has introduced the Green Transport Strategy, this policy lacks specifics regarding direct incentives or tax relief to encourage the transition to electric vehicles. Economic incentives, such as tax breaks or subsidies, are essential to overcoming the cost barriers associated with adopting electric vehicles. Implementing these incentives would not only accelerate adoption but also help alleviate the financial burden on businesses, making the transition to a low-emission transport sector more attainable.

5.8 Conclusion

This chapter is a presentation and discussion of the findings in the context of the literature review for the three research propositions outlined in Chapter 2. Section 5.2 discussed the results pertaining to research proposition 1 where it was proposed that battery-powered trucks and better alternatives to diesel-powered trucks for i) reducing emissions, ii) protecting the environment, and iii) protecting human health. Section 5.3 discussed the results pertaining to research proposition 2 where is was proposed that currently the total cost of ownership of diesel-powered trucks is much lower however, with i) decreasing cost of battery packs, ii) economies of scale, iii) less maintenance, and iv) lower cost of energy, the total cost of battery-powered trucks will reach cost parity of diesel-powered trucks and ultimately be lower than diesel-powered trucks in the future. Section 5.4 discussed the findings pertaining to proposition 3 on the barriers to adoption, where it was proposed that with i) government support and investment, ii) technological advancements, and iii) infrastructure readiness, these barriers will gradually be addressed and the adoption of battery-powered trucks will increase over time which will be beneficial for the environment.

Each theme was substantiated by data in the literature review, which was aligned with the respective propositions. A key emerging theme was that battery-powered trucks offer significant environmental and health benefits compared to diesel-powered alternatives. While current data indicates that the TCO for diesel-powered trucks is lower than that of battery-powered trucks, projections suggest that cost parity can be achieved within the next four to five years. After this period, battery-powered trucks are expected to become the more cost-effective option.

The final theme, drawn from the last proposition, emphasises that barriers to adopting new technologies, such as battery-powered trucks, remain high. However, economic, regulatory, or technological barriers can be overcome with the right combination of economic incentives, regulatory frameworks, and advancements in technology and infrastructure. There was no new finding.

Chapter 6 answers the research questions as a response from the research findings and the literature review. It also recommends areas for future research.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Diesel engines have been a cornerstone of underground mining operations for decades. This is mainly due to their high torque and power, which enable them to handle heavy loads in challenging conditions. Their durability, fuel efficiency, and operational flexibility make them essential for productivity and efficiency in mining. Despite these advantages, diesel engines release harmful emissions, including nitrogen oxides (NO_x), particulate matter, and carbon monoxide, which pose significant health risks to miners and damage the environment. Results of a study done in Malaysia showed that medium diesel trucks exhibit higher CO_2 than electric trucks (Mustapa et al., 2024).

As a result, there is a growing movement in the mining sector toward the adoption of battery-operated electric trucks, which offer the advantage of having no tailpipe emissions, contributing to a cleaner working environment and reducing the carbon footprint of mining operations (Nieto et al., 2020). Replacing diesel trucks with battery-operated trucks, however, has significant implications some of which are i) economic, ii) regulatory compliance, iii) operational efficiency, and iv) environmental.

This research study offers data-based themes from secondary data that BETs are better for the environment and, over time, with the support of government, can be an economically viable option to be used in underground mining in SA. The research study made three evidence-based contributions to the body of knowledge, namely: i) diesel-powered trucks are harmful to the environment and human health in underground mines compared to BETs, ii) the TCO of diesel trucks in SA is lower than BETs; however, with the high cost of diesel and reducing cost of renewable energy coupled with reducing cost of battery packs, BETs will be cheaper in SA in four to five years, and iii) barriers to adoption can be overcome with the right policy support and advancement in technology.

Conclusions outlined in this chapter are structured within these three contributions, including the context and findings of this research study, as well as the established differences with the literature. The chapter ends with suggestions for future research.

6.2. Conclusions regarding research question one

The first research question is as follows: What is the environmental impact of using medium and heavy-duty BETs and how does it compare to diesel? The environmental impact of using BETs is centred around their potential to significantly reduce GHG emissions, improve air quality, and mitigate climate change (Ulrich et al., 2022). Increased demand for critical minerals such as copper emphasises the need for the mining sector to look at the sustainability of future mining operations in the context of technological advancements, increased ore body complexity as surface resources diminish, and health and safety of the miners as depth increases and climate changes (Moreau et al., 2021). As a signatory to the Paris Agreement, the South African government has taken on international commitments to address climate change (Loser, 2024). Mining activities in SA should be performed to produce less waste, extract responsibly, use safer procedures, adopt innovative sustainable technology, reduce emissions, increase the well-being of local communities, and promote environmental stewardship (Mvile & Bishoge, 2024). These practices will assist the government with the NDC goals it has signed up to.

There is strong evidence that using BETs will be better for the environment in terms of greenhouse gas emissions. Studies done by Li et al. (2021), Bie et al. (2023), Cheng et al. (2020), and Zhang et al. (2021) all conclude that ICET emissions are harmful to the environment and should be replaced by either BETs or hydrogen fuel cell trucks. Azam et al. (2024) note that the findings of many studies show the harmful effects of DPM on human health and there should therefore be an urgency to enhance emission control and exposure prevention strategies, paving the way for a healthier mining work environment. Rai et al. (2021) refer to a study done in Western Australia over seven years (2006-2012). The data collected over this period found that underground miners were exposed to a higher level of elemental carbon concentrations than surface mine workers, which was possibly due to a range of factors such as improper ventilation, maintenance of machinery, type of diesel equipment, etc. (Rai et al., 2021).

Historically, sustainability and mining were thought to be mutually exclusive. However, there are mining corporations that are investing in research and development together with OEMs to supply battery-powered drilling equipment and underground trucks to reduce their emissions and improve worker safety (Onifade et al., 2024).

BETs have lower life cycle emissions especially when powered by renewable energy. Iyer et al. (2023) argue that a careful analysis should be done on the environmental effects associated with the manufacturing of these alternative powertrains which are metal intensive.

The findings from this study overlap with the literature, specifically the harmful impact of the ICET emissions on the environment and human health. In the answer to research question 1 the data showed:

"Exposure to NO_x can result in adverse respiratory effects such as pulmonary inflammation or exacerbation of asthma" (Balboa-Espinoza et al., 2023).

"Research has shown that mine workers have an increased risk of lung cancer death that correlates to increasing exposure to diesel exhaust' (Meshginqalam et al., 2024).

"Diesel exhaust was classified as Group I 'carcinogenic to humans' in 2012 by the World Health Organization" (Meshginqalam et al., 2024).

"Air pollutants, such as fine particulate matter (PM2.5) and nitrogen oxides (NO_X), are major risks that affect human health, crop yields, and environments worldwide" (Huang et al., 2022).

The above offers an answer to the question and aligns to the significance of the study and the literature review. The key difference was the **NEW** finding that the environmental impact of medium and heavy-duty BETs is significantly lower than that of diesel trucks, particularly in the operation phase where BETs produce zero tailpipe emissions. However, challenges remain in terms of the upfront energy costs of battery production and mineral extraction. Over time, as technology improves and the energy grid of mining companies in SA shifts toward more renewable sources, BETs are expected to be more environmentally sustainable than diesel trucks across their entire lifecycle.

6.3 Conclusions regarding research question two

The second research question is as follows: How do medium and heavy-duty BETs compare to diesel trucks in terms of total cost of ownership? The TCO of alternative vehicles technologies have gained momentum over the years. Medium and heavy-duty vehicle alternative technologies have gained momentum recently, driven by the imposed emissions standards and regulations worldwide on those vehicle segments (Mao et al., 2021b). Several studies have been done on TCO of zero-emission trucks.

Table 17 TCO studies

Study	**Application**	**TCO component**	**Energy efficiency**	**Main findings**
Institute of Transportation Studies, UC Davis, US (Burke, 2020)	• Diesel, electric, and hydrogen HDV trucks • 100,000 to 134,000 mi/ year and 150 to 300 mi daily driving range • 5-year analysis period	• Truck purchase • Energy • Maintenance • Residual value	• Electric: 240 kWh/100 mi (~1,5kWh/km) in 2030 • Diesel: 8.7 mpg (~27 l/100 km) in 2030	• Battery cost should drop below $100/kWh to become cost competitive with diesel • BETs are more cost competitive in comparison to FCETs • FCETs can be more cost competitive than BETs for very high mileages (~600 mi)

Transport and Environment, Germany (Unterlohner, 2021)	• Diesel, electric, hydrogen, and e-diesel long-haulers • 136,750 km/year and 800 km daily driving range • Five-year analysis period	• Truck purchase • Energy infrastructure • Road charges • Taxes and levies	• Electric: 1.52 kWh/km in 2020 and 1.15 kWh/km in 2030 • Diesel: 29.86 l/100km in 2020 and 23.47 l/100 km in 2030	• BETs have a superior economic performance over all other alternative technologies • BETs powered by renewable electricity can reach TCO parity by 2025
Lawrence Berkeley National Laboratory, US (Phadke et al., 2021)	• Diesel and electric 36 tonnes long-haulers • 78,000 to 104,000 mi/year and 375 to 500 mi daily driving range • Three- to 15-year analysis period	• Truck purchase • Energy infrastructure • Maintenance • General operation	• Electric: 2.1 kWh/ mi (~1,32 kWh/km) in 2020 for a 36 tonnes truck • Diesel: 5.9 mpg (~40 l/100 km) in 2020	• BETs present a 13% reduction compared to TCO and a three-year pay-back period • Negligible payload penalty that can be overcome by lightweighting

Source: Basma et al. (2021)

Table 17 demonstrates the findings from various studies, all of which conclude that BETs are becoming increasingly cost competitive. The primary factors contributing to this trend include the falling price of battery packs and the use of renewable energy as a power source.

Globally, China is leading the transition to zero-emission trucks which accounted for 7% of truck sales in 2023. The EU follows with 1,6%. China, the EU, and the United States have introduced ambitious zero-emission truck policies involving a combination of demand incentives and regulations. BETs in all these three markets are near cost competitiveness with their diesel counterparts driven by these incentives (Kaur et al., 2024a).

The findings from this study overlap with the literature, specifically that the TCO of BETs will decrease over time and will reach cost parity in the next decade and will then be cheaper than the ICETs. In answer to research question 2, the data showed that:

- BETs have a higher initial purchase cost due to the battery pack while ICETs are as much as 60% cheaper.
- BETs powered by renewable energy at the mines have a lower cost of energy relative to diesel which is expected to increase over time and remains volatile to the oil price and the ZAR/USD exchange rate in SA.
- BETs have a lower maintenance cost as the engine is less complex relative to ICETs. However, battery replacement has not been considered in the calculations, which could significantly alter the result as the battery pack makes up approximately 60% of the cost of BETs.
- BETs have higher insurance costs as the technology is nascent relative to ICETs where the technology is well understood.
- Charging infrastructure costs for underground mines have not been considered and could be a substantial upfront capital cost for the mines. However, this can be offset over time due to the savings in diesel costs.
- Resale value has been ignored as data on the resale value of electric trucks is not forthcoming.
- BETs will reach cost parity in four to five years.

The above offers an answer to the question and aligns with the significance of the study and the literature review. While BETs have a higher initial purchase cost and require investments in charging infrastructure, they tend to have lower operating costs due to reduced fuel and maintenance expenses. Insurance and battery-related costs may still be higher, but the energy efficiency and potential savings from renewable energy sources at the mines make them a more cost-effective option over the long term, particularly for mining companies aiming to reduce their carbon footprint. Diesel trucks, although cheaper upfront, face rising diesel costs, maintenance requirements, and regulatory pressures, which increase their TCO over time. Ultimately, BETs present a compelling economic case for the future, especially as battery technology improves and renewable energy becomes more widely available at South African mines. The key difference was the **NEW** finding that BETs used in underground mining offer significant long-term cost advantages, both in terms of capital and operating expenses. In addition, the absence of tailpipe emissions not only eliminates harmful pollutants but also *drastically reduces ventilation and air conditioning costs*, as there are no emissions to manage and less heat is generated compared to diesel trucks. This makes BETs a more efficient and sustainable choice for underground mining operations, providing both environmental and economic benefits.

6.4 Conclusions regarding research question three

The third research question is as follows: What are the barriers to the adoption of medium and heavy-duty BETs in mining? While the transition to BETs presents sufficient value in terms of reduced emissions and potential long-term cost savings, the barriers to the adoption of this technology remain prevalent (Bao et al., 2024). Davoren et al. (2024) identified some of these barriers as high upfront costs of BETs and lack of proper infrastructure planning and incentives schemes before considering the rollout of BETs. Bao et al. (2024) note that one of the crucial considerations in adopting BETs is the energy disparity between diesel fuel and battery technology. Some of the considerations preventing BETs from being adopted as mines' main production equipment are machine productivity, whether can they be the same as diesel, fire and safety as employees are not familiar with the technology and will need training, potential electric-related accidents, and the need to find suitable change management in the mining sector who have the vision to adopt this new technology (Halim & Hooli, 2024).

Currently, SA's electricity generation is mainly from coal; however, the REIPPPP, a renewable energy auction programme affected the re-design of the Integrated Resource Plan to allow for more pro-renewable energy planning (Schmid & Lumsden, 2023), which makes charging of BETs using renewable energy more attractive and improves grid stability.

Mirzania et al. (2023) identified a myriad of challenges to the adoption of low-carbon technologies in SA, being lack of strategic direction by the government, lack of cohesion between municipal and national government on policy, the lack of availability of resources to support low-carbon technologies or to compensate for losses, lack of institutional capacity to carry forward JET strategies, and a deficit of relevant skills in developing manufacturing capacity of resources needed for JET.

Onifade et al. (2024) highlighted the social factors of transitioning to green technologies. Mines operate in a community and need to have the community involved in their transition plans, achieving a social licence to operate and ensure that there will be no job losses with new technology, and this requires effective engagement with local communities (Onifade et al., 2024).

The findings from the study overlap with the literature especially the themes of economic, technological, infrastructure, and regulatory barriers. In answer to the research question, the data showed that:

"*High acquisition costs were the primary reason they were not considering electric trucks" (Sugihara et al., 2023).*

"The most concerning barrier is the high purchase price" (Tanco et al., 2023).

"To optimise the use of electric trucks, the number of electric charging stations has to increase" (Tanco et al., 2023).

"BETs can be charged through plug-in chargers but there are still challenges associated such as heavy battery packs and the time taken to charge" (Ruoso & Ribeiro, 2022).

"One of the main barriers to adoption is operational reliability of driving range and battery capabilities coupled with lost downtime" (Konstantinou & Gkritza, 2023).

"The most concerning barriers are low incentives, charging infrastructure, and driving range" (Ruoso & Ribeiro, 2022).

"The slow adoption of electric vehicles in SA is due to a lack of political will and the absence of incentives" (Ruoso & Ribeiro, 2022). "Barriers to adopting electric vehicles in SA require policy changes, regulatory framework, and skill set" (Ruoso & Ribeiro, 2022).

"There should be tax breaks for mining and manufacturers fostering an appropriate policy environment for change to BETs" (Cloete, 2020).

The above answers the question and remains relevant to the significance of the study and the literature review. The adoption of medium and heavy-duty BETs in mining in SA faces specific barriers that are influenced by the country's unique economic, regulatory, and infrastructural landscape. Overcoming these barriers will require collaboration between the government, the private sector, and stakeholders in the mining industry. Investments in renewable energy, supportive government policies, and advances in battery technology could help accelerate the transition to BETs in SA. The **NEW** finding as a barrier to adoption is inclusive decision-making; the success of transitioning to BETs requires involving all key stakeholders, including workers, local communities, and unions, in the decision-making process. Transparent communication about the benefits and challenges of adopting BETs, as well as the potential for job displacement, can help to build trust and minimise resistance to change.

Table 18 Consistency table: research questions, conclusions, and contribution to knowledge

RQ #	State research question or objective	State literature-based proposition or hypothesis	State conclusion or answer based on own research	Highlight key differences between your initial propositions / hypotheses and your findings – this is your contribution to knowledge
1	What is the environmental impact of using medium and heavy-duty BETs and how does it compare to diesel?	It is proposed that BETs are better alternatives to diesel trucks for reducing emissions, protecting the environment, and protecting human health.	The data shows that BETs are more beneficial for the environment than ICETs as there are no tailpipe emissions.	The key difference was the **NEW** finding that the environmental impact of medium and heavy-duty BETs is significantly lower than that of diesel trucks, particularly in the operation phase where BETs produce zero tailpipe emissions. However, challenges remain in terms of the upfront energy costs of battery production and mineral extraction.
2.	How do medium and heavy-duty BETs compare to diesel trucks in terms of total cost of ownership?	It is proposed that currently, the total cost of ownership of diesel-powered trucks is much lower. However, with improving technology, economies of scale, and government support, the total cost of ownership of BETs will reach parity and	The data shows that in the next three to five years, cost parity will be reached between BETs and ICETs.	The key difference was the **NEW** finding that BETs used in underground mining offer significant long-term cost advantages, both in terms of capital and operating expenses. In addition, the absence of tailpipe emissions not only eliminates harmful pollutants but also *drastically reduces ventilation and air conditioning costs*, as there are no emissions to manage and less heat is generated compared to diesel trucks. This makes BETs a more efficient and sustainable choice for

RQ #	State research question or objective	State literature-based proposition or hypothesis	State conclusion or answer based on own research	Highlight key differences between your initial propositions / hypotheses and your findings – this is your contribution to knowledge
		ultimately be lower than ICETs in future.		underground mining operations, providing both environmental and economic benefits.
3.	What are the barriers to the adoption of medium and heavy-duty BETs in mining?	Despite these barriers, it is proposed that with ongoing technological advancements, government support, and investments, these challenges will be gradually addressed and the adoption of BETs will increase over time.	The data shows there are many barriers to the adoption of BETs in mining in South Africa.	The **NEW** finding as a barrier to adoption is inclusive decision-making, the success of transitioning to BETs requires involving all key stakeholders, including workers, local communities, and unions, in the decision-making process. Transparent communication about the benefits and challenges of adopting BETs, as well as the potential for job displacement, can help to build trust and minimise resistance to change.

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Appendix 1

Table of secondary sources

Author	Year	Title	Source Type	Relevance to research
Adu-Gyamfi, G., Song, H., Nketiah, E., Obuobi, B., & Djanie, A. K	2024	Remedying driving range and refueling challenges in electric mobility: Consumer adoption of battery-swappable electric vehicles	Journal Article	Supports argument for driving range of BETs
Agboola, O., Babatunde, D. E., Fayomi, O. S. I., Sadiku, E. R., Popoola, P., Moropeng, L., Yahaya, A., & Mamudu, O. A.	2020	A review on the impact of mining operation: Monitoring, assessment and management. Results in Engineering	Journal Article	Provided overview of mining operation and what trucks are used.
Ahluwalia, R. K., Wang, X., Papadias, D. D., & Star, A. G.	2023	Performance and Total Cost of Ownership of a Fuel Cell Hybrid Mining Truck. Energies,	Journal Article	Supports TCO argument for BET as opposed for fuel cell trucks.
Akinbami, O. M., Oke, S. R., & Bodunrin, M. O	2020	The state of renewable energy development in South Africa: An overview. Alexandria Engineering	Journal Article	Supports argument for charging infrastructure barriers.

Albatayneh, A., Juaidi, A., Jaradat, M., & Manzano-Agugliaro, F.	2023	Future of Electric and Hydrogen Cars and Trucks: An Overview. Energies	Journal Article	Offers perspective of BETs and fuel cell trucks.
Amante García, B., & Canals Casals, L.	2024	Barriers to electrification: Analyzing critical delays and pathways forward. World Electric Vehicle	Journal Article	Supports data on barriers to adoption
Cheng, S., Zhang, B., Peng, P., Yang, Z., & Lu, F.	2020	Spatiotemporal evolution pattern detection for heavy-duty diesel truck emissions using trajectory mining: A case study of Tianjin, China.	Journal of Cleaner Production	Supports data of diesel emissions
Chidambaram, K., Ashok, B., Vignesh, R., Deepak, C., Ramesh, R., Narendhra, T. M., Muhammad Usman, K., & Kavitha,	2023	Critical analysis on the implementation barriers and consumer perception toward future electric mobility.	Journal of Automobile Engineering	Supports data for barriers of adoption
Cloete, D	2020	Futures of Mining: Implications of Large-Scale EV Adoption.	Journal Article	Provides data for barriers to adoption of BETs
Davoren, B., Ferg, E. E., & Foli, E	2024	From kilowatts to kilometers: Unpacking the Potential of	South African Journal of Chemistry	Supports data for electric mobility and emissions

		Electric Mobility in Africa.		
Delevingne, L., Glazener, W., Grégoir, L., & Henderson, K	2020	Climate risk and decarbonisation: What every mining CEO needs to know	McKinsey Report	Supports data for decarbonisation
Domela, M. G., Ze, T., & Zakirullah, Z.	2023	Literature Review on Chinese Foreign Direct Investment in the South African Mining Sector: Determinants and Development.	Journal Article	Combines data from multiple sources on the Mining Sector in South Africa
EActros 600	n.d	Mercedes Benz Trucks	News Article	Provides a summary of recent developments in the BET market
Ediriweera, A., & Wiewiora, A.	2021	Barriers and enablers of technology adoption in the mining industry.	Industry Report	Analyzes trends, forecasts, and data on electric truck adoption and market growth.
El Sayed, M. A., & Salah, W.	2023	Secondary data-associated challenges for environmental assessment in developing countries	Case Study	Summarises environmental challenges in developing countries
Epiroc.	n.d	Battery swap Scooptram ST14.	News Article	Provides a summary of recent developments in the BET market
Fiscor, S.	2021	Electrification Leads the Way	Journal Article	Provides data on why BETs are better for emissions
García, A., Monsalve-Serrano, J.,	2023	Carbon footprint of battery electric vehicles	Journal for Cleaner Production	Supports data for argument of emissions of the value chain for BETs

Martinez-Boggio, S., & Alcaide, R. S.		considering average and marginal electricity mix.		
Geldenhuys, G., Wattrus, M., Fox, M., & Forbes, P	2023	Investigations into the transition to sustainable alternative fuels in a South African underground platinum mine.	Journal Article	Supports data for alternate fuels in underground mines
Ghorbani, Y., Nwaila, G. T., Zhang, S. E., Bourdeau, J. E., Cánovas, M., Arzua, J., & Nikadat, N.	2023	Moving towards deep underground mineral resources: Drivers, challenges and potential solutions.	Policy Paper	Provides data for underground emissions and ventilation
Gonen, A.	2021	Energy savings in auxiliary ventilation systems of underground mines.	Journal Article	Supports data and case studies to assess ventilation systems
Gunawan, T. A., & Monaghan, R. F.	2021	Techno-econo-environmental comparisons of zero-and low-emission heavy-duty trucks	Journal of cleaner Production	Provides data for TCO analysis
Halim, A., & Hooli, J.	2024	A Snapshot of the Use of Battery Electric Vehicles in Underground Hardrock Mines.	Industry report	Analyses data on electric truck adoption in underground mines
Hovi, I. B., Pinchasik, D. R., Figenbaum, E., & Thorne, R. J.	2019	Experiences from Battery-Electric Truck Users in Norway.	Industry report	Analyses data on electric truck adoption

Huang, W., Xu, X., Hu, M., & Huang, W.	2022	A license plate recognition data to estimate and visualise the restriction policy for diesel vehicles on urban air quality: A case study of Shenzhen.	Journal Article	Supports emissions data for diesel trucks
IEA	n.d	Global EV outlook	Industry Report	Analyses trends, forecasts, and data on electric truck adoption and market growth.
IM Mining.	n.d	Landmark study by IGO confirms technical feasibility of an all-electric underground fleet for Cosmos.	Industry Report	Provides data on electric truck adoption
Jacobs, D., van Laar, J., & Schutte, C	2022	Strategy to identify and mitigate hazards in deep-level mine ventilation systems using a calibrated digital twin.	Journal Article	Supports data for ventilation and emissions
Kaur, H., Yadav, A., & Deo, A.	2024	Total cost of ownership parity between battery electric trucks and diesel trucks in India.	Journal Article	Provides data and case studies to assess TCO
Kim, H., Hartmann, N., Zeller, M., Luise, R., & Soylu, T	2021	Comparative TCO analysis of battery electric and hydrogen fuel cell buses for public transport system in small to midsize cities.	Journal Article	Supports data for TCO

Konstantinou, T., & Gkritza, K.	2023	Examining the barriers to electric truck adoption as a system: A Grey-DEMATEL approach.	Journal Article	Provides data for barriers to adoption
Kurien, C., & Srivastava, A. K.	2020	Impact of electric vehicles on indirect carbon emissions and the role of engine posttreatment emission control strategies	Journal Article	Summarises emissions data
Mohammed, L., Niesten, E., & Gagliardi, D.	2020	Adoption of alternative fuel vehicle fleets–a theoretical framework of barriers and enablers.	Journal Article	Provided data on barriers to adoption
Morla, R., Karekal, S., & Godbole, A.	2021	Analysis of Diesel Particulate Matter Flow Patterns in Different Ventilation and Operational Conditions of Underground Mines. Introduction to Diesel Emissions.	Journal of Clean Production	Supports data on diesel emissions
Müller, C.	2024	Transition to battery-electric and fuel cell heavy-duty trucks: A multi-level, multi-dimensional approach. Transportation Research Part D:	Journal Article	Provided data on BET batteries

		Transport and Environment,		
Nkambule, M. S., Hasan, A. N., & Shongwe, T.	2023	Performance and techno-economic analysis of optimal hybrid renewable energy systems for the mining industry in South Africa.	Journal Article	Supports data for TCO analysis
Qasim, M., & Csaba, C.	2021	Major Barriers in Adoption of Electric Trucks in Logistics System.	Journal Article	Provided data on barriers to adoption
Rajagopal, D., Gopinathan, N., Khandekar, A., Karali, N., Phadke, A., & Abhyankar, N.	2024	Comparative Evaluation of Total Cost of Ownership of Battery-Electric and Diesel Trucks in India.	Transport research paper for India	Provided data on TCO
Speth, D., Plötz, P., Funke, S., & Vallarella, E	2022	Public fast charging infrastructure for battery electric trucks	Journal Article	Supports data for charging infrastructure
Wang, G., Fulton, L., & Miller, M.	2022	The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage.	Industry report	Supports TCO data