Energy Intensity Trends and Prospects in South African Open-Cast Mine: A case study of a coal mine

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A research report submitted to the Faculty of Commerce, Law and Management, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Management in Energy Leadership

Johannesburg, 2024

SUMMARY

The mining sector in South Africa is a major energy consumer, relying extensively on diesel and electricity, which results in increased carbon dioxide emissions. This sector represents a significant portion of the nation's electricity consumption and petroleum usage. Given increasing global pressures to lower carbon emissions, companies face an increased desire to focus on energy efficiency as an important strategy.

Moreover, the growing expectations from regulators and stakeholders necessitate that companies disclose information regarding energy intensity, carbon emissions, and sustainability practices, highlighting the importance of clear and quantifiable advancements. The environmental impact, rising costs, and operational expenses associated with high energy consumption make it clear that sustainable practices are essential for the future of the industry.

This study uses a quantitative methodology to examine energy consumption and intensity at an opencast coal mine in South Africa. The objective is to evaluate trends in energy intensity and identify potential avenues for enhancing energy efficiency within an open-cast coal mining environment.

The results indicate that factors such as hauling distance, coal quality, operational sequencing, and seasonal production played a significant role in shaping energy demand at the case study mine. Enhancing energy efficiency leads to a notable reduction in energy use and carbon dioxide emissions, which is essential for tackling climate change and advancing global sustainability effort.

KEYWORDS - Energy efficiency, energy intensity, energy consumption, South Africa, open-pit coal mining.

DECLARATION

I, Mosebetsi Olga Tlhoaele, declare that this research report is my work except as indicated in the references and acknowledgments. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in 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.

Name: Mosebetsi Olga Violet Tlhoaele Signature:

Signed at: Pretoria On the 18 day of February 2025

DEDICATION

I dedicate this thesis to my parents, family, and friends, whose unwavering support and encouragement have been invaluable throughout the course of my studies.

ACKNOWLEDGEMENTS

I would like to express my heartfelt appreciation to my parents for inspiring me to pursue knowledge and work diligently towards my goals.

I would like to extend my gratitude to my supervisor, Dr. Bruce Young, for his steadfast support and encouragement throughout this journey. Your guidance and willingness to assist whenever I needed help have been invaluable.

I am grateful to Prof. Diane Hildebrandt and the research community under Dr. Bruce's leadership. The collaborative spirit and conceptually stimulating environment have significantly impacted both my research and personal growth.

Lastly, I want to thank my family and friends for their constant support and faith in my abilities, which have made this journey much more manageable. Your encouragement has been a driving force behind my perseverance.

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LIST OF ACRONYMS and ABBREVIATIONS

AA – Automobile Association

DMRE - Department of Mineral Resources and Energy

DMR - Department of Mineral Resources

DFFE - Department of Environmental Affairs, Forestry and Fishing

EC - European Commission

EnM – Energy Management

EE – Energy Efficiency

GHG – Greenhouse gas

IRP – Integrated Resource Plan

KPI – Key Performance Indicators

MMS – Middleburg Mine Services

NERSA – National Energy Regulator of South Africa

NEES – National Energy Efficiency Strategy

ROM – Run of mine

CHAPTER1. INTRODUCTION

1.1 Purpose of the study

This study aims to assess energy intensity trends and identify potential opportunities for improving energy efficiency specifically focusing on Middleburg Mine Services (MMS), an open-cast coal mine in Mpumalanga Province, South Africa.

1.2 Context of the study

Energy is an essential component of economic development, globally and in South Africa. The mining sector, as one of the country's most energy-intensive industries, is vulnerable to increasing energy costs and pressure to adopt environmentally sustainable practices. Efficient energy use has become not just an economic need, but also a key component of environmental stewardship.

Bashir et al. (2021) emphasise that energy intensity and consumption are critical metrics for assessing efficiency and understanding the environmental implications of energy use. These measurements provide useful information on how effectively energy is used and how consumption habits contribute to climate change. As the global push towards sustainable development intensifies, countries and companies must achieve a balance between economic growth, cost-effectiveness, and environmental stewardship.

Energy efficiency has emerged as a financially viable solution to these two concerns. According to Makridou et al. (2016), it is critical in accomplishing environmental goals while improving economic performance. Similarly, Levesque et al. (2014) highlight the challenges that mining businesses encounter when implementing energy-efficient methods into their operations, despite their potential to improve both environmental and financial sustainability.

In response to these issues, the South African government has established measures such as the National Energy Efficiency Strategy (NEES), which emphasises the need of good energy management in reducing total demand and increasing efficiency DME (2005) These strategies are consistent with international trends that encourage businesses and individuals to contribute to environmental protection through better energy habits.

Energy efficiency is also directly related to larger policy goals. Blok (2005) and Patterson (1996) emphasise that increasing energy efficiency considerably reduces greenhouse gas emissions, improves energy security, and strengthens industrial competitiveness. As such, it is a critical component of national and international efforts to counteract climate change and promote sustainable development.

Compared to other businesses, the mining sector has significant sustainability concerns. Azapagic (2004) emphasises the importance of monitoring and improving sustainability performance in mining, particularly given the volatility of energy costs and rising consumption trends. In this setting, improving energy efficiency is critical for lowering operational costs, guaranteeing responsible resource use, and meeting national sustainability goals.

To contribute to this goal, detailed study will be conducted at Middleburg Mine Service (MMS), an Open-cast mine in Mpumalanga Province, to identify ways to optimize energy use, reduce consumption and costs, and minimize environmental impact, aligning with national energy efficiency goals.

1.3 Research Problem

The mining industry faces a significant challenge in improving energy efficiency due to the declining availability of easily accessible reserves in South Africa. As mining operations delve deeper, the energy requirements escalate owing to the heightened complexities of extraction. This highlights the necessity for focused approaches to address the operational and energy-related issues linked to resource depletion.

As noted by Bogunovic et al. (2009) enhancing energy efficiency is crucial for achieving industrial goal, with reducing energy use per tonne of extracted ore being a key focus.

South Africa, as a signatory of the Paris Agreement, has pledged to lower emissions and tackle the challenges posed by climate change RSA (2020). Nonetheless, in spite of this dedication, the shift towards clean energy has progressed at a sluggish pace, and recent power shortages have significantly affected private businesses. The identified challenges highlight the critical necessity for improved energy efficiency and diversification to improve energy security and reduce potential future crises.

(Winkler & Marquand, 2009) highlight that South Africa, similar to numerous other countries is a major energy consumer and needs to priorities focus on energy conservation to address climate change. He further underscore that in the short term, prioritising energy efficiency is crucial for environmental sustainability.

Bunse et al. (2011) observe that industries with energy consumption, such as mining, have been reluctant to implement energy management practices, even though these practice could significantly lower energy usage and expenses. Obstacles like limited awareness, financial limitations, and a lack of prioritization regarding energy efficiency hinder progress. The study will focus on assessing energy intensity trends and identifying ways to improve energy efficiency in coal mining at Middleburg Mine Service

1.5 Research Objectives

The objective of this study is to examine the energy intensity patterns at MMS, pinpoint areas within the mine where energy efficiency can be improved.

To attain this objective, the following research questions need to be addressed:

How effectively is MMS progressing towards sustainable coal mining practices?

This overarching research question can be further divided into the following sub-questions:

- What has been the trend in the mine's energy (electricity and fuel) consumption over the years?
- What noticeable patterns and trends can be identified in the energy intensity processes at the mine?

The study aims of this study is to analyse energy intensity trends and pinpoint avenues for enhancing energy efficiency. The main goal is to enhance sustainability and reduce energy costs.

1.6 Significance of the study

Studies on energy efficiency, particularly energy intensity in South African coal mining, have largely focused on underground operations, as highlighted in the works of Mogodi (2012) and Majola and Langerman (2023). Conversely, studies on open-pit mining, as seen in research conducted by Bogunovic et al. (2009) in the United States and Patterson et al. (2016) in Australia, have revealed a gap in empirical evidence regarding energy intensity in South Africa's open-cast coal mining. This study seeks to address this gap by analysing the energy intensity trends of an open-cast coal mine in South Africa.

The study seeks to pinpoint avenues for enhancing energy efficiency in mining, crucial for optimising production and minimising environmental consequences. Considering the sector's significant energy consumption and emissions, enhancing efficiency is crucial for attaining sustainability. The results will provide valuable insights into consumption patterns, inform enhancements, and foster collaboration among stakeholders. Through the reduction of energy consumption, enhancement of efficiency, and the adoption of cleaner energy sources, South Africa can achieve economic sustainability while limiting its environmental impact in alignment with global climate objectives.

1.7 Delimitations of the study

The study has several delimitations, which include:

i. Since the data collection centres on a specific mine in Mpumalanga, the findings of this study might not be widely applicable to other mines situated in diverse regions that function under varying practices and contexts.
ii. The study does not include explosive energy. This arises from the necessity for specialised expertise and abilities, and it operates differently from other forms of energy use, such as electricity and fuel.
It is essential to consider these delimitations when assessing the findings of the study. This study concentrates on a specific mine and explore themes related to with energy intensity, offering detailed insights into energy efficiency, as well as the challenges, and opportunities within the mining sector.

1.8 Definition of terms

Climate change - as defined by NASA (National Aeronautics and Space Administration), encompasses various global phenomena resulting mainly from the combustion of fossil fuels, which release heat-trapping gases into the Earth's atmosphere (Lee et al., 2009).

Energy efficiency - refers to decreasing energy demand while ensuring effective energy utilization for achieving equivalent output, as outlined by (Winkler & Marquand, 2009).

Energy Intensity – refers to the amount of energy used to generate a single unit of GDP, as defined by Burnett and Madariaga (2017). This metric is crucial for assessing the efficiency of energy utilization in economic activities, highlighting the relationship between energy consumption and economic output.

Energy consumption – refers to the quantity of energy used, and its unit of measure is kWh.

Energy performance -refers to the effectiveness of energy usage.

Energy management involves optimizing energy production, usage, and distribution to reduce energy expenses while maintaining the quality and quantity of output, as stated by Abbas et al. (2018). This process includes monitoring and improving energy consumption, analysing data, pinpointing areas for optimization, and enhancing energy efficiency.

1.9 Assumptions

The analysis assumes that the data collected is precise, ethically obtained, and dependable. The results and suggestions hold significant credibility and are essential for informing decision-making processes among regulatory authorities, investors, and stakeholders within the mining industry. The investigation highlights the critical need to maintain data integrity to generate actionable insights that aid in policy development, strategic planning, and sustainable investment within the sector.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The literature review establishes the foundation for the theoretical framework by detailing key theories and concepts relevant to the study. The analysis of energy efficiency occurs within the wider framework of sustainability, incorporating aspects of environmental management, energy management, and economic factors. This is essential for reducing resource use, lessening environmental effects, and improving operational effectiveness. Effective energy management encompasses a range of policies, technologies, and strategies designed to optimise energy consumption in harmony with sustainability objectives.

2.2 Sustainability and Environmental Management

The relationship between greenhouse gas emissions and energy is crucial and represents a global challenge that necessitates focused efforts to mitigate the effects of climate change. This section examines the global perspective and South Africa's approach to enhancing energy efficiency to mitigate the effects of climate change. The mines are gradually integrating continuous updates about energy sustainability into their comprehensive reporting framework, accessible on the company website. This illustrates a commitment to aligning energy efficiency initiatives with the organization's goals and sustainability objectives.

2.2.1 A Global perspective on Energy and GHG emission

The European Commission is targeting a significant decrease in greenhouse gas emissions, aiming for an 80 to 90% reduction by 2050, as detailed in the Energy Roadmap 2050 EC (EC, 2011) . This dedication underscores the necessity of enhancing energy efficiency as a fundamental approach to address the effects of climate change. Improving energy efficiency is crucial for tackling climate change and greatly reducing greenhouse gas emissions (IEA, 2015).

The Kyoto Protocol, created in 1997 and implemented in 2005, sought to lower global greenhouse gas emissions Indukuri (Indukuri, 2022). This treaty established targets the countries to collectively lower their greenhouse gas emissions linked to climate change. The Kyoto Protocol represented a significant milestone in the fight against global climate change, establishing concrete emission reduction goals and fostering international cooperation to mitigate greenhouse gas effects. Carbon taxation and emission trading systems were implemented to enhance energy efficiency and minimise unnecessary energy consumption Dimitrov (2016). The objective of these measures was to reduce carbon emissions and promote the adoption of more sustainable practices among industries and individuals.

2.2.2 South Africa's response to Energy and GHG emission

In 2005, the Department of Minerals and Energy (DME) introduced the Energy Efficiency Strategy (EES) as a proactive measure by South Africa to address climate change (DME, 2005). This strategy highlighted the use of diverse methods and interventions, including economic and legislative measures, informational campaigns, the setting of energy performance benchmarks, conducting energy audits, implementing energy management practices, and promoting energy-efficient technologies. The aim was to enhance energy efficiency in multiple sectors. Regulations and fiscal policies have been implemented by the government to lower greenhouse gas (GHG) emissions while promoting behavioural changes that support the shift towards a low-carbon society, as noted by Devarajan et al. (2009).

The initiatives were designed to reduce GHG emissions and to promote societal behaviours that encourage sustainability. South Africa's strategy for mitigating carbon dioxide emissions, as detailed in the South Africa Low Emission Development Strategy (SA-LEDS), emphasises the importance of managing energy demand and regulating its expansion via the National Energy Efficiency Strategy (DEA, 2018).

2.3 Energy efficiency in mining

The processes used for coal extraction are significantly dependent on electricity and diesel, leading to a rise in energy usage for every unit generated. This underscores the significance of energy efficiency in promoting sustainability and minimising environmental impact within the sector. Energy intensity refers to the amount of energy needed to attain a certain output level or to carry out a specific activity, as noted by Burnett and Madariaga (2017).

According to Ryan (2014) the drive for adopting energy management practices in mining companies stems from the objectives of enhancing competitiveness, profitability, and productivity. This underscores the acknowledgement within the industry that effective energy management reduces environmental impact and is essential for improving overall business performance.

A variety of initiatives aimed at enhancing energy efficiency have been put into practice within South African mining operations. An illustrative case is the Anglo-American Group, a prominent platinum producer, which had successfully implemented 223 energy-saving projects by Ryan (2014) . The installation of compressors, ventilation fans, heat pumps, and subterranean lighting has become the most common approaches to improving energy efficiency. The committee evaluated the outcomes of their initiatives as outstanding, achieving notable savings of US$75 million Ryan (2014). Anglo American's energy-saving project efforts resonate with the viewpoint of Awuah-Offei (2016), who suggests that demand management techniques are essential for energy efficiency initiatives in the mining sector, emphasising the importance of reducing electricity consumption and associated costs.

Bogunovic et al. (2009) highlight that the processes of extraction, material handling, and beneficiation demand substantial energy, pinpointing to an important opportunity for improving efficiency. Similarly, Kecojevic et al. (2014)) note that the coal extraction and overburden removal processes are heavily reliant on diesel and electricity, with diesel being the primary energy source.

However Awuah-Offei (2016) argues that material handling and comminution are the processes with the highest potential to improvements efficiency. While automated feature in beneficiation plants help with energy management, the author points out that improvements in comminution and handling might significantly boost overall efficiency. According to Liu et al. (2015)I trucks are the main culprit when it comes to carbon emissions in open cast pit coal mine transportation. Their energy consumption is four to twelve times higher than that of conveyor belts. Also, according to Kecojevic et al. (2014) a lot of diesel energy is used up when coal is being exposed and when it is being extracted. In contrast to previous viewpoints, Majola and Langerman (2023) identified underground mining and beneficiation processes as having the highest energy consumption. To navigate this complexity, it is necessary to understand the energy requirement at various phases of mining, as pointed out by Bogunovic et al. (2009). Identifying potential pathways for energy conservation should be the initial approach to decreasing energy usage in the mining sector, as noted by Bogunovic et al. (2009). He emphasises the significant challenge of obtaining more reliable data on energy consumption, a common issue encountered by numerous mining businesses. This assertion aligns with the perspective of Abbas et al. (2018), who emphasise that effective energy management involves comprehensive data collection and analysis, identifying areas needing improvement, and subsequently enhancing energy efficiency.

Dessureault (2007) contends that although mining operations often gather production data, its genuine value is realised only through effective utilisation. He emphasises that effective energy-saving strategies rely on the establishment of an information system that provides accurate data on energy consumption during mining operations. Dessureault emphasises the necessity of developing a comprehensive data system, rather than merely collecting data, to effectively minimise energy consumption in mining operations.

Energy needs in mining can vary greatly from one commodity to another, as pointed out by Mogodi (2012). Compared to other mining activities, he finds that ventilation systems, coal transport, and mining operations consume significantly more energy. An increase in production according to Mogodi, will results in high electricity consumption.

Tshisekedi (2008) notes that underground mining operations require significantly more energy than surface mining. Surface mining predominantly utilises energy via diesel fuel for its haulage operations. On the other hand, underground mining relies heavily on electricity, especially for the hoisting of ore to the surface and ensuring adequate ventilation within the mine. Jeswiet and Szekeres (2016) contend that while open-pit and underground mines exhibit distinct energy requirements, both rely on water flow pumps, which constitute approximately 25% to 32% of the overall motor energy consumption at a standard mining location. The authors emphasise the significance of energy consumption in mining, pointing out its pervasive impact on operational costs throughout all stages of the mining process.

Awuah-Offei (2016) emphasises that the design of mines and the planning of production play a crucial role in determining how equipment is deployed, which in turn affects operating conditions, the interactions between equipment units, and the overall efficiency of equipment utilisation. Sahoo et al. (2014) emphasise the significant influence of operator skills and practices on the energy efficiency of loading and hauling operations. The integration of strategic mine design, production planning, and proficient operator practices plays a crucial role in enhancing energy efficiency in loading and hauling operations.

Investigating these interdependencies is crucial for enhancing operational strategies and fostering sustainable practices within the mining sector.

Another significant step towards improving energy efficiency in the mining industry was made by SRK (2022), as highlighted in Table 1.

Table 1: Key areas for improving energy efficiency in mining operation by SRK (2022)

Area	Improvement
Less movement	Streamline the process to minimize movement.
	Reduce frequency of movement.
	Optimize transportation routes.
Reduce long haul	Optimize logistical process
	Reorganize the mine layout to minimize the distance materials need to be hauled.
	Use of hydrogen as an alternative to power the haul trucks.
Cooling down	Optimise cooling energy efficiency
	Energy efficiency cooling technologies
Evolving technology	Embrace advanced and more energy-efficient technologies

Kumar (2023) underscores seven essential strategies for reducing energy consumption in the mining sector, building upon prior academic research on improving energy efficiency. These strategies are outlined in Table 2 below.

Table 2: Seven key recommendations crucial for decreasing energy usage within the mining sector, as outlined by Kumar (2023).

Category	Improvement
Creating strategy plan	Set a clear objective that involves conducting a comprehensive review of existing operation energy usage and equipment efficiency. Identify areas where energy consumption is high.
Brainstorm	Encourage the team to brainstorm ideas on capturing and utilizing energy efficiently.
Energy management strategy	Designing an energy strategy that involves less energy. Deploy and monitor motor controls and optimize the processes to optimize energy.
Monitor and measure	Monitoring and measuring energy consumption within a mining operation. Identify areas for improvement and implement effective energy management strategies.
Monitoring power consumption	This is specific for the underground compressors and ventilation systems. Shifting compressors closer to the load and considering alternatives to pneumatic equipment are practical strategies that can yield substantial energy savings.
Implement an advanced Energy Management System (EMS)	This improvement involves integrating mine production systems for real-time energy consumption monitoring, analysis, and optimization.
Invest in a smart meter.	Smart meters offer several advantages, including detailed data collection, real-time monitoring, and energy usage optimization.

According to (Apeaning & Thollander, 2013) market factors including cost savings from reduced energy consumption and the potential for increasing energy prices, serve as primary motivators for the adoption of energy efficiency methods or technologies.

Xu et al. (2023) highlight that mining operations have the potential to decrease energy consumption by implementing several strategies such as removing high-energy-consuming equipment, reducing extraction time, optimizing belt conveyor systems, and improving production processes.

Yu et al. (2017) alongside Wang et al. (2018) conducted an investigated into energy efficiency within the coal mining sector. Yu et al. (2017) developed a multi-objective model focused on investments in energy-efficient measures and methods for reducing emission. Wang et al. (2018) developed a benchmarking system specifically for coal production utllising both product-based and process-based methodologies. The proposed categories serve as thorough indicators of energy efficiency, enabling an analysis of the factors that contribute to variations in energy efficiency across coal mines:

1. Basic indicators reflect the fundamental energy conditions of coal mining operations, typically encompassing total raw coal production and energy consumption during raw coal mining (Wang et al., 2018) .
2. Composite evaluation indicators: These assess the energy or power efficiency of coal mines (Wang et al., 2018).
3. Single-process indicators isolate the influence of natural conditions on energy consumption in coal production by examining the energy use of critical processes. (Wang et al., 2018)

2.4 South Africa Policies on Energy Efficiency

To tackle the challenges associated with climate change and energy, multiple departments in South Africa have formulated policy documents, as demonstrated in Table 3. The policies highlight the strategies and objectives that the nation is promoting in response to climate change, concentrating on both mitigation and adaptation initiatives. The 2018 White Paper on Energy Policy was published, detailing the nation's overarching objectives in the energy domain. The objectives encompass the enhancement of access to affordable energy services, the improvement of energy governance, the addressing of environmental impacts related to energy, the promotion of economic growth, and the assurance of a diversified and secure energy supply (DMEA, 1998).

The Integrated Resource Plan (IRP) suggests that coal and nuclear energy will maintain significant roles in the nation's energy mix DMRE (2019). The White Paper on Renewable Energy Policy emphasises the need to reduce fossil fuel consumption and encourages the integration of renewable energy technologies. The White Paper on Renewable Energy outlines the government's dedication to fostering the development, demonstration, and utilisation of renewable energy sources at multiple scales, ranging from small to large (DME, 2003).

The establishment of the Renewable Energy Independent Power Producers Programme (REIPPP) was promoted, incorporating a competitive bidding process for renewable energy technology across five bid windows DME (2003). The goal is to achieve 3725 MW of renewable energy, marking a significant step forward in the utilisation of sustainable energy sources.

Table 3: South Africa Departmental Policies on Energy

Department	Policy on energy
DMRE	White Paper on Energy Policy DMEA (1998)
	Integrated Resource Plan (DMRE, 2019; Energy, 2019)
	Energy Security Master Plan DME (2007)
	White paper on renewable energy policy DMRE (2021)
National treasury	Carbon tax (Treasury, 2019)
Department of Environmental Affairs, Forestry and Fisheries	National Climate Change Response White Paper (DEA, 2011)
	National Climate Change Strategy (DEA, 2011)

The Department of Environmental Affairs, Forestry, and Fisheries has reaffirmed its commitment to the National Climate Change Response White Paper (DEA, 2011) , which highlights energy efficiency and demand-side management as key strategies for mitigating climate change. The white paper calls for urgent measures to cut greenhouse gas emissions, encourage sustainable energy practices, and shift towards a low-carbon economy. It also emphasizes carbon budgeting to identify mitigation opportunities across critical sectors and calls for appropriate carbon pricing to support this transition.

The National Treasury has put into effect a carbon tax aimed at reducing greenhouse gas emissions and facilitating as shift towards a low-carbon energy economy (Treasury, 2019). This tax imposes a financial burden on emission of greenhouse gases, adhering to the principle that those who pollute should be responsible for the costs associated with environmental harm. The influence extends across multiple sectors, including mining, liquid fuels, transport, and electricity generation, resulting in increased expenses for energy products reliant on coal, such as petroleum.

According to UNIDO (2011), the consistent implementation and evaluation of robust policies stand out as the most successful and effective method for enhancing energy efficiency. The results demonstrate that the implementation of industrial energy-efficient technologies correlates with increasing energy costs, underscoring the essential importance of financial incentives in encouraging energy-efficient practices. Apeaning and Thollander (2013) indicate that a weak policy framework, financial constraints, and insufficient information systems all hinder the growth of industrial energy efficiency in developing nations.

Building upon this, Athukorala et al. (2019) emphasise the importance of improving consumer awareness to decrease energy usage and encourage the uptake of cost-effective and accessible energy-saving options. The results indicate that initiatives from the government focused on promoting and informing consumers about these technologies could improve environmental and energy efficiency.

Implementing these measures would facilitate enduring shifts towards sustainable practices and concurrently reduce energy consumption. In summary, the National Climate Change Response Policy, the Integrated Resource Plan (IRP), and carbon taxes illustrate the misalignment between energy initiatives and climate change efforts. The National Climate Change Response Policy emphasises the necessity of shifting towards renewable energy and improving energy efficiency to tackle climate change, while the IRP supports a sustainable dependence on coal and nuclear power within the energy mix. Unlike the IRP's endorsement of fossil fuels, carbon taxes aim to reduce carbon emissions mainly originating from these sources. This contradiction underscores the tension among environmental sustainability, energy security, and economic growth.

2.5 Exploring energy efficiency past research on open pit coal mines

A considerable amount of studies have been carried out to improve the energy efficiency of open-pit coal mining Patterson et al. (2016). Patterson et al. (2016) explored strategies to improve energy efficiency in open-pit coal mining, focussing on haulage, excavation, stockpile management, processing plants, and conveyor operations.

The study employed a mixed integer linear programming (MILP) framework to assess energy consumption in different mining processes, considering variables such as excavation volumes, hauling distances, and conveyor power usage. This method pinpointed opportunities for improvement and informed choices through the analysis of marginal energy expenses and critical equipment requirements. The methodology underwent validation via a case study conducted in Southeast Queensland, Australia, showcasing its practical application in improving energy efficiency.

(Shuzhao et al., 2011) investigated energy consumption in open-cast coal mining, highlighting the influence of production practices and equipment selection on energy use. The benefits of moving from oil to electricity were emphasised, leading to reduced energy usage and associated expenses. The study explored approaches to reduce energy usage in transportation and proposed that enhancing the stripping inclination angle might be an effective energy-saving tactic. The results demonstrate that resource conditions and production capacity are essential factors influencing energy consumption in open pit mining operations.

Smerichevskyi et al. (2022) highlight significant trends that enhance energy efficiency in the coal sector. This involves comprehensive and transparent oversight of all energy resources, improving and modernising manufacturing facilities, establishing benchmarks for energy usage and the environmental impact of equipment and technologies, and implementing systems for government-backed financial and technical support in collaboration with global organisations. The incorporation of energy-efficient technology and processes improves operational efficiency, reduces environmental impact, and encourages industrial innovation. The authors further identify both internal and external factors impacting energy efficiency in coal mining, such as energy source prices and current market supply-demand dynamics. Key subsystems influencing energy efficiency include:

- **Marketing**: Involving the supply and competitiveness of energy-efficient technologies and energy source pricing.
- **Production**: Encompassing factors like the complexity of mining and geological conditions, mine depth, seam thickness, production capacity, and the technological status of core facilities, as well as characteristics of coal extraction processes and technologies.
- **Financial, Personnel, and Control Systems**: These areas impact energy efficiency through financial resources, workforce expertise, and accountability measures.

In conclusion, the reviewed studies collectively highlight the critical importance of adopting a multifaceted approach to advancing energy efficiency in the coal sector. This approach encompasses technical advancements, such as optimising production methods and adopting energy-efficient technologies, alongside regulatory measures, including the establishment of energy consumption and environmental standards. Additionally, financial strategies, such as state-sponsored support and collaboration with international partners, are essential to drive innovation and implementation. By addressing these interconnected dimensions, the coal industry can achieve not only enhanced energy efficiency but also long-term sustainability and reduced environmental impact.

2.6 Energy Management at a macro level

Some nations have implemented energy management standards aimed at enhancing energy efficiency by equipping organisations with the necessary tools and guidelines for effective energy management. Research conducted by (Abbas et al., 2018) indicates that the nation's energy sector has seen improvements as a result of energy policies aimed at reducing carbon emissions through effective energy management. Public awareness has been identified as a potential strategy for conserving energy, which can lead to more efficient resource management (Abbas et al., 2018)

The study also highlighted the importance of diversifying the energy mix to foster a competitive power market and enhance South Asia's energy economy. However, the study was limited to countries and regions in South Asia and did not include high-energy-consuming firms, which is a limitation of the research.

According to Hasan et al. (2021), there is a growing necessity for implementing energy management practices in developing nations. The study also highlighted the need for a more comprehensive approach at a detailed level. Furthermore, the research indicated that there is a need for more dedicated and specialized energy professionals in these industries, calling for an increase in their numbers. The findings suggest that energy efficiency could be enhanced with more support from top management and addressing bureaucratic complexities. Critical drivers for improving energy efficiency, as identified in the study, include cost-saving through reduced energy usage and compliance with energy-related regulations and standards.

Hasan et al. (2021) highlight that examining the nation's energy consumption and the balance between supply and demand indicates inadequate energy efficiency measures and energy management practices within the country.

2.7 Conclusion

The literature review has offered an in-depth exploration of the diverse elements related to energy efficiency, sustainability, and energy management in the mining industry.

The discussion covers various topics, such as global perspectives on energy and greenhouse gas (GHG) emissions, South Africa's strategies for managing energy and GHG emissions, the effectiveness of energy utilisation in mining operations, and the nation's policies on energy efficiency. The implementation of laws and regulations in South Africa is prompting the sector to explore innovative approaches to improve environmental performance. Energy efficiency stands out as the most effective strategy for decreasing GHG emissions and minimising energy consumption.

Improving energy efficiency requires collaboration between private entities, governmental bodies, and various stakeholders. This partnership is crucial for addressing corporate goals and wider societal challenges related to energy consumption, environmental sustainability, and economic development.

The mining sector holds significant promise for contributing to the overall energy solution through improvements in energy efficiency, thereby reducing energy consumption. Based on the comprehensive analysis conducted through a thorough literature review, there is a pressing need for detailed investigations in the mining industry. The objective of these studies is to determine the measurable factors related to energy consumption, trends in energy intensity, and the corresponding costs. The primary goal is to assess the energy usage of MMS, with a particular emphasis on pinpointing areas for improving energy efficiency.

The literature indicates that mining companies have the potential to lower operational costs by implementing a proactive strategy focused on energy efficiency. This approach is essential for minimising their overall environmental impact and tackling global climate change issues.

The literature highlights the importance of data monitoring and analysis, as well as the implementation of energy-efficient equipment, in enhancing energy efficiency.

Market forces largely determine commodity prices, which limits the mining sector's capacity to secure higher premiums for its products. As a result, mines must enhance profitability by focussing on operational efficiency and discipline, with energy efficiency becoming a crucial strategy.

A thorough examination of existing literature offers an in-depth understanding of the energy dynamics within the mining industry, emphasising the necessity for cohesive strategies that merge technological innovations, policy alignment, and collaborative efforts among stakeholders to promote sustainable energy practices and reduce environmental consequences.

Table 4. Consistency table: research question and propositions

RQ #	Research question	Prop	Hypothesis
1.	How has the mine's energy consumption (electricity and fuel) trended over the years?	1.	1.1 The mine's energy consumption (electricity and fuel) has shown significant variability over the years, influenced by changes in production levels, operational efficiency, and external economic factors.
2.	What patterns and trends are evident in the mine energy intensity processes?	2.	2.1 The mine's energy intensity processes exhibit significant fluctuations due to varying operational practices and external factors affecting energy use.

CHAPTER 3. RESEARCH METHODOLOGY

This chapter details the methodological framework designed to test the hypothesis established in Chapter 2. Chapter 3 delves into the approach to the study, outlining the design, methods for data collection, sample selection, research instruments utilised, procedures for gathering data, limitations of the study, and considerations regarding validity, reliability, and ethics pertinent to the research.

The study will utilize a single explanatory case study approach, with Middleburg Mine Service (MMS) serving as the focal point for the study. The historical secondary data from mine is utilized to analyse the energy efficiency trends and potential developments of a coal mine between 2015 and 2022. This data assists in assessing the evolution of energy intensity over the specified period and identifying opportunities for enhancing energy efficiency in the coal mining industry.

3.1 Area of the study

The study was conducted at Middleburg Mine Services (MMS) in Mpumalanga Province. The mine uses electricity, diesel energy, and explosives for coal extraction, which is subsequently processed and distributed. The energy intensity in the case study fluctuates based on exposure, extraction, and beneficiation processes.

3.1.1 Mine background

The coal mine operates three active pits, a mined discard dump, and three washing plants. Coal is extracted using draglines, shovels, trucks for the pits, and loaders and trucks for the discard dump. MMS produces around 7 million tonnes of thermal coal annually for local and export markets, primarily supplying the

Duvha power station, which has six 600 MW units with a total capacity of 3600 MW (Eskom, 2010)

3.1.2 Main consumer of energy at the Mine

Figure 1 displays the mine process flow and primary energy consumers by type. Initially, surface mining involves pre-stripping to remove topsoil and subsoil, done by diesel-powered trucks and loaders. Drilling follows with diesel-driven drills, and the mining area is exposed using either an electric-driven dragline or a diesel/electric shovel. After excavation, coal is drilled and blasted. Run-of-mine (ROM) coal is loaded onto diesel trucks by a diesel-powered loader, then crushed and ground in a crusher. Processed coal is conveyed to the plant using electric-driven conveyor belts.

ROM coal is stockpiled at the plant using electric conveyors and reclaimed electrically for processing. The plant operates with modules concurrently, each containing screening for sizing and dense medium separation for waste removal, resulting in a marketable product. This product is stockpiled, reclaimed electrically, and conveyed via electric conveyors to the loadout station for dispatch to customers.

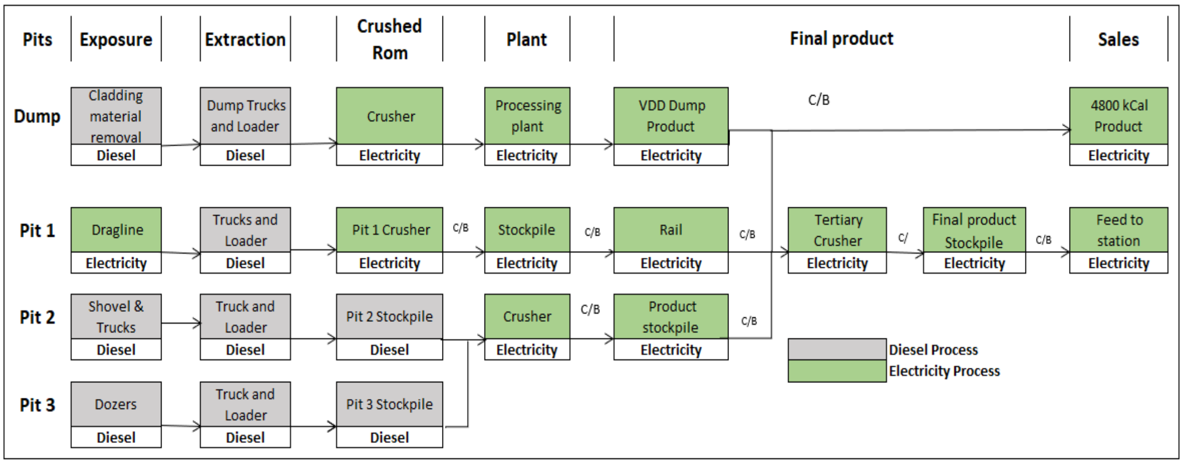

Figure 1: Mine process flow and primary consumers of energy by type.

Energy is vital in various mine operations, powering draglines, shovels, conveyor belts, crushers, trucks, and crushing plants. Eskom powers the mine through the three substations and has three diesel tanks for its mobile equipment. The mine consumes approximately 290 gigawatt-hours (GWh) of electricity annually, which costs approximately R260 million. Fuel costs, primarily diesel, amount to an average of R430 million annually. This coal mine was chosen for study due to its significant economic importance in South Africa's energy sector and its challenges, including high energy expenses and declining mineral ore grades.

3.2 Research Approach

The study followed a quantitative approach, using statistical tools to measure and quantify significant factors. This approach enabled the researcher to draw findings based on the interpretation of secondary data (Arghode, 2012).

The study was conducted using the following steps:

1. Collection of datasets from the mine internal database, historical records on electricity and fuel usage, production output, and the equipment employed.

2. Convert energy consumption of diesel from litres to MJ and electricity from MWh to MJ.
3. Energy intensity calculated using energy consumption divided by the saleable product.
4. Determined the relationship between the variables.

3.3 Research design

The metrics utilised in the study to estimate energy intensity were based on the framework created by Wang et al. (2018) These included basic variables as total raw coal output and energy consumption from coal extraction. Figure 2 shows the variables and units of measurement used in the derivation of these basic indicators.

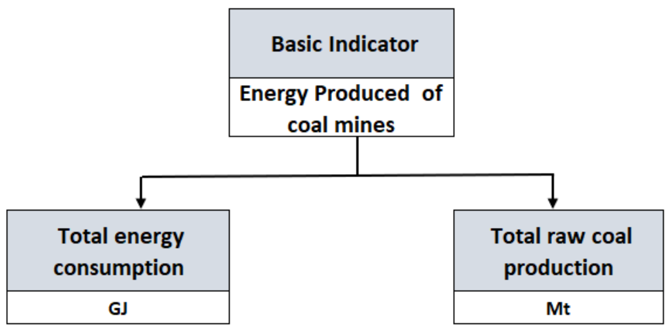

Figure 2: Basic indicator for energy intensity. Authors developed based on (Wang et al., 2018)

Wang et al. (2018) defined composite evaluation metrics to indicate coal production's overall energy intensity. The intensity was calculated using the formula in Equation 1. Figure 2 depicts the indicators, and their corresponding units of measurement used to calculate total energy intensity.

EE = Energy Consumption(GJ)/ Coal Production (Mt) Equation 1

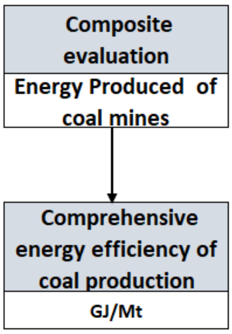

Figure 2: The Comprehensive energy efficiency indicator and unit of measure.

The study examined the third type of indicator, known as single-process measurement indicators. These metrics measured energy intensity in coal production by focussing on critical operational activities (Wang et al., 2018). Figure 3 outlines the calculate energy intensity processes and the unit of measure.

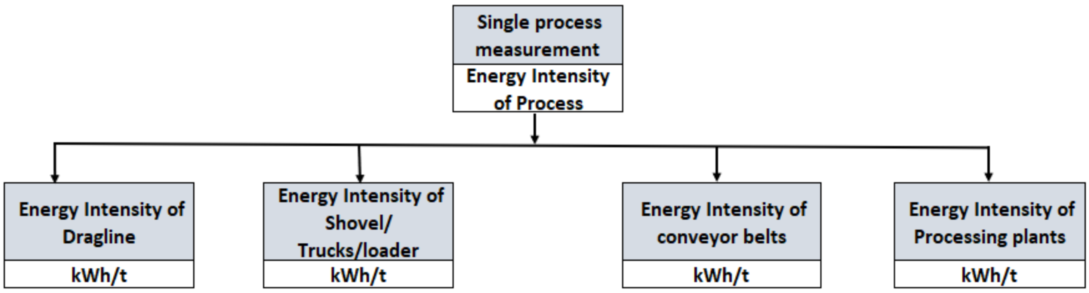

Figure 3: Single process energy intensity and unit of measure.

3.4 Data Collection Methods

The analysis used time series data for the period of 2015 – 2022. This time also saw considerable changes in South Africa's energy scene, including large rises in electricity and fuel prices. Data on electricity use, diesel consumption, production output, and equipment specifications were obtained from the case study database. Figure 4 presents the data collection instrument used by for date collection by the study mine and the outcomes from the data gathered.

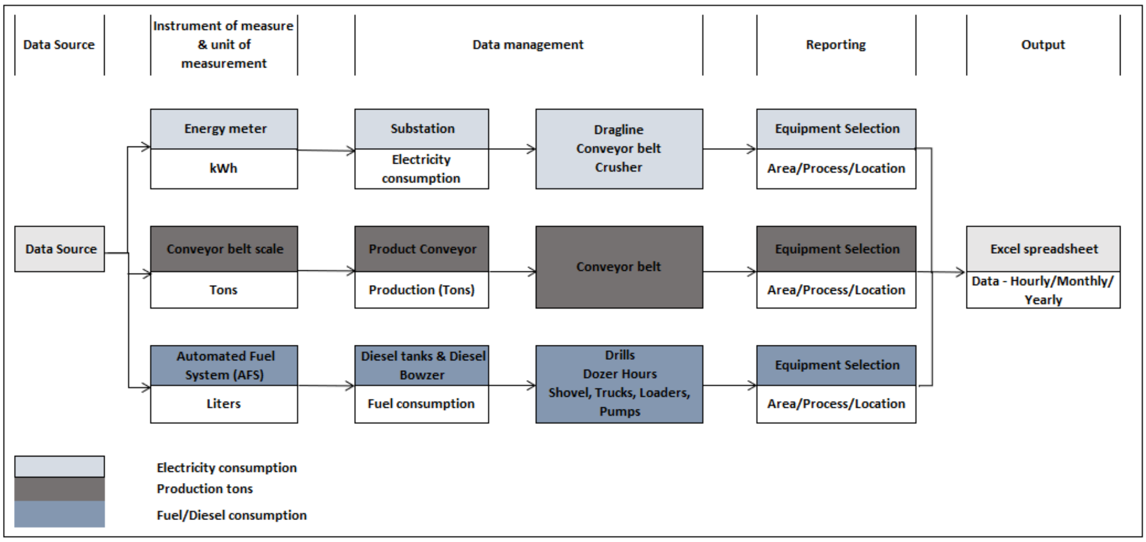

Figure 4: The approach for data collection and instrument of measure.

3.5 The Research Instrument

The literature review served as a foundation for identifying both the data needs and the methodological approached used in this study. The research process was structured in the following steps.

1. Key processes with the significant energy consumption were identified.
2. The total energy consumption relative to production from 2015 till 2022 was analysed
3. Energy consumption was classified by type of energy carrier.
4. Energy intensity was calculated using formular provided in Equation 1.

3.6 Data analysis and interpretation

The secondary data collected from the period of 2011 – 2022 was analysed using a descriptive statistical analysis. The following metrics were tested was:

- Total energy consumption relative to saleable coal.
- Energy intensity of equipment and processes relative to saleable coal.
- Energy consumption per energy carrier.
- Total energy consumption relative to coal produced.
- Time series analysis of energy intensity

1. A complete time series analysis was carried out to look at trends in energy consumption, energy consumption per energy and coal production from 2015 to 2022. A time series graph was created to visually portray changes in time, allowing for the detection of patterns, fluctuations, and long-term trends. This investigation sought to assess the mine's energy performance in the perspective of larger issues such as climate change and energy supply restrictions. Correlation analysis was also used to investigate the links between energy consumption, production levels, and their fluctuations over time, providing quantitative information about the degree and direction of these interactions.

2. A stacker column chart was used to illustrate how the mine's energy-consuming processes evolved over time. This analysis helped in isolating the process with the highest energy demands, as well as identifying processes where energy efficiency measures could have the biggest impact.

3. A pie chart was used to assess energy use by carrier, providing a visual representation of the mine's energy mix. This aided in understanding the proportional contributions of various energy sources, as well as evaluating the diversity and sustainability of the mine's energy portfolio.

4. Another time series graph focused on tracking energy intensity performance over time. This visualisation aimed to assess whether any improvements had been achieved through energy-saving initiatives and to identify potential areas for further optimisation.

3.7 Limitations of the study

The mine's usage of various technologies and equipment that evolved during the research period have impacted the consistency of energy efficiency comparisons over time.

3.8 Validity and reliability

The data were compared to previous study findings To establish the legitimacy of data acquired from secondary sources, it was noted that previous studies conducted by (Majola & Langerman, 2023) and Wang et al. (2018), used comparable data and methodology to analyse both energy intensity and energy performance.

3.8.1 External Validity (generalisability)

The study's findings offered valuable insights into reducing energy consumption in mining operations. Caution was exercised regarding generalisability as it was important to consider the specific characteristics of each industry before drawing broad conclusions. A previous study conducted by (Wang et al., 2018) using a similar analysis had demonstrated that energy consumption could indeed be reduced.

3.8.2 Internal Validity

As a mining company, the case study mine is inherently energy-intensive and relies heavily on electricity and fuel energy for production. Given these characteristics, analysing energy consumption was essential for assessing internal validity. The study's internal validity was further strengthened by considering the specific operational factors and industry dynamics that influenced energy consumption patterns within the mining sector.

By examining the unique challenges and requirements faced by the case study mine, the study established stronger internal validity ensuring that the analysis and findings are relevant, accurate, and aligned with the company's operational context. This contextual understanding enhanced the study's ability to draw conclusions about energy consumption reduction strategies that were tailored to the mine operational needs and challenges.

3.9 Objectivity and confirmability

Relying on a secondary source dataset enhances objectivity, as it reduced the potential for researcher bias in during data collection. By adhering to methodology and ensuring data validation, the study maintained an unbiased approach, strengthening its objectivity.

The use of secondary data sources increased the confirmability of the research as other researcher could access the same dataset and independently verify the findings. Following the methodology approach and utilising secondary data helped minimise bias and supported the confirmability of the study’s outcomes.

3.10 Ethical considerations

To ensure that sensitive data collected from the mine, such as production reports and energy usage details, are handled with strict confidentiality, a consent letter was signed between the company representative and the researcher. This process fostered trust and ensured the protection of confidential information throughout the research. Additionally, authorization was obtained from the university's Research Ethics Committee prior to the commencement of data collection.

CHAPTER 4. PRESENTATION OF RESULTS

4.1 Introduction

This chapter presents the findings based on the data analysis outlined in Chapter 3. Energy intensity trends were examined using production and energy consumption data from the case study mine over the period 2015 to 2022.

1. Overall energy consumption
   1.1 Overall energy consumption and monthly patterns.
   1.2 Overall energy consumption in relation to production levels.
   1.3 Energy consumption categorised by type of energy carrier.
   1.4 Energy consumption of the mining process.
2. Energy intensity
   2.1 Analysis of energy intensity over time, determined by dividing total energy consumption by the saleable production on a monthly and yearly basis.
   2.2 Energy intensity of the mining process.

4.1.1 The conversion factors

The case study mine, diesel consumption was first measured in litres while the electricity was recorded in consumption was first recorded in megawatt-hours (MWh). To convert diesel consumption to consistent energy unit of GJ, a standard conversion approach was used, using a diesel density of 0.85 kg/L (Turns, 1996). and a lower heating value (LHV) of 35.8 MJ/kg (Turns, 1996) table 5. The energy content of diesel was estimated by first converting the volume to mass and then multiplying by the lower heat value. The resulting energy figures were then expressed in gigajoules (GJ), with one litre of diesel equivalent to 0.0358 GJ. This conversion enabled a direct comparison to electricity use, which was likewise measured in GJ."

To guarantee consistency in energy accounting, the electricity consumption figures were converted to gigajoules (GJ) using a standard conversion factor, with 1 MWh equal to 3.6 GJ. Thus, the total electrical energy usage in MWh was multiplied by 3.6 to produce the equivalent GJ figures.

Table 5 Conversion factor applied for the analysis of energy consumption of diesel.

Description	**Unit of measure**	**Density of Diesel**	**Lower Heating value**
Diesel Fuel	L	0.85 kg/L	35.8 MJ/kg

Source: Turns (1996)

4.2 Results pertaining research question 1. Total energy consumption

4.2.1 Total case study energy consumption and monthly trend

The formular used to calculate the total energy consumption is as follows:

Total Energy consumption (GJ) = Total electrical energy consumption process (GJ) + Total diesel fuel consumption process (GJ) Equation 2

From 2015 to 2022, the case study mine saw an annual rise in energy consumption of 4283 GJ, leading to an overall energy consumption of 3.8 petajoules (PJ) (figure 5). Peak energy consumption was recorded in the years 2015, 2021, and 2022, exceeding 500,000 GJ. In contrast, the lowest levels of consumption, below 500,000 GJ, were noted between 2016 and 2020. In 2022, the highest consumption reached 518,616 GJ, whereas the lowest was 389,999 GJ in 2017. The significant decrease in energy consumption from 2016 to 2020 is largely attributed to variation in hauling distances between 4.4 km to 10.5 km, and some sections of the mine placed under care and maintenance, employing a dragline for coal exposure. On the other hand, energy use rose dramatically in 2021 and 2022 as work resumed in previously idle areas and a new pit that required trucks and shovels for ROM exposure was developed. The monthly energy consumption trends (Figure 6) offer further insights into seasonal trends. Energy consumption exhibited a steady decrease in January, February, September, November, and December, while significant rises were recorded from March to August and in October.

The lowest monthly energy consumption recorded was 28,398 GJ in February 2017, while the highest was 51,673 GJ in October 2020. The increase aligns with winter seasons, characterised by increased energy demands to meet the electricity demands whereas the decrease in consumption is associated with the holiday period.

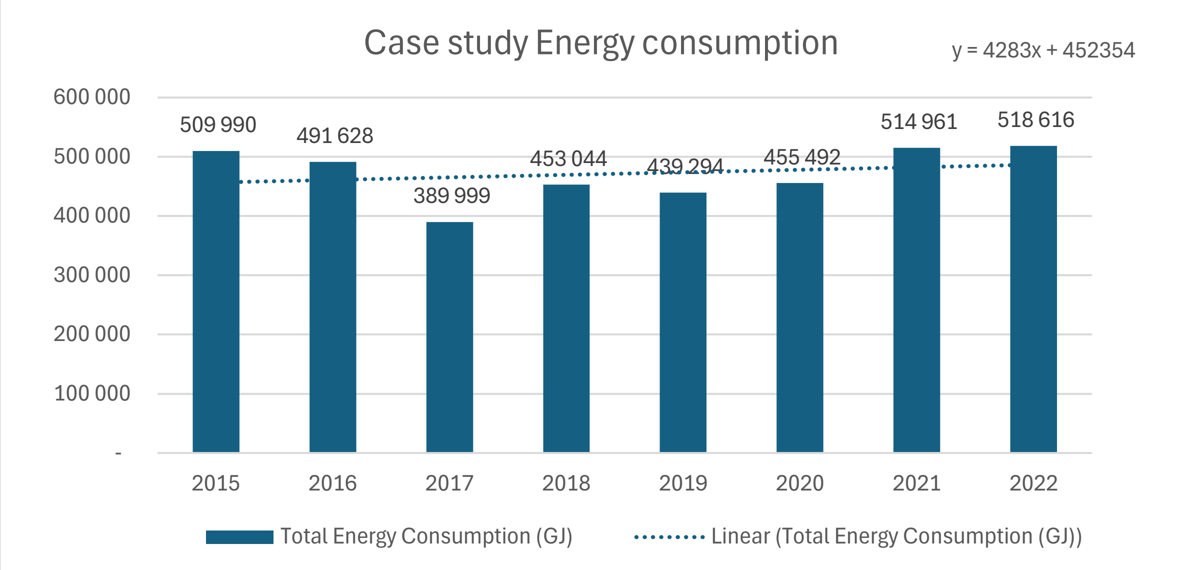

Figure 5: Yearly energy consumption of the case study for period of 2015 to 2022.

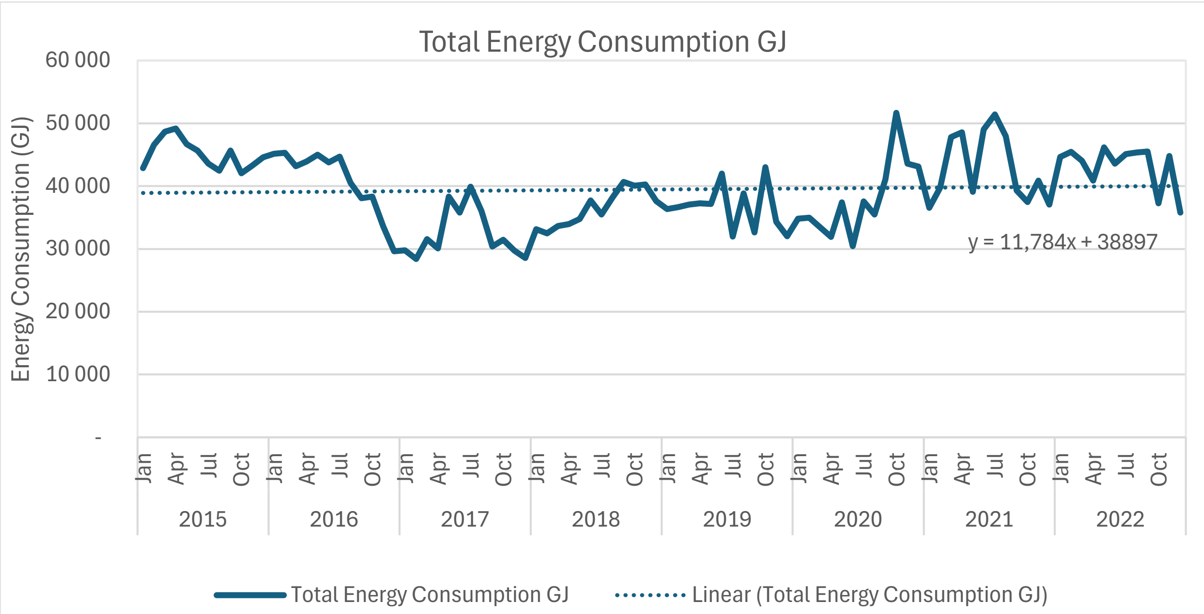

Figure 6: Time series trend in monthly of energy consumption for the period of 2015 to 2022.

4.2.2 Overall energy consumption as a function of production

Between 2015 and mid-2017, there was a notable alignment in energy consumption and production trends, indicating a period of operational stability. Throughout this period, one beneficiation plant was used to process coal, with hauling distances varying from 4.4 km to 10.9 km from the mining phase to the tipping are, ensuring consistent energy consumption and production levels.

Between August 2017 and 2022, energy consumption experienced an upward trend, while the output of marketable coal witnessed a decrease. The changes were prompted by modifications in the extraction of different coal seams (2, 1, and 2A), the establishment of new pits with hauling distances between 6.1 km and 10.9 km, and the initiation of a second beneficiation plant aimed at processing low-quality coal as highlighted in Appendix A and Appendix B. Collectively, these factors played a significant role in the rise in energy demand.

Seasonal variations influenced trends, with energy consumption and production declining in January, February, September, and December for various reasons. The period from December to January coincides with the holiday season, during which a substantial portion of the workforce is typically unavailable. Additionally, this timeframe often overlaps with the rainy season, leading to reduced operational activity and a corresponding decline in the demand for coal. Conversely, between May and August, both saleable production and energy consumption rose to accommodate the energy demand in winter period (April to July).

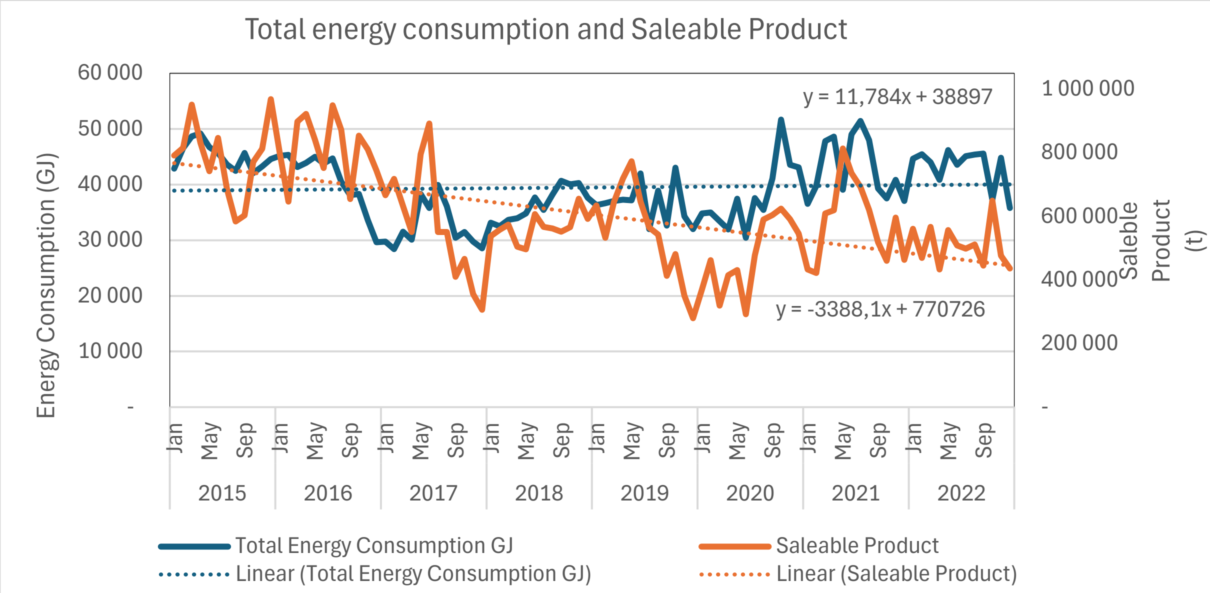

Figure 7: Monthly behaviour energy consumption and saleable product between 2015 – 2022

4.2.3 Energy consumption by energy carrier type

The electricity consumption of the mines has shown notable fluctuations, with a decrease of 89 GJ over the eight-year span, while diesel consumption has consistently increased, rising by 121 GJ (Figure 8). The data shown in Table 6 indicates that electricity continues to be the primary energy source, despite a gradual decline in its usage over the years, with a slight uptick observed in 2020. By the end of 2022, electricity consumption reached its lowest level during the study period, attributed to the implementation of the pit utilising shovels for coal exposure.

In contrast, diesel consumption, which started at relatively low levels, saw a significant increase, ultimately surpassing electricity consumption in 2022. The rise can be primarily attributed to the incorporation of shovels for coal exposure at the new pit, in conjunction with the extended hauling distances that increased from 4.4 km to 10.9 km, as well as alterations in the ore qualities. The change in energy consumption patterns indicates a significant evolution in the energy dynamics at the mine, characterised by a growing reliance on diesel due to operational adjustments.

Table 6: Basic Indicator of case study energy consumption by energy source

Basic Indicator	2015	2016	2017	2018	2019	2020	2021	2022	Total
Electricity consumption in GJ	344 866	342 914	249 375	265 220	289 853	300 493	286 357	239 863	2 318 941
Diesel consumption in GJ	165 125	148 249	140 625	172 865	149 440	154 999	228 604	278 753	1 438 659
Total Energy Consumption (GJ)	**509 990**	**491 163**	**389 999**	**438 085**	**439 294**	**455 492**	**514 961**	**518 616**	**3 757 600**
Saleable Product (t)	**9 403 971**	**9 741 372**	**6 895 247**	**6 770 399**	**6 583 030**	**5 723 835**	**6 985 172**	**6 111 661**	**52 103 027**

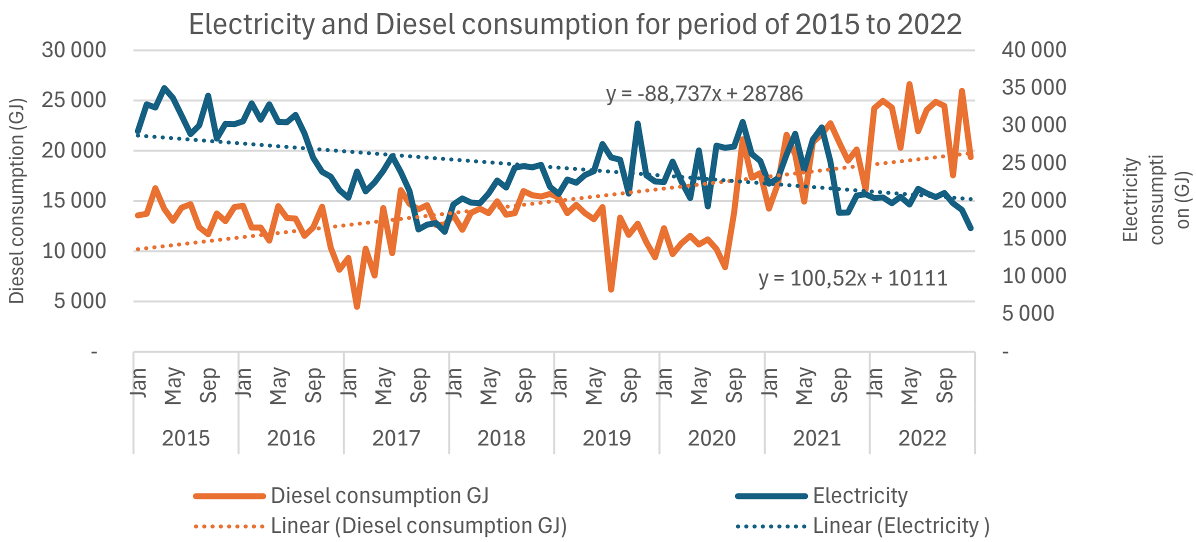

Figure 8: Time series trend in monthly of energy consumption per energy source for the period of 2015 to 2022

Based on the total energy consumption for the period of 2015 to 2022, electrical energy was the primary source of energy at the case study mine, accounting for 62% of the overall consumption. Diesel energy made up the remaining 38%, indicating a strong reliance on electricity to support core mining operations during this timeframe (Figure 9). The analysis highlights the mine's substantial reliance on electricity to facilitate critical operations, which include crushing, screening, dragline excavation, and processing, all of which demand considerable energy resources. On the other hand, diesel serves as the primary energy source for mobile equipment such as haul trucks and shovels, which are essential for transportation and material extraction processes. The analysis of energy consumption reveals the unique operational requirements of the mine, illustrating that stationary processes primarily utilise electricity, while activities driven by mobility are reliant on diesel fuel.

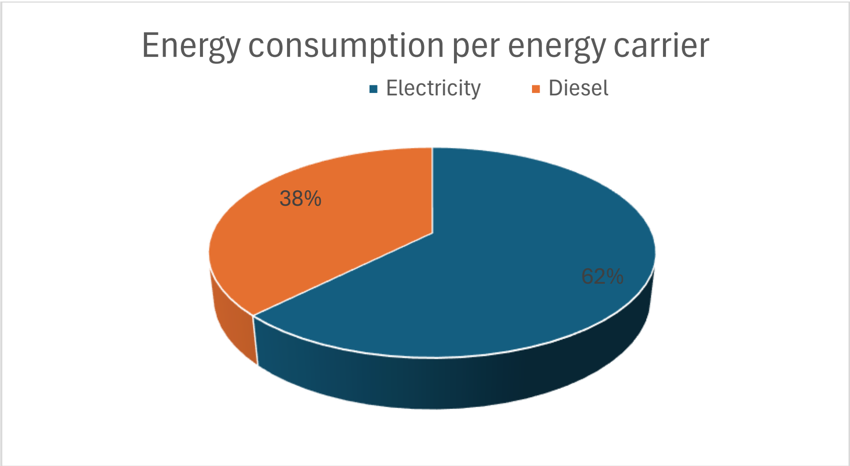

Figure 9. Energy consumption per energy source 2015 – 2022

4.2.4 Energy consumption by mining process.

This section provides a comprehensive analysis of energy consumption across various mining processes from 2015 to 2022, highlighting the energy contributions of four key activities: beneficiation plant operations, coal extraction, coal crushing and conveyance, and ROM (run-of-mine) exposure using shovels and draglines (Figure 10). The extraction of coal serves as the main contributor to energy consumption at the case study mine, amounting to 1.741 PJ, while the beneficiation process accounts for a consumption of 1.01 PJ from 2015 to 2022.

The total consumption for the ROM exposure and the coal crushing and conveyor belt process over the 8-year period was 0.65 PJ and 0.35 PJ, respectively. The energy consumption of the extraction process was notably affected by changes in hauling distance, ranging from 4.4 km to 10.9 km to 9.6 km. The distance of hauling and the arrangement of pits significantly influence the effectiveness and overall performance of extraction activities.

The beneficiation process stands out as the second-largest energy consumer at the case study mine, underscoring its essential role in converting raw coal into marketable products. From 2015 to 2022, the facility processed run-of-mine material of diverse qualities obtained from multiple seams, including Seam 1, Seam 2, Seam 2L, and Seam 2A, each exhibiting different characteristics. The handling of lower-grade coal requires a more energy-intensive method. In the years 2019 and 2020, energy consumption experienced a decrease due to seasonal influences and the operational choice to temporarily halt certain sections of the mine. The ROM exposure process is identified as the third highest energy-consuming activity at the case study mine. The energy consumption associated with this process has shown a consistent increase since 2018, culminating in a notable peak in 2022.

The rise can be attributed to the addition of a second auxiliary piece of equipment, the shovel, as well as the creation of new pits in 2021. The coal handling process, encompassing conveying, stacking, and reclaiming coal, functions continuously and is recognised as the fourth-largest energy consumer at the case study mine. A notable decrease in energy consumption was recorded during the periods when the facility was subject to care and maintenance in 2019 and 2020.

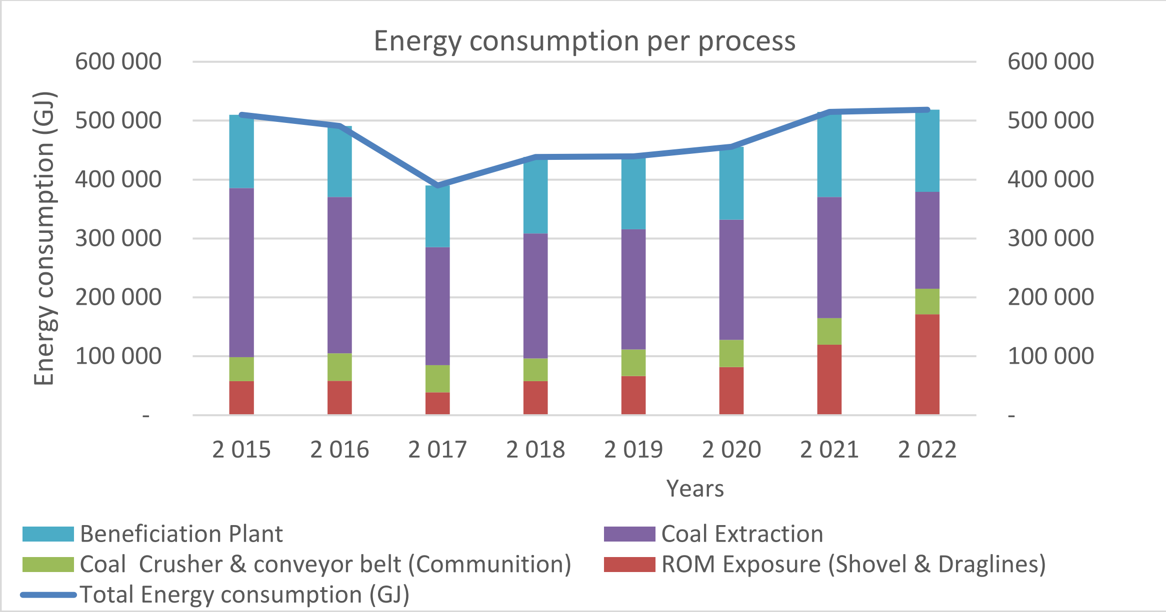

Figure 10: Energy consumption at by process at case study mine (2015 – 2022)

4.3 Results pertaining research question 2. Energy Intensity

This section outlines findings relevant to the investigation: What observable patterns and trends can be identified in the energy intensity and processes of the case study mine? The assessment of energy intensity required a thorough analysis of energy consumption in relation to the saleable coal produced over an 8-year period. The analysis indicated an upward trend in energy intensity, marked by monthly increments of 0.00040 GJ/t (Figure 11). The observed increase in energy consumption per unit of saleable coal output can largely be attributed to operational changes at the case study mine. These include extended hauling distances resulting from the development of a new pit, along with the mining and processing of multiple coal seams namely seam 1, seam 2, seam 2L, and seam 2A which vary in quality and processing requirements. Detailed information on seam characteristics and haulage distances is provided in Appendix B and Appendix C.

The linear trend equation, Energy Intensity = 0.0004x + 0.051, shows a consistent increase in energy intensity over time. The positive slope indicates a continued upward trend, driven mostly by the mine's operational sequence from extracting coal near the tip to more distant areas resulting in longer haulage distances and increased energy consumption per unit of saleable output Appendix B. Moreover, the variations in coal seam lithology among different seams, each exhibiting unique characteristics, play a crucial role as well. As mining progresses, the distances for transportation expand, and the growing energy demands lead to an increase in energy intensity. The rise in energy intensity at the case study mine primarily stems from energy usage per unit of saleable production, which is significantly associated with extended hauling distances and the complexities involved in mining and processing different seams, including S1, S2, S2A, and S2L.

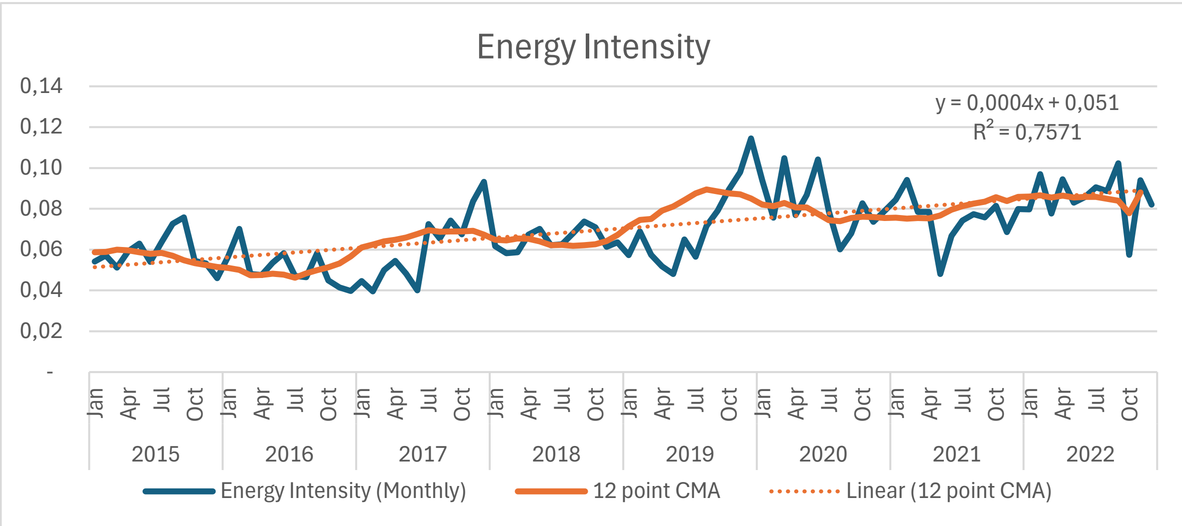

Figure 11: Monthly behaviour of energy intensity 2015 – 2022.

4.3.1 Energy Intensity by process

The analysis of energy intensity throughout mining processes reveals both opportunities for improvement and persistent challenges. Figure 12 indicates the energy intensity of various processes at the case study mine. The coal extraction process starts with a higher energy intensity, which then declines during 2016 and 2017, falling below 0.03 GJ/t.

Following 2018, there is a resurgence in energy intensity, indicating heightened demands; however, it experiences a decline again in 2021 and 2022, ultimately falling below 0.03 GJ/t. The trend in energy intensity is subject to changes primarily due to changes in hauling distances and the variability of coal quality and seam. The energy intensity of the beneficiation process rose from slightly above 0.01 GJ/t in 2015 to over 0.02 GJ/t in 2022, demonstrating a steady increase. The rise can be linked to the commissioning of a new beneficiation plant in 2018, which resulted in increased energy demands. Furthermore, the handling of various coal seams exhibiting differing qualities has resulted in heightened energy requirements.

The ROM exposure process (shovel & dragline) shows a consistent rise in energy intensity as time progresses. The initial value was more than 0.01 GJ/t in 2015 and increased to nearly 0.03 GJ/t by 2022. The rise can primarily be linked to the implementation of shovels and the associated diesel-powered hauling trucks, resulting in heightened energy consumption. Furthermore, the increase in hauling distance from 4.4 km at the beginning of operations to 10.9 km, driven by the establishment of new pits, has significantly raised energy requirements. The increase in energy intensity highlights the energy demands associated with the development of coal mining activities.

The energy intensity of the coal crusher and conveyor belt process has demonstrated a remarkable stability over the eight-year period, remaining below 0.01 GJ/t. During the interruption of the crushing lines, the energy intensity consistently held at a low level of 0.01 GJ/ta, with a minor increase observed between 2019 and 2020, yet remaining below 0.01 GJ/t. The observed stability indicates that the crusher and conveyor belt processes exhibit lower energy intensity and are not sensitive to variations in coal qualities.

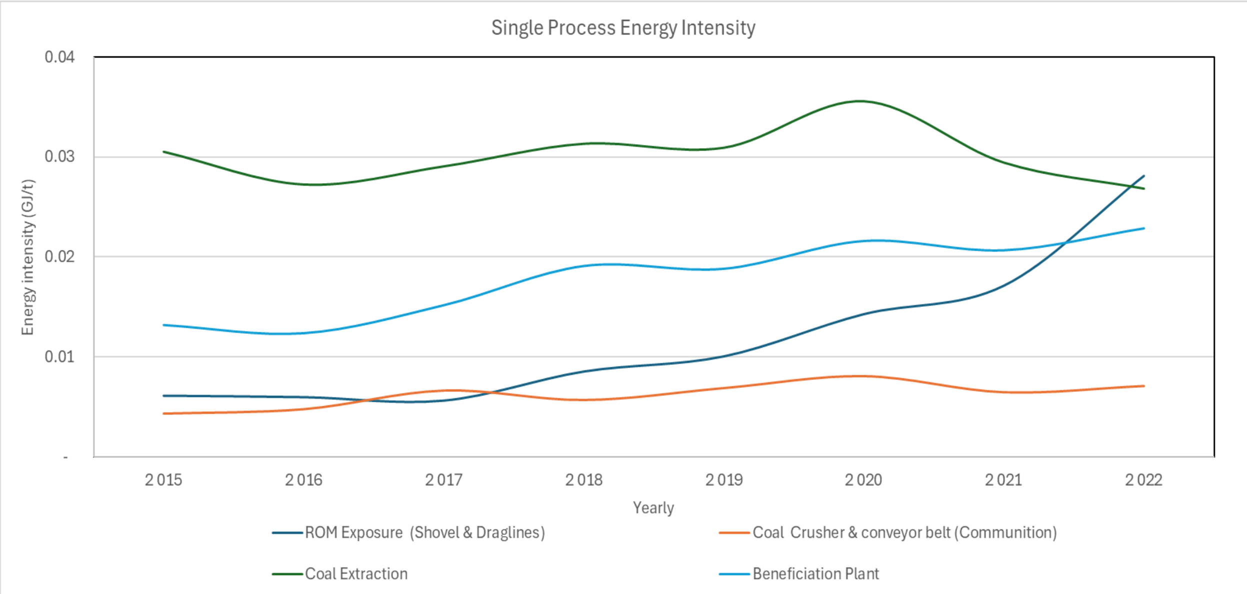

Figure 12: Energy intensity of various process

4.4 Summary of Presentation of Research Results

Chapter 4 presents the results of the analysis of the study.

Research question 1: How has the mine's energy consumption (electricity and fuel) trended over the years?

The findings indicate that multiple operational factors have notably elevated the energy consumption levels of the mine. This involves incorporating new equipment for coal exposure, creating more pits, an interim pause for equipment maintenance, and increased haul distances. Moreover, the requirements for seasonal production, particularly during the winter months, resulted in a significant increase in energy consumption to meet the heightened demands for coal production.

Research question 2: What patterns and trends are evident in the mine energy intensity processes?

Throughout an eight-year period, the energy intensity recorded at the case study mine exhibited fluctuations influenced by a range of operational and geological factors. The expansion of mining activities in diverse areas and locations has significantly raised total energy consumption.

The expansion resulted in heightened energy consumption, subsequently contributing to the overall rise in energy intensity. As mining operations progress into new pits and strips situated further from the tipping point, there is a notable increase in hauling distances from 4.4 km to 10.9 km. The increased distance necessitates additional trips and extended hauling durations, resulting in higher diesel usage and, as a result, greater energy intensity. Additionally, the geological features of the run-of-mine (ROM) have varied from high-grade S2 and S2L to low-grade ROM S1 and S2L seam, requiring thorough processing to produce a marketable product. The significant impurities found in low-grade ROM require more energy for beneficiation, which in turn raises energy consumption and diminishes the saleable product. The extended hauling distance and the processing of low-grade ore have notably elevated the energy intensity of the mine.

4.5 Comparison of literature review and own findings

Table 7. Comparison of literature review and findings

RQ #	State Research Question or Objective	Prop / hyp #	State Proposition or Hypothesis (literature review response to RQ)	Findings from own study
1	How has the mine's energy consumption (electricity and fuel) trended over the years?	1.	1.1 The mine's energy consumption (electricity and fuel) has shown significant variability over the years, influenced by changes in production levels, operational efficiency, and external economic factors.	The results indicate that multiple operational factors have notably impacted the energy usage of the mine. This involves the deployment of shovel, the establishment of additional pits, a temporary halt of equipment for maintenance, and increased haul distances. Furthermore, the demands of seasonal production, especially in the winter months, led to a notable rise in energy consumption to satisfy the increased requirements for coal production.
2	What patterns and trends are evident in the mine energy intensity processes?	2.	2.1 The mine's energy intensity processes exhibit significant fluctuations due to	The qualities of coal and hauling distance play a crucial role in influencing the overall

RQ #	State Research Question or Objective	Prop / hyp #	**State Proposition or Hypothesis** (literature review response to RQ)	**Findings from own study**
			varying operational practices and external factors affecting energy use.	energy intensity. Lower quality coal typically necessitates longer processing times, consequently increasing energy consumption rates.

CHAPTER 5. DISCUSSION OF THE RESULTS OR FINDINGS

5.1 Introduction

This chapter aims to discuss the findings reported in Chapter 4. The results will be used to address the study's purpose, research objective, and research question, and will be connected to the prior study as detailed in the literature review.

5.2 Time Series, trendline and 12 point centred moving average

Time series analysis was used to identify seasonal patterns and identify inconsistencies or anomalies in energy consumption. A trendline, generated using linear regression, was employed to ascertain the anticipated trajectory of energy consumption over time. According to Adhikari and Agrawal (2013), time series analysis proficiently investigates the periodicity of seasonal and irregular components, whereas the linear regression trendline elucidates the fundamental long-term patterns of energy consumption in the case study. The monthly energy intensity was forecasted with the highest precision using a 12-point centred moving average. This approach was selected for its effectiveness in reducing short-term fluctuations in data while preserving essential long-term trends and seasonal variations.

This method effectively balanced noise reduction with the preservation of essential fluctuations, yielding a clear and dependable depiction of the underlying energy intensity dynamics across time, thereby rendering it an optimal choice for analysis and forecasting.

5.3 Discussion pertaining to question 1

5.3.1 Total energy consumption

The objective of the study is to evaluate how effective is the case study mine in promoting sustainable coal mining practice. The findings reveal that the mine's energy consumption has risen by 4283 GJ per year, highlighting a continuous rise in energy demand. The data suggests that the mine has not successfully implemented strategies focused on enhancing sustainability. This trend corresponds with projections from the International Energy Agency (IEA, 2009),which suggest an anticipated rise in energy consumption, as well as findings by Wang et al. (2016) regarding a Chinese coal mine that saw an increase in energy usage.

The rise in energy usage at the mine in 2021 and 2022 is attributed by the addition of the shovel. This is in line with the conclusions of Shuzhao et al. (2011) who emphasis that equipment selection and production methods affect energy consumption in open-pit coal mining.

5.3.2 Energy consumption as a function of production

Over the course of eight-years, the case study mine has extracted coal from various seams of different qualities, leading to increased energy consumption. The rise in energy consumption and a decline in production is ascribed to variations in seam depth, quality, and extraction complexity. The finding is supported by Shuzhao et al. (2011) who highlighted that resource circumstances and production capacity are critical determinants of energy usage in open-pit mining operations.

5.3.3 Energy consumption by energy carrier type

Diesel consumption has increased significantly from 165,125 GJ in 2015 to 278,753 GJ in 2022 while the hauling distance has seen an increase from 4.4 km to 10.9 km, reinforcing Tshisekedi's (2008) assertion that surface mining predominantly depends on diesel fuel for haulage operations.

5.3.4 Energy consumption by mining process

Patterson et al. (2016) emphasised the importance of assessing energy consumption throughout different phases of the mining process to identify opportunities for enhancing efficiency. The processes of extraction and beneficiation were recognised as the most energy-intensive at the case study mine. This finding aligns with the work of Bogunovic et al. (2009), who emphasised that extraction, material handling, and beneficiation demand significant energy input, revealing a crucial opportunity for optimisation.

The process of coal extraction at the mine predominantly utilises diesel, with both electricity and diesel employed for coal exposure. The findings indicate that the introduction of a shovel in 2021 heightened the mine's dependence on diesel as the main energy source for both coal extraction and exposure. This change was evident in a significant increase in diesel consumption from December 2021 to 2022. The results align with the findings made by Kecojevic et al. (2014), indicating that coal extraction and overburden removal are significantly reliant on diesel and electricity, with diesel serving as the primary energy source.

Liu, Cai, Chen, and Zhou (2015) established that the energy consumption of trucks is four to twelve times greater than that of conveyor belts. The case study demonstrated this trend through the relatively low energy usage of the coal crushing and conveyor system (comminution), which exhibited the lowest energy consumption among all processes. The energy consumption of the coal crusher from 2015 to 2022 was 0.35 PJ, which is five times less than the extraction process that consumed 1.74 PJ of energy.

5.4 Discussion pertaining to question 2

5.4.1 Energy intensity

The evidence suggests that the case study mine exhibits a trend of increasing energy intensity. From 2015 and 2022, energy intensity increased by 0.00040 GJ/t per month. As noted by Bunse et al. (2011), that energy-intensity industries including mining are energy-intensive industries and highlighting the need for effective energy management practices.

The results indicate that energy intensity at the case study mine has increased over time, mainly due to variations in ore quality stemming from the extraction of different seams, the development of new pits, and longer haul distances that have expanded from 4.4 km to 10.9 km. According to SRK (2022), there are crucial strategies for improving energy efficiency in mining, such as minimising movement, shortening long hauls, and adopting advanced technologies.

From 2015 to 2022, diesel prices increased by 12.93 cents per kWh each year (AA, 2022), whereas electricity prices experienced a more gradual rise of 9.3 cents per kWh (Eskom, 2022) in South Africa. The increasing energy intensity at the mine, resulting from extended haul distances and greater reliance on diesel, underscores the failure to implement energy efficiency measures. Apeaning and Thollander (2013) emphasised that the primary drivers for the adoption of energy-efficient technologies were the cost savings realised from decreased energy consumption and the expected rise in energy prices. However, the case study reveals that the mine's increasing reliance on diesel has limited the realisation of these benefits, ultimately resulting in higher energy intensity.

CHAPTER 6. CONCLUSIONS & RECOMMENDATIONS

6.1 Introduction

This chapter presents an overview of the conclusions and findings in related to the research topic. The study seeks to assess energy consumption and trends in energy intensity and identifying potential opportunities for enhancing energy efficiency. Conclusion for each the research question is accompanied by recommendations as well as suggestions for further investigation.

6.2 Conclusion

An analysis of energy consumption patterns at the case study mine from 2015 to 2022 illustrates a significant and concerning rise in energy intensity, mostly due to operational and geological changes. Additionally, the transition from mining blocks positioned close the tip to those situated farther aways distances, combined with changes in active pit locations, has resulted in longer haulage routes and increased energy consumption at the case study mine.

This change reflects a rising reliance on diesel-powered equipment, which is both less efficient and more carbon-intensive than electricity, especially when the latter can be generated from renewable energy. Furthermore, the results show that human operated processes use far more energy than automated systems, highlighting the potential for automation to enhance energy efficiency.

Despite continual monitoring, total energy consumption continues to rise implying that tracking alone is insufficient without actionable operational changes. The mine’s transition from high-grade to lower-grade coal has also increased processing demands, further compounding energy use per unit output. These findings highlight the urgent need for targeted actions aimed at lowering energy intensity. Adopting battery-electric haul trucks, increasing automation, and incorporating renewable energy sources like solar can all enhance energy efficiency while lowering emissions. In addition, energy considerations must become an inherent part of mine planning and operating choices, rather than a secondary consideration. Future investigations ought to delve into the practicality and financial consequences of incorporating renewable energy, battery-electric mining fleets, and enhancing automation to promote greater energy efficiency within the industry.

6.3 Contribution to Literature

This paper presents a comprehensive evaluation of energy intensity, using open cast coal mine as a case study. The findings contribute to the knowledge of sustainable mining practices and provide a significant resource for industry stakeholders focused on minimising energy consumption and environmental effects. This study adds to the ongoing dialogue concerning energy efficiency within the mining sector and acts as a crucial resource.

6.4 Recommendations

The energy intensity trends highlight the need for operational flexibility and resilience.

It is recommended that

- The case study mine must investigate the possibility of diversifying its energy mix by integrating renewable sources such as solar power. This approach could help diminish dependence on electricity and diesel, while also contributing to cost reduction and emission decreases. Integrating a system with battery storage has the potential to significantly improve efficiency and bolster energy security.

- In the process of developing new pits, it is essential to meticulously plan hauling distances from the beginning to optimise fuel consumption and decrease emissions. Integrating effective pit design, streamlined haul road configurations, and alternative transport methods can significantly improve sustainability and operational efficiency.

6.5 Suggestions for further studies

Further research is necessary to explore the influence of human elements, including driving habits and fuel efficiency, to pinpoint effective methods for reducing energy use. A thorough feasibility study is essential to evaluate the economic viability, potential advantages, and challenges associated with the integration of renewable energy and battery storage solutions aimed at reducing emissions and improving energy sustainability in mining operations.

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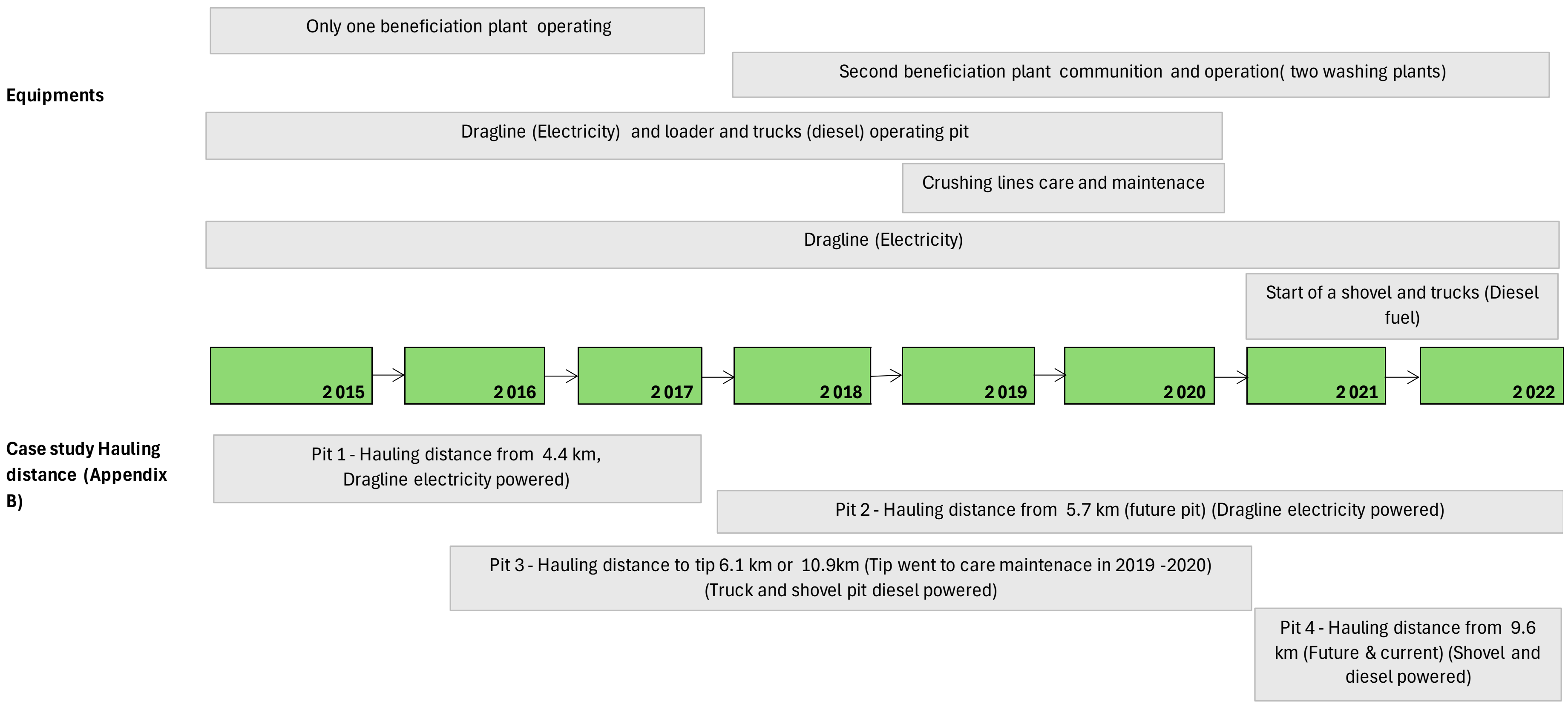
APPENDIX A: Case study time line on equipments and hauling distances

Case study time line on equipments and hauling distance



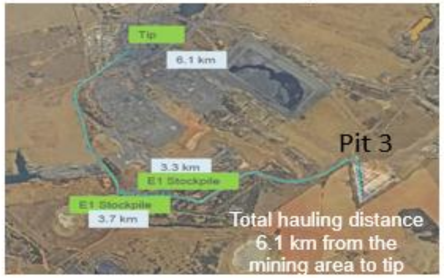
APPENDIX B: Hauling distance timeline: The hauling distance illustrate past, current and future hauling distance at the case study mine

Pit Mine between 2015 – 2017.
Dragline pit uses electricity

Pit Mine between 2016 – 2020. and future mine. Dragline pit use electricity

Pit Mine between 2015 – 2022.
Trucks and loader diesel pit.

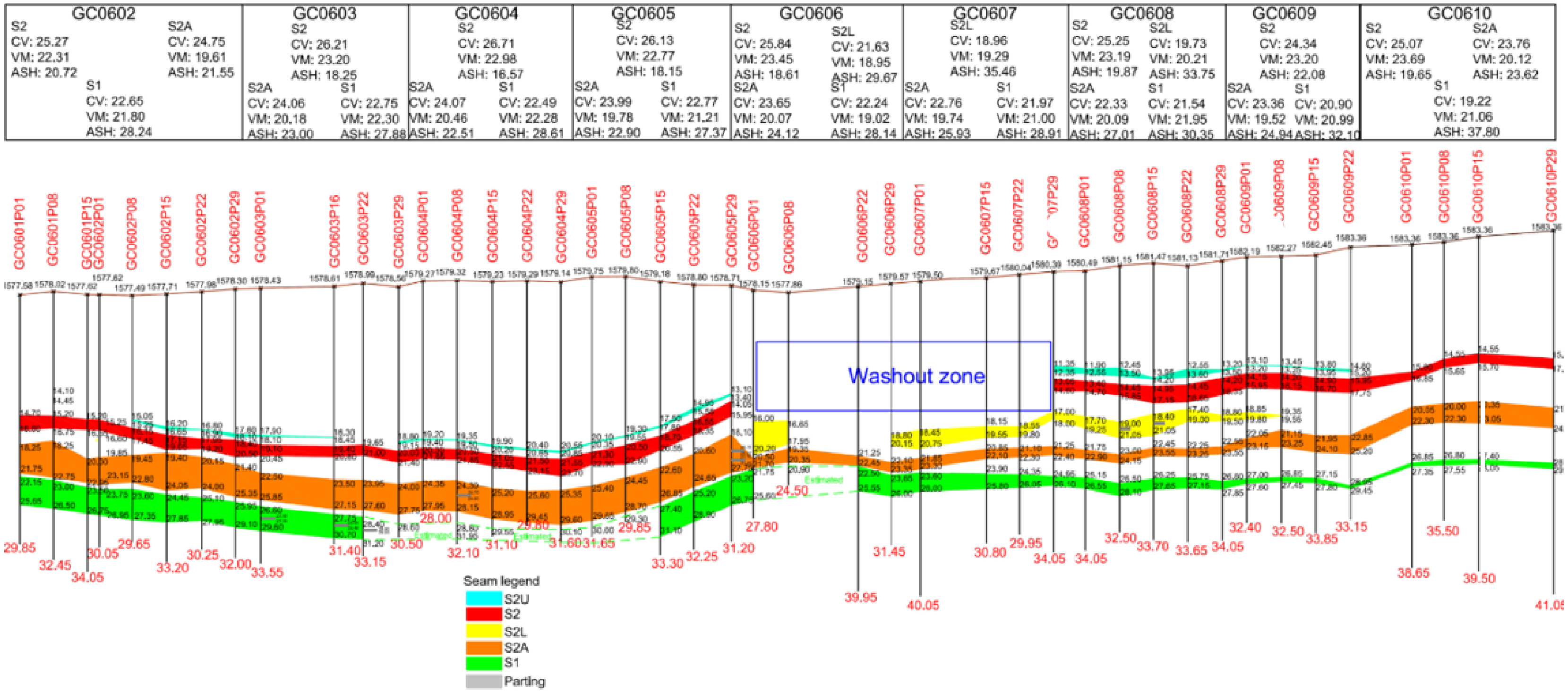
Pit Mine between 2021 – 2022 future mine.
Truck and shovel pit diesel pit.



Pit Mine between 2017 – 2022.
Dragline trucks and loader diesel pit.

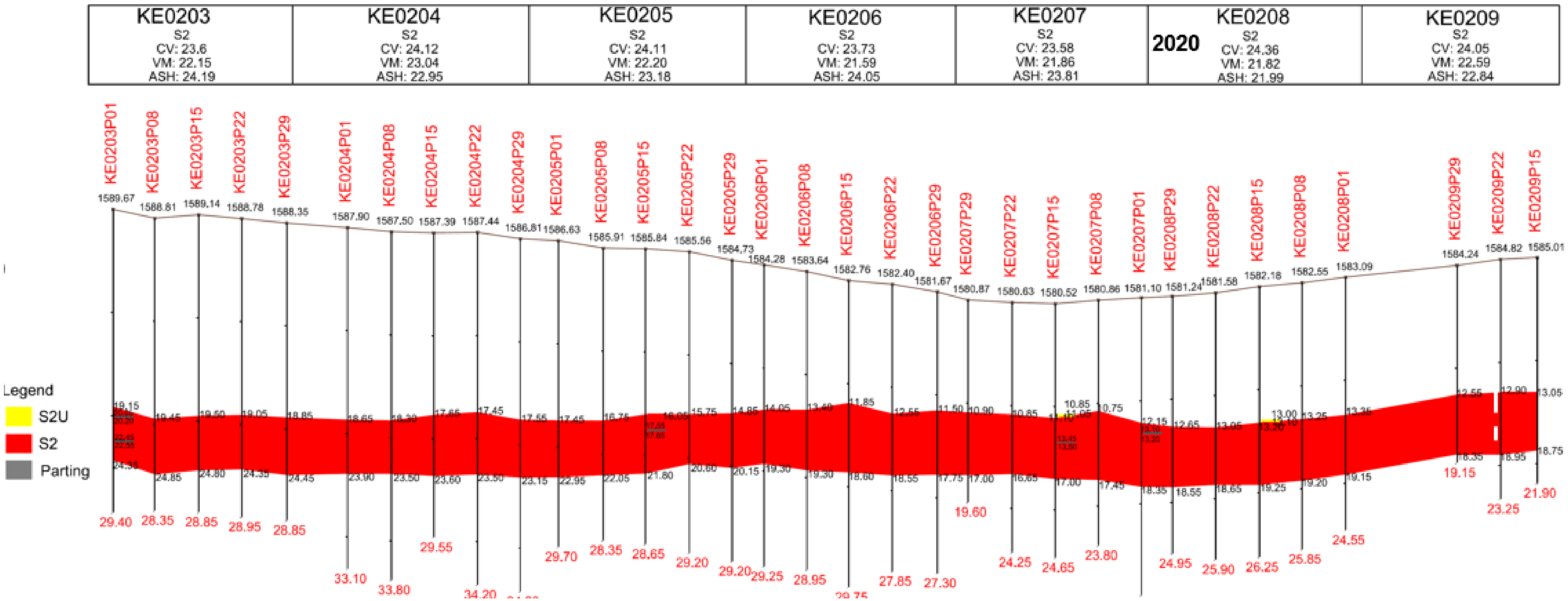
Data from the case study mining information which include seam and qualities

APPENDIX C: Coal quality timeline: The coal quality timeline illustrates past at the case study mine.



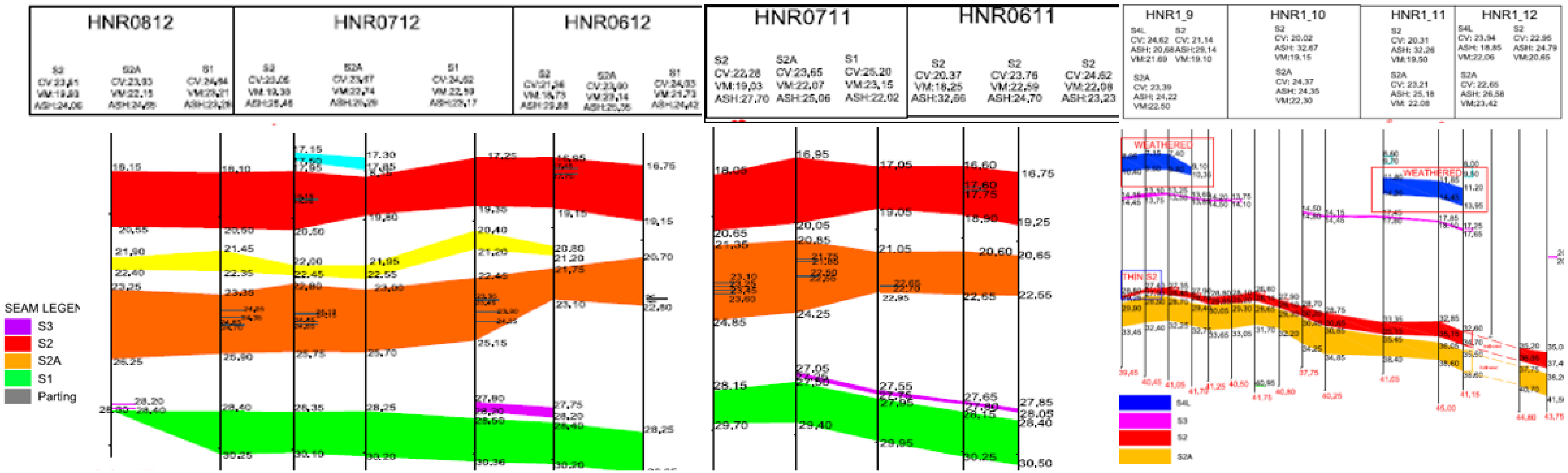
Data from the case study Geology information which include seam and qualities

APPENDIX C: Coal quality timeline: The coal quality timeline illustrates past at the case study mine.



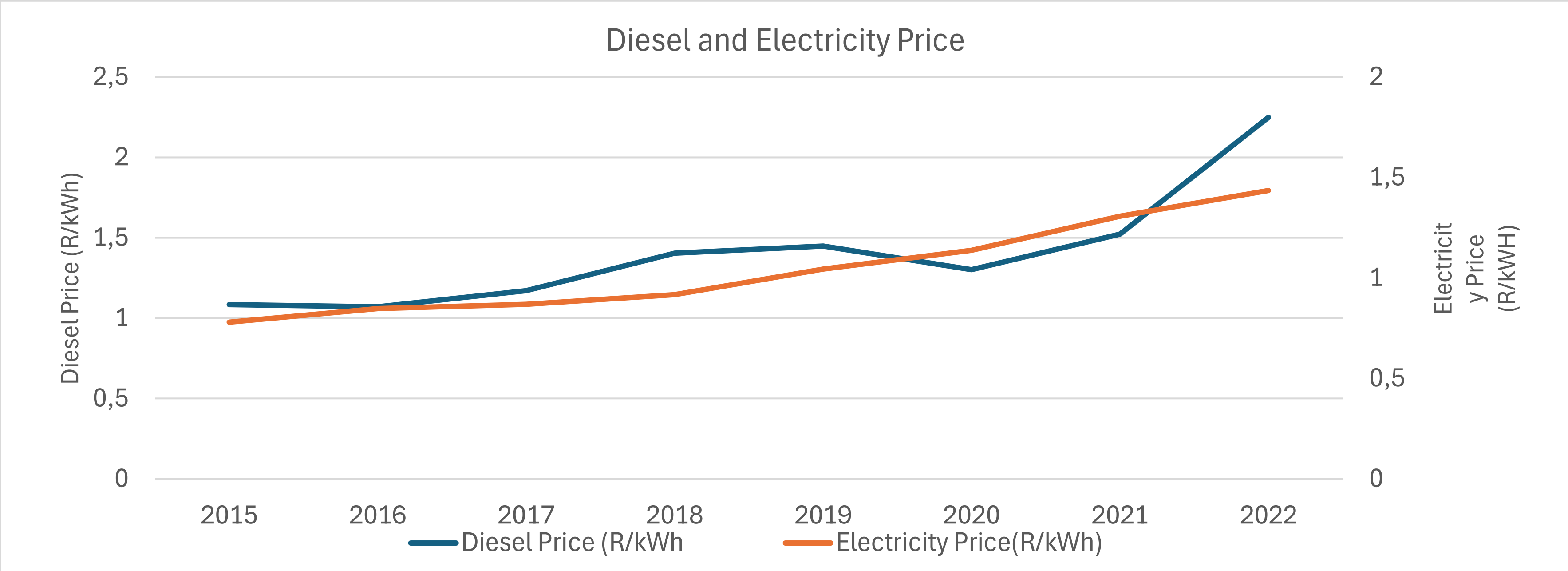
Data from the case study Geology information which include seam and qualities.

APPENDIX C: Coal quality timeline: The coal quality timeline illustrates past at the case study mine.



Data from the case study Geology information which include seam and qualities

APPENDIX D: Diesel and Electricity price for 2015 – 2022.



Prices for diesel (AA, 2022) and Electricity (Eskom, 2022)