Politecnico di Torino

Master Degree in Geoenergy and Georesources Engineering

A.Y. 2024-2025

March 2025

Optimizing Mining Operation: E-LHD Machine for Sustainability, Efficiency and Safety

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Abstract

Optimizing Mining Operation: E-LHD Machine for Sustainability, Efficiency, and Safety

This study looks at replacing old, diesel-powered Load-Haul-Dump (LHD) machines with modern, battery-electric ones. Focusing on IMI Fabi's operations, it highlights how electric LHDs, like the Scooptram ST14 Battery, can make mining more efficient and much pleasanter to both the environment and the workers.

Traditionally, diesel LHDs have been standard machine used in mining, but they come with their own set of problems. They're loud, they emit a lot of pollutants, and they generate a lot of heat. All this makes the mining environment tough for workers and heavy on ventilation systems. Enter electric LHDs: they emit no pollutants, make much less noise, and are cooler to operate, reducing the need for complex ventilation and making mines safer and more comfortable places to work.

At IMI Fabi's talc mine, the benefits of switching to electric are clear. These machines not only help cut down carbon dioxide emissions and operational costs but are also better at using energy efficiently. Showing through energy analyses just how much more efficient these electric machines can be in real mining conditions.

Thus, shifting to this new technology isn't simple. The initial investment can be high enough, and setting up the necessary charging infrastructure takes effort and planning. But the long-term advantages, like cost savings and a better working environment, make a convincing case for change. By using real-world data and simulations, my research confirms that electric LHDs are a practical solution that offers a cleaner, safer, and more cost-effective future for mining.

Table of Contents

Table of Figures

1. Introduction

For a while now in mining activities have relied on diesel fueled Load Haul Dump (LHD) machines due, to their energy output and reliability, in getting the job done efficiently in tight spaces where productivity is crucially important. Nonetheless even though these machines have been used for a time the use of diesel-powered machinery poses hurdles concerning environmental effects, operational expenses and the well-being and safety of workers. As mining activities expand further and regulations become stricter over time there is an increasing need, for energy efficient options.

The transition from traditional diesel-powered Load Haul Dump (LHD) machines to battery electric (E-LHD) alternatives is a significant technological innovation in underground mining. Battery electric LHDs solve various problems of diesel-powered machinery, ventilation constraints, emissions, energy efficiency and operational cost savings (Barnewold & Lottermoser al., 2020). These developments associate with the mining industry's growing emphasis on sustainability, automation and digital combinations.

This research focuses on the IMI Fabi talc mining operations, a leading international producer of high-quality talc with a strong commitment to sustainability and process innovation. IMI Fabi operates several mines and processing plants worldwide, ensuring a consistent and reliable supply of talc for industries such as polymers, coatings, cosmetic, and pharmaceuticals. As part of its efforts to improve energy efficiency, reduce environmental impact, and enhance workplace safety, IMI Fabi has taken advantage the integration of battery-electric LHDs within its underground mining operations.

The focus of this research is IMI Fabi, one of the biggest producers of high-quality talc in the world, paying attention to the sustainability. This work aims to demonstrate how IMI Fabi has applied E-LHDs underground to improve energy consumption, minimize environmental effects, and enhance safety. IMI Fabi owns several mines and processing facilities worldwide to supply consistent talc to the polymers, coatings, cosmetics, and pharmaceuticals industries. To this end, to reduce energy consumption, IMI Fabi has embraced the use of battery electric LHDs in its mining operations.

Furthermore, this study is positioned within the larger context of sustainable mining practices, consistent with global environmental policies and industry-wide efforts to decrease dependence on fossil fuels. Because future technological developments will build on what we've learned about how battery electric technology affects mining operations on a large scale, it's important to understand those implications as we make investment and regulatory decisions.

This study aims to enhance the existing knowledge, on mining practices by examining IMI Fabis mining operations and providing suggestions for industry professionals in leadership positions and policymakers to consider. By assessing energy efficiency levels and operational safety measures along with their repercussions, in underground mining activities this research endeavors to shape the future of mining practices amidst a period of rapid technological advancements and heightened environmental consciousness.

1.2 Research Objective

The main goal of this study is to assess how well battery powered Load Haul Dump (or LHD, for machines work in mining at IMI Fabi Brusada mine and to see what effect they have on operations there. We have set following goals, for this research.

1. Evaluate the Energy Efficiency of Electric LHDs:

To evaluate how energy the Scooptram ST14 Battery uses compared to diesel powered LHD machines in terms of energy, per ton of material moved and operational efficiency; and also examine how the size of the battery availability of charging stations and regenerative braking affect the overall energy efficiency of electric LHD operations.

2. Assess Environmental Benefits:

Comparatively assess how electric LHD usage reduces CO_2 emissions and other harmful pollutants, like NO_x and CO when contrasted with diesel options. Analyze the effects on mine ventilation expenses caused by phasing out diesel exhaust emissions and reducing the necessity, for ventilation setups.

3. Examine the Impact on Worker Health and Safety:

In studying the enhancement of air quality and the positive impacts, on workers' health by reducing illnesses and limiting exposure to diesel emissions in the workplace safety context; particularly exploring how eliminating diesel, in underground operations can enhance worker safety by minimizing fire hazards.

4. Analyze the Operational Feasibility and Cost Savings:

To assess the operational costs of using battery-electric LHDs, including fuel savings, maintenance costs, and charging infrastructure costs.in order to evaluate the return on investment (ROI) for transitioning to electric LHDs, factoring in capital investment in the equipment and infrastructure compared to the savings from reduced fuel consumption and maintenance requirement.

5. Identify Challenges and Barriers to Full Integration:

To further examine the technical challenges of incorporating battery electric LHDs into current mining operations, including charging times, battery life, battery management systems, and charging infrastructure. The economic and logistical barrier that may limit the widespread adoption of electric LHDs in underground mining operations, especially in smaller and medium sized mines.

6. Develop Recommendations for Future Adoption and Scaling:

To recommend for improving electric LHD operations optimization of battery management, charging infrastructure and fleet management strategies are found in this study. With focus on sustainability, cost-effectiveness, and operational efficiency, strategies for overcoming the barriers in order to adoption and scaling up the use of electric LHD in mining operations globally are proposed.

1.3 Overview

Traditionally, in mining operations, Load Haul Dump (LHD) machines have been diesel powered for material handling. However, the consequences of using diesel equipment such as emissions and ventilation requirements are not something that the mining industry can ignore anymore. This paper will discuss how, there is a growing push towards implementing mining practices and embracing battery electric technology to promote energy efficiency and reduce environmental impact.

Battery-electric LHDs are becoming a viable option to replace diesel-powered machines in this context. These electric vehicles have several advantages over diesel models, including zero emissions, lower noise levels, and lower operating costs. Also, integrating battery electric machines into mining operations is consistent with global efforts for cutting carbon footprints, improve worker safety, and improve operational efficiency.

In this research the performance evaluation of battery electric LHDs is reported, specifically the Scooptram ST14 Battery in the underground mining operations at IMI Fabi's Lanzada Mine. IMI Fabi, the leading talc producer has started the electrification process as a part of its sustainability policy improvement in energy efficiency, carbon emissions, and HSE.

The study evaluates energy consumption and carbon emissions, fuel savings and improved worker safety related KPIs of electric LHDs versus traditional diesel-powered machines. It also evaluates the economic feasibility of switching for electric machines by evaluating capital investment costs, charging infrastructure, and long-term operational savings.

Through this case study, the research intends to offer a comprehensive analysis of the practical benefits and challenges of electric LHDs adoption in mining industry. Thus, based on real world data and performance metrics from IMI Fabi, the study will assist in determining the best approaches for incorporating electric machines into underground operations and the findings will be useful for mining companies, policymakers, and equipment manufacturers planning to embrace sustainability in future.

This research also pursues to add to the literature, specifically regarding the long-term performance and the operational challenges of battery electric LHDs in demanding mining environments, which is an important contribution in order to developing field of sustainable mining technologies.

2. *State of the art: the use of the E-LHD machine in the mines*

The increasing focus, on sustainability and technological progress has led to a rise in the adoption of Load Haul Dump (LHD) machines in mining operations instead of traditional diesel-powered equipment. Research into the shift towards mining machinery has intensified as companies, in the mining sector strive to tackle issues while cutting operational expenses and enhancing safety measures underground.

Scientific literature offers useful findings concerning the operational efficiency, energy consumption, and maintenance aspects of electric LHDs as opposed to their diesel-powered counterparts. An important area of academic focus has been the economic feasibility of electrification, with specific focus on capital investment costs, battery lifecycle analysis, and the long-term savings from reduced fuel consumption and maintenance. Studies also highlight the significance of the developments in battery technology which have improved the economic feasibility of electric LHDs and helped them to work effectively in demanding underground environments. Hence, this paper finds that there is sufficient evidence to support the hypothesis that electric LHDs are more economical than their diesel-powered counterparts.

Beyond the energy and economic benefits, research has been conducted on how electric LHDs impact safety and health in the workplace. Studies have shown the decrease in exposure to diesel particulate matter, or DPM, which is a major health hazard to miners and can lead to respiratory diseases. The displacement of diesel engines results in lower ventilation needs, meeting both energy consumption and air quality issues. Furthermore, the lower risk of fire hazards associated with electric drivetrains makes electric LHDs safer to use in underground mining operations.

Real world data and performance metrics has been provided by technical reports from industry leaders, equipment manufacturers, and mining associations to this field as well. The existing mining systems are also where real world data and performance metrics on the operational constraints, battery performance, and charging infrastructure needed to integrate electric LHDs has been provided by these reports. They also explore the challenges of electrification, like battery charging times, energy storage capacity, and the general incompatibility of electric LHDs with an underground mining environment.

Based on a review of academic studies, technical reports, and industry case studies, this state-of-the-art review provides a comprehensive overview of the status of electric LHD adoption in underground mining. The significance of this paper is that it highlights the technical, economic and environmental benefits of battery electric LHDs and provides a foundation for future work that will evaluate the performance, scalability, and other impacts of electrification in the mining industry.

2.1 Advancements in Battery Electric Load-Haul-Dump (E-LHD) Technology for underground mining

The transition from traditional diesel-powered Load-Haul-Dump (LHD) machines to battery-electric (E-LHD) alternatives represents a significant technological innovation in the case of underground mining. Battery-electric LHDs address multiple challenges associated with diesel-powered machinery, such as ventilations constraints, emissions reducing, energy efficiency, and operational cost savings (Barnewold & Lottermoser, 2020) . These developments, associate with the mining industry's increasing focus on sustainability, automation, and digital combinations.

Automation in mining is not a new concept but has rapidly advanced in recent years, fundamentally reshaping how mining operations are managed. The use of autonomous systems in underground mines, such as load-haul-dump (LHD) systems, is a prime example of this transformation. Automation aims to improve operational efficiency, reduce human exposure to hazardous environments, and enhance productivity. A study reviewed in the document (Dragt et al., 2005) emphasizes that autonomous LHD systems are crucial for improving the safety and operational efficiency of the underground mines by reducing the risk of human injurines and improving the accuracy of operations.

Automation can also, in the long term, lower operational costs at the expense of large initial investments. The integration of real time data analytics, GPS based systems and communication technologies has enabled operators to improve the surveillance and control of mining operations to reduce time and improve the recovery of resources. Also, remote control and autonomous vehicles eliminate the need for human presence in the worst mining conditions, thus ensuring the safety of the workers.

The adoption of E-LHDs is driven by several technological innovations, including advancements in battery chemistry, powertrain design, charging infrastructure, and automation. As underground mining environments impose severe constraint on vehicle mobility, energy availability, and maintenance, the shift towards battery-electric solutions requires a thorough assessment of system reliability, operational efficiency, and economic viability (Sayadi et al., 2012)

2.2 The Role of Electrification in Underground Mining Operations

Electrification is rising as a foundation in modern underground mining operations, offering solutions to environmental concerns, operational efficiency, and regulatory requirements. Diesel LHD's have traditionally dominated underground mining due to their reliability and high-power output. However, they contribute to poor air quality, increased ventilation costs, and high carbon footprints (Rahimdel & Mohammadpour, 2025). Battery-electric LHDs reduce diesel particulate matter (DPM), improve air quality, and lower ventilations demands, significantly cutting operational costs in deep underground mines. These improvements support the mining industry's broader push towards green and sustainable operations (Salas et al., 2025)

2.3 Energy Efficiency and Sustainability in Mining: The Evolution of Battery-Electric LHDs

The advancement of battery powered Load Haul Dump vehicles is greatly shaped by the mining industries dedication to conserving energy and promoting sustainability. The key driver, behind the adoption of battery mining machinery is the aim to decrease greenhouse gas emissions and cut down on expenses. (Barnewold & Lottermoser, 2020). When you look at battery LHD vehicles, versus the diesel ones in the mining operations. The electric versions are energy thanks, to their regenerative braking systems and smart power management techniques. The inclusion of smart battery management systems (known as BMS) helps in maximizing energy usage and prolong the battery life span This all adds up to making mining operations more sustainable. (Kim & Choi, 2025)

2.4 A Comparative Analysis of Diesel and Electric Load-Haul-Dump Machines in the Mining Industry

A comparison between diesel and battery electric LHDs shows that electrification is advantageous from an economic, environmental, and operational point of view. High power density and more operational range are offered by diesel powered LHDs, but at a cost of high fuel costs, stringent emission regulations, and the need for extensive ventilation (Priyadarshini Nayak, 2023) Operating expenses are also reduced considerably by battery electric LHDs, by not incurring fuel costs and requiring minimal or no investment in ventilation infrastructure. In addition, electric LHDs improve on worker safety by reducing the generation of heat and emissions. (Godwin et al., 2008) . However, limitation such as battery charging time, energy storage capacity, and early capital investments remains critical barriers for widespread adoption (Sayadi et al., 2012)

2.5 Technological Innovations in Battery-Electric Mining Equipment: Trends and Challenges

The focus of the latest technological advancements in battery electric mining equipment has been on improving the operational efficiency, automation and digital connectivity. The field of battery chemistry has especially been enhanced with respect to energy density and charging cycles by lithium-ion and solid-state batteries (Salas et al., 2025). The integration of autonomous navigation systems, real-time monitoring, and predictive maintenance strategies further enhances the efficiency and reliability of E-LHDs in underground mining environments. Nevertheless, challenge such as battery degradation, charging infrastructure development, and thermal management continue to impede large-scale implementation (Mäkelä et al., 1995a)

2.6 The Impact of Electrification on Mine Ventilation, Worker Safety, and Environmental Sustainability

The shift towards battery-electric Load-Haul-Dump (E-LHD) machines significantly impacts mine ventilation, worker safety, and environmental sustainability. Diesel-powered mining equipment generates substantial heat and harmful emissions, including diesel particulate matter (DPM) and carbon monoxide, necessitating extensive ventilation systems to maintain air quality (Rahimdel & Mohammadpour, 2025). electric mining equipment eliminates direct emissions, leading to reduced ventilation requirements and operational costs. Moreover, electrification enhances worker safety by lowering exposure to toxic gases and minimizing heat stress, contributing to improved underground working conditions (Godwin et al., 2008). From an environmental perspective, battery-electric solution must be aligned with global sustainability goals, significantly reducing greenhouse gas emissions in underground mining operations (Barnewold & Lottermoser, 2020)

The mining sector now sees sustainability as an aspect, due to the increasing emphasis on reducing harm and optimizing resource utilization in coal extraction operations as illustrated by the role of cleaner coal mining technologies and efficient waste management strategies in reducing the environmental footprint of coal extraction. The implementation of cutting-edge technologies, in coal washing and processing has led to a decrease in the release of gases and particles while enhancing the impact of coal mining operations. In addition to this advancement in technology is the focus, on mining practices that highlight the importance of resource preservation, recovery and integrating circular economy principles into mining operations.

2.7 Charging Infrastructure and Battery Management Strategies for E-LHDs in Underground mines

Challenges arise in the realm of battery mining equipment due to the need for charging infrastructure and battery management techniques to keep operations running smoothly and efficiently (Salas et al., 2025). Unlike diesel fueled LHD machines that can be refueled quickly on the go; E LHD equipment requires charging stations and downtime for battery recharging purposes. Though, recent innovations in rapid charging technologies and battery swap systems have been able to tackle this issue effectively; ensuring that mining activities face minimal interruptions, along the way. Furthermore' intelligent battery management systems (IBM)' enhance energy efficiency. Extend battery lifespan through the adjustment of charging patterns and real time monitoring of battery condition ((Kim & Choi, 2025)

2.8 Operational Reliability and Maintenance of Battery-Electric Loaders in Harsh Mining Environments

OHS reliability of E-LHDs in harsh underground environments is a key factor in their adoption. Battery electric mining equipment must endure severe conditions, including high humidity, dust, and temperature variations that can affect battery life and overall machine reliability (Sayadi et al., 2012). The advanced predictive maintenance strategies enabled by digital sensors and IoT-based condition monitoring ensure that faults are identified at an early stage and that downtime is minimized and unexpected (Mäkelä et al., 1995b). Nevertheless, the long-term durability of the batteries in such conditions is an issue that requires further study of robust battery designs and thermal management systems (Rahimdel & Mohammadpour, 2025)

2.9 Automation and Digital Integration of E-LHDs: Enhancing Efficiency and Safety

The combinations of automation and digital technologies in E-LHDs has revolutionized underground mining operations. Autonomous LHDs equipped with AI-driven navigation systems and real-time data analytics can improve the productivity by optimizing haulage routes and reducing the human intervention (Salas et al., 2025). Machine learning algorithms and deep reinforcement learning models further improve autonomous loading and unloading capabilities, minimizing cycle times and maximizing efficiency (Kim & Choi, 2025) . The incorporation of teleoperation systems also ensures worker safety by allowing remote control of LHDs from surface operations, reducing exposure to hazardous underground conditions (Godwin et al., 2008)

2.10 Economic and Environmental Justifications for Transitioning to Battery-Electric Mining Equipment

Switching from diesel powered to battery mining equipment makes sense from both an environmental standpoint. Even though the upfront costs of E LHDs are higher compared to diesel options (Sayadi et al., 2012) the potential savings, in fuel usage and maintenance, over time can offset this investment. Additionally, " with pressures and carbon taxes pushing companies to embrace energy solutions " battery electric mining equipment is becoming an attractive long-term investment (Barnewold & Lottermoser, 2020) . The decrease, in carbon emissions and adherence to regulations provide additional support, for the widespread integration of E LHD technology (Rahimdel & Mohammadpour, 2025)

2.11 Regenerative Braking Systems in Battery-Electric Loaders: Principles and Performance Implications

Regenerative braking technology is particularly important in enhancing the energy efficiency of battery and electric mining equipment. Conventional braking systems are inefficient as they act by converting kinetic energy into heat, whereas regenerative braking recovers kinetic energy during deceleration and uses it to charge the batteries (Kim & Choi et al., 2025). This innovation enhances the energy efficiency of the E-LHDs and reduces the number of charging cycles, thus enhancing the overall productivity (Salas et al., 2025). Nevertheless, the possibility of recovering braking in the conditions of the underground mining depends on specific factors, including gradients of the haul roads, load on the machines and the efficiency of the braking system (Mäkelä et al., 1995a)

2.12 The Future of Underground Mining: AI, Machine Learning, and Smart Energy Management in LHD Fleets

The future of underground mining is more and more driven by artificial intelligence, machine learning, and smart energy management systems. Strategies of fleet optimization powered by artificial intelligence can enhance the coordination of the LHD movements and improve productivity generally (Barnewold & Lottermoser, 2020). The future predictive maintenance models are based on machine learning algorithms and are used to detect potential failures before they occur and decrease the frequency of unplanned downtime (Godwin et al., 2008).

Furthermore, smart energy management systems control battery usage, which equally distributes energy use throughout the entire fleet (Rahimdel & Mohammadpour, 2025). The technologies have greatly improved the operations of the operations to make them safer. As the paper (Onifade et al., 2023) notes, innovations in geotechnical monitoring, ventilation and hazard detection equipment enhanced safety of mine.

2.13 Occupational Health Benefits of Electrification: Reducing Toxic Emissions in Underground Mines

The electrification of mining equipment significantly improves occupational health by reducing workers' exposure to hazardous emissions. Diesel-powered LHDs produce high levels of DPM, nitrogen oxides (NOx), and carbon monoxide, which pose serious health risks to underground miners (Rahimdel & Mohammadpour, 2025) Battery-electric mining equipment eliminates these emissions, resulting in improved air quality and reduced respiratory diseases among workers (Godwin et al., 2008) . Moreover, lower noise levels from electric machinery contribute to a safer and more comfortable working environment (Salas et al., 2025)

2.14 Fleet Optimization Strategies for Battery-Electric Mining Equipment: Case Studies and Industry Applications

Fleet optimization strategies are very vital in optimizing the performance of E-LHDs in underground mines. AI based fleet management systems review real time data to determine the best time to dispatch, minimize on idle time and improve load balance (Kim & Choi, 2025). The advantages of digital fleet optimization from the real-life examples of the mining companies are briefed up in (Barnewold & Lottermoser, 2020) such as enhanced equipment utilization, reduced energy consumption and improved productivity. These strategies provide for a very smooth integration of the E-LHDs with the regular mining operations (Sayadi et al., 2012).

2.15 Research Gaps and Justification of the Study

Although there is growing interest in the electrification of underground mining equipment, there are still many research gaps, especially concerning the long-term performance, economic feasibility, and operational challenges of battery electric Load-Haul-Dump (LHD) machines. Although the theoretical advantages of electric mining equipment are well documented, there is little real-world data on how far this has been implemented. Many papers concentrate on the short-term benefits, but there is virtually no information available on the performance of electric LHDs over time, particularly in high load mining conditions. The long-term reliability of battery systems, their wear rate, and energy efficiency in various underground environments are factors that need further empirical investigation.

One of the most critical gaps in current research is the absence of thorough investigations into the integration of charging infrastructure in underground mining operations. However, the actual efficiency, reliability, and the logistical challenges of fast-charging and battery swapping technologies in real mining conditions are still unclear. Furthermore, the effects of large-scale electrification on mine power grids, such as changes in energy demand and grid stability, are not fully understood. These factors are significant in identifying whether underground mines are capable of transitioning to electric fleets without a reduction in the productivity. The financial aspect of electrification also presents uncertainties. While studies confirm that battery-electric LHDs reduce ventilation costs and fuel expenditures, the economic feasibility of this transition varies significantly depending on the size and type of the mining operation. Current cost benefit studies primarily concentrate on mining operations. Overlook the adjustment strategies of smaller, to medium sized mines towards electrification needs attention too! Moreover, research has not fully explored the return on investment (ROI) of battery LHDs encompassing aspects, like initial capital outlay operational efficiencies gained, maintenance expenditures and regulatory perks.

While its widely known that using battery powered vehicles underground enhances air quality by eliminating diesel emissions; there's a lack of data, on how this impacts worker health and mine ventilation efficiency in the long run. Historical studies generally recognize the decrease in diesel particulate matter and heat emissions. They haven't delved into how these enhancements impact worker fatigue health over time and safety incidents. Further research is required to measure these advantages through health studies, in mines that have transitioned to fleets.

There is a gap, in the existing research when it comes to the adjustments needed by mining companies switching from diesel powered to battery electric LHDs (Load Haul Dump vehicles). This transition doesn't just entail updating equipment; it also involves revisiting fleet management approaches and maintenance procedures while providing training for employees to effectively handle machinery. Currently lacking are guidelines on how mines should optimize workflow planning and create efficient charging schedules or train their staff to operate electric equipment. The absence of frameworks for electrification introduces uncertainty, for mining companies contemplating this transition.

Battery electric LHDs are praised for their environmental sustainability benefits; however, the complete environmental impact of battery production and recycling, in the mining industry is still not thoroughly researched. Even though electrification helps decrease greenhouse gas emissions the extraction of lithium cobalt and nickel, for batteries has its repercussions. Additional lifecycle assessments are necessary to determine whether battery electric mining fleets offer sustainability advantages compared to diesel powered alternatives.

Considering these research deficiencies cited earlier on the role of this study in exploring the practicality and sustainability over time of battery powered LHD vehicles used in underground mining operations is evident. By comparing the performance of diesel powered LHD vehicles, with their battery-operated counterparts this study aims to provide data that can assist mining firms, government officials and machinery producers in making informed investment choices. This research endeavors to offer perspectives on the expenses involved in owning something revenue generated from the initial investment and reduced operating costs, over a period of time. These insights aim to connect the predictions with economic results, in practice.

Addressing the infrastructure issues concerning charging and battery management is crucial to understand how mines can incorporate these advancements into their setups effectively. The research will also investigate how the switch, to electrification impacts worker safety and ventilation efficiency in mines with evidence of the advantages of phasing out diesel exhaust. Through an analysis of mines that have already adopted battery LHDs in their operations this study will highlight the operational adjustments needed the training programs for staff and the key strategies for a successful transition, to electrification.

This research holds value in meeting environmental standards and sustainability goals alike. With the enforcement of emission regulations, by governments worldwide miners must shift towards eco-friendly solutions to meet compliance requirements. Through an examination of the incentives related to electrification. Regulatory and financial this study aims to provide insights on how mining activities can leverage government grants clean energy credits and sustainable strategies, for long term success.

3. Electrification Trends in Underground

3.1 Characteristic of IMI FABI's Talc Mine

The Brusada talc mine is taken by IMI FABI company consist of several aspect as geographic and and geology of the mine. Moreover, in the following section you can find the brief explanation of mining Tools, Technique and structure of the organization.

3.1.1 Geographic Location and Structure

The Brusada talc mine, situated in Valle del Lanterna, a tributary to Valmalenco, is located approximately 5 km from the Swiss border. The mine's elevation ranges from 1165 meters above sea level at the mine adit to 1500 meters at the Lareson tunnel. Covering a total area of 540 hectares, the mining operations are divided between the Sasso della Pradaccia and Brusada-Ponticelli-Valbrutta sites, spanning approximately 200 hectares and 340 hectares respectively. These sites were previously managed by I.M.I. and under UT's administration. The mine boasts significant talc reserves, with proven reserves estimated at 16 million tons and probable reserves around 22 million tons.

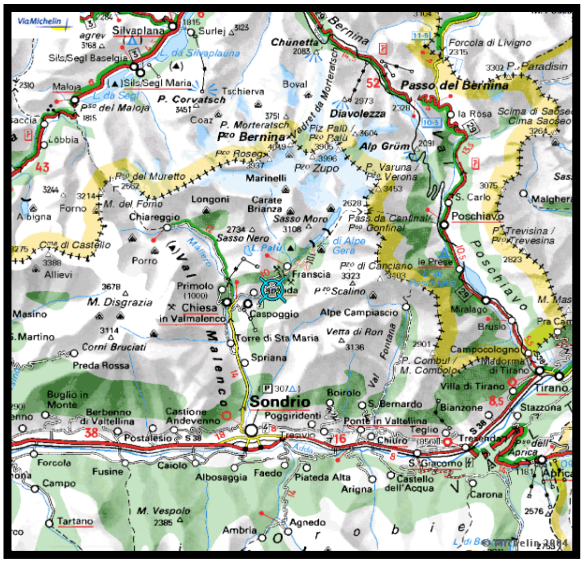


Figure 1: location of the mine

3.1.2 Geology and Ore Formation

The geology of the area is relatively recent, dating back 25 to 35 million years (Oligocene-Miocene). The region is characterized by fractures in ultramafic rocks known as Malenco Units, which have undergone hydrothermal activity leading to fluid circulations within these fractures (a process known as metasomatism due to CO_2 circulation). The geological formation of these features occurred under pressure conditions of 3-5 kbar and temperatures ranging from 350 to 530°C. Overall tunnel development **50Km**

- Average tunnel section**36 m^2**
- Tunnel width **6m**

- Extracted ore **2.8 Mton**
- Proven **2.5 Mton**
- Probable**1.5 Mton**

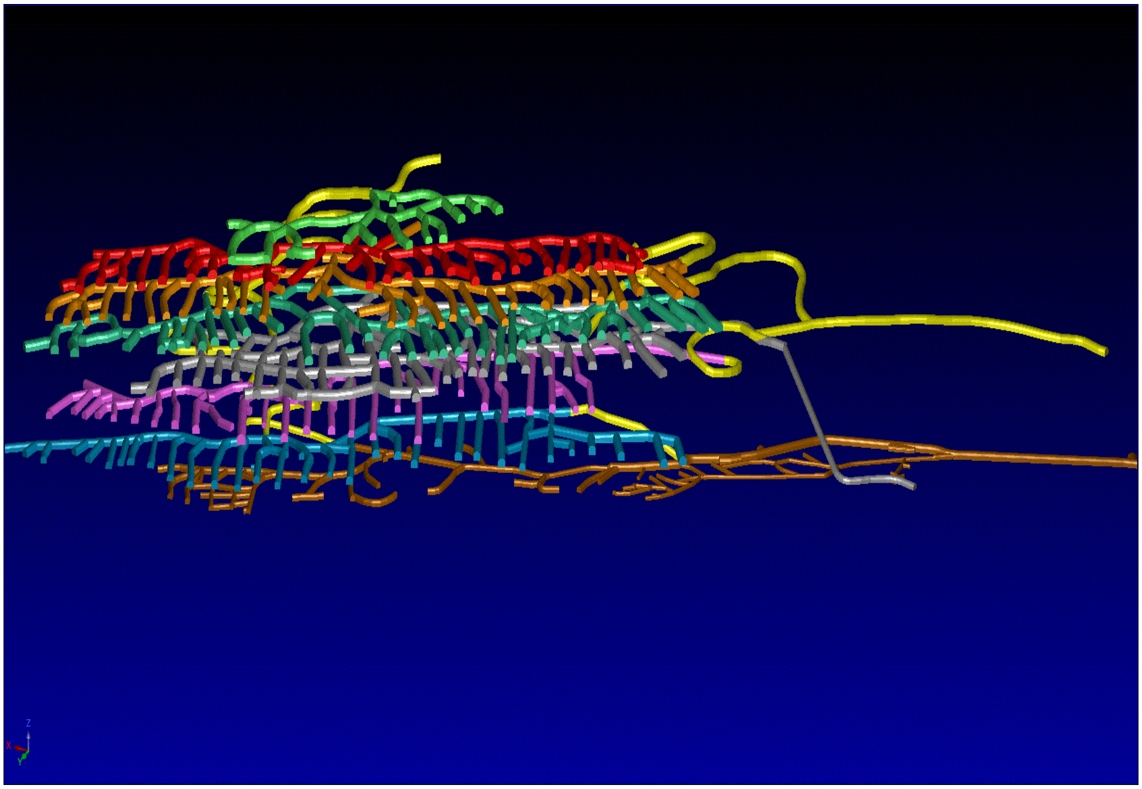


Figure 2: 3D view of the Tunnel and Drifts

3.1.3 Mining Techniques and Cycle

Techniques: Utilizes stope and pillar mining with void backfilling, employing upward development, drilling, and explosive blasting.

Mining Cycle: Includes tunnel advancement, ore extraction by drilling and blasting, ore haulage, tunnel stabilization, stope extraction, voids backfilling, use of a jaw crusher and an over belt magnetic separator, and train haulage.

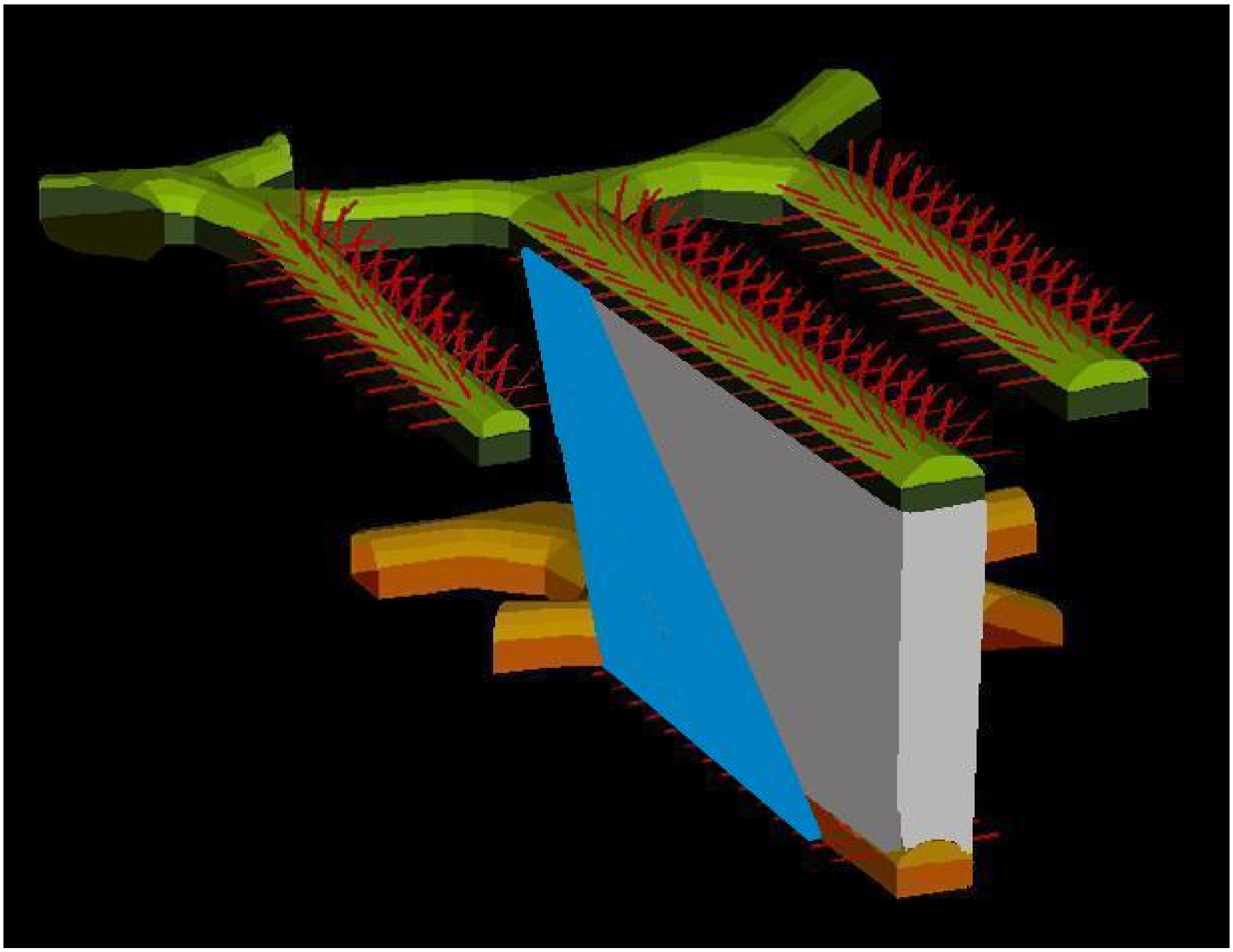


Figure 3: applying stope and pillar, blue one is under back filling

3.1.4 Equipment and Technology

Loaders: Includes several models such as ST14B (payload of 14 tons), Wagner ST 1030R, and others with varying capacities.

Transport: Utilizes train transport with GIA DHS-60 and DHS-90 locomotives and 85t Bischoff carts.

Figure 4: Wagner ST 1020 LHD

3.1.5 Mine Organization and Ventilation

Organization Chart: Managed by a registered manager, foreman, chief mine service manager, assistant managers, chief surveillants, and 24 miners over two shifts per day, five days a week.

Ventilation System: Includes primary ventilation for the western mine sector and natural ventilation throughout, supplemented by main forced ventilation for eastern sectors and secondary forced ventilation for newly opened sectors.

3.1.6 Process Controls and Management System

Controls: Monitoring includes dustiness, noise levels, air flow, microclimate conditions, exhausts (CO, CO_2, SO_2, NO_2, IPA), deformation of excavations, and quality of mined ore.

Management Systems: The mine operates under several certifications, including ISO 9002, ISO 14001, OHSAS 18001, HACCP, KOSHER, and FAMI-QS, with ongoing implementation of ISO 50001:2011 for energy management.

3.2 Introduction to Scooptram ST14 Battery

The Scooptram ST14 Battery is an underground loader crafted for effective and eco friendly material handling, in mining sites by Epiroc companies engineering expertise plays a vital role in cutting down on diesel emissions and enhancing air quality while reducing operational expenses, within underground settings. The loader powered by a battery is capable of hauling 14 tones which suits it well for tough mining tasks.

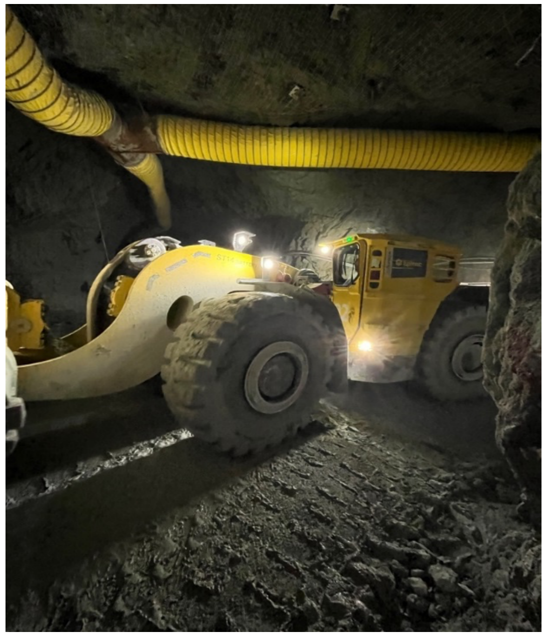


Figure 5: Scooptram ST14 of EpiRoc

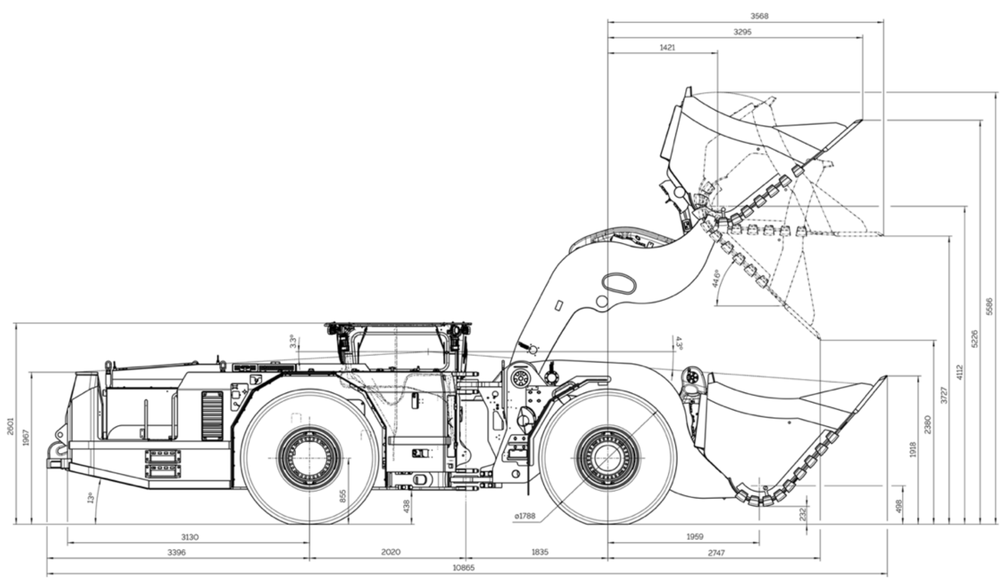


Figure 6: Bidimensional scheme of Scooptram ST14

3.3 Key Benefits of the Scooptram ST14 Battery:

- Zero Emissions: Eliminates diesel particulates and toxic gases (e.g., NOx, CO, hydrocarbons).
- Cost Reduction: Reducing ventilation and cooling costs, as no diesel combustion occurs.
- Compact and Powerful: Offer high productivity while maintaining a compact size.
- Optimized Service & Maintenance: Fewer moving parts result in lower maintenance costs.

3.4 Transmission System, High-Efficiency, Gearless Design

The Scooptram ST14 Battery is equipped with a modern transmission system that eliminates need for the traditional torque converters and reverse gears, providing higher efficiency and lower energy losses.

3.4.1 Transmission Features:

Eliminates Torque Converter & Reverse Gears**:** Instead of conventional transmission systems, it relies on direct-drive electric motors (figure 7). This reduces power losses associated with mechanical transmissions.

Optimized for Underground Applications**:** Provides smooth acceleration on steep ramps **and** sharp turns**.** Designed to minimize vibration and mechanical wear**.**

Front and Rear Axles**:** Ensures equal load distribution**.** So**,** it Improves stability in uneven underground terrains

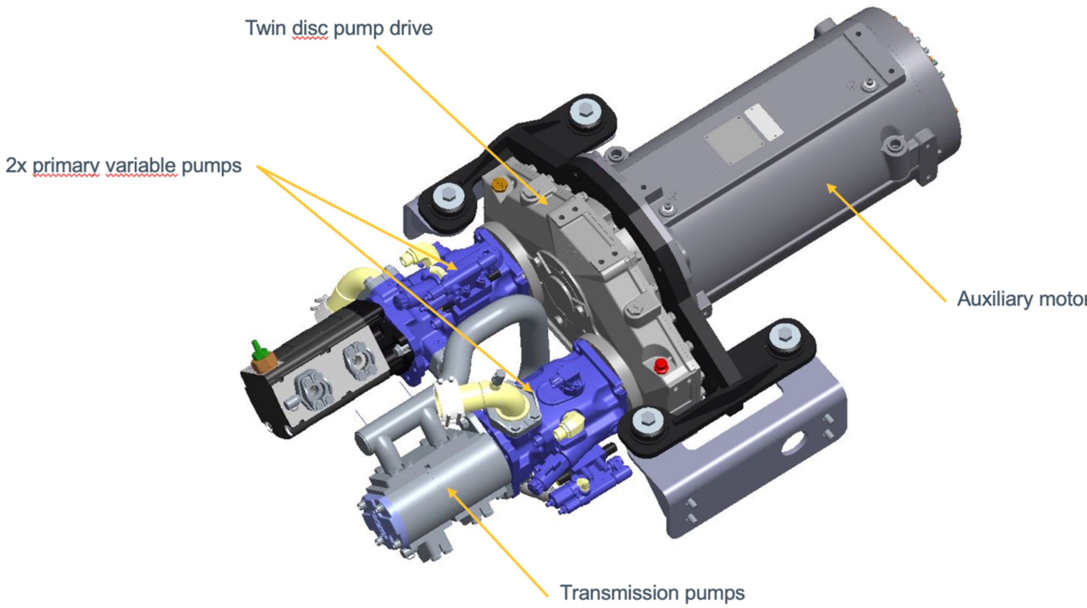


Figure 7: Internal part of Engine

3.5 Battery Technology, High-Efficiency Energy Storage

The battery system of the Scooptram ST14 Battery (figure 8) is at the core of its performance, enabling zero-emission operations with high energy density and extended runtime.

3.5.1 Battery Specifications

- Battery chemistry: Lithium Nickel Manganese Cobalt Oxide **(**Li-Ion NMC**)**
- Voltage rating: 800V
- Battery sub-packs: 4 modular battery sub-packs
- Total weight: Approximately 4,500kg
- Energy capacity: 370 kWh

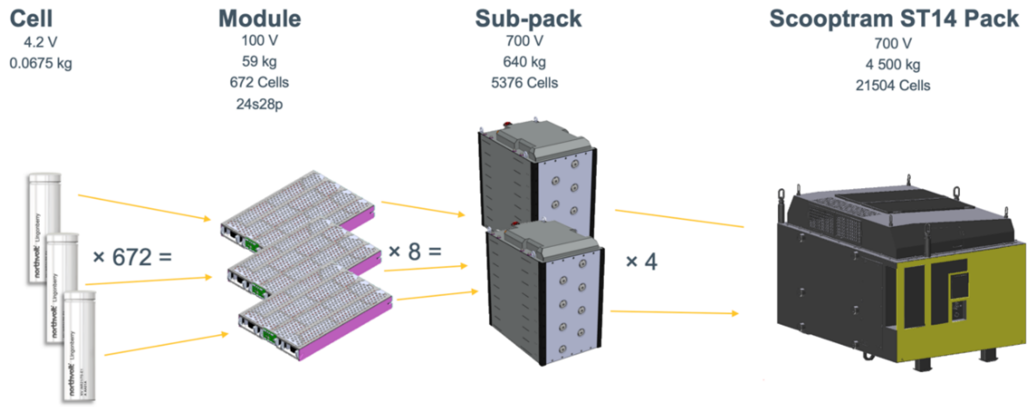


Figure 8: structure and component of the battery

3.5.2 Battery Safety and Protection

The battery is built with multiple safety layers to avoid electrical faults (Table 1), overheating, and hazardous failures:

Battery Management System (BMS): Constantly monitors voltage, temperature, and current. for providing real-time diagnostics for predictive maintenance.

Thermal Management System (figure 9): Uses liquid cooling to maintain battery temperature between 20-30°C to prevent overheating and extending battery duration**.**

Short-Circuit Protection and Isolation Monitoring: Automatic disconnects by high-voltage interlock loops (HVIL) also Fuses and circuit breakers prevent electrical overloads**.**

Table 1: Thermal abusing system inside the machine

Thermal Management Method	Description
Liquid cooling system	Circulates the battery cells to prevent heat from spreading between them and reduce the chances of fires occurring.
Thermal insulation	Wraps the battery cells to prevent heat from spreading between them and reduce the chances of fires occurring.
Battery management system (BMS)	Constant monitoring of battery cell temperature and voltage, in time enables the system to take action such as activating cooling mechanisms or disconnecting the battery if any cell surpasses safe threshold values for current.
Temperature sensors	Throughout the machine sensors are positioned to constantly feedback temperature information to the BMS and cooling system to prevent the build up of unused heat.
Automatic power reduction	Shuts down and reduces power output when it gets too hot preventing it from overheating.
Fire suppression system	It triggers the release of fire suppressing substances such, as foam or gas when a potential fire hazard is sensed to safeguard both the equipment and the operator.
Ventilation design	Optimized air flow and ventilations channels allow natural heat dissipation, helping maintain consistent temperatures across the machine.

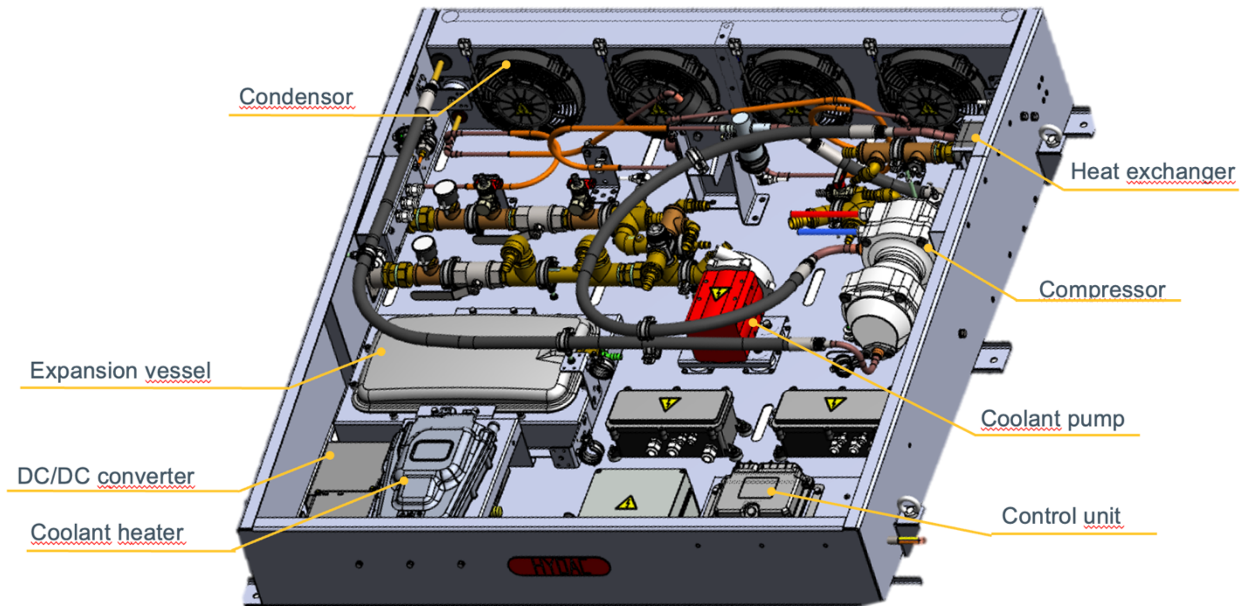


Figure 9: Thermal management system

3.6 Regenerative Braking – Energy Recovery System

One of the key efficiency-enhancing features of the Scooptram ST14 Battery is its regenerative braking system.

3.6.1 How It Works:

When the loader moves downhill. Slows down its speed the traction motor changes to generator mode. Of dissipating energy as heat, like, in conventional braking systems this system captures and returns the energy to the battery. This method helps to save energy and extend the duration of operations**.**

3.6.2 Benefits of Regenerative Braking:

Extends battery runtime up to10-15%. Then, it extends the life of brake components reducing on wear and tear which results to lower maintenance costs and enhancing the machines efficiency and sustainability.

3.7 Charging Technology – Optimized for Underground Mining

The Scooptram ST14 Battery can be charged in multiple ways to adapt to operational needs.

3.7.1 Charging Methods

On-Board Charging: The battery stays in the vehicle and is recharged by an external charger. for continuous use with little downtime. slower charging times to prevent further stress on the electrical infrastructure.

Off-Board Charging (Battery Swapping): Battery is removed and replaced with a fully charged battery then Swap time is less than 10 minutes**.** so that**,** Ideal, for settings, with high productivity demands that require downtime.

3.7.2 Charging Infrastructure

- Charger model is ABB Terra HP 160 kW charger which contain charging connector type with CCS 2.0 standard the chargers should be located in the low zones of the mine so that the empty vehicles can easily get to them, and should be integrated with ventilation & cooling systems to prevent overheating.

Figure 10: Charging station of Scooptram ST14

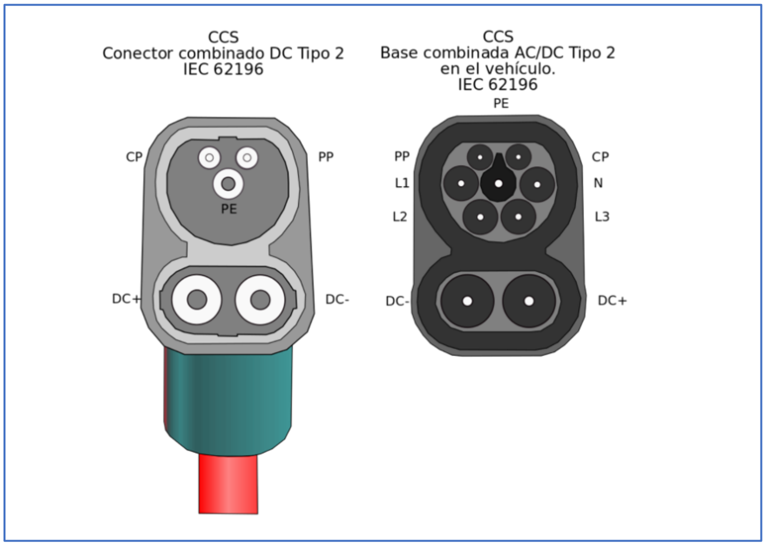


Figure 11: Connector of charging station

3.8 Durability & Reliability – Engineered for Harsh Mining Conditions

3.8.1 Mechanical Durability:

Heavy-duty steel frame of the machine to withstand underground impacts during the operation. Moreover**,** sealed battery casing (IP67-rated, standard) to prevent dust and moisture ingress also by utilizing Reinforced wheel assembly for extreme underground environments.

3.8.2 Safety in Harsh Conditions

- Designed to be operated in high vibration environments.
- Protected against falling rocks and debris**.**
- Fire suppression systems integrated into battery packs.

Figure 12: Robust body of Scooptram ST14

3.9 Smart System Integration – Advanced Control and Automation

The Scooptram ST14 Battery is integrated with a Rig Control System (RCS) for smart operation and data tracking.

3.9.1 Key Features of the RCS:

Real-time Performance Monitoring: Tracks battery charge levels, motor efficiency, and temperature. Automated Diagnostic Alerts include Notifies operators of potential failures or inefficiencies**. Also,** Predictive maintenance, Uses AI-driven analytics to detect issues before they become critical**.** Moreover, Remote monitoring capability of the machine can be monitored and controlled remotely for improved safety and efficiency.

4. Safety of Work

4.1 Quality of the air for the works

One of the most pressing concerns associated with diesel LHDs is their emission output, which significantly impacts air quality, worker health, and ventilation costs. Diesel engines produce substantial amounts of carbon monoxide (CO), nitrogen oxides (NOx), and diesel particulate matter (DPM), all of which pose severe health risks to underground workers (Xiao et al., 2022). Prolonged exposure to DPM and other pollutants has been linked to respiratory diseases, cardiovascular issues, and increased cancer risk, leading regulatory agencies to implement stricter air quality standards in underground mines. To mitigate these risks, mining companies must invest heavily in ventilation systems to disperse toxic gases and maintain a safe working environment. However, ventilation accounts for a significant portion of mine energy consumption, making diesel-powered LHDs not only hazardous but also increasingly costly and inefficient.

4.2 Impact of Electrification on Worker Safety and Mine Environment

Switching from diesel powered Load Haul Dump (LHD) machines to battery alternatives, offers a safety benefit, for workers in the mining industry. Hazardous conditions in mines like emissions and excessive heat pose risks, to workers safety and healthy the use of battery mining equipment helps mitigate these dangers and enhances workplace safety and health standards.

4.2.1 Reduction in Toxic Emissions and Respiratory Health Improvements

One of the most critical health risks associated with diesel-powered LHDs is prolonged exposure to exhaust emissions. Diesel engines produce significant amounts of carbon monoxide (CO), nitrogen oxides (NOx), and diesel particulate matter (DPM), all of which have been linked to serious respiratory conditions, cardiovascular diseases, and increased cancer risk (Hasan et al., 2010). In underground mining, where ventilation is limited, these pollutants can accumulate quickly, increasing the risk of chronic lung diseases such as silicosis and chronic obstructive pulmonary disease (COPD) among workers. as you can see, The provided (figure 13), represents the CO_2 equivalent emissions per unit of talc production (kg/t) over time, spanning from January 2022 to December 2024.

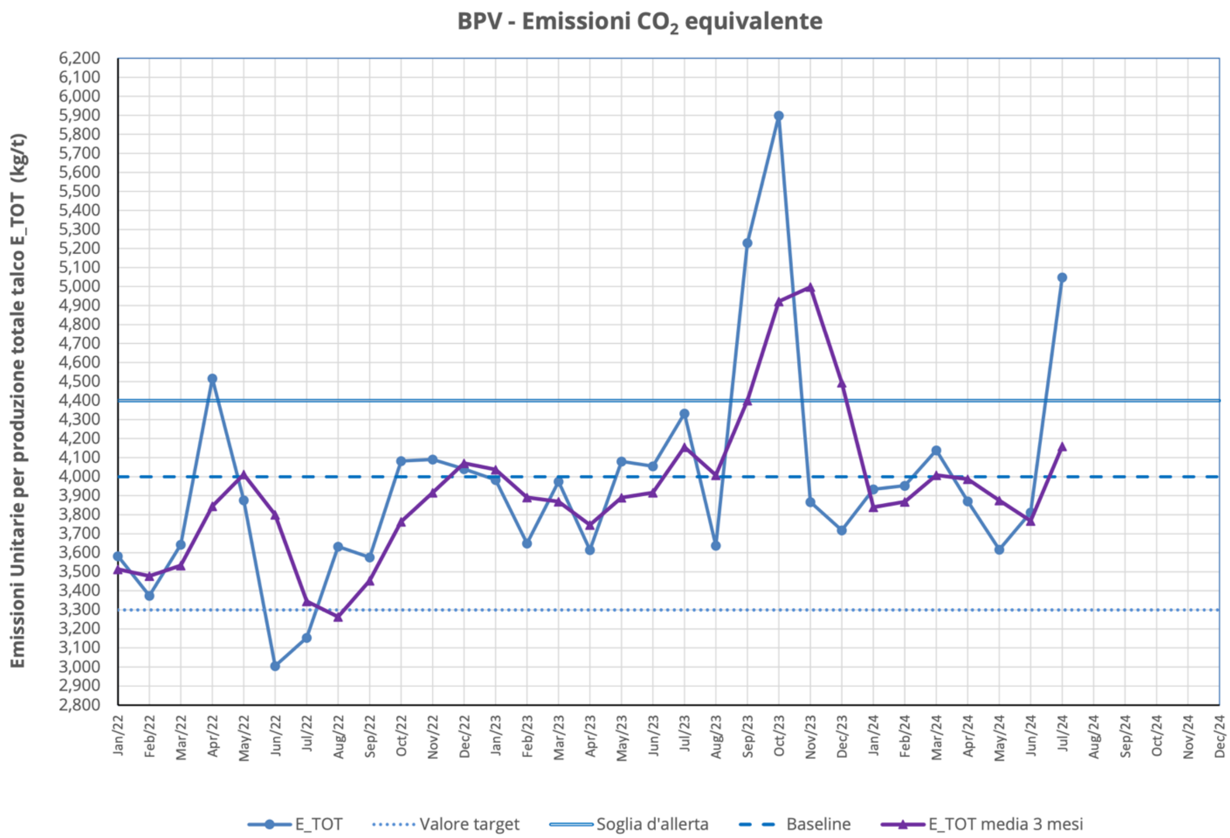


Figure 13: CO_2 emission, based on the KPI of the mine

1. E_TOT (Blue Line):

- This line represent the actual value of CO_2 emissions over time and the emissions are quite fluctuating with some peaks especially around August 2023 and January 2024 which may be due to some changes in operational or process variations.

E_TOT 3-Month Average (Purple Line):

This line smooths the short-term fluctuations and provides a moving average of emissions over a three-month period. It follows the trend of E_TOT but with less volatility, helping to identify longer-term patterns.

Baseline (Dashed Blue Line):

A benchmark emission level for comparison., Used to determine if emissions are within the expected operational range.

Alert Threshold (Solid Blue Line):

Indicates the critical CO_2 emission threshold beyond which it may be necessary to take corrective action. However, some spikes in the E_TOT curve are above this threshold, especially at the end of 2023 and in the middle of 2024.

Target Value (Dotted Blue Line):

This is the desired CO_2 emissions target, which defines the level to which operations should be maintained or even enhanced. The actual emissions (E_TOT) stay above this target through the actual values and hence there is scope for enhancing the energy efficiency or emission reduction measures.

Overall Emission Trends:

The emissions have been fluctuating a lot and there are some peaks above the alert threshold. The three-month moving average shows the same general trend but does not react to short-term changes as aggressively.

7. Periods of High Emissions:

- In the months of September to October 2023 and January 2024, extreme emission spikes which may be due to changes in operations, higher energy use or low efficiency of the mining process.
- These spikes indicate possible constraints or weaknesses in equipment performance, which could be a result of higher diesel consumption or a poor electric fleet management strategy.

8. Progress Toward Emission Goals:

- The actual emissions are still above the target level, which means that there is still room for improvement in the efficiency of battery electric LHDs, ventilation control or the process itself.

All of the diesel exhaust emissions are eliminated by adopting battery electric LHDs, which improve the air quality of the underground mines. Research on improvements in air quality in mines that have switched to electric mining equipment shows that there is a significant decrease in airborne pollutants and thus better working conditions. The electric mining equipment reduces the risks of exposure to hazardous fumes, respiratory distress, and long-term lung diseases to the operators of mines.

4.2.2 Lower Heat Generation and Prevention of Heat Stress

Another major occupational hazard in underground mining is heat stress, it is caused by hot temperature conditions and low ventilation. The chief source of heat in mining is the diesel engines, which are a major source of heat through the combustion process, especially in deep mines. In the most severe cases, heat stress can lead to heat exhaustion, dehydration and heat stroke, all of which reduce the worker's productivity and safety.

4.2.3 Noise and Vibration Reduction for Long-Term Health Benefits

Diesel operated LHDs known for their loudness, in mines contribute significantly to the noise pollution issue within these environments. Being frequently exposed to levels of noise can result in hearing issues like noise induced hearing loss (NIHL). Although the operator's cabin is soundproofed, due to the loudness from diesel engines combined with vibrations and rock excavation processes in mining activities; proper hearing protection is crucial, for working environment.

for eliminating diesel emissions and contributing to much lower noise levels with battery electric LHDs. They are less noisy than diesel engines; thus, electric motors reduce occupational noise exposure and improve the ability to communicate verbally with workers. The low noise pollution increases situational awareness and thus reduces the chances of accidents and equipment-related injuries.

In addition, battery electric LHDs emit much less vibration than their diesel-powered counterparts and therefore cause less physical strain on the operator. Research has revealed that exposure to whole body vibration (WBV) – a feature that is typical of diesel LHDs – increases the risk of musculoskeletal disorders, joint pain and spinal injuries among underground equipment operators. Electric LHDs' reduced vibration means lower operator fatigue and fewer long-term health risks, as well as better employee retention and job satisfaction.

4.2.4 Fire Risk Mitigation and Enhanced Workplace Safety

Underground mines present a serious fire safety threat owing to the presence of combustible diesel fuel as well as high temperature engine components. All diesel powered LHDs need to have on board fuel storage and handling which will lead to more chances of spills, leaks and ignition. These include engine overheating, fuel line ruptures and exhaust system failures which have been identified as some of the common causes of underground mine fires which may cause devastating consequences and even deaths of workers.

Battery electric LHDs do not require diesel fuel thus reducing the risk of fire by fuel combustion and storage. The presence of no flammable liquids and hot exhaust components reduces the chances of ignition thus improving the fire prevention measures in the underground mining. Also, today's battery electric mining equipment is designed with better safety features such as fire suppression systems, thermal monitoring sensors, and protective battery casings.

Furthermore, in the event of an emergency, electric LHDs can be safely shut down and restarted Furthermore, in case of an emergency, electric LHDs can be safely shutdown and restarted remotely, putting the user in better control of hazardous situations. Those mines that have adopted battery electric vehicles have reduced their frequency of fire incidents to a large extent, thus confirming the superiority of electrification over the conventional internal combustion engine-based vehicles for underground mining operations.

4.3 Automated Systems and Remote Monitoring Technologies

The integration of automation and remote monitoring systems has also played a crucial role in the feasibility of electrified mining equipment. Advances in real-time data analytics, AI-driven maintenance, and fleet management software have allowed mining companies to optimize battery usage, predict maintenance needs, and enhance overall efficiency. Autonomous and semi-autonomous electric LHDs are now capable of operating with minimal human intervention, further improving productivity and worker safety in hazardous underground conditions.

Automation, remote control, and real time monitoring systems bringing about a change in the way underground mining operations are done are directly related to the electrification of mining equipment. The conventional LHD machines have for a long time been manually controlled, needing as well as experienced personnel and presence of super vision in the hazardous underground environments. But, with the mining industry shifting towards electrification, automation is gradually becoming essential to improve efficiency, safety, and costs.

4.3.1 Autonomous and Semi-Autonomous Battery-Electric LHDs

Autonomous battery powered Load Haul Dump vehicles are becoming thanks, to the progress in sensor technologies and real time monitoring systems as well as the use of machine learning algorithms. trajectory planning and collision avoidance capabilities along, with efficient fleet management have enabled electric LHD vehicles to function with minimal human involvement. The combination of sensors, along with computer vision and radar-based navigation systems has greatly enhanced the maneuverability of LHD machines, in underground settings.

Besides fully autonomous vehicles, many mining operations are using semi-autonomous electric LHDs, where operators can operate equipment from a central control station. This avoids the exposure of people to dangerous situations including geotechnical hazards, poor ventilation zones, and high temperature mining areas. The battery electric LHDs are also able to operate for longer shifts as shifts can be extended without having a body of people in the underground.

4.3.2 Real-Time Health Monitoring and Predictive Maintenance

The new generation of electric Load Haul Dump machines comes with the ability for the operator and maintenance personnel to keep a watch on the battery health, temperatures and mechanical component wear and tear, real time. These advanced systems are using IoT. Ai powered analysis to analyze indicators of potential component failures or problems like overheating or unusually high energy consumption.

The electric Load Haul Dump machines are equipped with the monitoring systems which enable operators and maintenance crews to keep tabs on temperature changes and wear and tear of mechanical components as they happen instantly, and to monitor battery health in time. Such advanced systems are leveraging IoT. Ai powered analysis to identify indicators of potential component malfunctions or issues, like overheating or unusual energy usage patterns. It shows that approach to reduces unplanned downtime and extends equipment lifespan, hence making battery electric mining equipment more cost effective in the long run. Unlike diesel powered machinery which needs frequent oil changes, engine overhauls, and fuel system maintenance, electric LHDs have reduced number of moving parts thus low probability of break down and their costly repairs. Load Haul Dump machines come with monitoring systems that enable operators and maintenance crews to monitor battery health in time and keep tabs on temperature changes and wear and tear of mechanical components as they happen instantly. These advanced systems leverage IoT. Ai powered analysis to identify indicators of potential component malfunctions or issues, like overheating or unusual energy usage patterns.

It shows that approach to reduces unplanned downtime and extends equipment lifespan, thus making battery-electric mining equipment more cost-effective in the long run. Diesel-powered machinery, on the other hand, needs regular oil changes, engine overhauls, and fuel system maintenance, due to it having fewer moving parts that lead to a lower risk of breakdowns and expensive repairs than electric LHDs.

Furthermore, remote diagnostics and automated reporting systems enable mining companies to perform proactive maintenance without stopping production. Any performance anomalies are alerted to maintenance crews automatically, enabling them to schedule repairs before failure occurs. This guarantees that there is better equipment availability, reliability, and, in total, cost savings. Some sensor is already installed at charging station of level 9 for measurement of temperature (figure 14), Humidity (figure 15) and Co2 releasing in real-time.

Figure 14: Temperature Monitoring of Charging station at level 9

Figure 15: Humidity Monitoring of Charging station at level 9

Figure 16: Carbon Dioxide Monitoring at Charging Station Level 9

4.3.3 Enhanced Safety Through Automation and Remote Operations

One of the greatest advantages of automation in battery electric mining equipment is the contribution it makes to worker safety. Electric LHDs that are fully or partially autonomous reduce the need for an operator to be physically present in hazardous mining zones thereby reducing accident risks from human error, equipment collisions and exposure to unstable geological conditions. Furthermore, automation minimizes operator fatigue, a common cause of workplace accidents in underground mining. By allowing AI-driven systems to handle repetitive tasks, human workers can focus on higher-level decision-making and oversight, reducing cognitive workload and improving overall operational safety.

Additionally, the integration of remote control systems enables mining companies to operate LHDs from surface-level command centers, eliminating the need for workers to enter deep mining shafts for routine operations. Remote operation technology is particularly beneficial in extreme environments, such as high-temperature mines or geologically unstable areas, where human exposure should be minimized.

4.3.4 Future Prospects: AI, Machine Learning, and Smart Mining Operations

New generations of battery-electric mining equipment will apply artificial intelligence (AI) and machine learning (ML) algorithms for autonomous decision making and process optimization in mining operations. They are capable of using historical mining data to predict the most efficient path for material transportation and control equipment performance according to real time conditions. In addition, it is expected that 5G enabled wireless communication networks would enhance the connectivity and response of the autonomous electric LHDs through the vehicle to infrastructure (V2I) communication where vehicles can communicate with control centers and underground monitoring systems. The companies are also looking into the application of digital twins, which are the copies of the mining sites, to model and improve the operations of the battery electric mining fleets. This approach is useful for risk analysis, performance comparison.

4.4 Environment for works

As mining operations continue to expand deeper underground, the technical and economic viability of diesel alternatives becomes increasingly apparent. Battery-electric LHDs not only reduce emissions and ventilation costs but also contribute to safer working environments by eliminating exposure to toxic fumes, reducing heat generation, and minimizing fire hazards. Moreover, the lower maintenance requirements of electric drivetrains compared to diesel engines result in reduced downtime and improved operational reliability.

4.5 Technology development of the battery

Industry leaders and equipment manufacturers are continuously working on improving battery chemistry, extending operational ranges, and enhancing energy efficiency to further accelerate the transition toward electrified underground mining. As more mining operations successfully implement battery-electric fleets, the lessons learned from these early adopters will serve as a foundation for broader industry-wide electrification.

The growing investment in research and development, coupled with policy-driven initiatives and economic incentives, ensures that electrification in underground mining is not just a trend but a fundamental shift toward a more sustainable, cost-effective, and technologically advanced future for the industry.

5. Examining of E-LHD parameters in the IMI FABI mine

In this research, the evaluation begins at Level 12, the designated loading area, with measurements starting from the stope. The analysis follows the machine's route through the external drifts and ramps leading to Level 11, continuing along Level 11's drift before reaching the shaft at Level 11, which serves as the discharging point. Since the shaft has not yet been completed to extended to Level 12, the machine must travel down to Level 11 for material discharge. This additional hauling requirement is a crucial factor in the analysis, as it affects battery consumption and operational efficiency

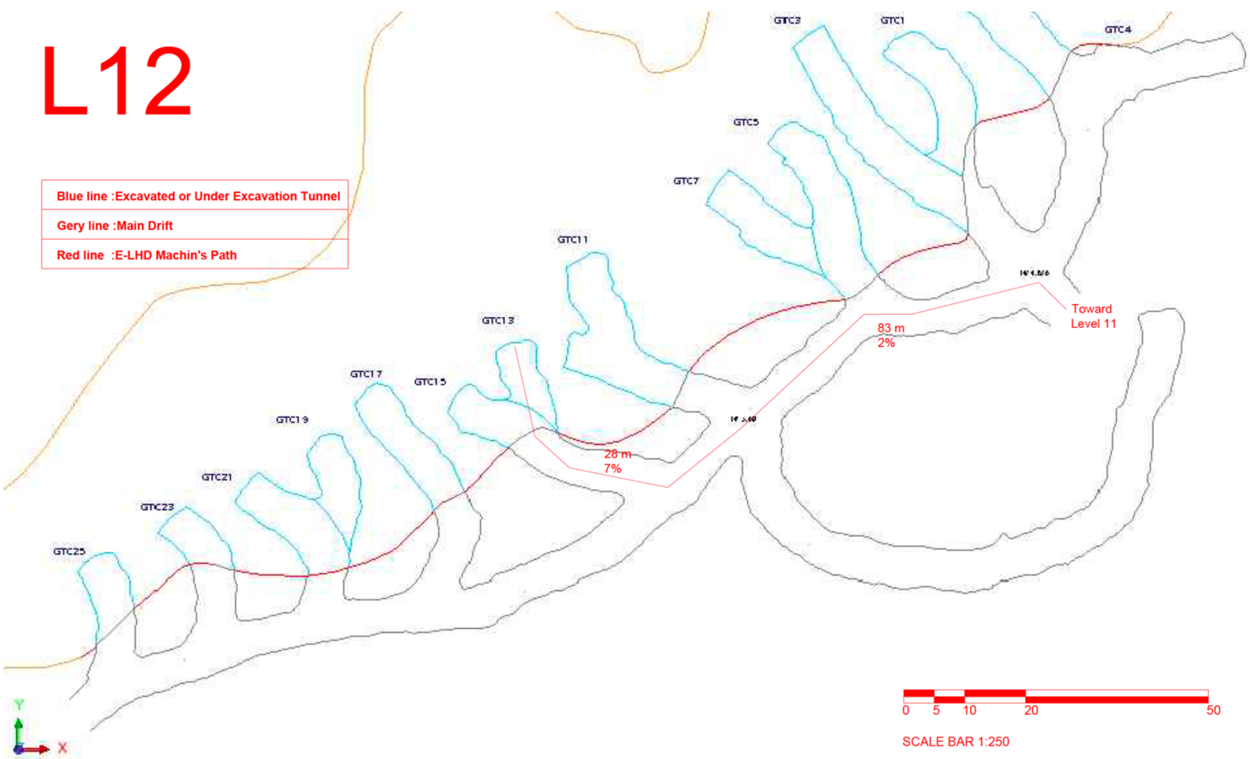
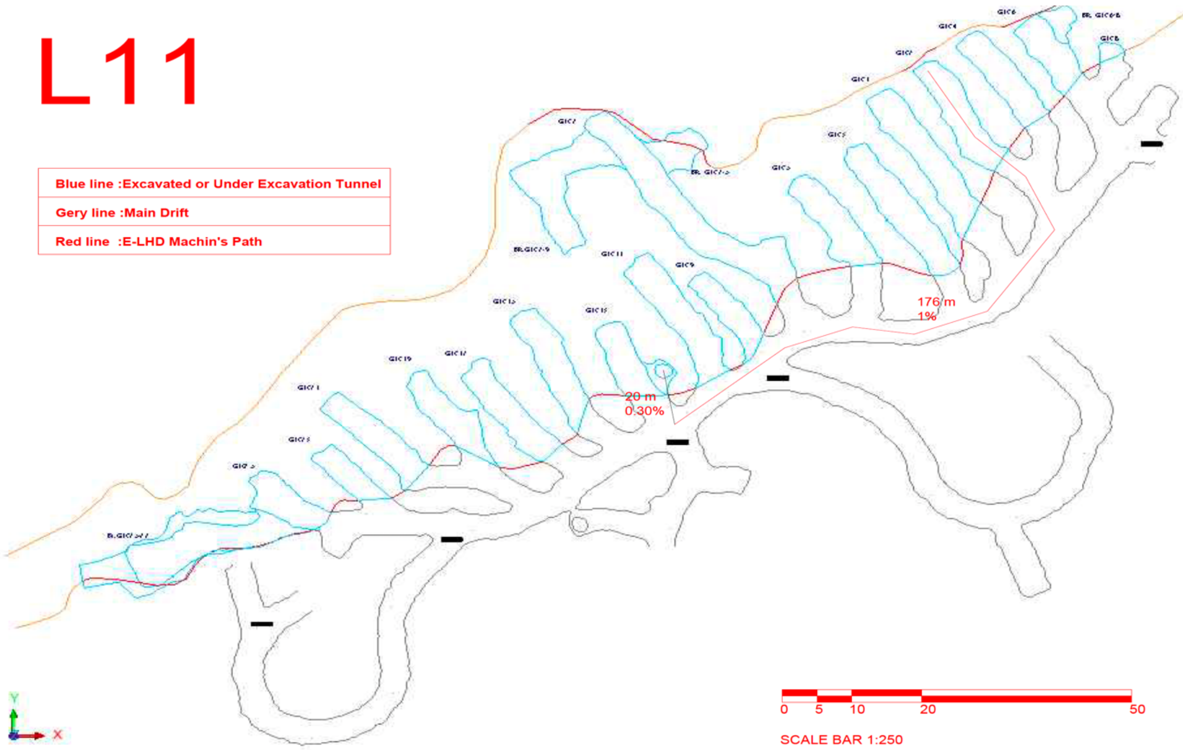


Figure 17: Level 12 of brusada mine



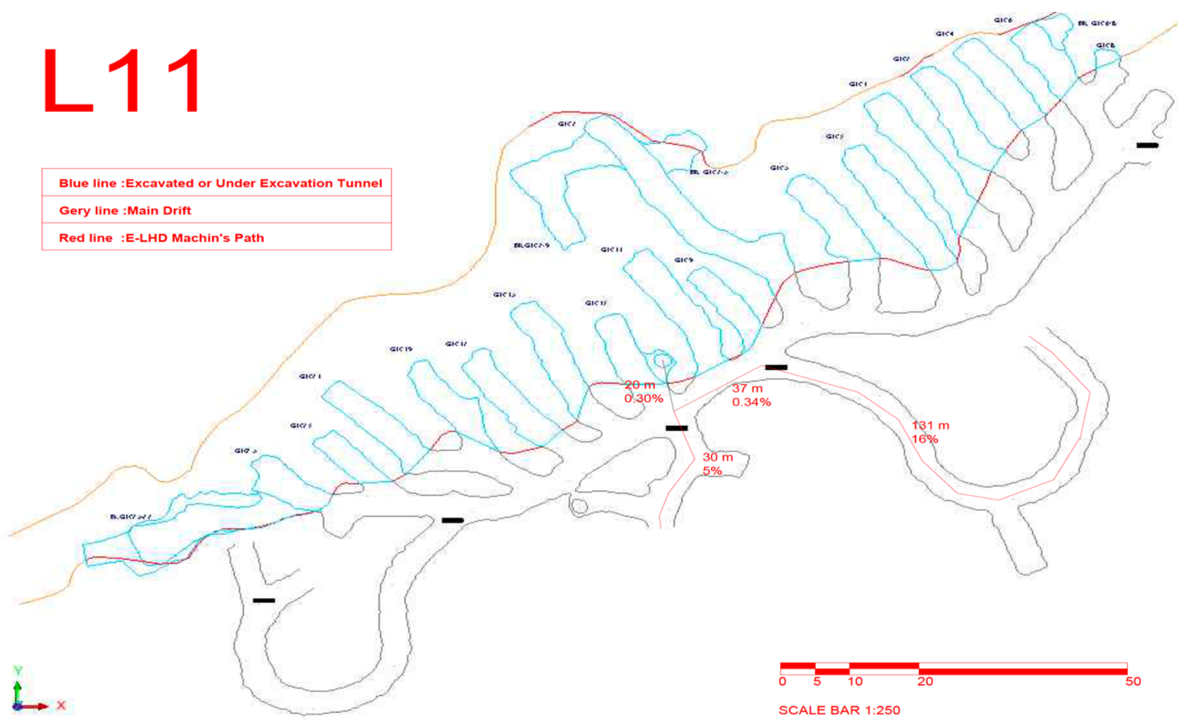


Figure 18: Level 11 of the Brusada mine

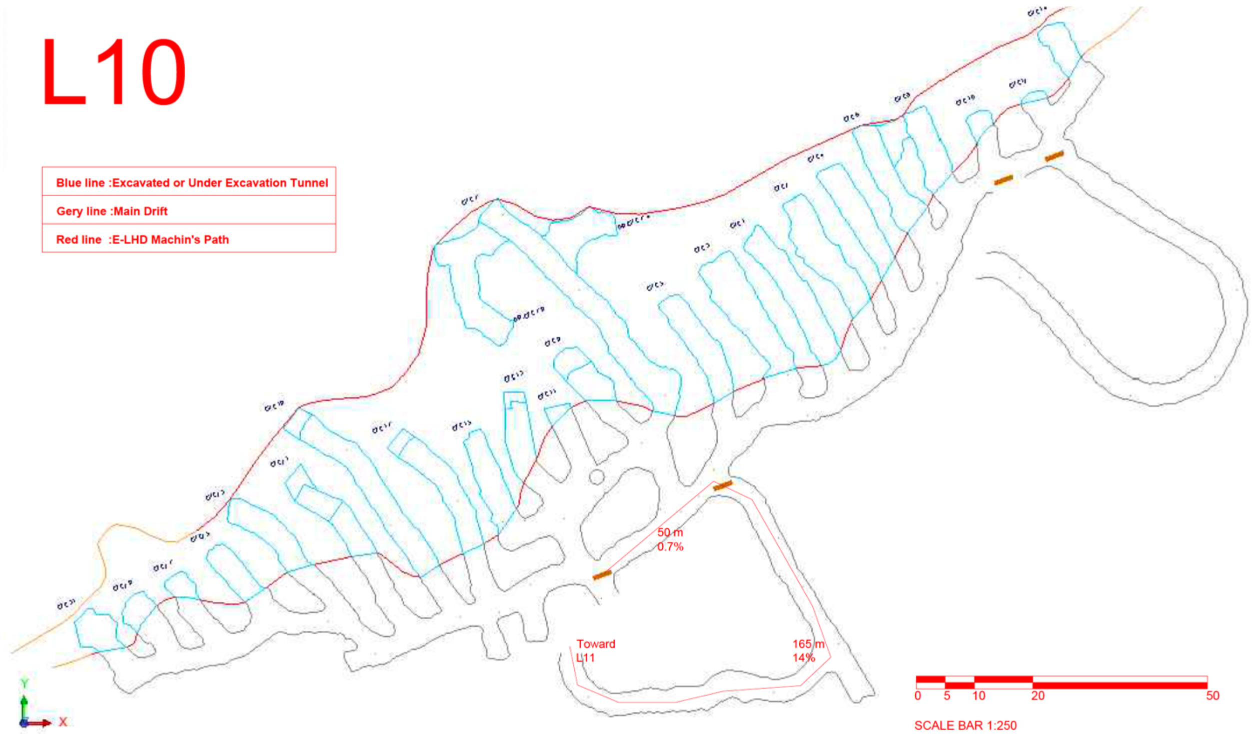


Figure 19: level 10 of the Brusada mine

Furthermore, the charging station is located at Level 9, while the machine operates primarily at Level 12. This spatial separation is a necessary safety measure, ensuring that the charging station is positioned at a safe distance from mine workers to minimize hazards related to battery charging operations. As a result, the machine experiences an additional battery drain when traveling from Level 9 to Level 12 before starting operations. This aspect is considered in the study to provide an accurate assessment of battery consumption, charging cycles, and overall energy efficiency in comparison to real-world performance data.

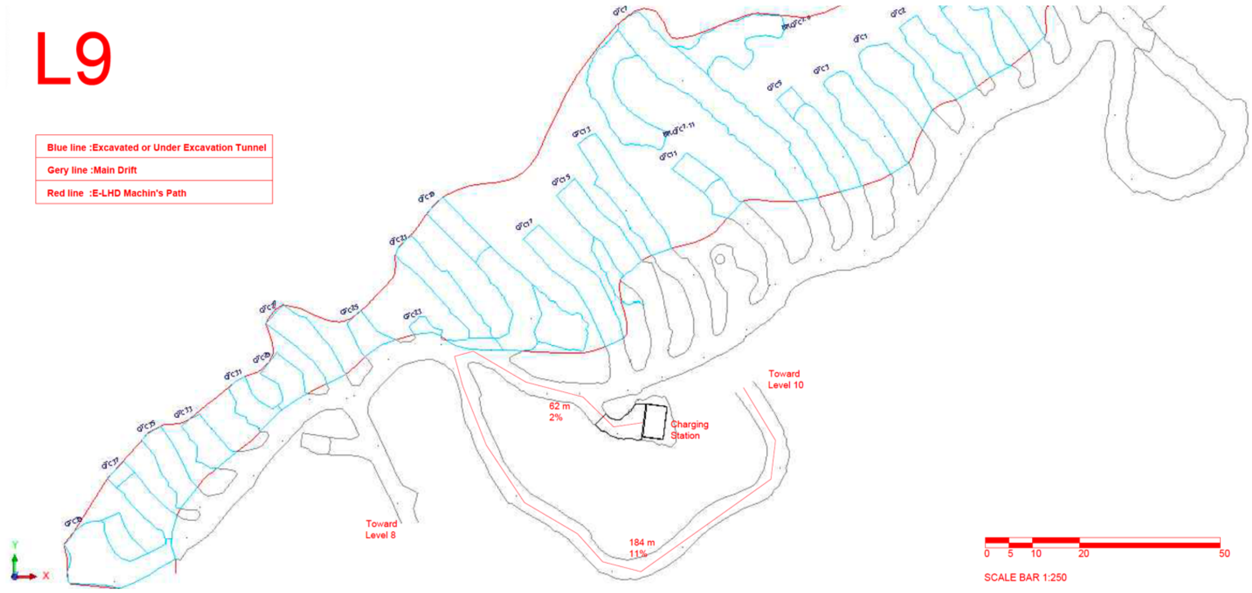


Figure 20: level 9 of Brusada mine

5.1 **Comparative Analysis: Theoretical vs. Real-World Performance**

A comparative approach is adopted to evaluate the real vs. expected energy consumption of the Scooptram ST14 Battery along the defined pathway. The study models the energy required based on:

Theoretical simulator using machine specifications, gradient inclinations, and the distance traveled by machine also Real-world measurements of battery depletion under normal operational conditions.

The value of the (Table 2) are inserted into the simulator providing by the Aramine Group according to the IMI Fabis' Brusada mine. This value corresponds to a single shift of the machine, beginning at the charging station on level 9, traveling to level 12 for loading, then hauling and dumping material at level 11.

Table 2: Pathway Measurement

pathway (m)	Inclination %	Level of the mine
184	11	9
62	2	9
165	14	10
50	0.7	10
131	16	11
37	0.34	11
30	5	11
83	2	12
28	7	12

The machine continues operating between these levels until the battery discharges to 85%.

5.2 **Pathway Breakdown and Energy Analysis**

The simulated pathway consists of multiple zones, each contributing differently to total energy consumption. The following key metrics were observed:

- Total distance covered: 262 meters
- Operating time per cycle: 1.6 hours
- Average speed: 9 km/h
- Battery discharges during work operation cycle (WOC): 76.2%
- Battery discharge during swap operations: 9%
- Total battery discharge: 85.2%
- Capacity hauled per full cycle: 301.2 tons
- Number of cycles per full charge: 21.5

Zone N°1	Zone N°2	Zone N°3	Zone N°4	Zone N°5	Zone N°6	Zone N°7	Zone N°8	Zone N°9	Zone N°10
28	83	131	20	0	0	0	0	0	0
7	2	16	0.3	0	0	0	0	0	0
OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Distance L vs UNL	262
Operating time	1.6 Average speed 9 km/h
Battery discharge in WOC	76.2
Capacity hauled (tons)	301.2
Number of cycles	21.5

Zone N°1	Zone N°2	Zone N°3	Zone N°4	Zone N°5	Zone N°6	Zone N°7	Zone N°8	Zone N°9	Zone N°10
184	62	165	50	131	37	30	83	28	0
11	2	14	0.7	16	0.34	5	2	7	0
OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Batter discharge in swap	9.0
Total battery discharge	85.2

Our Recommendation : no more than 85% Depth of Discharge (DOD)

Figure 21: simulator of the efficiency of the machine when it works between two level

Zone N°1	Zone N°2	Zone N°3	Zone N°4	Zone N°5	Zone N°6	Zone N°7	Zone N°8	Zone N°9	Zone N°10
20	176	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Distance L vs UNL	196
Operating time	1.82 Average speed 9 km/h
Battery discharge in WOC	77.4
Capacity hauled (tons)	464.9
Number of cycles	33.2

Zone N°1	Zone N°2	Zone N°3	Zone N°4	Zone N°5	Zone N°6	Zone N°7	Zone N°8	Zone N°9	Zone N°10
184	62	165	50	131	37	0	0	0	0
11	2	14	0.7	16	0.34	0	0	0	0
OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Batter discharge in swap	7.5
Total battery discharge	84.9

Our Recommendation : no more than 85% Depth of Discharge (DOD)

Figure 22: simulator of the efficiency of the machine when it works on the single level

$$Rate\ of\ Decreasing\ the\ Efficiency\ of\ the\ machines's\ battery\ \ due\ to\ existance\ of\ the\ ramp =$$

$$RDE = \left(1 - \left(\frac{operating\ time\ by\ considering\ the\ ramp}{operating\ tiome\ of\ the\ machine\ without\ any\ ramp}\right)\right) \times 100$$

Thanks to the above equation the RDE of the machine can be calculated:

$$RDE = \left(1 - \left(\frac{1.6}{1.82}\right)\right) \times 100 = 12\%$$

As we can see, the efficiency of the machine undergoes the great improvement about **12%**. when it works in the only one. in the other word, when the charging and discharging is located on the same level, we can reach to higher efficiency by using electric vehicle and obtain higher number of cycles.

In this case, the machine operates on two different levels, with the most critical incline on our path being 16%. However, since the machine cannot traverse such a steep ramp frequently, the highest practical value for consideration is 12%. For an average estimation, we can assume that each ramp contributes approximately 10% to the battery's energy consumption. This is a reasonable average because while steeper grades are rare and challenging for the machine, gentler slopes are also present but tend to be longer (as the ramp between level 9 and 10 has the inclination of 11, with higher distance should be traveled). Therefore, an average energy consumption of 10% per ramp is a practical and acceptable assumption for RDE.

$$\boldsymbol{RDE\ (for\ another\ level) = \left(\left(\frac{Calculated\ RDE\ \times\ Desired\ Ramp\ Inclination}{Calculated\ ramp\ inclination}\right)\right)}$$

So

$$RDE(for\ level\ 10\ to\ 11) = \left(\left(\frac{12\times14}{16}\right)\right) = 10.5\%$$

And

$$RDE(for\ level\ 9\ to\ 10) = \left(\left(\frac{12\times11}{16}\right)\right) = 8.25\%$$

5.3 Battery Depth of Discharge Considerations

The simulator suggests that the optimal depth of discharge (DOD) should not exceed 85% to maintain battery longevity. The calculated total battery discharge of 84.9% closely align with this recommendation, ensuring that battery performance remains within safe operating limits. Excessive DOD values may lead to accelerated battery degradation, requiring frequent replacements and higher maintenance costs.

5.4 Operational Implications and Future Optimization

Based on the simulator's data, several operational strategies can be considered:

1. Utilization of Regenerative Braking: Efficient use of regenerative braking, particularly in descending sections, can further extend battery life.
2. Load Distribution Adjustments: Examining the haul weight distribution in different zones can help reduce unnecessary energy expenditure (in the case of high inclination is suggested to use diesel LHD machine, and flat area with E-LHD, Like Cleaning the drift before starting each shift by E-LHD).
3. Machine Speed Optimization: Maintaining an optimal speed can balance battery efficiency and productivity without excessive power loss (which was already selected 9 Km/h by simulator as a most efficient speed).

6. Energy Efficiency and Cost Analysis

One of the primary reasons for transitioning from diesel-powered Load-Haul-Dump (LHD) machines to battery-electric alternatives is the potential for energy cost savings. Underground mining operations require continuous material transportation, which translates into high fuel consumption and frequent maintenance for diesel-powered machinery. The reliance on diesel engines drives up operational costs due to rising fuel prices, extensive ventilation demands, and engine wear-related expenses (Peila et al., 2024).

Battery-electric LHDs, on the other hand, offer a more energy-efficient alternative by eliminating the need for fossil fuels and reducing overall energy consumption per ton of material moved. Studies comparing diesel and battery-electric LHDs have consistently demonstrated that electric models consume significantly less energy, leading to lower operating costs and improved efficiency. An analysis by (Peila et al.,2023) found that electric LHDs can reduce energy costs by up to 40%, primarily due to:

- Lower maintenance requirements, as electric motors have fewer moving parts compared to diesel engines.
- Absence of fuel expenditures, removing the financial burden of diesel procurement and storage.
- Improved energy efficiency, as electric drivetrains convert a higher percentage of energy into usable power compared to combustion engines.

Beyond direct fuel savings, electrification also minimizes logistical costs associated with diesel storage, transportation, and handling. Underground mining operations often require fuel stores, secure storage areas, and refueling logistics, all of which contribute to additional expenses and operational complexity. By eliminating the need for on-site fuel infrastructure, battery-electric LHDs reduce fire hazards, improve safety standards, and simplify mining logistics. In the following paragraph (chapter 6.4) the cost analysis have been carried out based on the early capital, long term and short term cost.

6.1 Early Capital Cost

Even though in the long term the use of battery electric LHDs brings many benefits, the problem of the red thread is the high initial capital investments. Electric mining equipment needs specific infrastructure, including:

- Charging stations to support fast charging or battery swapping technologies.
- Fleet management systems for monitoring battery health, energy distribution, and predictive maintenance.

These upfront costs can deter companies from immediate adoption, particularly for mines that lack the necessary electrical infrastructure. Fernández et al. (2023) emphasize that transitioning to electric mining equipment requires strategic planning, as integrating charging infrastructure into existing underground networks can be both technically and financially demanding.

6.2 Long-Term and Maintenance Cost

However, long-term cost-benefit analyses indicate that the return on investment (ROI) is favorable. Mining companies that have already adopted electric LHDs report:

- Reduced ventilation costs, as eliminating diesel exhaust reduces the demand for high-powered air circulation systems.
- Lower maintenance expenses, as electric motors require fewer replacements and repairs compared to internal combustion engines.
- Regulatory incentives, including tax credits, emissions reduction funding, and government subsidies for sustainable mining technologies.

In addition, to that the progress in battery tech and energy control systems is consistently enhancing the feasibility of mining fleets. The enhancement of batteries with energy density charging options and energy retrieval mechanisms is tackling worries, about operational interruptions and efficiency declines. Mining firms that are putting money into eco technologies nowadays are setting themselves up for savings in the run and gaining a competitive edge in a sector that is becoming more regulated.

As global sustainability targets and carbon reduction policies push industries toward low-emission solutions, the financial justification for electrifying underground mining equipment is becoming more compelling. While initial capitals investment remains a barrier, declining battery cost, improved energy efficiency, and long-term operational savings ensure that battery-electric LHDs are not just an environmental importance, but also an economically strategic decision for the future of mining.

6.2.1 Reduction of the fuel cost

The rising costs of diesel fuel, maintenance, and ventilation requirements, combined with tightening environmental regulations, have prompted the mining industry to explore battery-electric alternatives. Governments and international organizations are imposing stricter emissions standards and carbon reduction policies, pushing mining companies toward low-emission or zero-emission solutions. Additionally, the introduction of carbon taxation and financial incentives for sustainable technologies has further accelerated the shift toward electrification.

Research by (Yu et al. 2010) highlights that electrification in mining is not a new concept, with early attempts dating back several decades. However, widespread adoption was historically hindered by technological limitations, particularly in battery performance, charging infrastructure, and energy storage capacity. In recent years, significant advancements in battery technology, automation, and real-time monitoring systems have made large-scale implementation of electric LHDs far more viable.

Modern battery-electric LHDs are now equipped with high-capacity lithium-ion battery packs, which offer longer operational durations, improved energy efficiency, and faster charging times. The introduction of regenerative braking systems has further enhanced efficiency by allowing vehicles to recover energy during deceleration, reducing overall power consumption. Additionally, fast-charging technologies and battery-swapping solutions have mitigated concerns regarding downtime, enabling continuous operations in underground mining environments. The graph represents the specific diesel consumption (CS(GM)) in liters per ton (L/t) for mining vehicles over time, spanning from January 2022 to December 2024. It tracks fuel efficiency trends, key operational changes, and the impact of electric vehicle integration in the mining fleet.

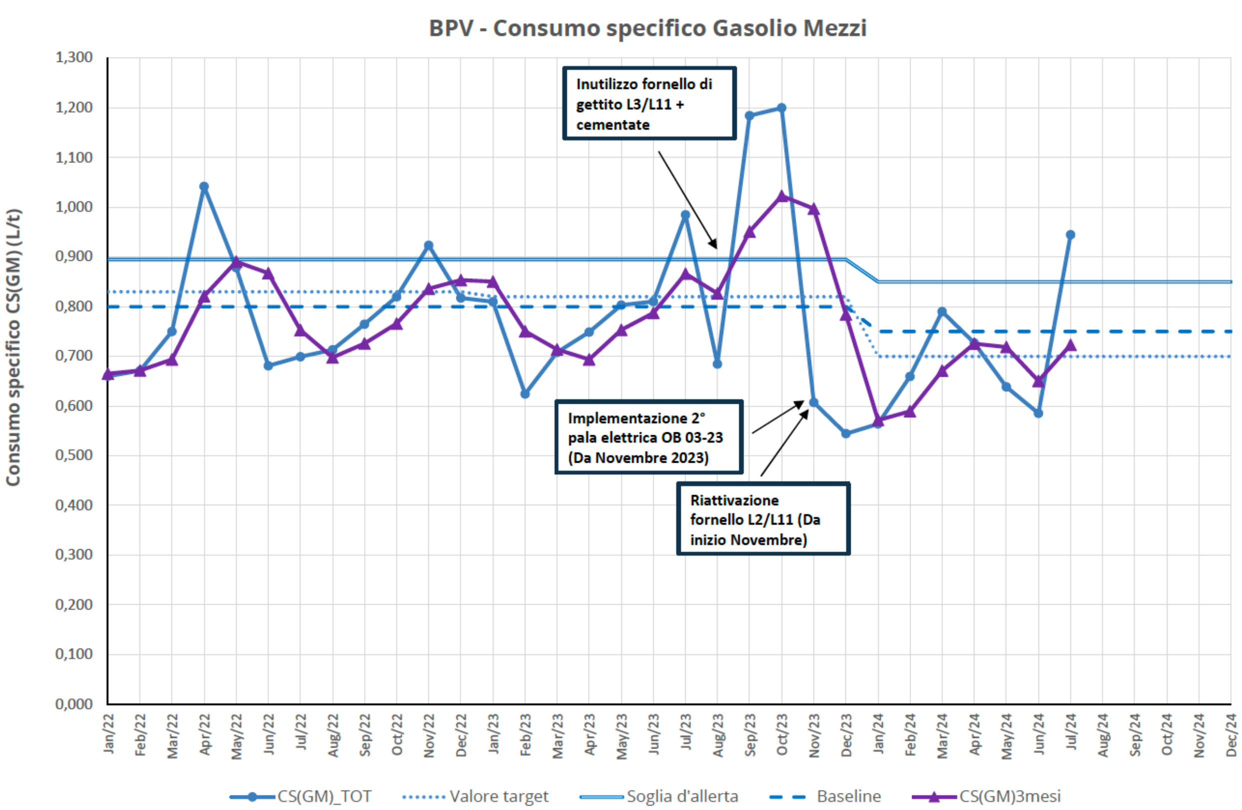


Figure 23: Specific gasoline consumption per month

6.2.2 Observations and Key Trends

Increasing Diesel Consumption Trends: Several spikes in fuel consumption occurred, notably around March 2022, August 2023, and November 2023, indicating periods of higher diesel dependance.

Impact of Electric LHD Implementation (November 2023): A significant reduction in diesel consumption is visible following the introduction of a second electric LHD (OB 03-23) in November 2023. This suggests that electrification efforts are effectively lowering fuel dependency.

Reactivation of L2/L11 Ore Pass (November 2023): Another notable shift in fuel consumption coincides with the reactivation of the L2/L11 ore pass. This might indicate increased haul distances or changes in material handling processes affecting diesel use.

High Diesel Consumption Events (2022-2023): Diesel consumptions exceeded the baseline multiple times, particularly when certain mining operations were adjusted or expanded. The closure of L3/L11 (cemented stope) may have contributed to a temporary decline in diesel use before fuel demand increased again.

Recent Trends (2024 Onwards): Diesel consumption appears to stabilize, with values hovering closer to the baseline and target levels. The impact of electrifications efforts is becoming more evident, contributing to an overall decreasing trend in fuel use.

CS(GM)_TOT (Blue Line): Represents the total specific diesel consumption over time. Noticeable fluctuation indicates periods of higher or lower diesel use, likely influenced by operational changes.

CS(GM) 3-Month Moving Average (Purple Line): Smooths out short-term variations to highlight longer-term trend in diesel consumption.

Baseline (Dashed Blue Line): A reference line representing expected average diesel consumption levels.

Target Value (Dotted Blue Line): The ideal diesel consumption goal, which operations should aim to stay below.

Alert Threshold (Solid Blue Line): Indicates the maximum acceptable diesel consumption level, beyond which corrective actions may be needed.

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Recent Trends (2024 Onwards): Diesel consumption appears to stabilize, with values hovering closer to the baseline and target levels. The impact of electrification efforts is becoming more evident, contributing to an overall decreasing trend in fuel use.

6.3 Fleet Optimization and Intelligent Energy Management

Intelligent fleet management systems have further enhanced the efficiency of electric mining equipment with their introduction. Real-time data processing and predictive analytics with AI-driven decision making is used to coordinate multiple electric LHDs and optimize material transport cycles and reduce energy consumption. Autonomous fleet management software can maximize productivity by analyzing battery charge levels, route planning and workload distribution and minimize operational downtime. An advantage of intelligent fleet coordination is its ability to schedule battery charging cycles efficiently, preventing unnecessary power losses and ensuring that LHDs remain operational for extended periods. Advanced charging strategies, such as opportunity charging (short bursts of charging between operations) and automated battery swapping stations, have further improved the operational uptime of battery-electric LHDs.

6.4 Cost Breakdown Comparison

To help understand the financial implications of moving from diesel powered to electric LHDs summarizing the cost breakdown of both types of equipment that compares the key cost elements of Diesel and Electric LHDs based on the lower and upper range is essential. As for the financial analysis of the machine (Table 3) provided a detailed breakdown of the costs of transitioning from diesel to electric LHDs by comparing the key cost elements of Diesel and Electric LHDs based on the lower and upper range in the table below:

Diesel LHDs:

1. **Capital Cost** (Amortized over 5 years):

- Lower Range: €250,000 / 5 = **€50,000 per year**
- Upper Range: €600,000 / 5 = **€120,000 per year**

2. **Fuel Cost**:

- **Annual Fuel Consumption**: 25 liters/hour × 16 hours/day × 230 days/year = **92,000 liters/year**
- **Fuel Cost**: 92,000 liters/year × €1.60/liter = **€147,200 per year**

3. **Ventilation Cost**:

- Lower Range: **€100,000 per year**
- Upper Range: **€200,000 per year**

4. **Maintenance Cost**:

- Lower Range: **€20,000 per year**
- Upper Range: **€30,000 per year**

5. **Extraordinary Maintenance**:

- Lower Range: **€80,000 per year** (due to the need for a machinist on-site)
- Upper Range: **€160,000 per year** (double of the lower range)

6. **Total Annual Cost**:

- Lower Range: €50,000 (capital) + €147,200 (fuel) + €100,000 (ventilation) + €20,000 (maintenance) + €80,000 (extraordinary maintenance) = **397,200 per year**
- Upper Range: €120,000 (capital) + €147,200 (fuel) + €200,000 (ventilation) + €30,000 (maintenance) + €160,000 (extraordinary maintenance) = **€657,200 per year**

Electric LHDs

1. **Capital Cost (Amortized over 5 years)**:

- Lower Range: **€1,000,000** / 5 years = **€200,000 per year**
- Upper Range: **€2,000,000** / 5 years = **€400,000 per year**

2. **Energy Cost**:

- **Annual Energy Consumption**: 50 kWh/hour × 16 hours/day × 230 days/year = **184,000 kWh/year**
- **Energy Cost**: 184,000 kWh/year × €0.20/kWh = **€36,800 per year**

3. **Ventilation Cost**:

- Lower Range: **€20,000 per year**
- Upper Range: **€50,000 per year**

4. **Maintenance Cost**:

- Lower Range: **€100,000 per year**
- Upper Range: **€150,000 per year**

5. **Cleaning Cost**: **€14,560 per year (based on the IMI FABI cost)**

6. **Tire Cost**:

• Lower Range: tires × €8,000 per tire × 2 times/year = **€16,000 per year**

• Upper Range: tires × €9,000 per tire × 2 times/year = **€18,000 per year**

7. **Extraordinary Maintenance**:

• Lower Range: 20% of ordinary maintenance = **€20,000**

• Upper Range: 20% of ordinary maintenance = **€30,000**

8. **Total Annual Cost**:

• Lower Range: €200,000 (capital) + €18,400 (energy) + €20,000 (ventilation) + €100,000 (maintenance) + €14,560 (cleaning) + €16,000 (tires) + €20,000 (extraordinary maintenance) = **€403,760per year**

• Upper Range: €400,000 (capital) + €18,400 (energy) + €50,000 (ventilation) + €150,000 (maintenance) + €14,560 (cleaning) + €16,000 (tires) + €30,000 (extraordinary maintenance) = **€678,960 per year**

Table 3: Cost analysis of the operation based on the diesel or electric LHD (€ per year)

Cost Element	Diesel LHDs (Lower Range)	Diesel LHDs (Upper Range)	Electric LHDs (Lower Range)	Electric LHDs (Upper Range)
amortized value	50,000	120,000	200,000	400,000
Fuel/Energy Cost	147,200	147,200	36,800	18,400
Ventilation Cost	100,000	200,000	20,000	50,000
Maintenance Cost	20,000+80,000	30,000+100,000	100,000	150,000
Cleaning Cost	N/A	N/A	14,560	14,560
Tire Cost	16,000	18,000	16,000	18,000
Extraordinary Maintenance	80000	160000	20000	30000
Total Annual Cost	397,200	657,200	403,760	678,960

Although the early cost of the machine is greatly varied, the operational cost of the machine is almost same, so it makes this machine more affordable when we consider the flexibility of the operation, safety and sustainability of the machine besides their own cost. the fuel cost is relay on the season and condition so the average price can be taken to the account. Ventilation cost is quite diminished by using electrification of mucking and hauling LHD machine in the mine due to absence of the Co2. In addition, maintenance cost due to hiring the machinist in the site is the setback in the terms of high operational cost for Diesel one, on the other hand for the cleaning of the battery periodically the E-LHD machine has a cost. Due to size of the machine in both diesel and electric the tire cost is almost same, because it is independent from the type of the engine. Furthermore, the extraordinary maintenance due to the high mechanical potion of the diesel engine is higher in compare with electronic one. However, the early capital for the E-LHD machine is excessively high, but it includes lots of sophistication in battery packing and whole the machine such as sensor, cooling liquid, thermal insulation etc. through which the more real time monitoring that we can obtain, the more safety that we will reach in our operation.

7. Conclusion and suggestion

The transition to electric Load-Haul-Dump (E-LHD) machines in underground mining operations is a significant shift to more sustainable, safer and more efficient practices. This thesis comprises a comprehensive study of this transition and its multifaceted advantages align with global environmental goals and effectively respond to the stringent safety standards needed in mining operations. Electrification reduces significantly hazardous gases and particulate matter emissions; this is CO2 and diesel particulate matter (DPM) which are typical of diesel-powered equipment. Not only does this shift help meet stringent environmental regulations, but it drastically improves the quality of the air in mines, improving safety and health for workers. E-LHD machines are responsible for a significant decrease in the mine's ventilation requirement due to the absence of diesel emissions, which eliminates the need for large-scale air ventilation systems and, in turn, reduces energy consumption and operational costs. The implementation of electric vehicles like the E-LHD machines in mining operations introduces enhanced efficiency. These machines provide increased mucking and hauling speed, especially in the case that two working environments are close to each other like excavating the two tunnels that are close enough to each other. The absence of diesel engines in such scenarios means that electric machines can operate without contributing to the threshold limit of CO2, thus maintaining a safer environment for workers. However, there are some economic concerns that come with using electric vehicles. The purchase cost of E-LHD machines and the battery systems are high. Although the operational cost saves by reduce using diesel and ventilation cost are return on investment. The performance of batteries is generally getting poor after five years and require either replacement or upgrade, which can affect long term financial planning. Furthermore, the volatility of electricity prices that can rise by 25% during peak months, such as January, requires careful management. Mines must respond not only to operational requirements but also to these price fluctuations to minimize costs.

Strategic Recommendations

To optimize the advantages of electrification and avoid its drawbacks it is advised that mining fleets are managed energetically and batteries used as such; in conjunction with smart energy management systems that can adapt AI-driven system that constantly monitor varying electricity prices and availability for optimal electric power and battery usage. Furthermore, the ongoing improvements in the battery technology and the possibility of the government encouragements for the clean energy usage are the ways to reduce the costs and increase the efficiency in the future. To achieve this, mining companies should be aware of the current trends and try to incorporate them into their operations. Thus, the shift to E-LHD technology in underground mining is not only compatible with global sustainability initiatives but also improves operational effectiveness and safety. Thus, through minimizing the economic implications of this shift in mining operations, it will be possible to optimize performance and sustainability and create a model for future mining practices globally.

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9. Tools and Software

Epiroc Software, KPI of the E-LHD machine

Aramine Group, Simulator of the E-LHD machine