



Energy management framework to reduce energy costs of deep-level gold mines nearing closure

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ABSTRACT

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There has been a consistent decline in gold production in the South African mining industry. This is primarily due to available ore reserves getting deeper, thus increasing energy costs. This contributes to the increased cost of production, leading to the infeasibility of operating gold mines in South Africa. These increasing costs, along with ageing infrastructure, have led to the closure of multiple gold mines over the years, with approximately 77% of existing gold mines planning to close between 2023 and 2040.

Compressed air systems and water reticulation systems form a significant portion of the underground infrastructure on conventional deep-level gold mines. These systems are also the most energy-intensive systems on these mines. The compressed air and water reticulation systems consist of vast underground reticulation networks of pipes that supply underground demands. Due to ageing infrastructure, a lack of maintenance, and inadequate downscale planning, the underground compressed air and water reticulation networks are prone to significant wastage. Therefore, there is a need to evaluate energy management strategies to reduce energy consumption on deep-level gold mines nearing closure.

A systematic literature study was conducted to evaluate relevant studies addressing these issues. The literature was categorised into three domains namely, life-of-mine (LOM) planning, baseline development, and energy management. A gap in literature was found between LOM planning as well as baseline development and energy management. This study aims to address this gap by accomplishing the following objectives: identifying key characteristics of mines nearing closure, evaluating the LOM production plans to determine changes in production location and output of mines nearing closure, developing resource and energy demand baselines for mines nearing

closure, outlining an energy management implementation strategy for mines nearing closure, and evaluating the impact of implementing energy management initiatives on mines nearing closure.

The objectives were addressed by developing an energy management methodology based on concepts obtained from literature. Step 1 involved evaluating the LOM characteristics of mines nearing closure. These characteristics include declining production trends, low capital expenditure, and high energy intensity. The two case study mines were selected based on these criteria. The LOM production trends of these mines were then evaluated. It was found that Mine A and Mine B planned to decrease production by 3 062 m³ and 617 m³ respectively over a five-month downscaling period. These values were used to determine the zero-waste baselines presented in Step 2. The zero-waste baseline method determined a potential energy reduction of 55% on Mine A's compressed air system and a 73% reduction on Mine B's refrigeration system over the planned production downscaling period. These results were used to identify the potential sources of wastage in the system.

A waste reduction and energy management initiative was outlined and implemented in Step 3. This involved closing inactive areas and reducing system wastage. This resulted in an energy reduction of 45% and 37% over the downscaling period on Mine A and Mine B respectively. The total energy and cost impact of implementing an energy management initiative on Mine A and Mine B was evaluated in Step 4. Mine A realised a LOM energy and cost reduction of 32 GWh and R32 million respectively. Mine B realised an energy and cost reduction of 0.89 GWh and R2.9 million respectively. The full extent of savings was not realised on Mine B due to the impact of a seismic activity and infrastructure breakdowns as the mine neared closure. Further savings could have been achieved on Mine B by conducting further investigations after the impact of the seismic event. However, the results obtained from the case studies validated the methodology and successfully addressed the study objectives.

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LIST OF NOMENCLATURE

Symbol	Description	Units
A_i	Face area	m ²
A	Face advance per blast	m
B	Energy baseline	kWh
C	Centares mined	m ²
D_{prod}	Number of production days in a month	Days
E	Energy	kWh
η	Efficiency	-
F	Flow rate	Nm ³ /s
g	Grade produced	g/t
g	Gravitational acceleration	m/s ²
H	Hole length	m
h	Effective head	m
$h_{support}$	Support hole density	holes/m
L	Face length	m
M	Metal produced	kg
m_e	Mass flow	kg/s
N	Number of blasts/ holes/ equipment	-
n	Number of panels	-
n	Number of time periods	-
O	Actual/ planned production	t
P	Electrical power	kW
P	Penetration rate	m/min
P_a	Actual production	t
P_i	Number of planned daily panels	-

P_p	Planned production	t
$\dot{Q}$	Volumetric flow rate	m ³ /s
ρ	Density	kg/m ³
S	Energy savings	kWh
sg	Specific gravity	t/m ³
t	Shift time	hours
T	Tonnes mined	t
T_e	Number of teams	-
W	Stoping width	m

LIST OF ABBREVIATIONS

Abbreviation	Description
BAC	Bulk air cooler
CA	Compressed air
CAPEX	Capital expenditure
COP	Coefficient of performance
FY	Financial year
HOD	Head of department
KPI	Key performance index
LOM	Life of mine
LOMP	Life of mine plan
M&V	Measurement and verification
MPS	Mine planning system
OAN	Optimised air network
PDCA	Plan-Do-Check-Act
ROI	Return on investment
SCADA	Supervisory Control and Data Acquisition

GLOSSARY OF TERMS

Glossary	Description
Crosscut	A tunnel branch out of the main haulage.
Eskom	South African power utility.
Haulage	Main horizontal tunnel of an underground level.
Ore	Precious metal-bearing rock.
Panel	A rock face being drilled.
Shaft	Primary vertical tunnels of a mine.
Workplace	Active mining area.

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CHAPTER 1: INTRODUCTION

1.1. Chapter introduction

This chapter presents the background context of this study in Section 1.2 and develops a problem statement addressing the key findings in Section 1.3. A literature study is conducted in Section 1.4 to identify and evaluate previous research conducted to address the identified problems. The gaps identified in existing literature are used to develop the need for the study presented in Section 1.5 which is used to guide the development of the study objectives in Section 1.6. The study methodology is developed in Section 1.7. Section 1.8 provides a conclusion to the chapter and introduces the next chapter.

1.2. Background

1.2.1. Decline in South African gold mining

The South African gold mining industry is facing a large-scale production decline due to various internal and external factors, including the increasing depth of the available ore body and increasing utility and labour costs [1], [2]. This has resulted in an absence of new gold mining developments in recent years, with many current operations planning to close within the next 10 years [3]. This section evaluates the extent of the decline in South African gold mining and provides background to the key factors leading to mine closure within this context.

Decrease in South African gold production

South Africa is a major global gold and platinum producer, contributing significantly to the world's mineral wealth. Once the largest gold-producing country, South Africa has ranked fifth since 2019, following China, Australia, Russia, and the United States. However, gold and platinum group metals (PGMs) remain some of the largest mining sector contributors to the nation's economy.

Gold mining has taken place in the Witwatersrand basin for over one hundred years. Due to this continuous exploitation, most of the accessible high-grade ore reserves have been depleted. As a result, current mining operations are left with lower-grade reserves which need to be extracted as efficiently as possible [2].

The Witwatersrand basin remains the largest gold reserve in South Africa. However, studies have shown that it has already surpassed its peak productivity. Current proven South African gold

reserves are expected to be depleted by the year 2042, a relatively short period compared to the PGM reserves, which are expected to deplete in 233 years [4]. It has been estimated that gold reserves amounting to 3300 tonnes are as deep as 4 km underground. The depths of these reserves limit the economic viability of production without advancements in mining methods [1], [3]. Gold has also seen a significant decrease in production compared to the relatively stable PGM production, as presented in Figure 1-1.

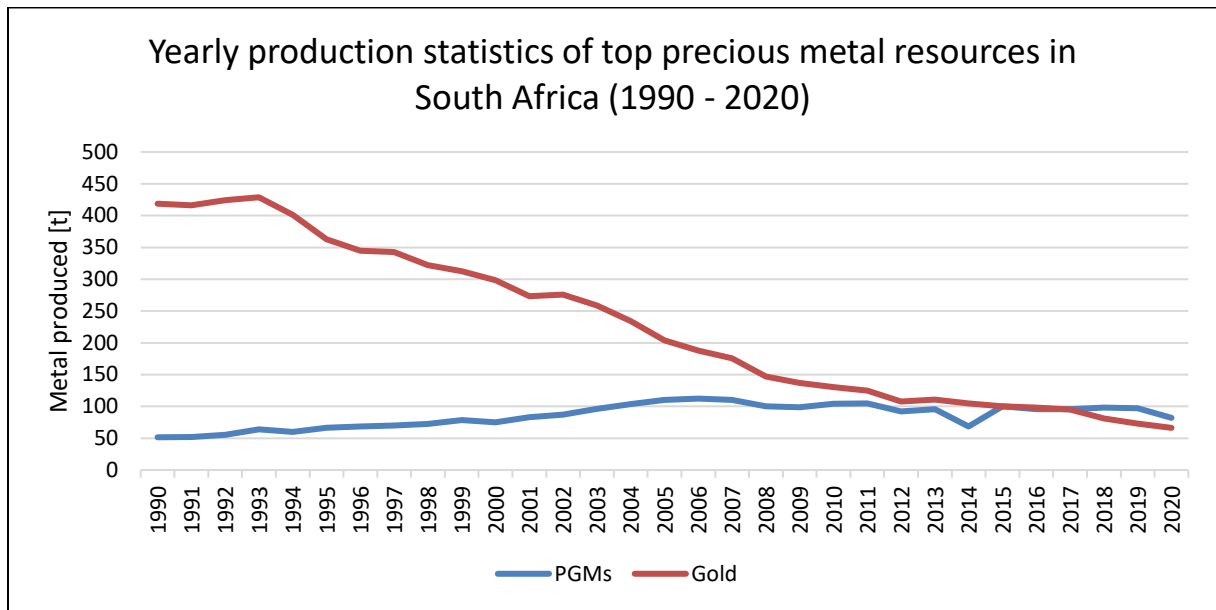


Figure 1-1: Major South African precious metal production trend [4]

Due to the lack of new exploration, approximately 77% of current gold mines will reach the end of their operating lives between 2025 and 2040. By 2035, only four mines are expected to remain in operation. The estimated life of mine (LOM) of active South African gold mines is presented in Table 1-1 [3]. This decrease in productivity and LOM of gold mines results from a multitude of factors, including a depletion in profitable mining opportunities as well as financial and geological reasons.

Table 1-1: Reported LOM of South African gold mines as of 2021 [3]

Mining Company	Deposit Name	Life of Mine [years]	End year
Goldfields Ltd	South Deep Mine	~80	2101
Harmony Ltd	Doornkop Mine	14	2035
	Joel Mine	9	2030
	Kusasaletu Mine	6	2027
	Masimong Mine	5	2026
	Moab Khotsoang Mine	24	2045
	Mponeng Mine	8	2029
	Target 1 Mine	7	2028
	Tshepong Operations	20	2041
	Kalgold Mine	12	2033
Sibanye Stillwater Ltd	Beatrix Mine	4	2025
	Driefontein Mine	10	2031
	Kloof Mine	11	2032
	Cooke Mine	4	2025
Pan African Resources Ltd	Fairview Mine	20	2041
	New Consort Mine	8	2029
	Sheba Mine	9	2030
	8 Shaft Mine (Evander)	5	2026

Reasons for mine closure

The gold mining industry in South Africa is facing multiple challenges, both socioeconomic and operational, making it difficult for many mines to maintain production and stay open [2]. The LOM is typically planned based on ore reserves; however, in many cases, mines are closed prematurely based on both external and internal factors. External factors include the impact of economic, environmental, and social effects on the viability of mining operations, while internal effects include increasing operating costs, an increase in seismicity, and decreasing ore grades [5], [6]. Some of these factors cause gradual mine closures, allowing mines to plan for shutdown within the available timeframe, while others lead to abrupt closures, limiting the planning capacity of the mine and leading to unintended consequences.

Closure due to geotechnical reasons results from potential seismic activities. This typically results in unplanned closure due to the high safety risk [7]. This may result in temporary or permanent closure, depending on the severity of the conditions. This places South African gold mines at considerably higher risk, as they venture deeper to extract the available gold deposits [2]. Closure due to geological reasons typically results from an overestimation of reserves. This typically results in a gradual, planned closure, albeit over a shorter period [7]. This is of particular concern for South African gold mines, as the average gold ore grade has decreased significantly from a peak of

approximately 12 g/tonne in the 1970s to a predicted drop to 0.9 g/tonne by 2050 as presented in Figure 1-2 [2].

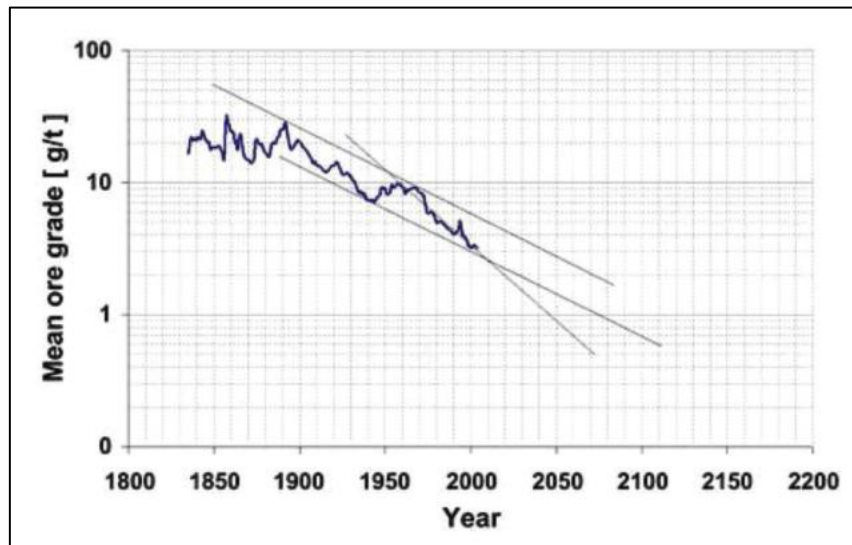


Figure 1-2: Predicted decline in ore grade [2]

Closure due to economic reasons may result in abrupt closure and is one of the primary reasons for mine closure, as presented in Table 1-2. These include both internal and external factors such as the mine going bankrupt and external market fluctuations. The gold price is determined by global supply and demand and is out of the control of the South African gold mining industry. Hence, the industry is sensitive to gold price fluctuations. This has a major impact on the operations' profitability, affecting the LOM of many shafts. Given the recent long-term decline in gold prices, many mines were forced to close either temporarily or permanently. While favourable gold prices kept mines on the verge of closure afloat, in many cases, even the increase in gold price cannot compete with the rise in operating costs [2], [7].

Table 1-2: Reasons for mine closure [8]

Sustainability Dimension and Premature Mine Closures.	
Sustainability Dimension	Percentage of Premature Mine Closures
Economic	44
Efficiency	34
Community	11
Environment	6
Safety	5

South African gold mines generally operate at greater depths due to the prevalence of deeper ore bodies. As such, they tend to be more resource- and energy-intensive and are particularly sensitive

to energy price fluctuations [2]. The increase in energy tariffs was proven to have had a detrimental effect on mining productivity [9], [10]. This is of particular concern for South African mines, as the cost of electricity has increased significantly since 2008, as presented in Figure 1-3 [9]. The mining sector has also been directly affected by continuous tariff increases, as presented in Figure 1-4 [11].

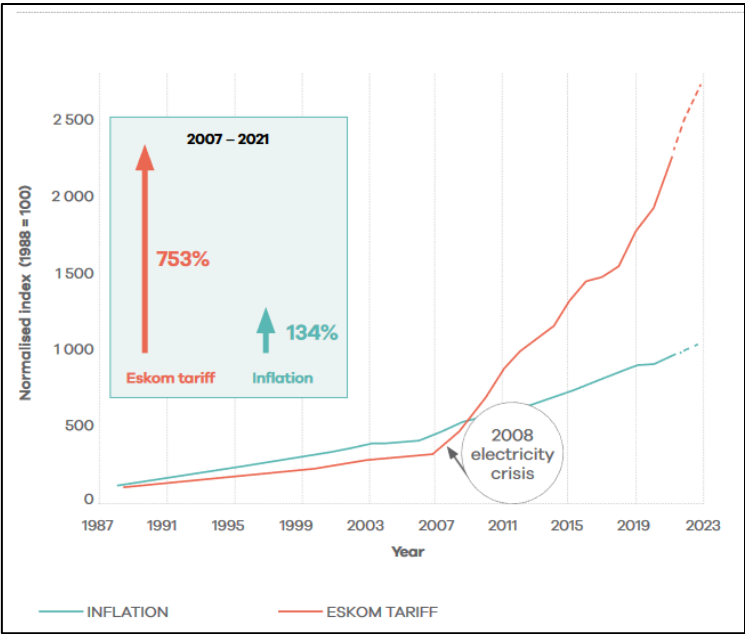


Figure 1-3: Eskom tariff increase against inflation rate [9]

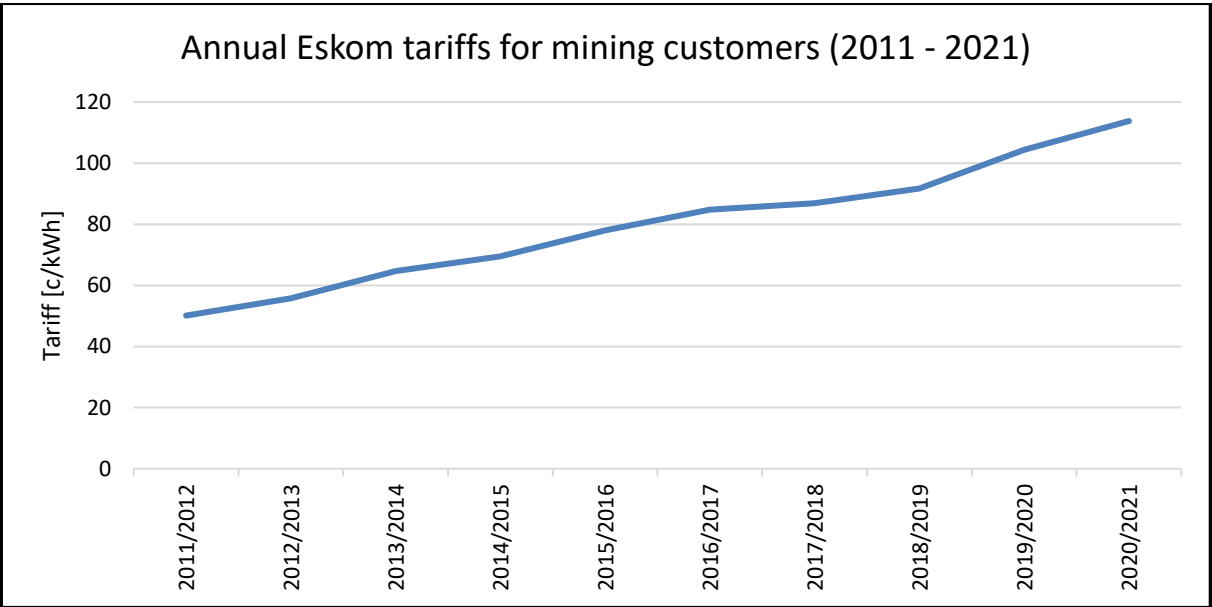


Figure 1-4: Eskom tariff trend for mining customers [11]

As a result of the above-mentioned factors, the depths of South African gold mines place them at a higher risk of closure. Due to these challenges, investors are hesitant to fund both new and existing

mining operations in South Africa, leading to a decrease in available capital [2]. Therefore, there is significant potential for research, development, and innovation to improve the productivity and efficiency in this field [8], [12].

1.2.2. Energy wastage in deep-level gold mines

Figure 1-5 presents a breakdown of the energy demand of a typical gold mine. The demand is categorised per sub-system based on the primary machine used. The compressed air system consists of the surface compressors. The refrigeration system consists of the refrigeration plants, evaporator pumps and condenser pumps. The ventilation system consists of surface ventilation fans. The pumping system consists of the dewatering pumps. The hoisting system consists of the rock and man winders. The mining system consists of electrical machinery used for mining, including winches and underground locomotives. Compressed air and water reticulation systems are one of the largest energy-consuming systems on deep-level gold mines, as shown in Figure 1-5 [13], [14].

The compressed air system consists of compressors on the surface and a vast underground network of pipes [15]. The water reticulation system consists of fridge plants, pumps, dams, and a vast underground network of pipes [16]. These systems are also sensitive to changes in production, as they directly feed the equipment responsible for production [17]. The extent of these networks makes them prone to inefficiencies compared to other systems [16], [18]. This section presents an overview of these systems as well as the possible causes of inefficiencies.

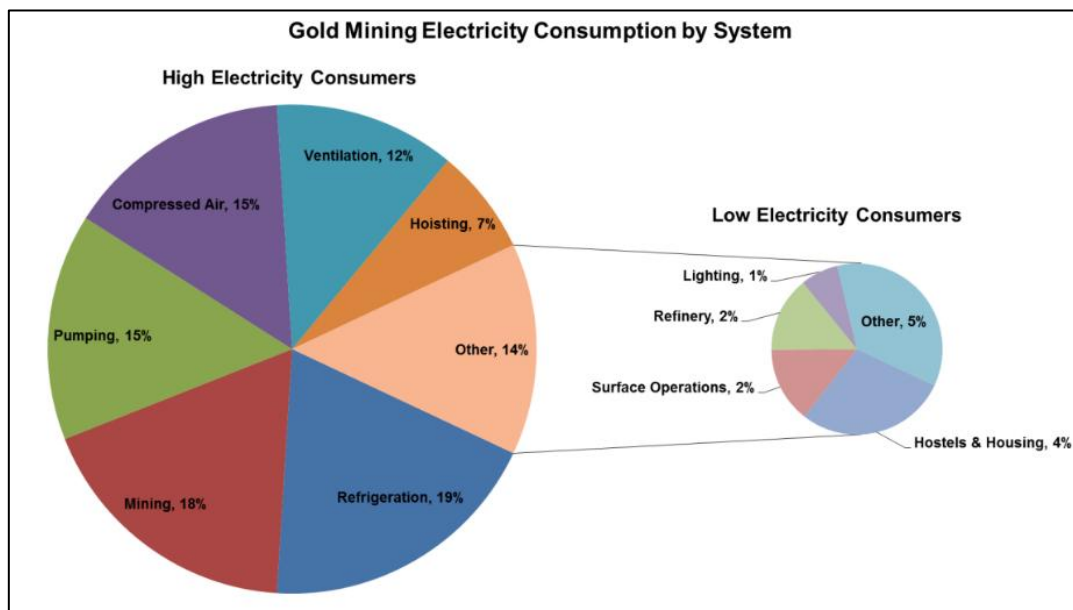


Figure 1-5: Energy demand breakdown on deep-level mines [13]

Compressed air systems and wastage on deep-level gold mines

Compressed air is used as the primary source of energy for mining on deep-level South African gold mines. The compressed air system is typically categorised into two subsystems, namely the supply side and the demand side. Each of these subsystems consists of multiple components that form part of the complete compressed air system, as presented in Figure 1-6 [15], [19], [20]. The primary component on the supply side is the compressor. South African mines typically use multistage centrifugal compressors due to their relatively high efficiency and ability to generate sufficient flow [21]. Many mines run multiple compressors in parallel to ensure the underground flow and pressure demands are met [15].

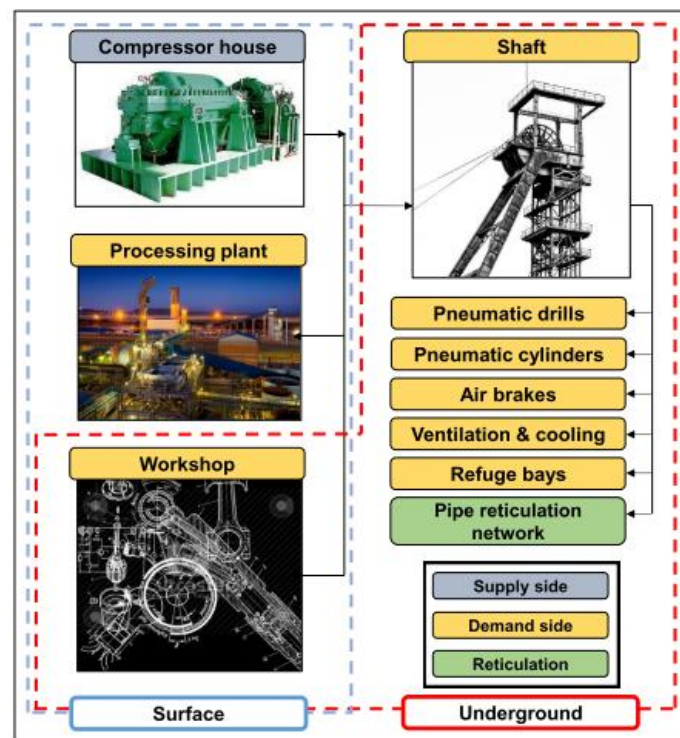


Figure 1-6: Overview of a typical compressed air system on a deep-level gold mine [15]

The demand side consists of the reticulation network and the end users. The reticulation network consists of a vast network of steel piping used to transport compressed air from the compressors to the end users [19]. This network includes underground control valves and water traps, which regulate the system. The control valves are typically controlled remotely and are capable of automated control [22]. The end users of the compressed air include rock drills, handheld tools, refuge bays, and loading boxes, amongst other consumers [23], [24]. The pressure requirements and air usage for high-demand systems are presented in Table 1-3.

Table 1-3: Typical underground equipment compressed air demand [23]

Equipment	Pressure requirements [kPa]	Average air usage [Nm ³ /s]
Rock drills	400 – 600	0.14
Rock loaders	400 – 500	0.28
Refuge bays	200 -300	0.01
Loading boxes	450	0.026

The typical production day compressed air demand follows the profile presented in Figure 1-7. There is a peak in demand during the drilling shift whilst the demand stays relatively constant during non-drilling shifts [20].

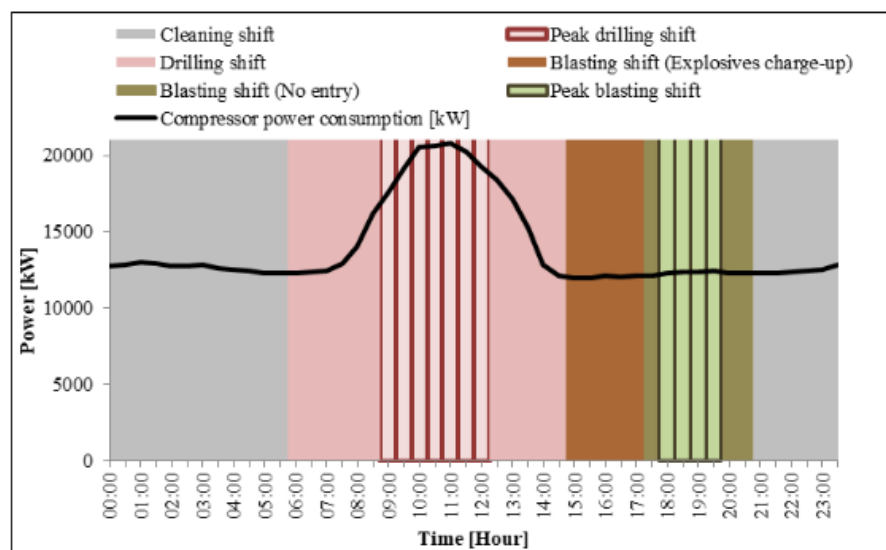


Figure 1-7: Typical daily profile of compressed air system [20]

Compressed air systems on mines are prone to significant energy wastage. The largest inefficiencies typically lie on the demand side of the compressed air system [25]. These include leaks and reductions in pipe diameter, resulting in pressure drops over the network, decreasing the overall efficiency of the compressed air system [18]. Leaks in compressed air pipes are typically caused by natural wear due to environmental conditions and thermal stresses, worsened by a lack of maintenance. This can lead to wastages of between 20% to 30% of the compressors' supply compared to the typical standard of 5% to 10% [20], [26]. However, locating, quantifying, and fixing these leaks remains a challenge [24], [27].

As mines age, their propensity for inefficiencies increases, as presented in Table 1-4. A major source of inefficiencies was found to be compressed air still going to inactive areas. On one deep-level gold mine in South Africa, approximately 8000 m³/h of compressed air was feeding leaks in inactive areas [27]. Given that mines nearing closure due to a depletion of resources generally have ageing

infrastructure, it is important to consider these challenges when developing energy management solutions.

Table 1-4: Compressed air wastage due to leaks¹

Mine	Age	Compressed air wastage due to leaks
Mine 1	20	39%
Mine 2	30	52%

Leaks on compressed air systems impact power consumption [18]. Identifying and fixing leaks on deep-level mine compressed air systems can lead to significant cost savings [20]. Compressed air networks should be designed to minimise wastage across the distribution line [24]. Energy savings on compressed air systems can only be realised once the demand has been reduced, allowing the supply side to reduce energy consumption [27]. Regular maintenance and leak repair can reduce wastage and improve flow, pressure, and system efficiency [26]. Reducing leaks can yield energy savings of between 20% - 60%, with a potential payback period of less than two years [28].

Water reticulation systems and wastage on deep-level gold mines

Chilled water is an integral resource for deep-level mining. However, water reticulation is an energy-intensive system [29], [30]. The water reticulation system on deep-level gold mines typically consists of two high-energy-consuming systems, namely the chilled water system and the dewatering system [31]. The chilled water system consists of refrigeration plants and a piping network which supplies the end user's demand [30]. The dewatering systems consist of a network of dewatering pumps, settlers, dams, and drain columns used to clean and pump return water back to the fridge plants [31].

Chilled water is used primarily for cooling purposes on deep-level gold mines. It is used to cool pneumatic drills, working places, and ventilation air, as well as for cleaning, sweeping, and dust suppression [32]. The return water from these users is chilled by refrigeration systems that consist of fridge plants and cooling towers, located on the surface or underground, as presented in Figure 1-8 [33].

¹ D. La Vergne, *Hard Rock Miners Handbook*, vol. 4, no. 4. 2008.

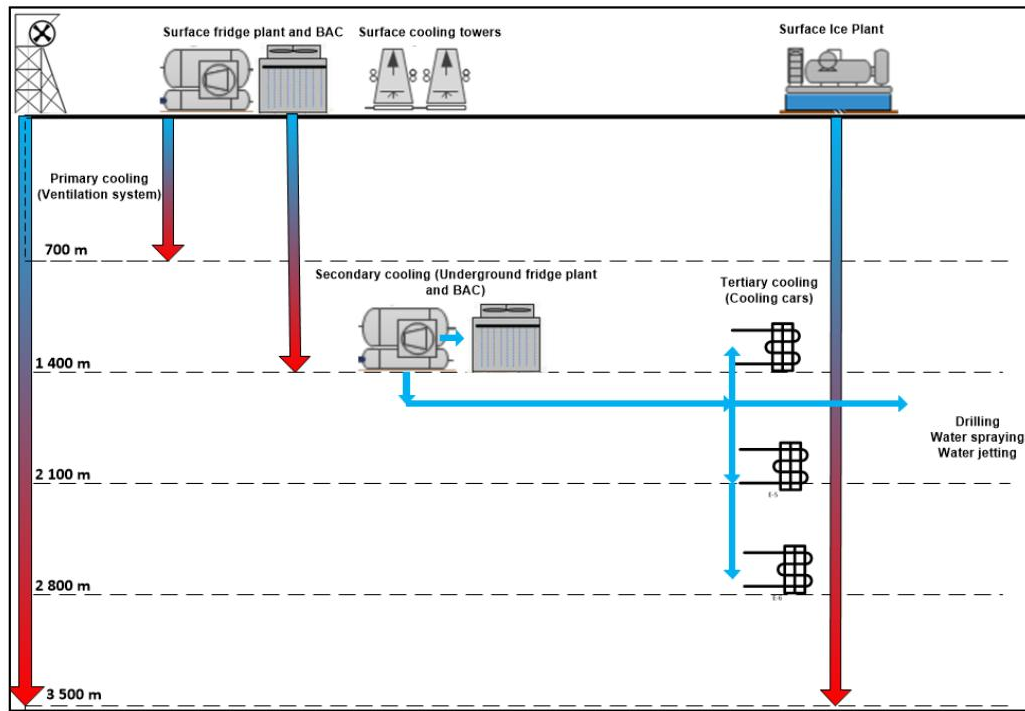


Figure 1-8: Schematic drawing of a typical deep-level mine cooling system [31]

These fridge plants use the typical refrigeration cycle, as presented in Figure 1-9. The evaporator circuit cools the return water from the dewatering system and pumps it into a chilled water dam. The refrigeration circuit circulates refrigerant between the evaporator and the condenser, while the condenser circuit is used to dissipate heat by circulating water between the condenser and the cooling towers [30]. The most energy-intensive consumers in the refrigeration cycle are the pumps used to circulate water in the condenser and evaporator circuits, and the compressor used to compress the refrigerant in the refrigeration circuit [34].

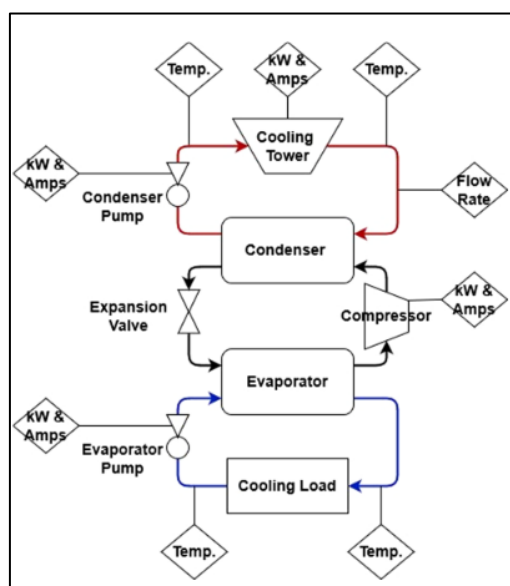


Figure 1-9: Typical refrigeration cycle [34]

The chilled water dam supplies the surface bulk air cooler (BAC) and the underground demand [30]. A surface BAC pre-cools the ambient air as it enters the downcast shaft. The used water from the BAC is returned to the fridge plant in a closed loop, with minor atmospheric losses through the BAC. Some operations use underground BAC systems as a secondary cooling measure to provide more localised cooling. The chilled water for these systems is provided by either surface or underground fridge plants that typically consist of cooling-coil heat exchangers. The water from these systems recirculates directly back to the hot water dams supplying the refrigeration plant [33].

Spot coolers or cooling cars are used to cool ventilation air in crosscuts or at workplaces as a tertiary means of cooling. These systems are fed with the same pipelines that feed the drilling and cleaning water and also use cooling-coil heat exchangers. The used water from these systems is typically dumped onto the footwall of the crosscut and returned to the dewatering system with the drilling, cleaning, and fissure water [33]. The chilled water demand used to cool ventilation air remains constant throughout the daily production schedule [16].

Chilled water is primarily used to cool drills during the production shift and is used by bazookas during the cleaning shift. Bazookas are a custom tool used to mix compressed air and water to provide a high-pressure stream for sweeping fine material after blasting. The water used by this equipment is discarded on the footwall. Due to these consumers, the water demand increases during the drilling and cleaning shifts, as presented in Table 1-5 [16]. This water is then collected at the underground settlers and recirculated via the dewatering system. Figure 1-10 presents the chilled water demand profile over various shifts during a typical production day [16].

Table 1-5: Mine service water consumer demand [16]

Consumer	Flow Requirement [l/s]
Pneumatic drills	0.2
Bazooka	5.5
Cooling car	4.0

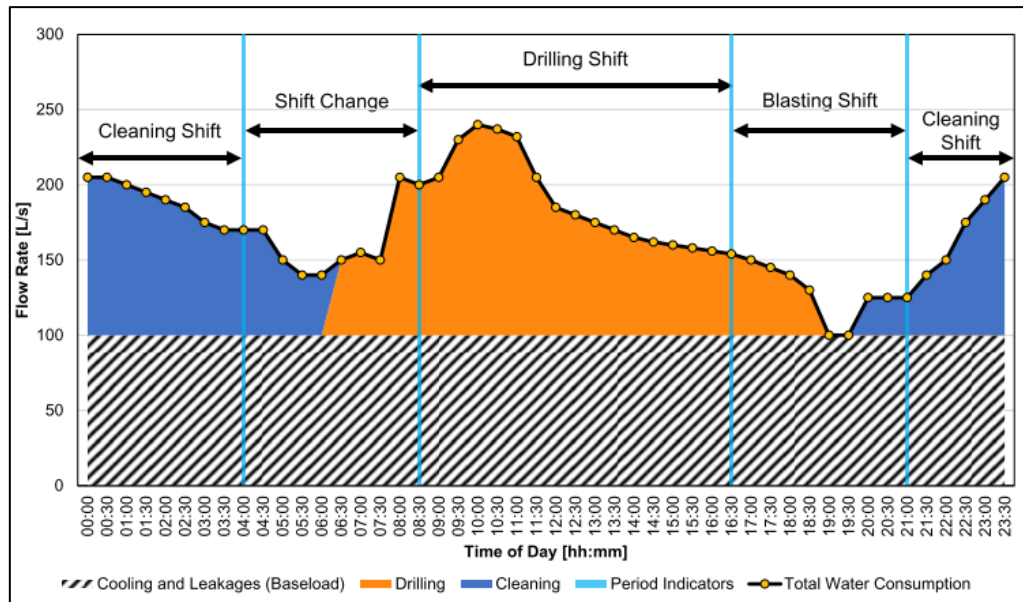


Figure 1-10: Typical daily chilled water demand schedule on a deep-level mine [16]

The dewatering system primarily consists of settlers, pumps, dams, and drain columns. The water discarded from the cooling cars, drills, and bazookas along with fissure water is pumped from the footwall to the settlers via a series of drainage ditches, drainage columns, diaphragm pumps, and spindle pumps. This water is then pumped back to the nearest refrigeration plant via a series of dams and multistage centrifugal pumps. The size of this network depends on the depth and complexity of the mining operation. Multistage centrifugal pumps on deep-level gold mines are energy-intensive systems, as they must pump water up hundreds of meters at a relatively high flow rate [30], [32]. A diagram of a typical dewatering system is presented in Figure 1-11.

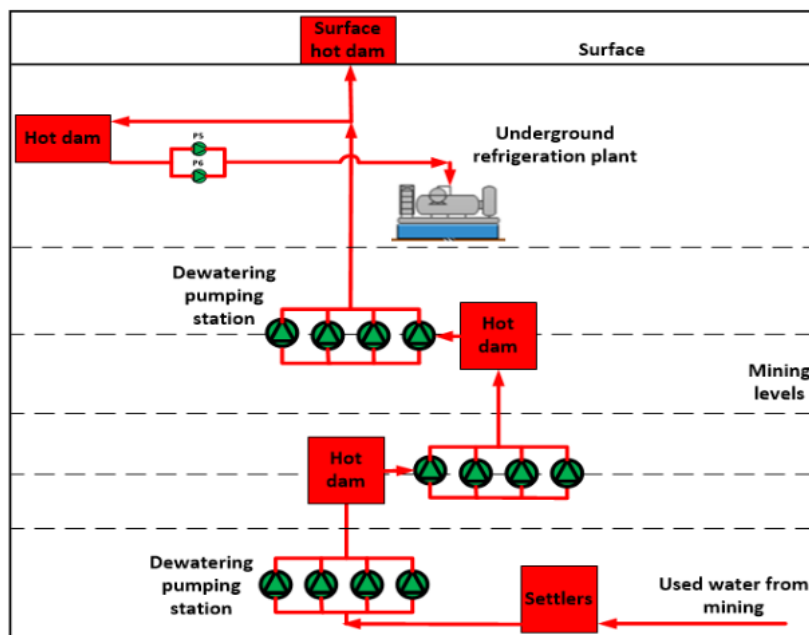


Figure 1-11: Typical deep-level mine dewatering system [31]

Chilled water reticulation systems experience similar wastages to compressed air systems. Due to the vast network of underground piping, they are prone to wear and inefficiencies, resulting in potential wastages of over 30% of total system consumption [35]. Older systems are more prone to wastage due to ageing and corroding infrastructure [31]. System inefficiencies are typically characterised by leaks [16]. Two types of leaks typically occur on water reticulation infrastructure, namely pipe bursts and background leaks. Pipe bursts are easier to detect since they are immediately visible by drops in system pressure. Background leaks are harder to detect as they are concealed, however, multiple background leaks can cause significant wastage over time [36]. These wastages can result in increased refrigeration and pumping energy demand and costs. As such, leak detection methods and valve control can be used to minimise wastage.

Energy cost wastages can also occur with inefficient management of the multistage centrifugal pumps and refrigeration plants [13]. Eskom implements a tariff structure according to time-of-use (TOU) on large energy consumers, including mines. This is divided into peak, standard, and off-peak periods, as presented in Figure 1-12 [37]. Pumps and refrigeration plants are typically run as required throughout the day without regard for the change in tariffs [38]. This has a sizable cost impact, especially in winter months when peak tariffs significantly increase [37]. Therefore, implementing load shifts on the dewatering pumps and refrigeration systems can provide substantial energy cost savings. The success of the load shifts relies on adequate dam capacities, sufficient chill water temperature, and chill water demand [13], [39].

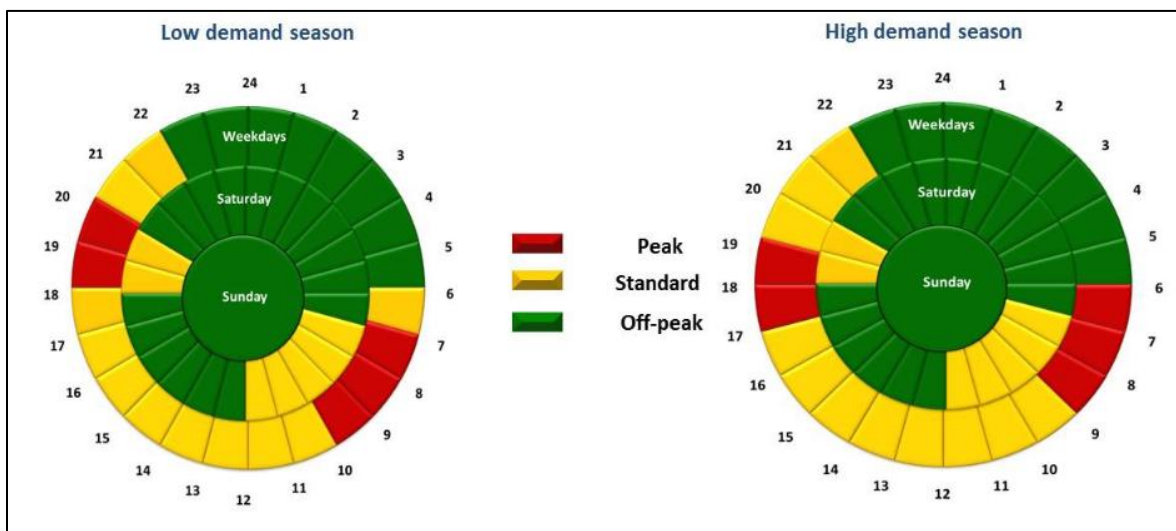


Figure 1-12: Eskom tariff time of use charts²

² Schedule of Standard Prices for Eskom Tariffs, 1 April 2023 to 31 March 2024 for Non-Local Authority Supplies, and 1 July 2023 to 30 June 2024 for Local Authority Supplies 1. Standard Prices

1.3. Problem statement

South African gold production is on the decline, and gold mines are nearing closure due to multiple reasons. The primary reasons for mine closure are increasing operating costs and depleting ore reserves. Energy costs have a large impact on the financial viability of operating gold mines, as they are energy-intensive endeavours. Compressed air and water reticulation systems are the largest energy-consuming systems on deep-level gold mines and are directly linked to production output. These systems are also prone to large amounts of wastage due to their vast underground piping networks.

Due to ageing infrastructure and limited time for planning production downscaling due to forced closure, mature mines are prone to larger amounts of wastage. Therefore, there is a need to develop a viable energy management strategy to reduce energy consumption on deep-level gold mines nearing closure.

1.4. Literature Study

A literature study was conducted based on the problem statement outlined in Section 1.3 to critically analyse previous research conducted on this subject.

1.4.1. Literature study methodology

A systematic literature review was conducted. A methodology adapted from *Mengist et al.* was used to define a protocol, search, appraise, synthesise, analyse, and report on relevant literature as presented in Figure 1-13 [40].

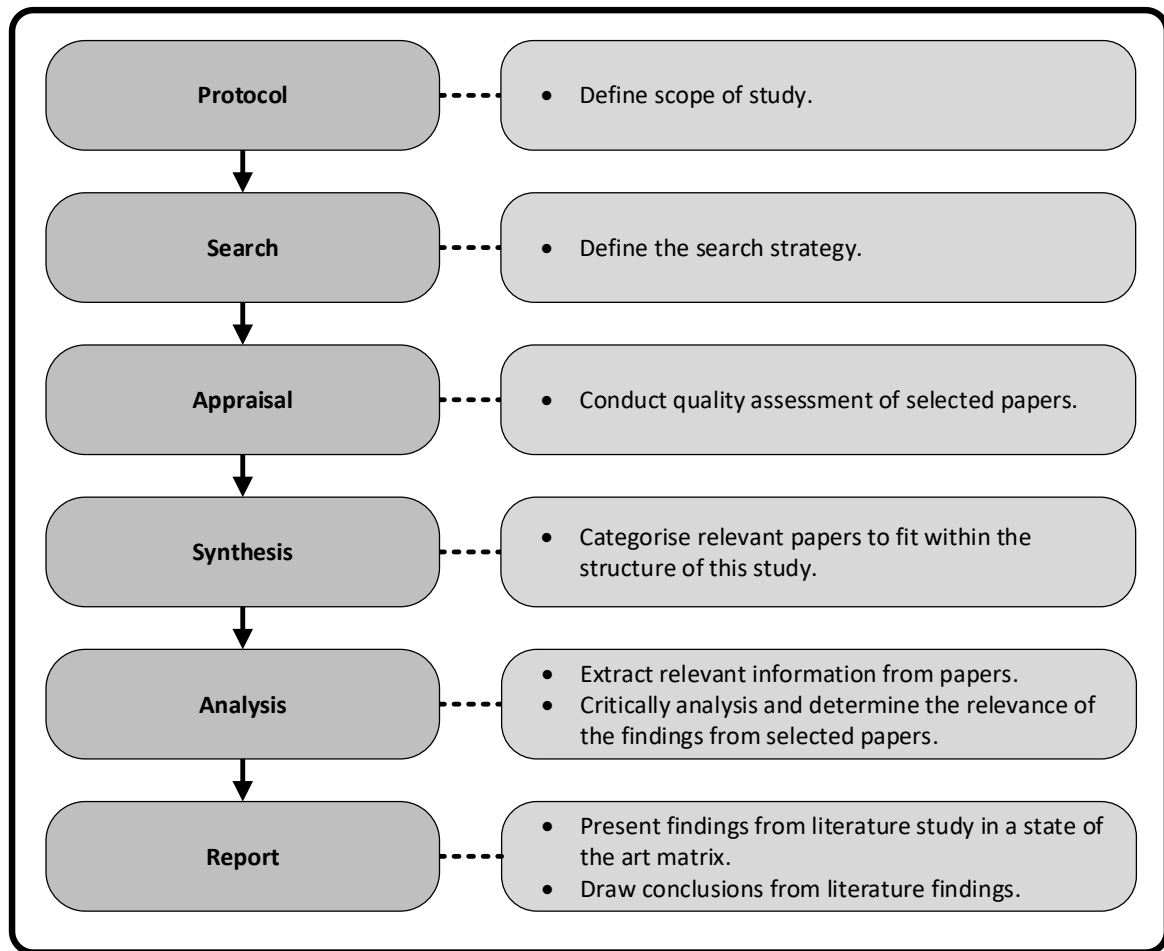


Figure 1-13: Literature search methodology [40]

Protocol

The scope of the literature study is based on the problem statement presented in Section 1.3. The scope includes the following considerations within the context of deep-level gold mines nearing closure: LOM production planning, mine closure, compressed air, water and energy demand baselining, and energy management frameworks.

Search

The literature study was primarily conducted by searching various academic databases using keywords related to the topic. The specific data sources, keywords, and databases are presented in Table 1-6.

Table 1-6: Literature study search outline

Sources	Peer-reviewed journal articles, PhD dissertations, conference proceedings, master's thesis and industry-specific reports.
Keywords	Life of mine planning, production downscaling, deep-level mine production planning, mine life cycle, baseline development, zero-waste baseline, baseline scaling, energy management, energy baselining, compressed air, compressors, dewatering system, chilled water system, pumping, refrigeration.
Databases	Google Scholar, IEEE Explore, Science Direct, SciELO SA, Springer, MDPI, NWU Repository, UP Repository.

Appraisal

The literature was filtered and prioritised based on the criteria presented in Table 1-7.

Table 1-7: Literature study appraisal criteria

Criteria	Decision
Academic and industry-specific sources of literature.	Include
Keywords exist within the title or abstract of the study.	Include
Studies published within the domain of mine planning.	Include
Studies published within the domain of mine engineering.	Include
Studies published within the domain of energy management.	Include
Inaccessible studies.	Exclude
Duplicate studies within research domain.	Exclude
Studies published before 2016.	Exclude

Synthesis

This study covers three domains of academic research. Relevant studies from these domains were evaluated and categorised within the context of this study as follows: Section 1.4.2 - mine planning, Section 1.4.3 - system baseline development, Section 1.4.4 - energy management. Studies that crossed multiple domains were categorised under the primary research domain.

Analysis

Each study was evaluated and critically analysed to determine its relevance within the context of this study. The literature analysis is presented in Sections 1.4.2 to 1.4.4 below.

Report

The findings from the literature study were presented as a state-of-the-art matrix and conclusion in Section 1.4.5. These findings were used to guide the development of the need for the study and study objectives presented in Section 1.5 and Section 1.6.

1.4.2. Literature study of papers presenting mine planning methods under a constrained life of mine

Financial planning in the mining industry under constrained life of mine [7]

Year: 2017

Authors: H. Nikkonen and H. Randtane

Overview

This study presents a financial planning model for mines nearing closure. This study is predicated on the notion that mines close based on a depletion of minable resources, hence there is a gradual decrease in production over time. This allows for sufficient planning to take place as the mine nears closure. This is illustrated by the five-phase timeline presented in Figure 1-14, which outlines the key financial and planning milestones relative to the planned closure date. This timeline is based on the typical mine life cycle starting with the feasibility study, mine construction, production, closure, and aftercare and maintenance.

This study uses the ore reserves as the primary factor for LOM planning. Given the gradual decline in minable resources as the operation matures, mining operations are typically run at a reduced capacity. During this period capital expenditure (CAPEX) is viewed with more scrutiny and return on investment (ROI) needs to be significantly shorter than the limited LOM. The ROI also needs to be significant to justify the capital costs. As CAPEX is reduced and eventually stopped, the focus shifts to maintaining machinery instead of replacing it. This study places particular emphasis on the need for planning during the end of the production phase and recommends that the mine plan be updated more regularly as the mine nears closure. This study also suggests that CAPEX is stopped three years before closure.

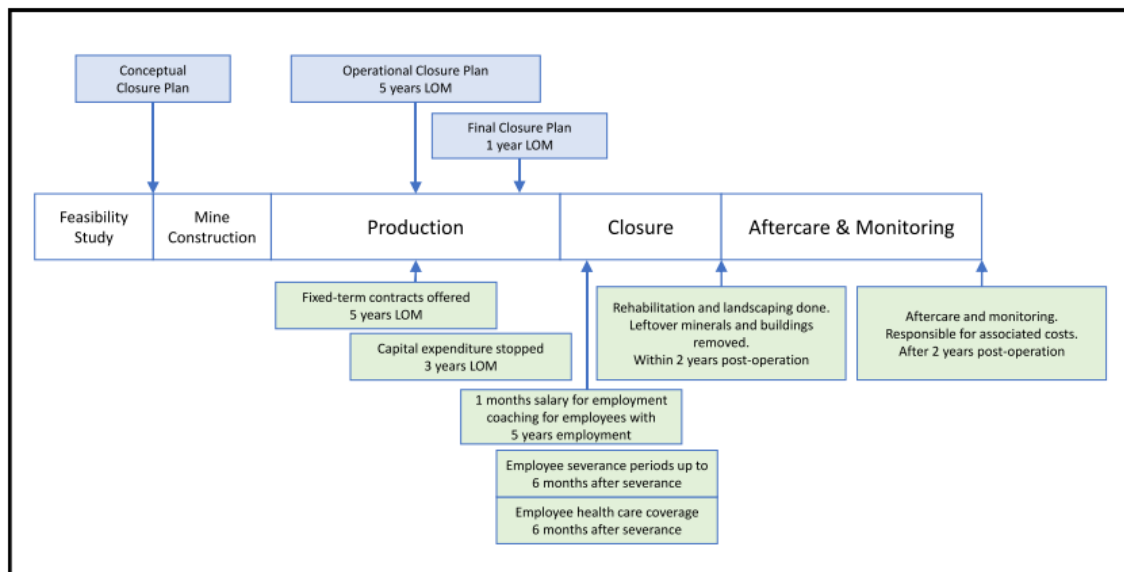


Figure 1-14: Mine life cycle proposed by Nikkonen et al. [7]

Analysis

This is one of the few studies that develops a planning framework for mines nearing closure. However, this study primarily focuses on the financial aspects of closure planning and provides important insight into the timelines and financial requirements for planning as a mine nears closure. While this study does not discuss energy management, it offers important insight of the financial implications of the mine nearing closure, including the indication that CAPEX is reduced and subsequently cut within three years of planned closure. This highlights the limited funding available for implementing projects beyond this period.

Mining region value and vulnerabilities: Evolutions over the mine life cycle [41]

Year: 2021

Authors: M. Forget, M. Rossi

Overview

This study presents a framework highlighting the changing values and vulnerabilities over a metal mine's LOM. This includes various aspects which affect the operation and surrounding region, including environmental, economic, geological, social, and cultural. The geological indicators are quantified by values such as mineral assemblage, ore grade, ore volume, ground stability, ore continuity, and ore dispersion. The economic indicators are quantified by the metal market value, available infrastructure, and investment required. Figure 1-15 presents the framework applied to a

case study mine. The trends indicate a peak and subsequent decline in the geological and economic value of an operation throughout its LOM, with the converse effect on the vulnerabilities.

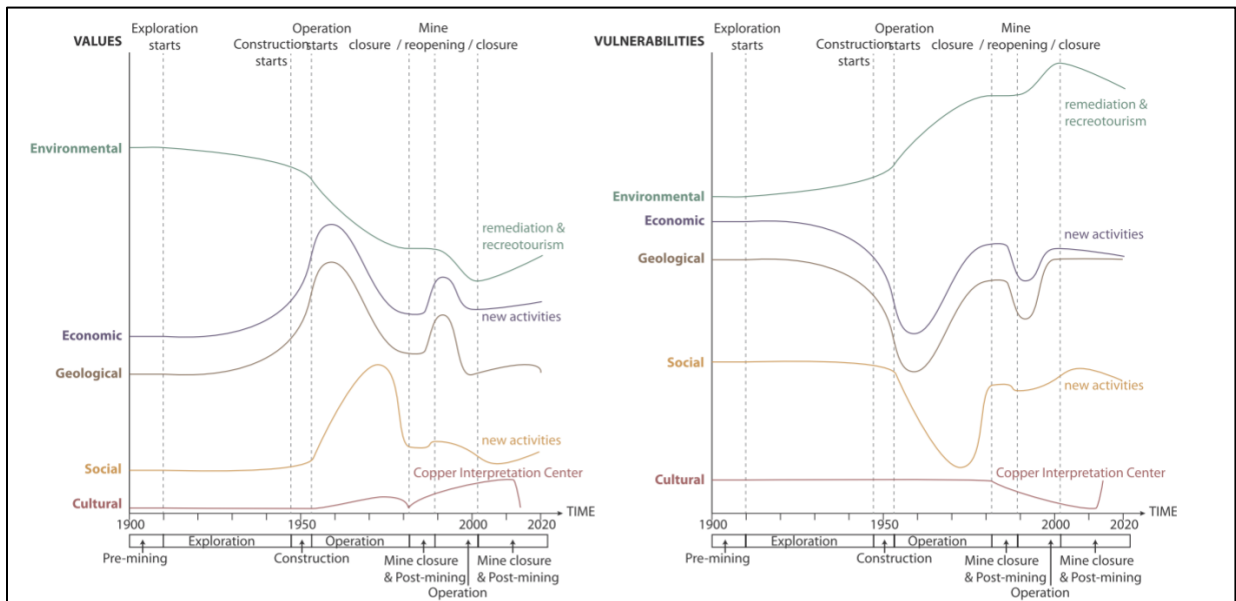


Figure 1-15: Expected values and vulnerabilities over a mine life cycle [41]

Analysis

The key focus of this study was evaluating the broader impact of mining on the surrounding environment and society using five key indicators. However, this study does not include any aspects of energy demand within the framework. The important outcomes from this study are the geological and economic trends which are clearly indicated over the LOM. The geological and economic values decrease in the latter half of the operation phase of the LOM, whilst the vulnerabilities increase over the same period. This indicates that there are opportunities to minimise the economic vulnerabilities by optimising energy demand as production downscales over the LOM.

An investigation into the impact of mine closure and its associated cost on life of mine planning and resource recovery [6]

Year: 2016

Authors: M. Nehring, X. Cheng

Overview

This study evaluates the financial impact of adequate closure planning over the LOM of an open-pit copper mine. It found that sufficient financial planning for closure can potentially extend the life of an operation. Since the financial plan has a significant impact on the production plan, optimising the operating schedule and mining location can have a significant impact on the financial viability of the operation.

Analysis

This study highlights the impact of adequate financial planning on mines nearing closure. However, it does not provide any indications of impact on energy consumption and is based on an open pit mine. This study proves the need for sufficient planning on mines nearing closure. The approach outlined in this study can be used to prioritise cost-effective mining blocks which determine the resource allocation and energy demand on mines nearing closure, potentially leading to significant energy savings.

Characterizing a mining production system for decision-making purposes in a platinum mine [42]

Year: 2017

Authors: T.C. Sebutsoe, C. Musingwini

Overview

This study investigates the relationships between the inputs and outputs of a mine planning system (MPS) to assist with decision-making. This study focuses on deep-level platinum mines which use narrow-reef conventional drill-and-blast methods. The inputs and production parameters were identified as the face advance, face length, number of teams, team efficiencies, and team size. A detailed breakdown of these parameters is presented in Table 1-8.

Table 1-8: Production parameters [42]

Production parameter	Description
Face advance	Distance achieved by blasting the face.
Face length	Length of minable face perpendicular to the face advance.
Achieved blasts	The number of blasts completed per shift.
Teams	The number of teams activity mining.
Team efficiency	The average centares mined per team.
Team size	The number of people in a mining team.

The outputs were classified as the centares (m²) mined which is classified as a KPI. This study found a statistically significant relationship between these input parameters and the production output. It was found that the face advance and face length had the closest correlation with the centares mined, as presented in Table 1-9.

Table 1-9: Correlation between production parameters and centares mined [42]

Parameter	Correlation to centares mined
Face advance	0.865
Face length mined	0.877
Achieved blasts	0.419
Teams	0.236
Team size	-0.238

The equations used to calculate the tonnes and metal produced based on the production parameters are presented below.

$$C = L \cdot A \cdot N \cdot T_e \quad \text{Equation 1}$$

$$T = C \cdot W \cdot sg \quad \text{Equation 2}$$

$$M = \frac{T \cdot g}{1000} \quad \text{Equation 3}$$

C = Centares mined [m ²]	T = Tonnes mined [t]
L = Face length mined per team [m]	W = Stopping width [m]
A = Face advance per blast [m]	sg = Specific gravity [t/m ³]
N = Number of blasts [-]	M = metal produced [kg]
T_e = Number of teams [-]	
g = grade produced [g/t]	

Analysis

This study highlights the key parameters used to determine planning requirements and proves a statistically significant relationship between these parameters and the production output. It also presents a means of calculating the expected production based on these input parameters. This study does not address the energy impact of these parameters or the planning impact of mines nearing closure. However, it is valuable, as it shows that the production parameters can be used for effective production planning with readily available planning data. Since these parameters form a key aspect of the MPS, they can also be used to estimate resource demand and, therefore, energy demand.

A Mine Closure Risk Rating System for South Africa [43]

Year: 2024

Authors: M. J. Cole

Overview

This study quantifies the risks associated with mine closure by developing a risk rating system that evaluates the likelihood of closure and the risk of the social and environmental impacts of closure. The case study evaluated these risks across gold, platinum, chrome, and coal mines across South Africa. It states that the generic risk rating methodology presented in this study can be used to assist with mine planning. Five quantifiable factors were identified as impacting the likelihood of closure: LOM, mineral resources and reserves, commodity markets, operating costs, mining methods and company type.

The LOM is quantified as the number of years the mine remains in operation. This is determined by the mining company and based on various factors including mineral reserves, economic climate, technical ability, financial feasibility and environmental feasibility. The LOM is typically updated yearly and can change depending on the aforementioned factors. This study states that the LOM is the most important factor when evaluating the likelihood of closure. The mineral resources and reserves indicate the availability of financially feasible ore bodies. The ore bodies for precious metal commodities are quantified in ounces. Commodity markets play an important role in determining the closure risk of a mine, as metal prices tend to be volatile. This factor is quantified as a unit cost value, and it determines the financial feasibility of operating the mine as well as whether a mine will be closing temporarily or indefinitely. Operating costs vary based on mining methods, operation

depth, ore recovery, and labour. Deep-level mines are the most complex and costly to operate due to their need for high energy-consuming systems such as refrigeration for ventilation. The type of mining company also plays a role in determining the risk of closure. Larger, more established companies tend to have sufficient reserves to offset low commodity prices in the short term, reducing their risk of closure.

Analysis

The focus of this study is evaluating the risks associated with mine closure on the society and the environment around the operation. Additionally, it provides a means of identifying and quantifying risks leading to mine closure. This study provides relevant information that serves two key purposes. First, it provides a method of identifying mines at the highest risk of closure and second, it identifies the key factors associated with mines nearing closure. The factors relevant to this study include the LOM, mineral resources and mineral reserves.

A Framework for Life of Mine Ventilation Planning with a Case Study of the Diavik Diamond Mine [44]

Year: 2017

Authors: R. Clarke

Summary

This paper presents a ventilation planning framework based on a deep-level mine's LOMP. The framework includes developing a ventilation model to forecast underground conditions according to mine ventilation standards. This model also determines possible inefficiencies in the underground ventilation system. A value-ease method presented in Table 1-10 is used to determine adequate ventilation initiatives to overcome these inefficiencies.

Table 1-10: Value-ease chart [44]

		Relative Impact on Business	
		High	Low
Ease of Implementation	Easy	Big Wins	Easy Street
	Difficult	Worth the Effort	Put Aside

The case study used in this study focuses on a mine with a LOM of less than eight years. It states that the ventilation plan can only provide as much detail as the production plan. It states mine plans should become increasingly more detailed as they approach the specified timeframe. Mine planning is integral to the efficient operation of a mine, as it aims to determine the location and quantity of the ore body that will be extracted daily.

This information is used to develop a schedule presented in Figure 1-16 which serves as the basis for resource allocation and consumption. The framework presented in this study primarily relies on the production plan, with design criteria outlined accordingly. Relevant measurements are taken to verify the design, and the system is iteratively modelled and simulated. The inefficiencies are identified based on the measurements, leading to the redevelopment and simulation of solutions. The most viable solutions are then presented and implemented.

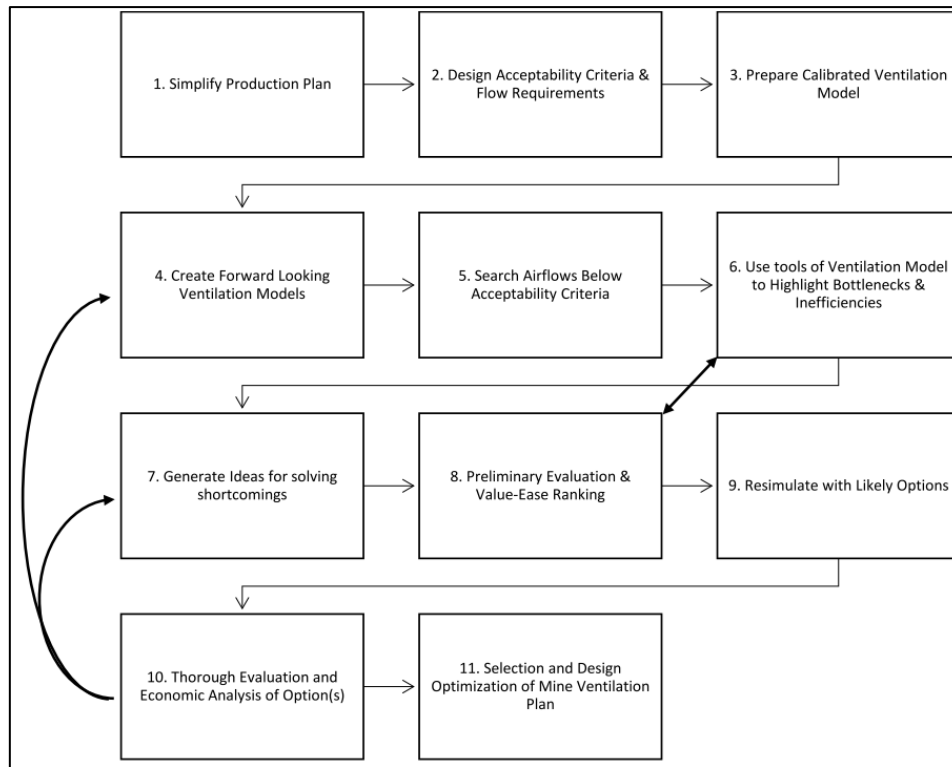


Figure 1-16: LOM ventilation planning framework [44]

This study states that mines planning to close within ten years or less typically reach peak production with limited further expansion. In these cases, the typical payback period for large equipment exceeds the LOM. At this stage of operations, the focus lies on sustainable production rather than expansion, which typically involves concentrating production into specific high-yield locations. This study emphasises the importance of developing a production plan, as it identifies the specific mining locations which assist with resource allocation.

Analysis

This study highlights the importance of the mine planning process and proactive decision-making to ensure uninterrupted mine operations. This is particularly important for mines nearing closure, as production is drastically downscaled within the final few months and years of the LOM. The study presents a framework for developing an adaptive and economic ventilation plan based on the life of mine plan (LOMP). This study primarily focuses on LOM ventilation planning and does not consider energy management within the framework. However, this framework can be adapted to plan for energy management. Despite this ventilation planning framework being implemented on an underground diamond mine in the Northern Hemisphere, it is generic enough to be adapted for various high energy consuming systems on deep-level gold mines in South Africa.

Establishing a Model to Reduce the Risk of Premature Mine Closure [45]

Year: 2019

Authors: M. Pouremaieli, M. Osanloo

Summary

This study outlined a risk management technique to identify, evaluate, and mitigate risk factors that lead to premature mine closures. This study aimed to assist investors with identifying and safeguarding against these risks. It was conducted across a broad range of mines in Iran. Decreasing commodity prices, a lack of investment, and increasing costs were found to be significant factors leading to premature closure, as presented in Table 1-11.

Table 1-11: Probability of risks [45]

Risk category	Risks	Risk value (%)
Economic	Decreasing the commodity prices	1.14%
Economic	Loss of markets	0.55%
Efficiency	Resources depleted	0.52%
Economic	Lack of sufficient investment	0.51%
Economic	Increasing of costs	0.40%
Economic	Low ore grade	0.33%
Efficiency	Lack of explorations	0.29%
Environmental and community	Company policies	0.29%
Efficiency	Geology or geotechnical problems	0.28%
Efficiency	Geological uncertainty	0.26%
Environmental and community	Acid mine derange	0.24%
Efficiency	Grade uncertainty	0.23%
Environmental and community	Pollution (water, air, surrounding)	0.22%
Efficiency	Safety	0.17%
Environmental and community	Equipment/technical problems	0.16%
Environmental and community	Official bureaucracy	0.13%
Environmental and community	Regulatory or government intervention	0.11%

Analysis

This study examines risk factors that contribute to mine closures across multiple operations in Iran. It does not specifically address the risks associated with deep-level mines or the implications on energy consumption, however, some of the major risks that have been identified can be used as criteria for developing an energy management framework. These risks are highlighted in Table 1-12.

Table 1-12: Mine closure risks relevant to energy management [45]

Risk	Relevance to energy management
Lack of sufficient investment	Since less capital is invested at the mine, less capital is allocated to energy management projects.
Increasing costs	Energy costs form a significant part of the overall operating costs, especially on deep-level mines.
Low ore grade	Low ore grade typically means an increase in production or a shift in focus to smaller higher-grade ore bodies. This narrows the production location, creating opportunities for downscaling energy consumption.
Lack of explorations	The decrease in new development indicates that a mine will be nearing closure, therefore, energy downscaling can be planned accordingly.
Equipment and technical problems	Equipment and technical problems are commonly associated with mature mines, as equipment ages and is irregularly maintained. This can lead to potential decreases in the energy efficiency of high energy-consuming systems through wastage.

1.4.3. Literature study of papers presenting resource- and energy baseline methodologies

Using zero-waste baselines to identify compressed air system inefficiencies in deep-level mines [46]

Year: 2022

Authors: A. van der Merwe, A.G.S. Gous and C.S.L Schutte

Overview

This study presents a simulation approach to developing a zero-waste baseline to identify compressed air inefficiencies on deep-level mines, as shown in Figure 1-17. The baseline is developed using current production data, equipment allocations, and equipment specifications. The baseline is used to determine the ideal demand, identify and quantify inefficiencies, isolate inefficient locations, and evaluate the potential waste reduction. The baseline estimated flow, pressure, and energy demands. The implementation of this method allowed for a daily reduction of 23.7% in compressed air energy consumption.

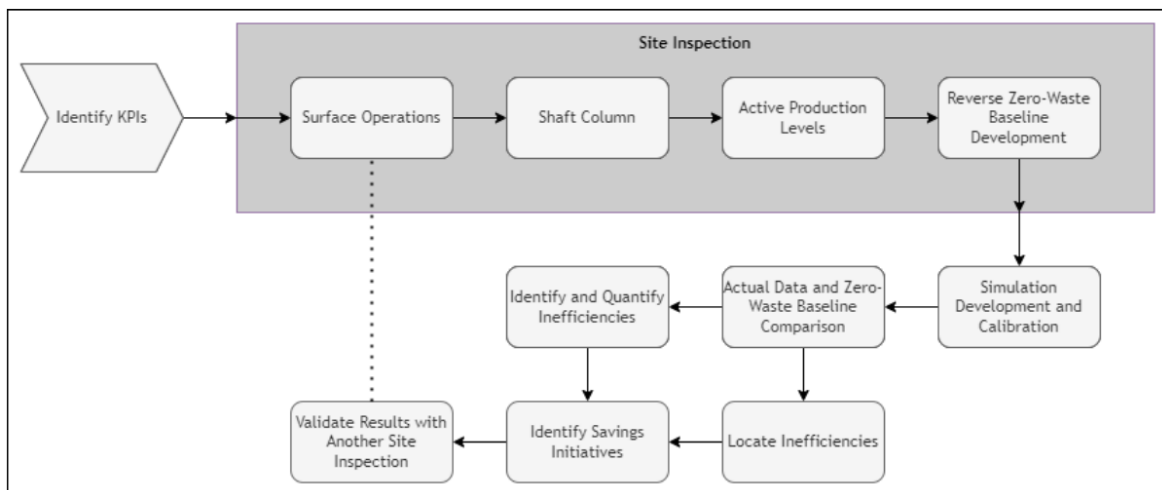


Figure 1-17: Compressed air zero-waste baseline development method [46]

Analysis

This study only considers the application of a zero-waste baseline on compressed air demand and the resulting energy impact thereof. This method is generic enough to be applied to a water reticulation system as well; however, it only evaluates the shaft's inefficiencies based on the current production requirements and does not consider the long-term requirements based on the LOMP.

Identifying water wastage in deep-level mines using novel simulation-based zero-waste baselines [16]

Year: 2024

Author: M. le Roux

Overview

This study presents a simulation based zero-waste baseline method to identify wastages on deep-level mine water reticulation systems. It found that a zero-waste baseline method identifies the highest levels of water wastage in a deep-level mining system. The zero-baseline in this study was primarily developed by quantifying the key water flow demand, F , in the system using Equation 4 for rock drills and Equation 5 for other underground consumers.

$$F_{sto,dev} = \left(\frac{F_d N_a H_a}{60 P_d t} + \frac{F_d N_r H_r}{60 P_d t} + \frac{F_d H_s H_s}{60 P_d t} \right) \cdot \left(\frac{O}{WLA\rho} \right) \quad \text{Equation 4}$$

F = Flow rate [Nm ³ /s]	ρ = Rock density [kg/m ³]
N = Number of holes	O = Actual/ planned production [tonnes]
H = Hole length [m]	Sto = Stoping
P = Penetration rate [m/min]	Dev = Development
t = Shift time [hours]	d = Drill
W = Panel width [m]	a = Advance
L = Panel length [m]	r = Roof tendon
A = Advance per blast [m]	s = Side tendon

$$F_{r,b,l,m} = N \cdot (F_e) \cdot \left(\frac{T}{t} \right) \cdot \left(\frac{O}{WLA\rho} \right) \quad \text{Equation 5}$$

F = Cleaning flow rate [Nm ³ /s]	L = Panel length [m]
N = Amount of equipment in operation	A = Advance per blast [m]
F_e = Rated flow rate of equipment [Nm ³ /s]	r = Refuge bay
T = Time of equipment usage [hours]	b = Bazooka
t = Shift time [hours]	l = Loading box
O = Actual/ planned production [tonnes]	m = Mechanical loader
W = Panel width [m]	

This method quantified the demand over a 24-hour period and considered the changes in demand over changes in shifts, as presented in Figure 1-18. This method identified water wastages of up to 70% within a 5% error margin.

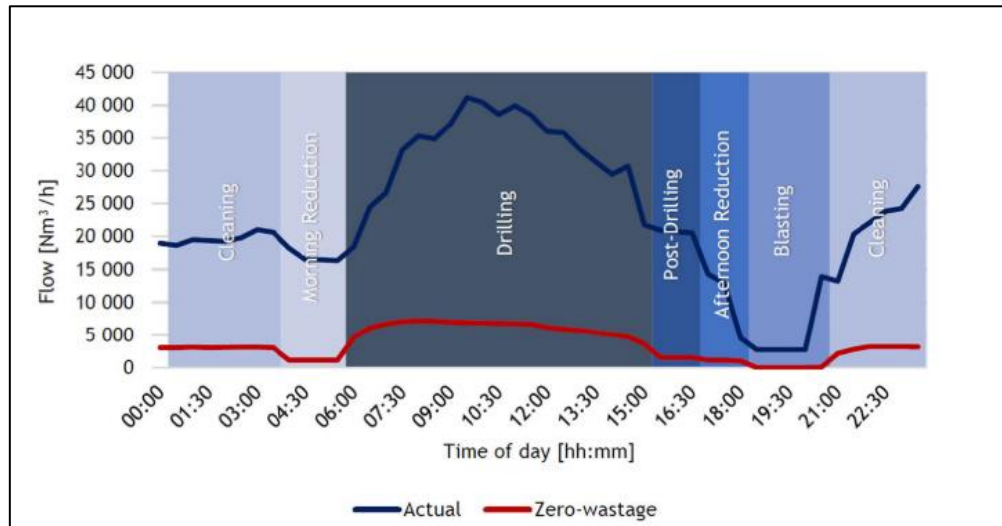


Figure 1-18: Example of zero-waste baseline profile [16]

Analysis

This study provided valuable information on developing accurate estimations for developing zero-waste baselines. The equations presented provided a holistic representation of the demands by considering the number of holes drilled and the time of use (TOU) when evaluating the equipment water demand. These equations can also be used to estimate the compressed air demand, as they share the same usage characteristics. However, the scope of this study did not address the application of a zero-waste baseline for LOM planning or the energy savings potential of implementing such a method.

Energy efficiency in the South African mining sector: A case study at a coal mine in Mpumalanga [47]

Year: 2023

Author: C.M.D. Majola and K.E. Langerman

Overview

This study presents methods for establishing a baseline and evaluating energy efficiency on deep-level mines based on production. This study evaluated multiple South African coal mines with either

steady or increasing production over time. Three methods of evaluation are proposed, namely a linear regression baseline, intensity baseline, and time series analysis. These methods were used to evaluate the long-term demand over a span of months and years. This study recommends using at least three years of data to develop the respective baselines to obtain the best estimates.

Analysis

The scope of this study addresses all potential energy sources of a deep-level mining operation. However, the proposed method works equally well with just electrical energy demand. Of the baselining methods presented, the linear regression model would be the most suitable method to evaluate the expected reduction in energy demand on a mine nearing closure. Unlike the intensity model, the linear regression model considers a baseline demand and places greater emphasis on the impact of production than the time series model. These factors are important when evaluating an operation with an expected decrease in production and when a set baseload is required for continuous production. Therefore, the regression model outlined in this study is ideal for developing a scaled baseline for medium- to long-term planning purposes.

Electrical load forecasting models: A critical systematic review [48]

Year: 2017

Authors: C. Kuster, Y. Rezgui, M. Mourshed

Overview

This study conducted a critical review of statistical energy forecasting methods, analysing 113 case studies across 41 papers. The methods were categorised based on different use cases and time horizons. The models include regression models, a bottom-up method, an ANN model, an SVM model, and time series analysis. The two key methods identified from this study are the regression model and the bottom-up method. The regression method is the most widely used method due to its versatility and dependency on external variables. It was found that regression models can be used for energy forecasting from sub-hour to annual periods with the potential to include seasonality by means of data clustering. The bottom-up approach is developed by identifying and quantifying all the key loads on the system. In this case, a statistical approach was used to estimate the demand. It was found that a bottom-up approach can be used for sub-hourly data and can be improved by including environmental data and time indexing.

Analysis

The cases evaluated in this study only considered residential and commercial energy demand forecasting. However, the regression and bottom-up approaches can be adapted to forecast energy demand on deep-level mine systems. The regression model proves useful in determining the scaled monthly baseline based on the change in monthly production while the bottom-up approach can be used to quantify the medium- to long-term resource and energy demand based on changes in demand according to both the daily schedule and monthly changes in production.

A simulation-based water management strategy for life-of-mine water planning [17]

Year: 2022

Authors: C.A. Monteiro, J.H. van Laar & C.S.L. Schutte

Overview

This study presented a generic simulation methodology to evaluate and plan water management on deep-level gold mines. This approach is used to model the complete water reticulation system of the mine, which includes both the chilled water and dewatering systems. The model is then used to forecast water demand and management capacity based on the LOM production plans. An overview of the methodology is presented in Figure 1-19.

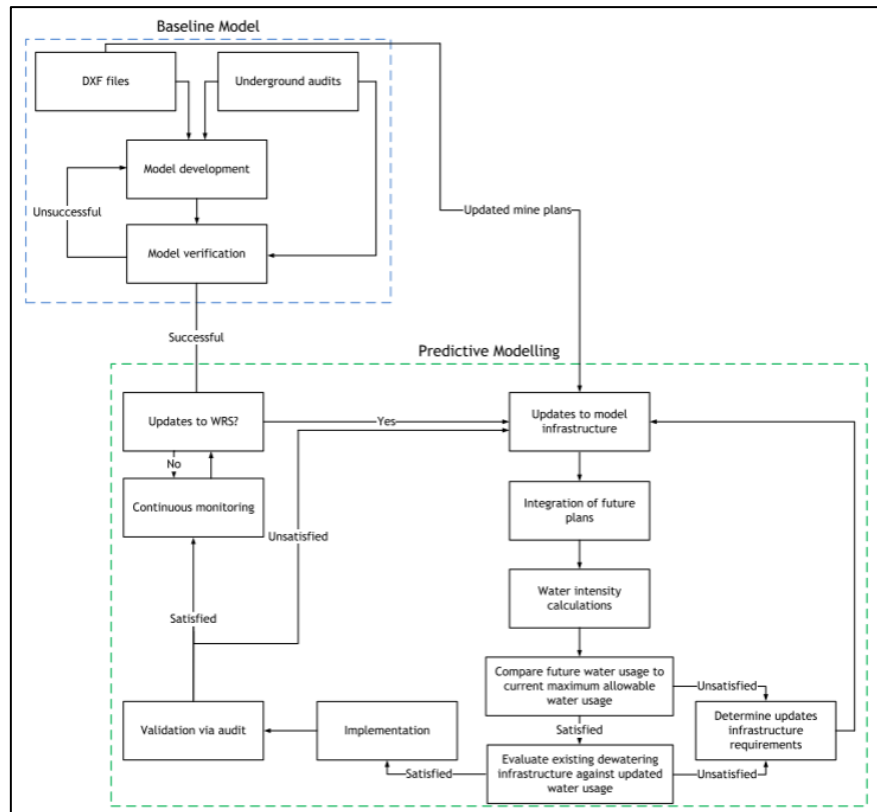


Figure 1-19: LOM simulated water management methodology [17]

The underground reticulation layout, valve locations, pump locations, underground pressure boundaries, dam locations, and overall water demand were used to build and calibrate the simulation model. This information was obtained from available mine plans and system audits. The chilled water and water reticulation systems were calibrated to different specifications. The chilled water system was calibrated using pressure valves and pipe loss specifications. The return water system was calibrated using pump efficiency, pipe losses, and dam levels. This study noted the importance of the availability of pump curves when building the simulation. The model considered the inlet and outlet flows of the system. The inlet flows included the service water, potable water, and fire water while the outlet flow considered the total water returning to surface.

The study used the baseline water intensity as well as the simulation model to predict changes in water demand and subsequent infrastructure requirements over the planning period. The model was able to predict demand with a 4.9% error, and recommendations were made to install additional infrastructure to adequately manage the increase in demand.

Analysis

This study developed a detailed simulation methodology to evaluate mine water demand based on the available LOM production plan. It is effective in identifying the key parameters required to develop a simulation-based approach to predict changes in water demand. However, this methodology does not consider the energy impact of these changes, and the case study mine evaluated was not nearing closure. However, this method remains generic enough to evaluate the water requirements for any changes in production demand.

1.4.4. Literature study of papers presenting energy management methodologies

Understanding the impacts of energy efficiency measures on a Company's operational performance: A new framework [26]

Year: 2022

Authors: E. Cagno, D. Accordini, A. Trianni, M. Katic, N. Ferrari, F. Gambaro

Overview

This study developed an empirical framework for implementing energy efficiency projects across a broad range of industries. The key focus of this study was to identify important context-specific characteristics which would impact the implementation of energy efficiency projects. The projects were evaluated based on their relative impact on KPIs. The three overarching KPIs were identified as production, social, and environmental. The framework developed and used in this study is presented in Figure 1-20.

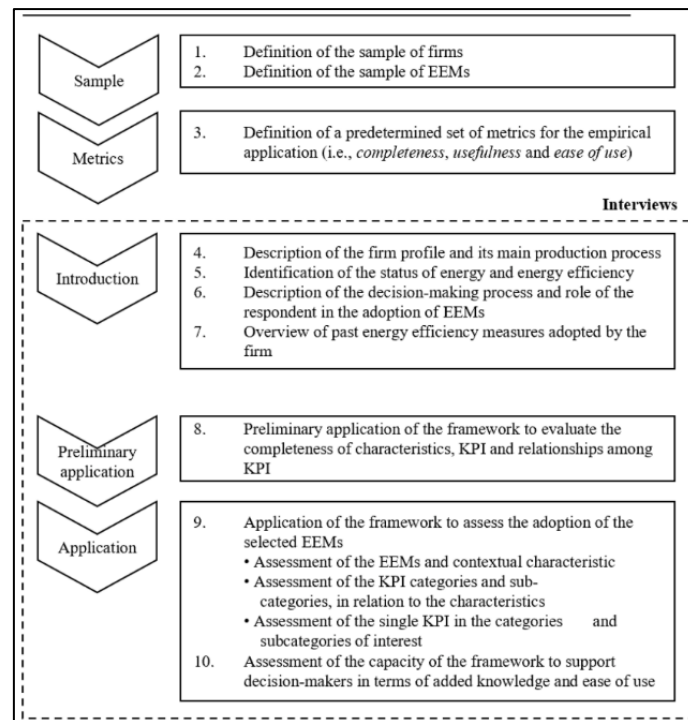


Figure 1-20: Empirical energy management framework [26]

Analysis

The framework presented in this study addresses the implementation of energy management projects across a broad range of applications with special consideration for specific contextual requirements. This is important because mines nearing closure have specific characteristics which differ from mines that are planning sustained production. However, the KPIs presented in this study are not relevant to the context of heavy engineering systems. This study also does not provide a quantitative method of baselining and measuring the impact of the energy efficiency projects.

An integrated energy management strategy for the deep-level gold mining industry [49]

Year: 2016

Authors: J.I.G. Bredenkamp, M.J. Mathews, J.C. Vosloo

Overview

This study implements an energy management strategy on deep-level gold mines using the ISO 50001 energy management standard. This standard uses the Plan-Do-Check-Act (PDCA) framework. This framework is used to evaluate and implement energy management initiatives across all the

major energy consuming systems on deep-level gold mines. A flow chart of the method is presented in Figure 1-21.

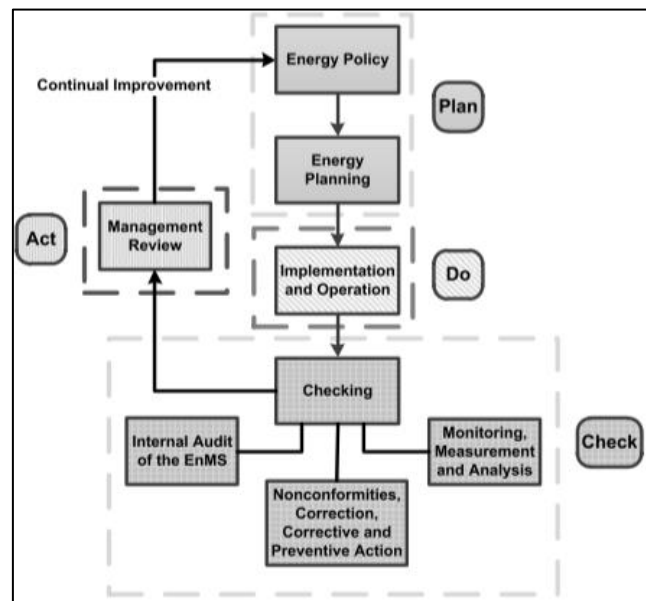


Figure 1-21: Plan-Do-Check-Act energy management framework [49]

The Plan phase is used to evaluate historic demand, determine a baseline, and identify KPIs. Based on these, the high-energy-consuming systems are prioritised based on energy impact and ease of implementation. The energy management initiatives are implemented based on the priorities outlined during planning in the Do phase. The energy and cost impact of the initiatives are measured during the Check phase. The impact of the initiative is evaluated against the KPIs, and the next steps are planned during the Act phase. The implementation of this framework resulted in an 18.5% reduction in total energy consumption on a single gold mine.

Analysis

This study provides a robust framework to identify, implement, and evaluate energy management initiatives on deep-level gold mines. This study does not explicitly consider the impact of production changes on energy demand over the LOM; however, it does consider the need for continuous monitoring and improvement. The PDCA framework presented in this study can be simplified and implemented on selected systems directly impacted by changes in production on deep-level mines nearing closure.

Evaluating compressed air operational improvements on a deep-level mine through simulations [23]

Year: 2017

Authors: P. Maré, J.I.G. Bredenkamp, J.H. Marais

Overview

This paper presents a simplified simulation method to identify and evaluate energy management initiatives on deep-level mine compressed air systems. Several important factors were considered to develop an effective compressed air simulation, namely the dynamic operation of the mine, the layout of the compressed air system, data availability and accuracy, compressor specifications, operating boundary conditions, and period of operation.

This method outlines three levels of detail of increasing complexity from simulating only the compressors, simulating the compressors and shafts/plants, to simulating the compressors shafts/plants and underground consumers, as presented in Figure 1-22. The increase in complexity results in more detailed information requirements and an increase in time required to simulate. Once the level of detail is determined, relative system parameters are collected. This includes compressor and demand data, process flow diagrams, system and component specifications, existing control philosophies, planned initiatives, and planned production targets.

The simulation model is then set up based on the system parameters for either evaluating energy savings or service delivery improvement. The simulation time periods are then established. Once the initial configuration is complete, the simulation is calibrated using known measured values. The simulation outputs need to be within 5% of the known values to establish the baseline from which the various scenarios are evaluated. This method outlines the importance of considering the cost of the potential solution, the effect on production, and time constraints of implementing the solution. This simulation method identified a potential increase in system pressure of 51 kPa as well as an energy cost saving of R 1.5 million per annum on a gold mining operation.

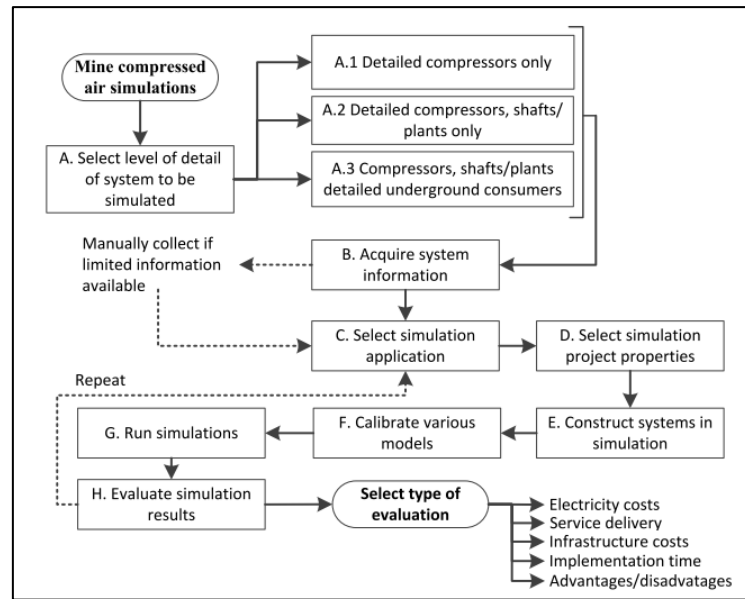


Figure 1-22: Simplified deep-level mine compressed air simulation method [23]

Analysis

The simplified methodology presented in this study was proven to quickly and effectively identify the impact of implementing energy management initiatives on mine compressed air systems. The use of dynamic compressors in the simulation allows for more accurate energy demand results. However, development of the simulation model requires the availability of system information. The scalability of this method to accommodate various degrees of complexity is important when only evaluating certain parameters such as energy consumption, surface flow, and pressure. However, this study does not consider the impact of production over the LOM on compressed air demand.

Optimising energy recovery in mine dewatering systems [32]

Year: 2018

Authors: W. Van der Wateren, H.P.R. Joubert, M. Kleingeld

Overview

This study presents a simulation-based methodology to evaluate the energy demands of a dewatering system on a deep-level mine. This methodology is presented in six phases. Phase 1 involves conducting an evaluation of the system and identifying the locations and specifications of the key components. Phase 2 involves developing specific baselines using the available flow and power data, including the supply and return flows. Phase 3 involves identifying the type of initiative

to implement based on baselines. Phase 4 involves constructing the simulation model. The dams are set as the boundaries of the model, and the model is used to solve for energy and mass flow, which is evaluated using Equation 6.

$$\sum \dot{m}_i t + m_i = \sum \dot{m}_e t + m_e \quad \text{Equation 6}$$

$\sum \dot{m}_i$ = Total mass flow into the dam [kg/s]	m_i = Initial mass of water within the dam [kg]
m_e = Mass of water in the dam after a given period [kg]	$\sum \dot{m}_e$ = Total mass flow out of the dam [kg/s]
t = Time [s]	

The supply flows are used as the inputs into the system and the return flow and pumping energy consumption are used to calibrate the model within 10% of the baselines. A theoretical Equation 7 can also be used to verify the pump simulation by determining the pump power, P , based on the input parameters.

$$P = \frac{\rho g h \dot{Q}}{\eta} \quad \text{Equation 7}$$

η = Pump efficiency [-]	g = Gravitational acceleration [m/s ²]
P = Pump electrical power [kW]	h = Effective head [m]
ρ = Fluid density [kg/m ³]	$\dot{Q}$ = Volumetric flow [m ³ /s]

The calibrated model is used to test various control philosophies which are then implemented at the mine in Phase 5. The system is then monitored and maintained to ensure system stability in Phase 6. This method was used to identify load shift opportunities on the case study mine. This facilitated a load shift of 4 MW outside the Eskom peak demand period, resulting in annual energy savings of R1.7 million.

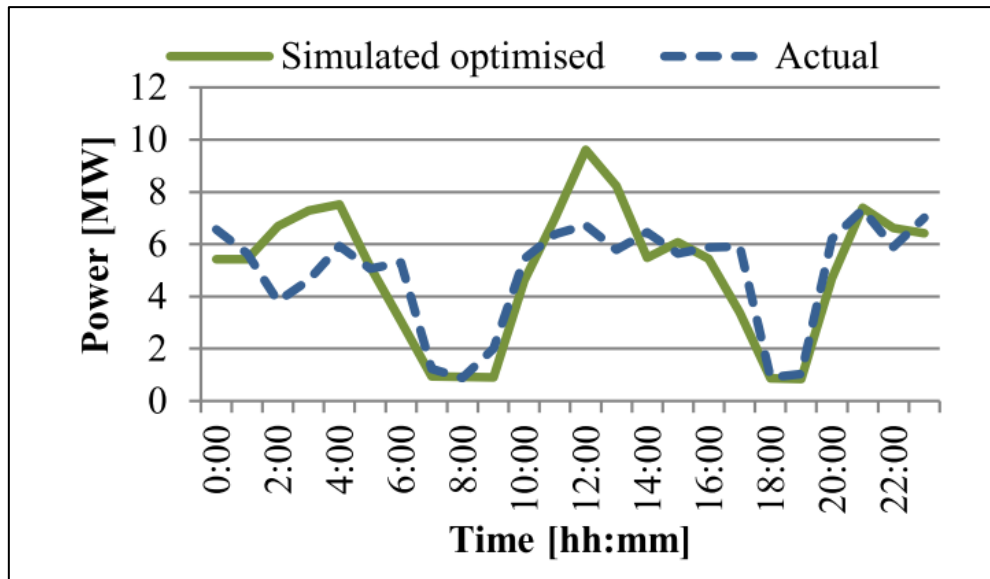


Figure 1-23: Pumping load shift vs simulation results [32]

Analysis

This study presents a useful simulation methodology to estimate energy savings on return water systems in deep-level mines. It provides a reasonable breakdown of the considerations and requirements for evaluating the pumping energy demand. However, this study does not consider the impact of production on water demand and the subsequent energy demand but rather focuses exclusively on optimising the pumping schedule. Additionally, it does not consider the energy impact on the refrigeration systems.

1.4.5. State of the art summary

16 studies were categorised and critically analysed using the research methodology presented in Section 1.4.1. The findings from the literature study are presented as a state-of-the-art matrix in Table 1-13. It is evident from this matrix that the studies typically only addressed two of the four overarching domains of research. It was found that studies presenting findings on LOM planning also addressed mines nearing closure and studies addressing baseline development also addressed energy management. However, there was minimal overlap in current literature between these two domains.

Table 1-13: State-of-the-art matrix

Domain	Source	Mines nearing closure	LOM planning	Baseline development	Energy management
LOM Planning	[7]				
	[41]				
	[6]				
	[42]				
	[43]				
	[44]				
	[45]				
Baseline development	[46]				
	[16]				
	[47]				
	[48]				
	[17]				
Energy management	[26]				
	[49]				
	[23]				
	[32]				

1.5. Need for the study

Section Chapter 1: concluded that South African deep-level gold mines are energy intensive, with many nearing closure as presented in Section 1.2.1. Due to ageing infrastructure, these operations are also prone to wastage on their compressed air and water reticulation systems, as presented in Section 1.2.2. The literature analysis presented in Section 1.4.2 concluded that mines nearing closure have unique characteristics such as limited capital allocation, a reduction in production, and a reduced operating timeframe. It also highlighted the importance of using production planning in determining resource allocation. The literature presented in Section 1.4.3 outlined methods for baselining resource and energy demand. Finally, methods of developing and implementing energy management initiatives were presented in Section 1.4.4. A gap in literature was identified between the domains of energy management and mines planning for closure, as outlined in Section 1.4.5. Therefore, there is a need to conduct a study to combine these findings to evaluate demand and develop an energy management strategy for the unique characteristics of deep-level gold mines nearing closure.

1.6. Study aim and objectives

Gaps in the literature were identified between energy management and mines planning for closure, as presented in Section 1.4.5. **The study aims to develop an energy management methodology to reduce energy consumption on deep-level gold mines nearing closure.** The following objectives need to be fulfilled to successfully address the need for this study:

1. Identify characteristics of mines nearing closure.
2. Identify changes in planned LOM production trends on mines nearing closure.
3. Identify resource and energy wastage on mines nearing closure.
4. Implement an energy management strategy to reduce energy demand on mines nearing closure.
5. Quantify the LOM impact of implementing an energy management strategy on mines nearing closure.

Each of the objectives build upon the previous one to guide the development of the method presented in Chapter 2. All these objectives need to be met to successfully fulfil the requirements of the study.

1.7. Development of study methodology

Since this study aimed to test the method in a real-world application with quantitative results, a case study methodology was used to develop this research. This methodology was adapted from S. Teegavarapu *et al.* and is presented in Figure 1-24 [40]. The problem statement and literature study are used to guide the study objectives, which are used to develop the methodology of reducing the energy demand on mines nearing closure. Case studies on two separate mines were conducted and analysed to validate the efficacy of the methodology.

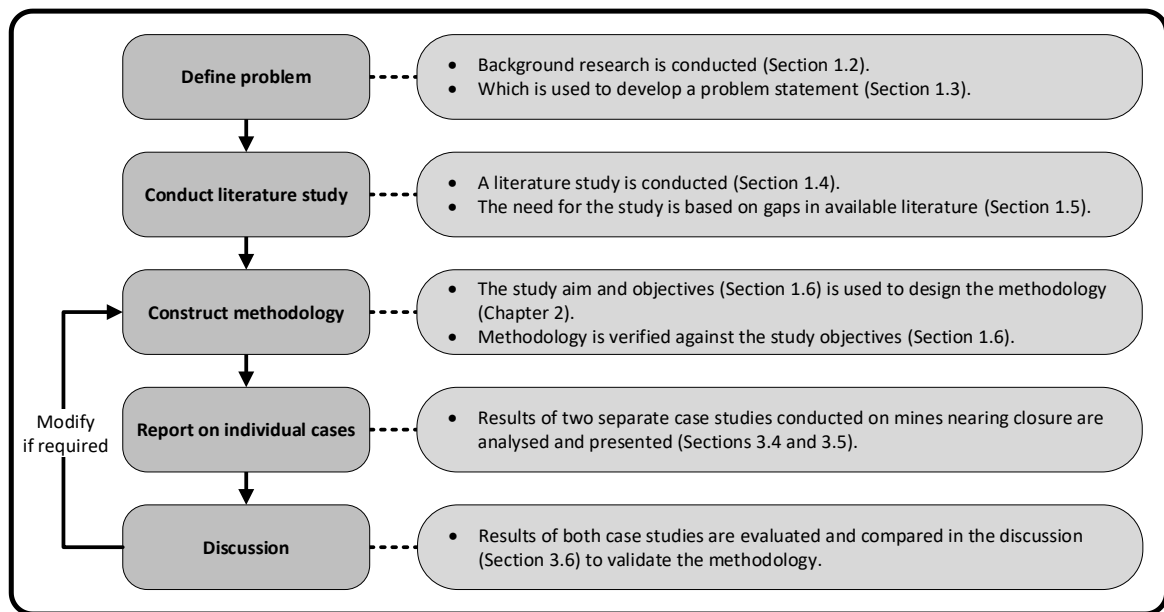


Figure 1-24: Overview of a case study research methodology [40]

1.8. Chapter conclusion

This chapter presented background context to problems experienced by the South African gold mining industry, which primarily include production downscaling, high energy costs, and infrastructure issues. This was used to guide the development of the problem statement and literature study. The literature study focused on three overarching domains, including LOM planning, baselining methodologies, and energy management. A case study methodology was adapted from literature to develop the methodology presented in Chapter 2.

CHAPTER 2: DEVELOPMENT OF METHODOLOGY TO REDUCE ENERGY DEMAND ON DEEP-LEVEL GOLD MINES NEARING CLOSURE

2.1. Chapter introduction

This chapter presents a methodology to reduce the energy demand of deep-level gold mines nearing closure. The methodology design was based on the study objectives outlined in Section 1.6 and is presented in Section 2.2. The methodology is divided into four steps and presented from Section 2.3. to 2.6. A verification of the methodology is presented in Section 2.7. and the chapter is concluded in Section 2.8.

2.2. Methodology design

The methodology was divided into four steps which aim to fulfil the study objectives outlined in Section 1.6. as presented in Figure 2-1. Step 1 of the methodology presented in Section 2.3. addresses the objectives of identifying the characteristics and quantifying the LOM production of mines nearing closure. Step 2 of the methodology presented in Section 2.4 addresses the objective of identifying system wastage on mines nearing closure. Step 3 of the methodology presented in Section 2.5 addresses the objective of implementing waste reduction and energy management initiatives on mines nearing closure. Step 4 of the methodology presented in Section 2.6 addresses the objective of quantifying the energy and cost savings of implementing energy management initiatives on mines nearing closure.

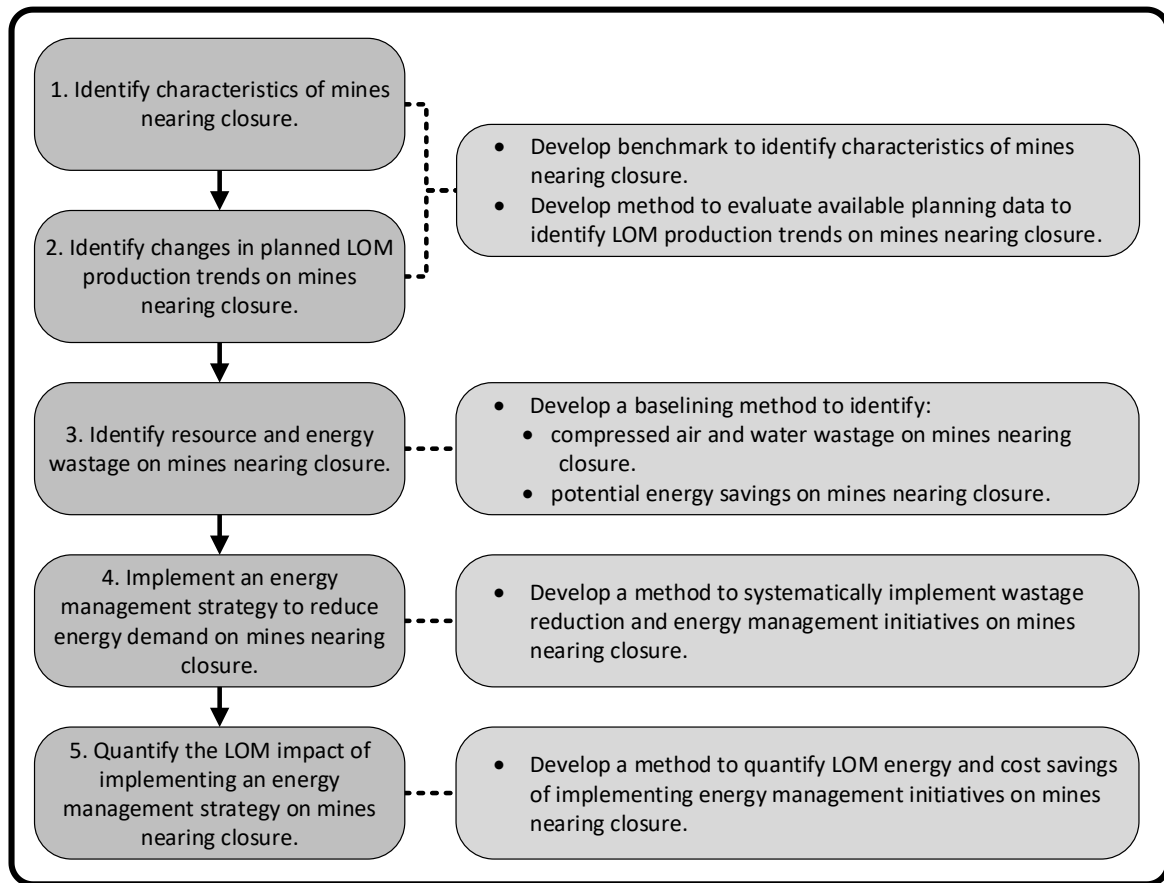


Figure 2-1: Methodology design

2.3. Step 1: Evaluating LOM characteristics of mines nearing closure

To implement viable waste reduction and energy management initiatives on mines nearing closure, the production, financial, and planning characteristics of these operations need to be determined. This section presents a process for evaluating these characteristics. First, a qualitative benchmarking method is presented to determine suitable operations nearing closure based on the LOM characteristics. This method is presented in Section 2.3.1. Second, a method evaluating the production planning time horizons is presented in Section 2.3.2. Third, a method used to quantify and extract information relevant to this study from the LOM production plan is presented in Section 2.3.3. An overview of this section is presented in Figure 2-2.

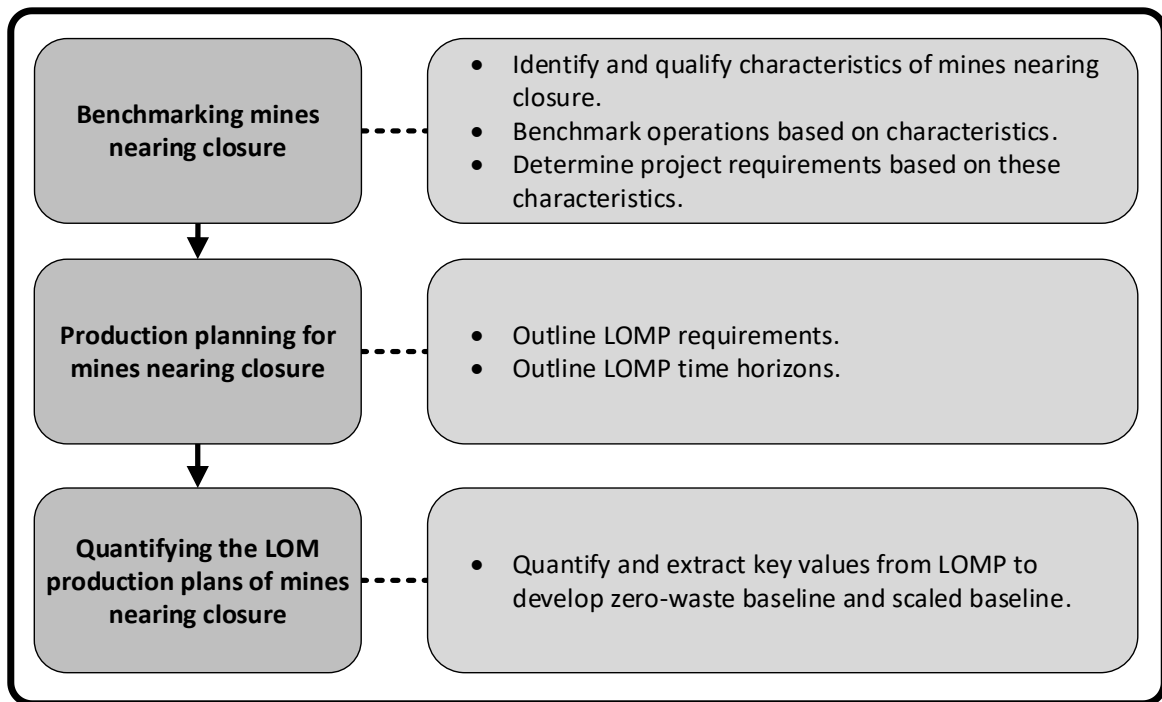


Figure 2-2: Evaluating LOM characteristics of mines nearing closure

2.3.1. Benchmarking mines nearing closure

Mine management typically selects the closure date for a mine well in advance. The mine production plan is developed according to this date. However, this date is flexible based on ground conditions and various internal and external factors [50]. Decreasing CAPEX, a short LOM, and a decreasing production trend are identified in Section 1.4.2 as key characteristics of mines nearing closure. These characteristics are benchmarked across deep-level mines operating within a similar region and with similar mining methods. These characteristics indicate the extent of production and capital downscaling trends of the relevant operations [43].

Viable operations were selected based on a downward trend in these characteristics [41]. These characteristics are also used to identify the types of projects to be considered when evaluating viable operations, as outlined in Table 2-1 [45]. Once viable operations are identified, their production plans can be evaluated to determine the extent of downscaling as the mine nears closure.

Table 2-1: Project characteristics for mines nearing closure [45]

Operation characteristic	Project characteristic
Decrease in CAPEX	This indicates that cost-effective solutions need to be identified.
Decrease in LOM	This indicates that projects with short implementation times need to be prioritised.
Decrease in production	This indicates the potential to reduce resource and energy consumption at the operation.

2.3.2. Production planning for mines nearing closure

The LOM production plan outlines monthly targets based on the subsurface geology and LOM schedule [51]. When mining operations have a LOM of 10 years or less, all major infrastructure has already been developed. Most of the equipment reaching the end of its serviceable life is not upgraded or further maintained due to constraints on the payback period based on the LOM. Therefore, these operations are not focused on growth but rather on safely maintaining production [44].

The financial and production plan is constructed using available geological data which determines the overall profitable production capacity and LOM of the shaft. All these factors form part of the LOMP. The LOMP plays an important role in determining the potential production output of the operation, especially as it nears the five-year and three-year LOM horizon [7]. According to *Campeau et al.*, there are three timeframes used for underground mine planning, as presented in Table 2-2 [45].

Table 2-2: Project characteristics for mines nearing closure [45]

Long-term plan	Used to evaluate a strategic high-level production plan for the extent of the LOM. The long-term mine plan must be updated yearly given uncertain geological conditions and fluctuating commodity prices.
Medium-term plan	The long-term plan is divided into medium-term plans. The medium-term plan is typically more precise and has a time horizon of one to three months.
Short-term plan	The medium-term plan is divided into short-term plans closer to the execution date. Short-term plans form the blueprint for execution and have a time horizon ranging from one month to one hour.

Reduced mining activity can lead to various planning scenarios which differ from operating conditions present during the standard operating phase of the mine life cycle. This will ultimately change the resource planning requirements for the operation as downscaling commences. Therefore, timely planning is critical for the successful downscaling of an operation [44].

Two planning periods are evaluated for this study. The short-term plan evaluates the daily production schedule while a hybrid of the medium- and long-term plan evaluates the monthly production plan. An example of the short-term production plan adapted from *van der Merwe et al.* is presented in Figure 2-3 [46]. An example of the medium-long-term production plan developed by *Khazaei et al.* is presented in Figure 2-4 [52].

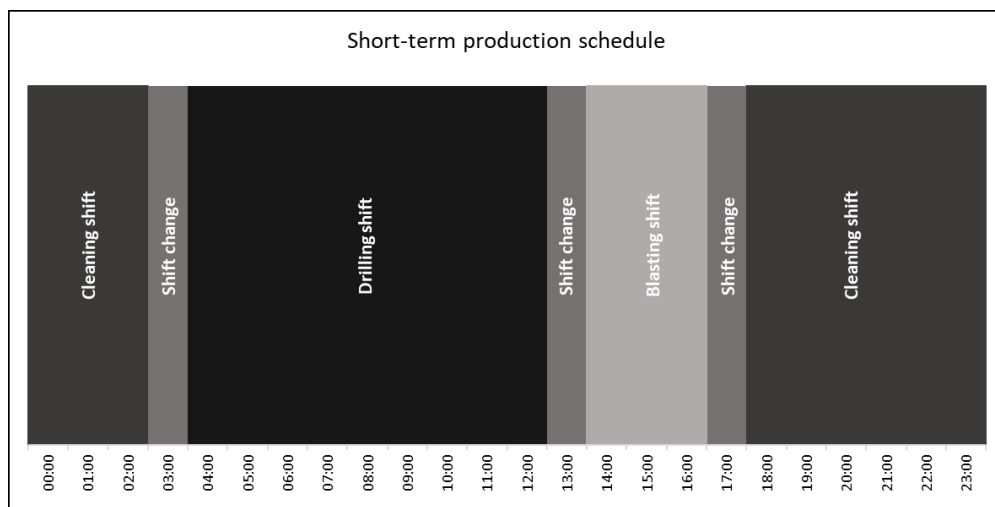


Figure 2-3: Example of a short-term production schedule [46]

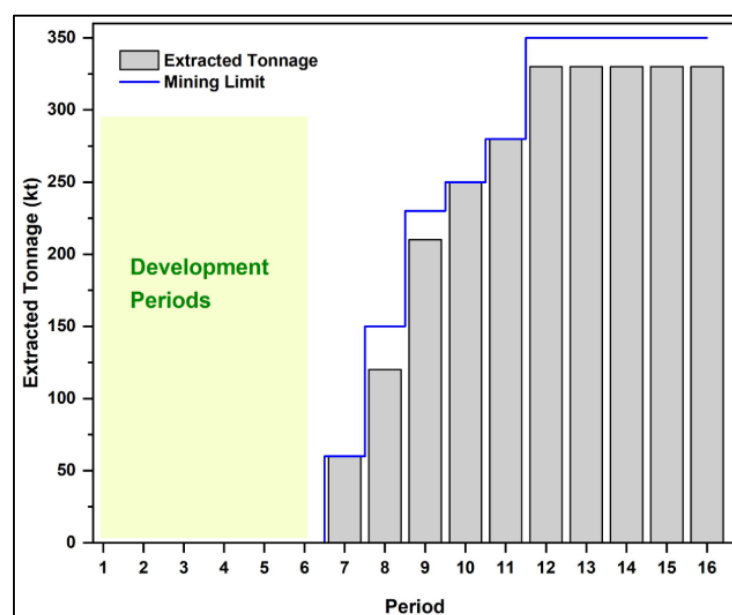


Figure 2-4: Example of a medium-long-term production plan [52]

2.3.3. Quantifying LOM production plans of mines nearing closure

Quantifying the production plan involves determining the number and locations of planned active levels and workplaces over the LOM. This also includes quantifying the planned LOM production of the operation. This information is used to determine the extent of downscaling at the operation. Resources are allocated based on the equipment required to reach the production target outlined in the production plan.

The workplaces are separated into two broad categories, namely stoping and development. These distinctions are used to determine the zero-waste baselines. The zero-waste energy baseline determines the minimum energy required for a system without waste; this will be expanded on in Section 2.4. Although these production plans are not strictly adhered to due to the dynamic nature of mining, they provide a reasonable indication of the required resource allocation. These workplaces serve distinct functions in underground mining operations. Stopping areas form the primary means of production and consist of a larger crew with more equipment while development areas are used to develop operational expansions and supporting infrastructure. This includes developing new stoping areas, ventilation holing, and ore passes. The development crews are generally smaller and require less equipment [53].

The production plans used for this study are obtained from the planning department. These plans outline the workplace location, blasting area, face advance, rock density, and planning month. This information is necessary for determining the planned tonnes, number of active workplaces, and drilled holes required within the planning horizon. These values form the basis for developing the zero-waste and scaled baselines presented in Table 2-3. A detailed example of a typical production plan can be found in Appendix A.

Table 2-3: LOM production data requirements for evaluating baselines for energy-intensive systems

Baseline	System	Time horizon	Requirements
Zero-waste baseline	Compressed air, water reticulation	Daily, monthly	- Planned blasting area. - Quantity of planned workplaces. - Location of planned workplaces.
Scaled baseline	All	Monthly	Planned production.

Evaluating LOMP for zero-waste baseline

The values obtained from the production plan are used to calculate the primary inputs for the zero-waste baselines. This information is used to estimate the number of holes that need to be drilled to complete a productive shift. It is also used to quantify the demand of fixed consumers. The planned monthly face area, $A_{monthly}$, is first calculated as the cumulative sum of the planned face areas, A_i , as presented in Equation 8. This is done separately for both stoping and development.

$$A_{monthly} = \sum_{i=1}^n A_i \quad \text{Equation 8}$$

$A_{monthly}$ = Total planned monthly face area [m²/month]

n = Number of panels [-]

A_i = Face area per panel per month [m²]

The monthly face area is divided by the number of planned production days to determine the average daily face area, A_{daily} , as presented in Equation 9. This calculation is simplified by assuming the planned face area is distributed equally between planned production days, D_{prod} . The number of production days differs between operations as well as months due to public holidays and planned shutdowns [54]. A high-level production schedule is typically drafted at the beginning of the year.

$$A_{daily} = \frac{A_{monthly}}{D_{prod}} \quad \text{Equation 9}$$

A_{daily} = Planned daily blasting area [m²/day]

$A_{monthly}$ = Total planned monthly blasting area [m²/month]

D_{prod} = Number of production days in a month [days]

The number of required daily blasting holes, $H_{blasting}$, is calculated by multiplying the daily face area, A_{daily} , with the blasting hole density, $h_{blasting}$, as presented in Equation 10.

$$H_{blasting} = A_{daily} \cdot h_{blasting} \quad \text{Equation 10}$$

H_{daily} = Planned daily blasting holes [-]

A_{daily} = Planned daily blasting area [m²]

$H_{blasting}$ = Blasting holes density [holes/m²]

The number of active daily panels, P_{daily} , is calculated by dividing the daily face area by the average panel size, A_p , as presented in Equation 11. The typical stoping panel in a deep-level South African gold mine ranges between 25 m and 30 m in length and between 1 m and 2 m in height. This is predicated on the geology of the ore body being mined [55]. The dimensions of the development panels depend on the type of development being done as well as the geology of the location.

$$P_{daily} = \frac{A_{daily}}{A_p} \quad \text{Equation 11}$$

P_{daily} = Number of planned daily panels [-]

A_{daily} = Planned daily blasting area [m²]

A_p = Average daily blasting area of panel [m²]

The number of support holes, $H_{support}$ is calculated as the product of the planned daily panels, panel face length, and hole density required for adequate support, as presented in Equation 12. The roof support holes are typically spaced every two meters over the length of the face.

$$H_{support} = P_{daily} \cdot F_l \cdot h_{support} \quad \text{Equation 12}$$

$H_{support}$ = Number of planned support holes [-]

P_{daily} = Number of planned daily panels [-]

F_l = Average face length [m]

$h_{support}$ = Support hole density [holes/m]

The number of required blasting and support holes calculated using the methods in this section are used to develop the compressed air and water reticulation zero-waste baselines presented in Section 2.4.

Evaluating LOMP for scaled baselines

This study uses tonnes produced as the only scaling factor when developing the scaled baseline [47], [56]. The scaled baseline is used to forecast the LOM energy demand of a system with no planned energy management initiatives. Further information on the development of the scaled baseline is outlined in Section 2.6.1. This section outlines the method used to obtain the planned production in tonnes from the LOM production plan. Most plans provide the planned production in square meters (m²) from which the planned tonnes can be inferred [42]. The planned monthly tonnes, $T_{monthly}$, are calculated as a product of the total planned monthly face area, the average monthly face advance, and the ore density, as shown in Equation 13.

$$T_{monthly} = A_{monthly} \cdot F_a \cdot \rho \quad \text{Equation 13}$$

$T_{monthly}$ = Planned monthly production [t]

$A_{monthly}$ = Total planned monthly face area [m²]

F_a = Average monthly face advance [m]

ρ = Ore density [t/m³]

2.4. Step 2: Developing a zero-waste baseline for mines nearing closure

As the mine is planned out over the various time horizons, it is important to consider the services required to supply the changing operation [57]. The first iteration of the mining plan focuses on high-level requirements such as development meters and production tonnes. Plans for further infrastructure development are built upon the initial plan. These include but are not limited to the compressed air and water reticulation infrastructure. Any required alterations are incorporated into the LOMP [44].

The zero-waste baseline method aims to determine the minimal resources required to supply the changing demand as the mine nears closure. The flow and subsequent energy consumption profiles are based on multiple factors, including the number of workplaces, the number of levels, the number of holes drilled, the equipment specifications, and the daily production cycle. The zero-waste baseline method is compared to historic daily and monthly consumption to evaluate the potential resource waste and subsequent energy savings that can be achieved if viable initiatives are implemented [35], [46].

This section will focus on developing a generic method adapted from *van der Merwe et al.* to determine zero-waste resource and energy baselines for compressed air and water reticulation systems on mines nearing closure, as presented in Figure 2-5 [46]. Section 2.4.1. outlines the KPIs for each system. Section 2.4.2. presents the theoretical resource demand for compressed air and water reticulation systems based on equipment specifications. Section 2.4.3 presents a generic simulation method used to evaluate the resource and energy demand of the system. Section 2.4.4 presents a methodology used to develop a resource zero-waste baseline. Section 2.4.5 presents the methodology used to evaluate the energy zero-waste baseline.

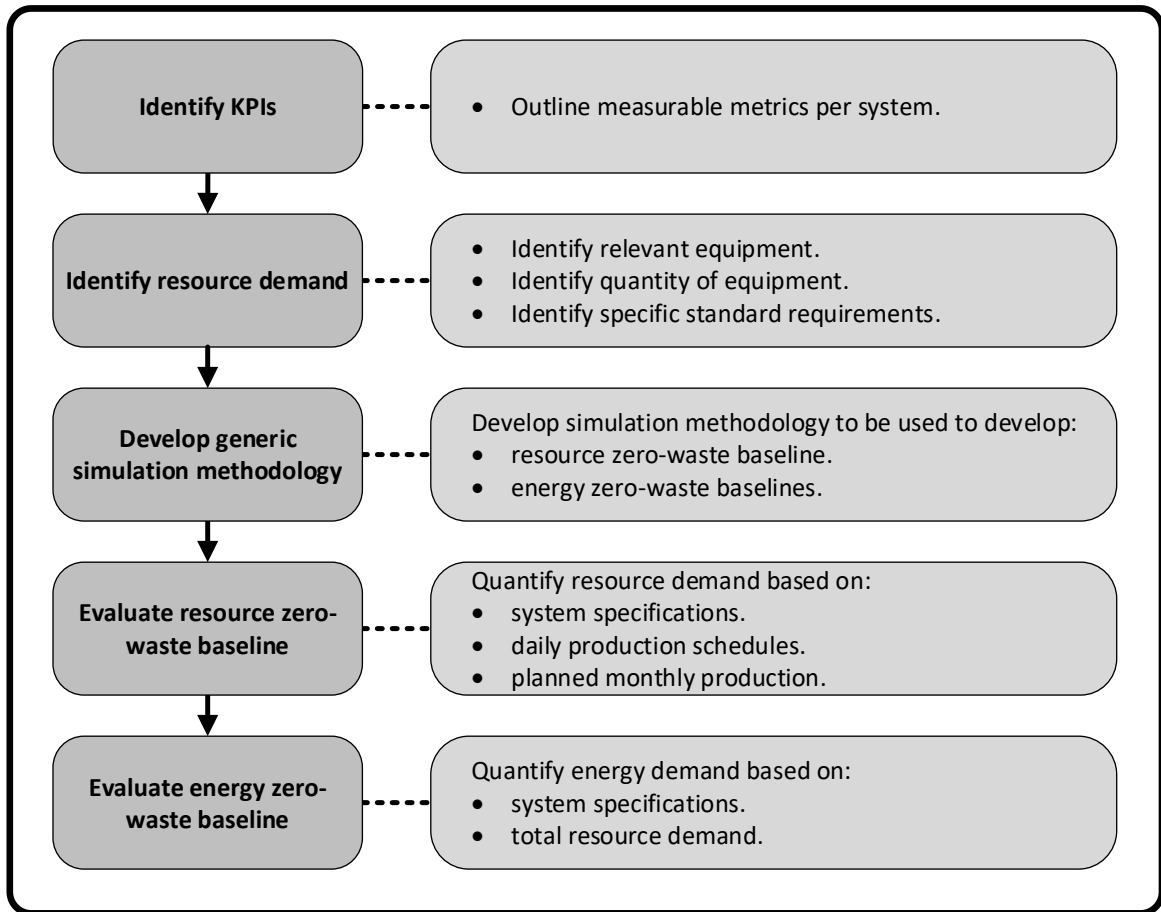


Figure 2-5: Developing a zero-waste energy baseline for a mine nearing closure [46]

2.4.1. Identifying key performance indicators

The flow and pressure are used as primary indicators to evaluate the resource requirements of each system [58]. These metrics were selected as KPIs since they are directly impacted by a planned decrease in production. These metrics are measured by either permanently installed instrumentation or mobile instrumentation in the case of unavailable infrastructure. The power and energy are measured across the systems to evaluate the savings potential of reducing demand as the mine downscales operations. The power and energy of the systems are measured using permanently installed power meters on the respective systems. Each machine in the system is typically individually metered.

Data from permanently installed instrumentation is generally stored on a historian and can be retrieved and analysed. Data obtained from mobile instrumentation can be retrieved and stored locally. Table 2-4 outlines the KPIs measured per system as well as the primary means of measurement.

Table 2-4: KPIs considered for evaluation

System	Component	Metric	Means of measurement
Compressed air	Compressors	Power	Power meters are installed on the electrical feeders of each compressor.
		Energy	
	Compressed air network	Mass/ Volumetric flow	Flow meters installed at strategic locations along the compressed air reticulation line.
		Pressure	Pressure transmitters installed at strategic locations along the compressed air line.
Water reticulation	Dewatering system	Power	Power meters are installed on the pumping electrical feeder.
		Energy	
		Dam level	Level sensors are installed at dewatering dams.
		Volumetric flow	Magnetic flow meters are installed on the dewatering line.
	Chilled water system	Power	Power meters are installed on the pumping electrical feeder.
		Energy	
		Volumetric flow	Magnetic flow meters are installed on the service water line and at the refrigeration plant.
		Temperature	Temperature sensors are installed on the evaporator inlet and outlet of the refrigeration plants.
		Dam level	Level sensors are installed on the chilled water dams.

2.4.2. Identifying resource demand

This section outlines the specifications for compressed air and water-consuming equipment used to quantify the demand. The resource demand for a zero-waste baseline is guided by the production plan and the equipment used in the case of compressed air and water reticulation. A summary of the metrics and requirements per system is presented in Table 2-5. The specifications for the resource consumers are obtained from the OEM as well as previous studies. A breakdown of the demand considerations for each system is presented below.

Table 2-5: Factors affecting resource demand [24], [59]

System	Metrics	Factors
Compressed air system	• Volumetric flow/ mass flow • Pressure	• Quantity and types of equipment used underground. • Production requirements.
Water reticulation system	• Volumetric flow	

Compressed air system

The underground compressed air demand is directly related to production, as all the significant compressed air consumers form a key part of the ore extraction and transportation process [60]. Pneumatic drills are used for drilling (blasting holes and support), bazookas are used for cleaning fine ore out of workplaces, and loading boxes and loaders are used for offloading ore from the workplaces to locomotives. Compressed air is also supplied to refuge bays to ensure a safe location during an emergency [25]. These compressed air consumers are categorised into constant consumers and variable consumers.

The variable consumers are dependent on production whilst the constant consumers have a constant demand regardless of production output. Since leaks are not considered when developing a zero-waste baseline, the only constant consumers are the refuge bays; all other consumers depend on the production plan [46]. Therefore, the compressed air baseline will fluctuate over daily and monthly evaluation periods. The daily baseline will vary based on the daily operating schedule and the monthly baseline will vary based on the planned monthly production. The consumer specifications and quantity considerations are presented in Table 2-6 below.

Table 2-6: Compressed air consumer specifications [23], [25], [61]

Consumer	Flow requirement [Nm³/s]	Pressure requirement [kPa]	Quantity considerations
Pneumatic rock drills	0.093	400 - 600	• Number of holes drilled. • Number of workplaces. • Operating schedule.
Loading box	0.026	450	• Number of workplaces • Operating schedule.
Bazooka	0.472	400 - 500	• Number of workplaces. • Operating schedule.
Refuge bay	0.046	200 – 300	• Underground audit.
Mechanical loaders	0.619	400 - 500	• Number of workplaces. • Operating schedule.

Water reticulation system

Rock drills and bazookas are primary water consumers used at the development and stoping faces underground. Cooling cars and BACs are also key water consumers. The rock drill and bazooka water consumption vary based on the daily operating schedule of the mine, while cooling cars and BAC water demand remain constant throughout the day to regulate underground temperatures [16]. The constant demand from leaks is not considered when developing the zero-waste baseline. The consumer specifications and operating considerations are presented in Table 2-7.

Table 2-7: Service water consumer demand [16]

Consumer	Flow Requirement [l/s]	Quantity considerations
Pneumatic drills	0.2	• Number of holes drilled. • Number of workplaces. • Operating schedule.
Bazooka	5.5	• Number of workplaces. • Operating schedule.
Cooling car	4.0	• Number of cooling cars.

2.4.3. Developing a generic simulation methodology to evaluate zero-waste baselines

A generic simulation methodology is used to determine the resource and subsequent energy zero-waste baseline for both the compressed air and water reticulation systems. This methodology is used to develop a dynamic simulation in 30-minute intervals over a period of 24 hours. This requires knowledge of the system layout and component specifications as well as measured data of the KPIs which will be used to calibrate the simulation. An overview of the methodology is presented in Figure 2-6 with a detailed explanation of each step below. A simplified simulation method developed by *P. Maré et al.* was adapted to develop a generic simulation method to evaluate the resource and energy zero-waste baselines on mines nearing closure [23].

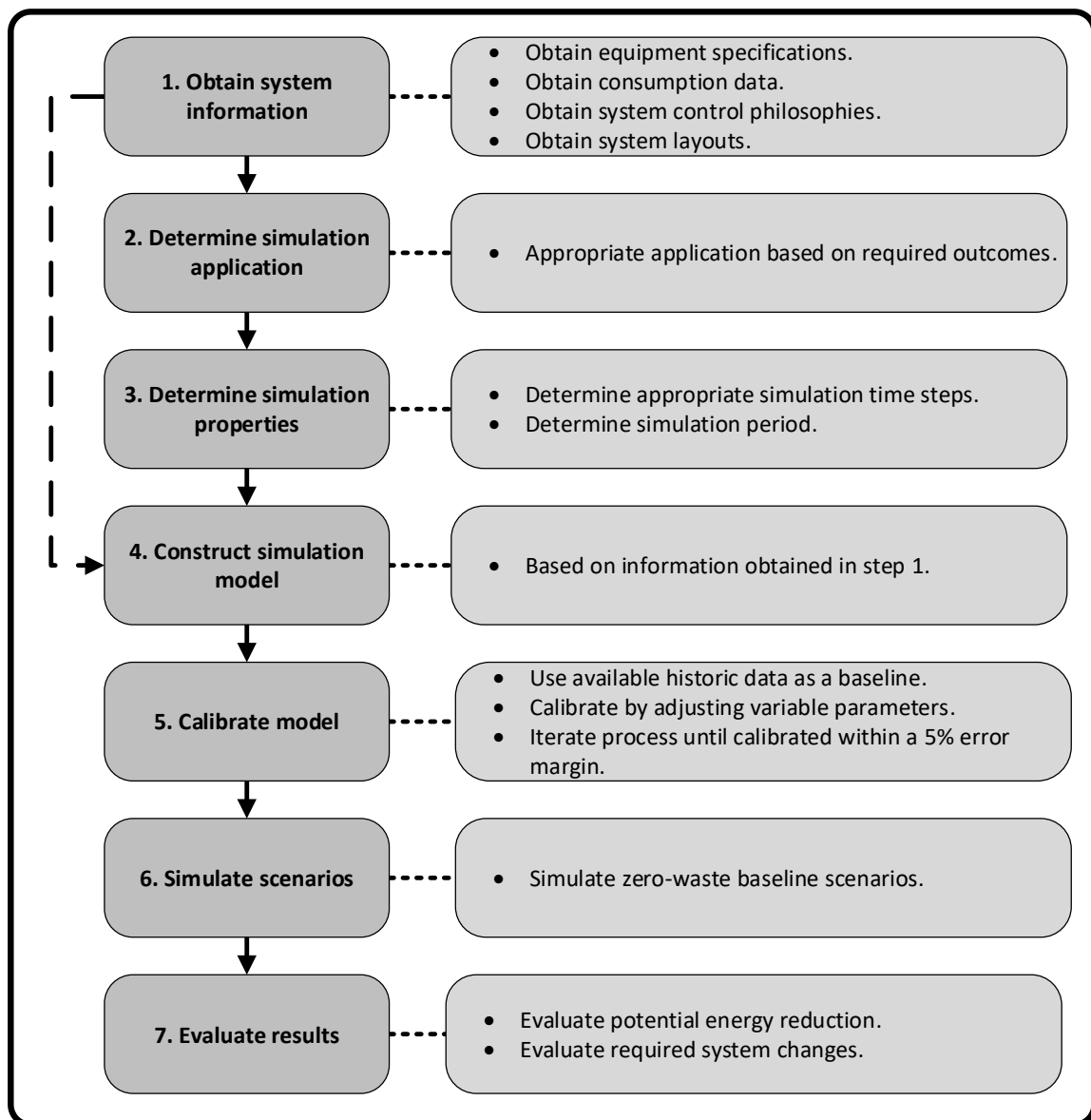


Figure 2-6: Simplified simulation method [23]

The simplified simulation method is segmented into the following steps. Step 1 of the method involves collecting all relevant information on the system, including systems specifications, available system demand data, current system control philosophies, and system layouts. The system layouts can be obtained from mine personnel; alternatively, a system audit needs to be conducted for further detail. The component specifications can be obtained from relevant mine personnel or the original equipment manufacturer (OEM). Step 2 involves identifying a viable simulation package for the specified application. Step 3 involves setting simulation time parameters, which include simulation timesteps and the simulating period. Step 4 involves constructing the system model and inputting the specifications obtained in Step 1.

Step 5 involves calibrating the model to historic baseline specifications. The model needs to be calibrated within a 5% error margin of the selected baselines. This is an iterative process and requires adjusting parameters on the model until the calibration requirements are met. Step 6 involves simulating the required scenarios of developing resource and energy zero-waste baselines. Step 7 involves evaluating the final simulated outcome against the measured energy and resource baselines and quantifying the wastage. Detailed requirements for developing simulations for the compressed air and water reticulation systems will be explained below.

2.4.4. Evaluating resource zero-waste baseline

This section presents the process for determining the zero-waste resource baselines for both the compressed air and water reticulation systems using a simulation-based model. The resource demands presented in Section 2.4.2 along with the production metrics evaluated from the production plan in Section 2.3.3 are used to develop the resource zero-waste baselines. The daily production schedule presented in Section 2.3.2. is used to develop the baseline profile. The simulation steps outlined in Section 2.4.3 are used to develop the resource zero-waste baseline. The following steps provide further details on the specifications used to create this model.

Step 1: Obtain system information

The following infrastructure specifications are required to develop a resource zero-waste simulation model. An underground layout is required to develop the piping layout as close to the actual system as possible and locate key underground locations. This can be obtained from the survey department. Relevant pipe sizes and valve locations are required as well, both of which can be obtained from a system audit. The equipment specifications and running schedules are also required to build a viable demand model. The equations used to determine the demands for the compressed air system and water reticulation system are presented below.

Compressed air system

The rock drill compressed air demand is calculated using Equation 14 [16]. This equation determines the total minimum compressed air flow demand, $F_{drilling}$, from the rock drills during the drilling shift. The primary factors that drive the compressed air demand are the drill specifications used and the number of holes drilled during the drilling shift. The second part of the equation is used to normalise the flow demand based on the ratio between the actual production output and the planned production output.

$$F_{drilling} = \left(\frac{F_d N_a H_a}{60 P_d t} + \frac{F_d N_r H_r}{60 P_d t} + \frac{F_d N_s H_s}{60 P_d t} \right) \cdot \left(\frac{O}{W L A \rho} \right) \quad \text{Equation 14}$$

$F_{drilling}$ = Total drilling flow rate [Nm ³ /s]	P_d = Drill penetration rate [m/min]
F_d = Specified drill flow rate [Nm ³ /s]	t = Shift time [hours]
N_a = Number of advance holes [-]	W = Panel width [m]
N_r = Number of roof holes [-]	L = Panel length [m]
N_s = Number of side holes [-]	A = Advance per blast [m]
H_a = Advance hole length [m]	ρ = Rock density [tonnes/m ³]
H_r = Roof tendon hole length [m]	O = Actual/ planned production [tonnes]
H_s = Side tendon hole length [m]	

The loading, cleaning, and refuge bay flow demand equation determines the minimum theoretical demand of the pneumatic equipment [16]. The primary pneumatic equipment used for cleaning and loading include bazookas, loading boxes, and mechanical loaders. Bazookas are used during the cleaning shift. Loading boxes and mechanical loaders are used during the drilling and cleaning shift. Refuge bays have constant demand throughout the day. This equipment is characterised by a constant flow over its operating period. The flow, $F_{r,b,l,m}$, calculation of each equipment is presented in Equation 15. It is a product of the equipment specification, the amount of equipment in operation, and the operating time. The second part of the equation is used to normalise the flow demand based on the ratio between the actual production output and the planned production output.

$$F_{r,b,l,m} = N \cdot (F_e) \cdot \left(\frac{T}{t}\right) \cdot \left(\frac{O}{WLA\rho}\right) \quad \text{Equation 15}$$

F_r = Refuge bay flow rate [Nm ³ /s]	t = Shift time [hours]
F_b = Bazooka flow rate [Nm ³ /s]	W = Panel width [m]
F_l = Loading box flow rate [Nm ³ /s]	L = Panel length [m]
F_m = Mechanical loader flow rate [Nm ³ /s]	A = Advance per blast [m]
N = Number of equipment in operation [-]	ρ = Rock density [tonnes/m ³]
F_e = Rated flow rate of equipment [Nm ³ /s]	O = Actual production [tonnes]
T = Time of equipment usage [hours]	

The compressed air flow demands are summed according to the equipment utilised during each shift of the daily schedule, as presented in Table 2-8.

Table 2-8: Daily production compressed air consumption schedule and demand

Day	Shift	Consumers	Flow demand
Production day	Shift change	• Refuge bays	F_r
	Drilling	• Rock drills • Loading boxes • Refuge bays	$F_{drilling} + F_l + F_r$
	Blasting	• Refuge bays	F_r
	Cleaning	• Bazookas • Loading boxes • Mechanical loader • Refuge bays	$F_b + F_l + F_m + F_r$
Non-production day	No shift	• Refuge bays	F_r

Water reticulation system

The daily service water demand follows the daily mining schedule similar to the compressed air demand. The schedule is typically divided into the drilling shift, blasting shift, cleaning shift, and shift changeover. Each shift has a different demand based on its respective consumers. The water consumption differs based on the equipment used during each shift. The drilling shift and cleaning shift are the primary consumers of water. Rock drills are the primary consumers of water during the drilling shift and bazookas are the primary consumers during the cleaning shift. Cooling cars constantly consume water throughout the production day. Equation 14 is used to determine the drilling water demand. Equation 15 is used to determine the bazooka and cooling car demand. The water flow demands are summed according to the equipment utilised during each shift of the daily production schedule, as presented in

Table 2-9.

Table 2-9: Daily production water consumption schedule and demand.

Day	Shift	Consumers	Flow demand
Production day	Shift change	• Cooling cars	F_c
	Drilling	• Rock drills • Cooling cars	$F_{drilling} + F_c$
	Blasting	• Cooling cars	F_r
	Cleaning	• Bazookas • Cooling cars	$F_b + F_c$
Non-production day	No shift	• Cooling cars	F_c

Step 2: Determine simulation application

A hydrodynamic simulation software package is required to effectively simulate the impact of flow and pressure demands on the system.

Step 3: Determine simulation properties

The resource zero-waste baseline model is simulated over the course of a 24-hour period with 30-minute time steps.

Step 4: Construct simulation model

The underground compressed air or water reticulation layout is constructed using relevant components outlined in Step 1 based on the underground layouts.

Step 5: Calibrate model

The model is calibrated using data from a day with known measured data according to the flow and pressure KPIs presented in Section 2.4.1. The compressed air reticulation model is calibrated to the surface air mass flow and pressure demand. The water reticulation model is calibrated to the surface volumetric flow demand. Equipment parameters in the models are adjusted until the model is calibrated within 5% of the measured KPI values over a 24-hour period.

Step 6: Simulate scenarios

Once the model is calibrated, the zero-waste baseline scenarios are simulated. The only variables that change when the zero-waste baseline is simulated are the demands on the levels and crosscuts, since these demands are based on the change in production over the periods being evaluated. The

average monthly production day and non-production day scenarios are simulated over a range of months with a planned decrease in production.

Step 7: Evaluate results

The results from the simulations include the surface flow and pressure for the compressed air model and the surface flow for the water reticulation model and are used for two key purposes: first, to quantify wastages on crosscuts or levels, and second, to use as inputs for the energy zero-waste baseline model. The results from the zero-waste baseline scenarios per crosscut or level are evaluated against the actual measurements before the waste reduction initiatives are implemented. This provides an indication of the locations with the highest wastage which need to be prioritised when conducting audits [16]. The total flow and pressure values evaluated from the model are used as inputs into the energy zero-waste baseline model outlined in Section 2.4.5.

2.4.5. Evaluating energy zero-waste baseline

The energy baseline is determined via a simplified simulation model based on the zero-waste resource baseline. A simulation model is used because it provides a dynamic response to demand conditions. In the case of determining the energy demand of compressors, the model accounts for the change in setpoint pressure, guide vane position, and blow-off valves. In the case of water reticulation, the model accounts for the dewatering pump and fridge plant schedule as well as dam limits.

Two scenarios are developed for the short-term zero-waste baseline which assists in developing the long-term baseline, namely a production day baseline and a non-production day baseline. The following section outlines the considerations and calculations used to determine the resource baselines of the various systems.

Step 1: Obtain system information

The system layout, pipe sizes, and valve configurations are specified according to the requirements outlined in Section 2.4.4. Machine specifications are also required to develop an accurate model. This includes specifications for the compressors, refrigeration plants, or pumps, depending on the system being simulated. The required specifications can be obtained from the machine's performance curve, which should be available from the OEM. When relevant documentation is not available, historic data can be used to model a performance curve, with adjustments being made during the model calibration process.

Step 2: Determine simulation application

A hydrodynamic simulation software package is required to effectively simulate the impact of flow and pressure demands on the system as well as determine the machine power consumption.

Step 3: Determine simulation properties

The energy zero-waste baseline model is simulated over the course of a 24-hour period with 30-minute time steps.

Step 4: Construct simulation model

The surface or underground model of the energy-consuming machines and adjacent infrastructure is constructed using relevant components outlined in Step 1 based on the surface and underground layouts.

Step 5: Calibrate model

The model is calibrated using data from a day with known measured data according to the KPIs presented in Section 2.4.1. The compressed air model is calibrated to the surface mass flow as well as pressure and compressor power demand. The water reticulation model is calibrated to the surface volumetric flow, chilled dam level, and machine power demand. Equipment parameters in the models are adjusted until the model is calibrated within 5% of the measured KPI values over a 24-hour period.

Step 6: Simulate scenarios

Once the model is calibrated, the zero-waste baseline scenarios are simulated. The pressure setpoints and running statuses are adjusted to simulate energy management initiatives from the compressed air system, and the running schedule is adjusted to simulate the energy management initiatives implemented on refrigeration plants and pumps. The average monthly production day and non-production day scenarios are simulated over a range of months with planned decreases in production.

Step 7: Evaluate results

The results from the energy zero-waste baseline are the power demand of compressors, fridge plants, or pumps. The results obtained from this model are used for two purposes. First, to evaluate

the progressive impact of waste reduction and energy management strategies, and second, to evaluate the LOM impact of implementing the energy management initiative.

The results from the model are progressively evaluated against measured power demand before the energy management initiatives are implemented and during the implementation of the waste reduction strategies outlined in Section 2.5.4.

These results are also used to estimate a long-term baseline to determine the potential LOM energy and cost savings of implementing a waste reduction and energy management initiative on a mine nearing closure. The method used to determine the long-term energy impact is presented in Equation 16. This equation uses the results from both production and non-production day zero-waste energy demands.

$$E_M = (D_{prod} \cdot \sum_{i=1}^n P_{prod} \cdot t + D_{non-prod} \cdot \sum_{i=1}^n P_{non-prod} \cdot t) \quad \text{Equation 16}$$

E_M = Total monthly energy consumption [MWh]

t = Measurement time interval [s]

D_{prod} = Number of production days in month [days]

$D_{non-prod}$ = Number of non-production days in month [days]

P_{prod} = Production day power [MW]

$P_{non-prod}$ = Non-production day power [MW]

n = Number of time intervals in a day [-]

2.5. Step 3: Implementing energy management initiatives on mines nearing closure

Viable energy management projects need to be identified and implemented to achieve the required reductions determined by the zero-waste baselines outlined in Section 2.4. The implementation primarily relies on reducing the resource demand based on the planned reduction in production. The project implementation method is adapted from the “Do” step outlined by *Bredenkamp* [13], with changes made to fit the scope of this study, namely mines nearing closure. This methodology aims to be generic enough to be implemented on compressed air and water reticulation systems and is presented in Figure 2-7. The implementation is planned based on the results of evaluating the production plan and the zero-waste baselines presented in Sections 2.3 and 2.4 respectively.

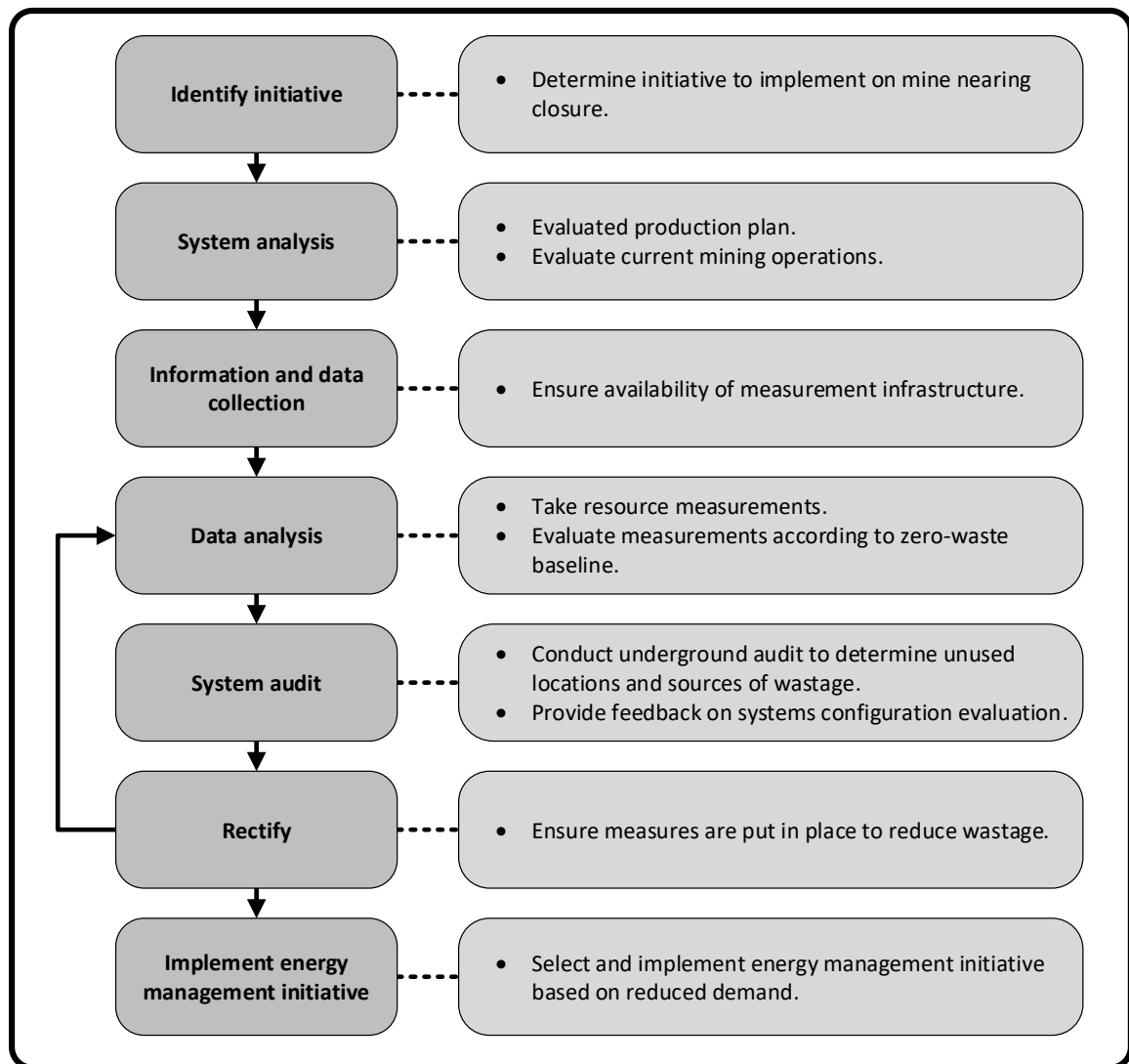


Figure 2-7: Outline of implementation plan [13]

2.5.1. Determine energy management initiative

Numerous energy management initiatives can be implemented at deep-level mining operations. Due to the constraints experienced by mines nearing closure, these need to be narrowed to be feasibly implemented [62]. The constraints are outlined in Table 2-10 based on the characteristics outlined in Section 2.3.1. The selected initiatives need to have low implementation costs, short implementation times, and a high energy impact. Initiatives of this nature tend to focus on improving existing infrastructure with little to no capital or operational expenditure. The focus typically lies on reducing wastage and improving the operating philosophy of the identified system [63]. The energy impact of these initiatives is limited by available funds and appetite to improve the existing infrastructure or install new infrastructure. However, a high energy and cost impact can be achieved if the overall resource demand is sufficiently reduced [64].

Table 2-10: Energy management project selection criteria

Criteria	Reason
Low implementation cost	• Since the operation is nearing closure, there is limited appetite to invest capital into the operation [65]. • In these situations, low-cost and no-cost projects tend to get approved faster.
Short implementation time	• Given the short and uncertain LOM, projects should be identified and implemented relatively quickly [66].
High energy impact	• Given the planned reduction in production, there is scope to reduce energy consumption [60]. • Projects with higher impact tend to have shorter payback periods. This is important given the short/uncertain nature of the LOM [67].

The potential initiatives that can be implemented on compressed air systems focus on updating guide vane control or switching off machines entirely when multiple machines are running [68]. On water reticulation systems, the pumps and fridge plants should see a decrease in running time and hence energy demand as soon as the demand decreases. Additionally, load-shifting initiatives can be implemented on the pumps and fridge plants to reduce the energy costs of pumping and cooling water; however, this is dependent on the underground and surface dam capacities of the operation [69].

The quantitative impact of implementing energy management initiatives differs across operations, hence a qualitative impact has been presented per initiative. Initiatives that are low-cost and relatively fast to implement based on an evaluation done by *J. Bredenkamp* are presented with a relative energy and cost impact in Table 2-11 [13]. These energy management initiatives are predicated on a compressed air and water demand reduction.

Table 2-11: Energy management initiatives [13]

System	Initiative	Description	Impact
Compressed air	Switch a compressor off permanently and use it as a backup.	In the case of multiple compressors running, selected compressors can be switched off due to a demand reduction.	High
	Update pressure setpoint.	A dynamic pressure setpoint can be implemented to reduce supply pressure during low-demand periods.	Low
	Implement a compressor control philosophy.	Switch selected compressors on and off during high-demand periods.	High
Water reticulation	Reduction in machine running time.	As the flow demand decreases, a decrease in the pump and fridge plant running time should be observed.	Low
	Implement a load shift.	A decrease in flow demand opens the opportunity to implement load shifts on the pumps and fridge plants. This will not reduce the system's energy demand. However, it allows loads to be shifted outside the Eskom peak demand periods, resulting in cost savings.	High

2.5.2. System analysis

The system needs to be analysed to determine potential sources of wastage. In this study, the production plan is evaluated as outlined in Section 2.3 and compared to the latest production schedule. This will provide the latest information on the current active and inactive workplaces. The results from the resource zero-waste baseline outlined in Section 2.4.4 are also used to identify

locations with high wastage, assisting with streamlining the auditing process. The latest iterations of the production plans can typically be obtained from the planning department.

2.5.3. Information and data collection

The availability of system measurement and data logging infrastructure is integral to quantifying the wastage and evaluating the results of initiative implementation. Instrumentation is required to continuously measure the system's key metrics. The data should be logged in at least 30-minute or one-hour intervals for the daily resource and energy demand to be accurately evaluated against the daily baselines.

Ideally, the instrumentation is permanently installed on all key measuring points. The installed instrumentation should be connected to a Supervisory Control and Data Acquisition (SCADA) system from which the data can be logged in a historian and used for analysis. However, in some cases, due to infrastructure and financial constraints, all systems do not have the relevant instrumentation installed and mobile instrumentation is required to measure the key metrics.

Typically, the compressed air and water reticulation systems are well-instrumented. The power consumption of the large machines being measured is metered since they are used to verify the monthly energy bill. It is important for the data obtained to be as accurate as possible, hence the installed instrumentation is to be verified using mobile instrumentation where required.

2.5.4. Analyse

Once the instrumentation and data infrastructure have been verified, the data is pulled and analysed. The analysis step takes place iteratively over the implementation process. The first analysis is conducted as a baseline before the initial audit. Production day and non-production day baselines are evaluated separately, as the demand differs significantly between the two days. The baselines are used to evaluate the savings realised from implementing downscaling, wastage reduction, and implementing energy management initiatives.

The zero-waste baseline developed in Section 2.4. is used as the target reduction. The difference between the baseline and zero-waste baseline determines the potential system wastage. This wastage is quantified to determine the impact of the planned energy management initiative. Further measurement and analysis are conducted after each audit and rectification to determine the changes in the key metrics.

2.5.5. System audit

After the initial flow and power baseline have been analysed, an underground audit is undertaken. The underground audit is integral to identifying the system conditions underground [70]. Initial preparations for the audit require understanding the layout of the underground infrastructure and the locations of inactive areas. The two key outcomes of the audit are identifying resources being supplied to inactive areas and resource wastage due to leaks, as they are the key challenges faced by mature deep-level mines nearing closure [27]. Due to the potentially dangerous nature of the locations, it is best to conduct the audits with a person familiar with the underground conditions. The key audit requirements are outlined in Table 2-12. The audit findings must be documented and reported to allocate time and resources to rectify the identified system inefficiencies. An example of an audit tracking sheet can be found in Appendix C.

Table 2-12: Underground audit requirements [13]

System	Requirements	Identifying inefficiencies
Compressed air	Identify leaks in piping.	- Compressed air leaks are identified by sound. The louder the sound, the larger the leak. - Fixing larger leaks are to be prioritised over smaller leaks.
	Identify charged lines going to unused working areas.	- Pipelines going to inactive workplaces should be followed to determine if they are still charged, as leaks and valves are typically only present at the end of the crosscut. - These pipelines are identified by open valves and leaks from open ends at the end of the line.
Water reticulation	Identify leaks in piping.	Water leaks in the haulages and crosscuts can be visually identified by the quantity of water leaking from the pipe.
	Identify charged lines going to unused working areas.	- Pipelines going to inactive workplaces should be followed to determine if they are still charged, as leaks and valves are typically only present at the end of the crosscut. - These pipelines are identified by open valves and leaks from open ends at the end of the line.

2.5.6. Rectify

Once the audits have been completed, a rectification plan is developed with the relevant mining personnel. The plan needs to outline the priorities, number of resources, cost of resources, and schedule of implementation. The leaks are prioritised based on their relative size to ensure the largest impact over the shortest period. Compressed air and water pipes leading to the unused workplaces should be blanked off. This requires pipe blank pieces, typically readily available, as they are standard components. However, blank pieces for larger pipe sections may require additional time to purchase or fabricate. Compressed air and water leaks typically require gasket or clamp replacements, these are standard parts that are readily available at the workshop. The biggest challenge in implementing compressed air and water rectifications is prioritising and scheduling the work to be completed, hence findings need to be communicated as soon as possible to allow for an adequate implementation lead time [71].

Given the extended time required to implement these rectification measures, they are implemented in stages. Locations with the largest inefficiencies are prioritised. After each stage is completed with verification from the responsible person, the key metrics are measured again. This process is continued until the desired reduction is achieved relative to the resource zero-waste baseline.

2.5.7. Implement energy management initiative

The energy management initiative can be implemented once a sufficient reduction in resource demand has been achieved. The demand reduction guides the extent of the initiatives implemented on the system. A control plan needs to be drafted and presented to the shaft engineer. Once the control plan has been approved, the initiative can be implemented. The initiatives need to be implemented with assistance from qualified mine personnel. The projects are implemented over a trial period and monitored to ensure no negative impact on underground safety and production. This includes monitoring the key metrics and evaluating feedback from mining personnel [13]. Once the project has been implemented, it needs to be continuously monitored to mitigate any deviations and realise continuous savings. This requires daily evaluation and reporting. The initiative and implementation requirements are presented in Table 2-13.

Table 2-13: Implementing energy management initiatives [13]

System	Initiative	Implementation
Compressed air	Permanently switch off a compressor and use it as a backup.	- The compressor is to be switched off on an agreed date. - The pressure and flow should be monitored over a trial period of at least one full production shift to ensure production and safety are unaffected.
	Update pressure setpoint.	A setpoint philosophy to be implemented according to an agreed plan.
	Implement a compressor control philosophy	In the case where compressors cannot be permanently switched off, a control schedule can be implemented to run selected compressors based on the daily mine production schedule.
Water reticulation	Reduction in pump and fridge plant running time.	As the water flow demand decreases, less water should be pumped and cooled.
	Implement pumping and refrigeration load shift.	- Evaluate the dam capacity and flow capacity of each pump station. - Once sufficient capacity has been identified, ensure the selected pumps and fridge plants are switched off according to the control plan.

2.6. Step 4: Evaluating the impact of energy management initiatives on mines nearing closure

The reduction in energy demand due to the implementation of waste reduction and energy management initiatives is evaluated to validate the methodology. The results are evaluated from the implementation of the initiative until the mine is closed. The result is measured as the actual energy demand of the selected system post-implementation. The results of implementing the energy management initiatives are evaluated against a scaled energy baseline. The methodology used to determine the scaled energy baseline is outlined in Section 2.6.1. The methodology used to determine the energy savings is outlined in section 2.6.2.

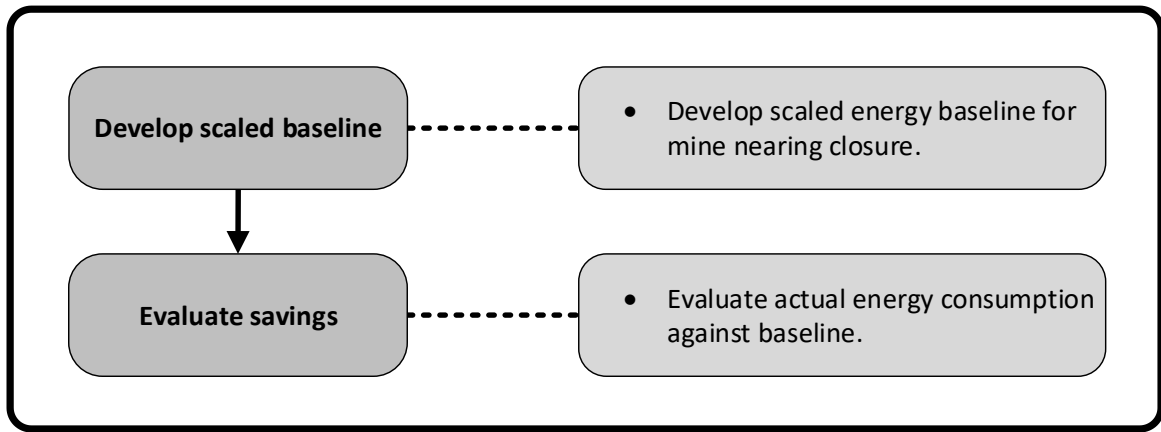


Figure 2-8: Outline of impact evaluation

2.6.1. Developing a scaled baseline

A monthly scaled baseline is developed to forecast the energy savings and validate the methodology. The scaled energy baseline represents the system energy demand if an energy management initiative is not implemented. There are multiple ways to scale an energy baseline using measurement and verification (M&V) standards. Since a reduction in production is presented as a key characteristic of a mine nearing closure in Section 2.3.1, a linear regression method is used to develop an energy baseline which scales according to the changing production [72]. The production is used as the single variable when determining the scaled baseline due to limited historic data availability. The method used in this study is outlined in the following steps [56]:

- Monthly energy and production data is compiled before implementing the energy management project.
- A linear function is determined between the production and energy consumption.
- The scaled monthly energy baseline is calculated using the linear function and production over the remaining LOM.

The linear regression model for the energy savings baseline, B_s , and the verification baseline, B_v , is presented in Equation 17. The same baseline scaling method is used to evaluate the energy savings and verify the findings. However, the production data used to develop each scaled baseline differs. The energy savings are evaluated using the planned production, P_p , data. This baseline is created before the initiative is implemented. The results are verified against the verification baseline, which is a function of the actual production data, P_a . This accounts for any actual production changes that

may have occurred over the LOM that may have an impact on the performance of the energy management initiative.

$$B_{s,v} = P_{p,a} \cdot \beta_1 + \beta_2 \quad \text{Equation 17}$$

B_s = Energy savings baseline [kWh]

B_v = Verification baseline [kWh]

P_p = Planned production [t]

P_a = Actual production [t]

β_1 = Line gradient [kWh/t]

β_2 = Constant [kWh]

2.6.2. Evaluating savings

The actual energy consumption is evaluated against the scaled baseline to determine the savings, S , from implementing the initiative [73]. The sum of the actual energy consumption measured over the remaining LOM period is subtracted from the scaled baseline to determine the overall energy savings over the LOM, as presented in Equation 18.

$$S = \sum_1^n B - \sum_1^n E \quad \text{Equation 18}$$

S = Energy savings [kWh]

B = Baseline [kWh]

E = Actual energy [kWh]

n = Number of periods [months]

2.7. Methodology verification

Table 2-14 presents the steps in the methodology where the specific study objectives presented in Section 1.6. were satisfied. This indicates all the study objectives were satisfied by the methodology.

Table 2-14: Methodology verification

Objectives	Steps satisfied in
1. Identify characteristics of mines nearing closure (literature).	Step 1
2. Quantify changes in planned LOM production trends on mines nearing closure.	Step 1
3. Identify resource and energy wastage on mines nearing closure.	Step 2
4. Implement an energy management strategy to reduce energy demand on mines nearing closure.	Step 3
5. Quantify the LOM impact of implementing an energy management strategy on mines nearing closure.	Step 4

2.8. Chapter conclusion

The methodology outlined a process to plan, baseline, implement, and evaluate energy management initiatives on compressed air and water reticulation systems on mines nearing closure. An overview of the methodology is presented in Figure 2-9. The methodology was developed based on an amalgamation of previous research conducted on implementing and evaluating energy and resource optimisation initiatives on deep-level mines.

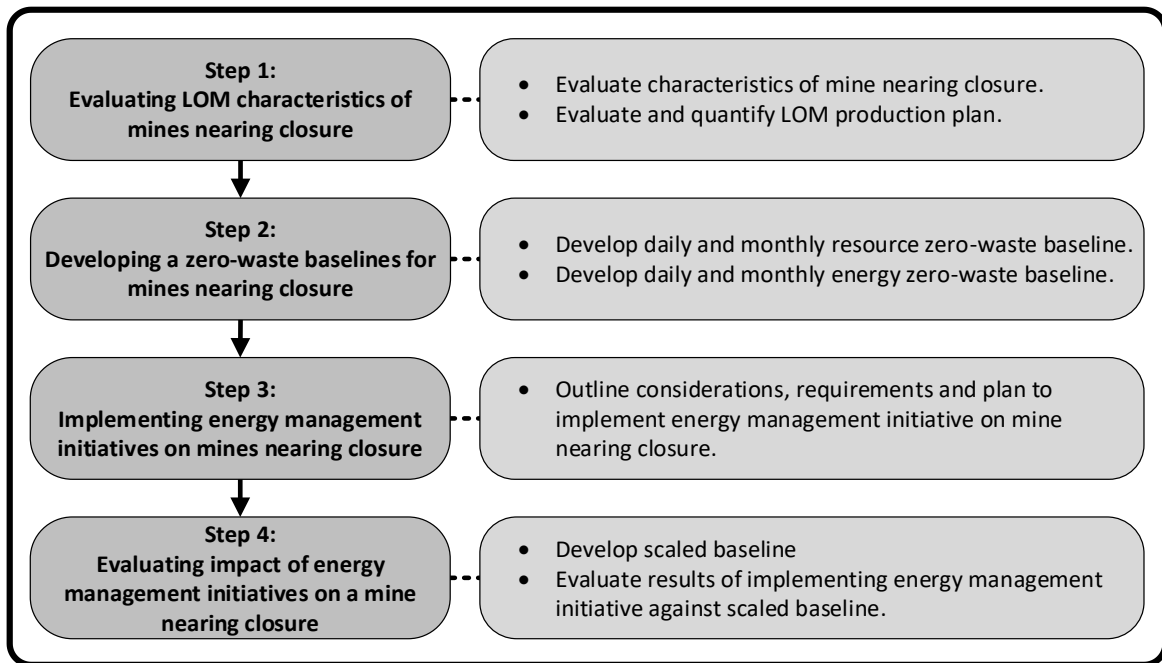


Figure 2-9: Overview of the methodology for reducing energy demand on deep-level gold mines nearing closure

Step 1 presented findings on the characteristics of mines nearing closure and a method to extract relevant production data from the LOMP to develop relevant baselines. Step 2 presented a method to develop zero-waste resource and energy baselines using a generic simulation method. Step 3 presented a method to implement waste reduction and energy management initiatives on mines nearing closure. Step 4 presented a method to quantify the results after implementing energy management initiatives on mines nearing closure. This included developing a scaled energy baseline using actual and planned production data which is used to validate the results after testing the methodology on case study mines. The steps outlined in the methodology sufficiently addressed the study objective requirements. Chapter 3 presents the two case studies conducted on deep-level South African gold mines and a discussion of the results.

CHAPTER 3: RESULTS AND DISCUSSION

3.1. Chapter introduction

This chapter presents two case studies used to validate the methodology presented in Chapter 2. An introduction to the case studies is presented in Section 3.2. The characteristics of mines nearing closure were identified in the two case study mines in Section 3.3. Case studies 1 and 2 are presented in Section 3.4 and Section 3.5 respectively. The case study results are critically analysed in the discussion presented in Section 3.6 to determine the validity of the study outcomes. The chapter is concluded with Section 3.7.

3.2. Case study introduction

The energy management methodology presented in this study was validated using case studies of two gold mines nearing closure. The methodology was used to identify, assess, and implement energy management initiatives on the two case study mines. Both mines were within five years of closure when evaluated for the case studies. Both mines were deep-level gold mines operating in the Witwatersrand basin which ran high energy-consuming systems such as compressors, refrigeration plants, ventilation fans, pumping systems, and winders. Both mines already had energy management initiatives implemented on the various systems. However, there was scope for further optimisation as the mines planned for reduced production as they neared closure.

3.3. Identifying characteristics of mines nearing closure

The gold mining company reports its yearly operations data at the end of every financial year (FY). The financial year starts in July and ends in June of the following year. An overview of the yearly productivity trends of the operations constituting the South African gold mining company is presented in the figures below. These figures justify identifying the shafts selected for the study. Mine A and Mine B have the shortest LOM, as presented in Figure 3-1. Additionally, a gradual decrease in production can be seen across multiple operations between FY16 and FY20, attributed to decreasing ore reserves as the mines near closure. Mine A experienced a continuous decrease from FY16 onwards. Mine A and Mine B have the lowest overall production, with Mine B seeing a decrease starting in FY20.

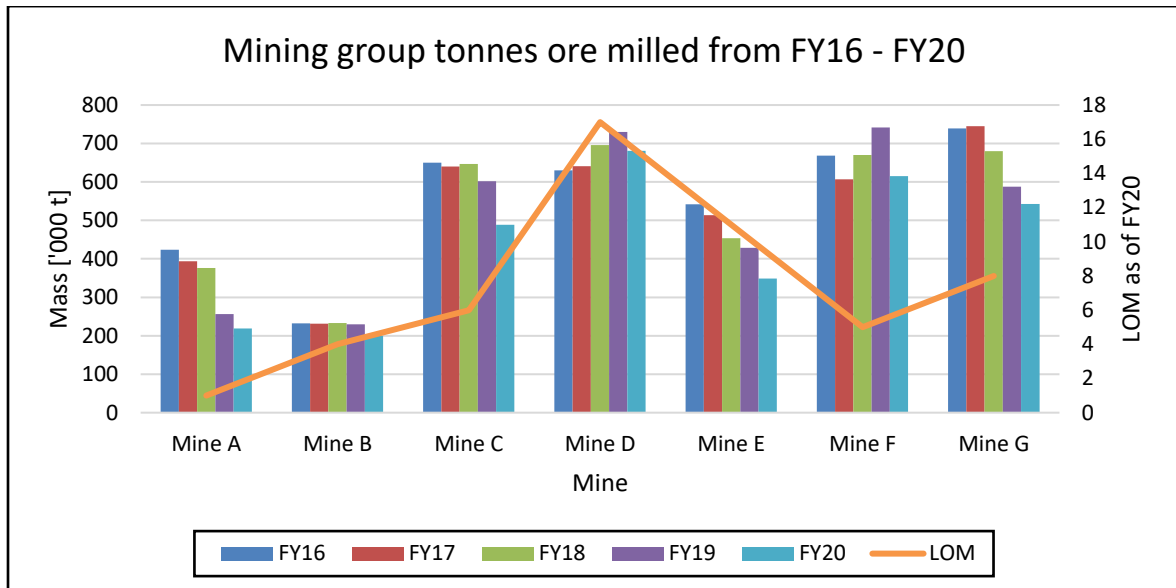


Figure 3-1: Mining group tonnes milled obtained from the mining company's annual reports

The trends in CAPEX highlight the reduced investment in Mines A, B, and C, with capital allocation trending downwards between FY16 and FY20 with a significant decrease seen between FY19 and FY20. Figure 3-2 shows that Mines A, B and C have the lowest CAPEX among all the mines in the group.

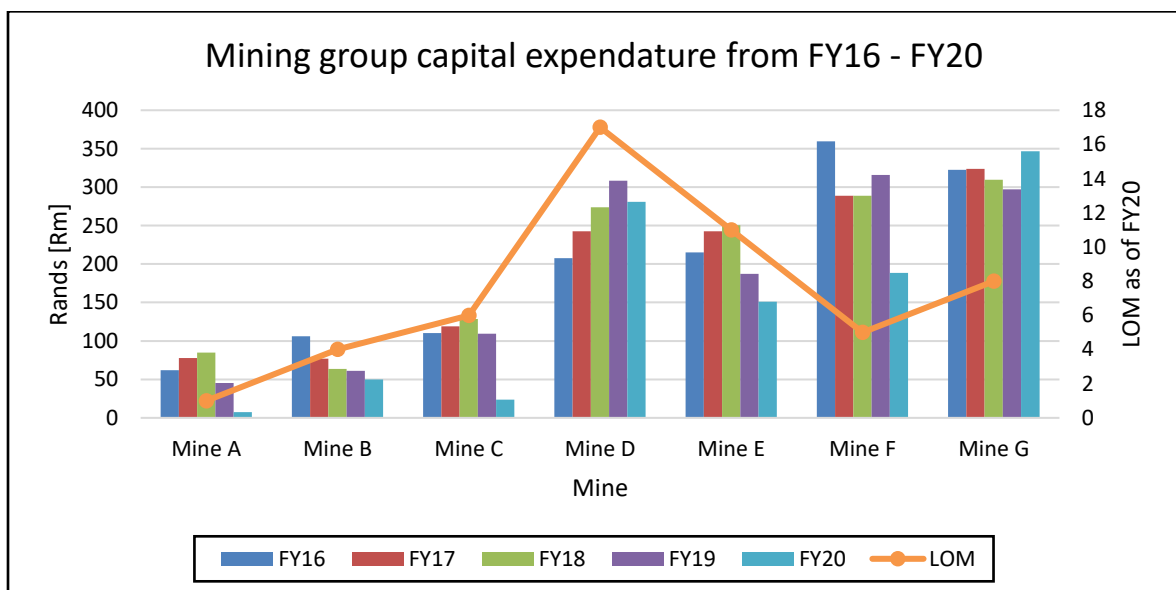


Figure 3-2: Mining group capital expenditure obtained from the mining company's annual reports

Finally, the energy intensity was evaluated to determine scope for efficiency presented in Figure 3-3. Mine B and F have a significantly higher energy intensity than the rest of the operations.

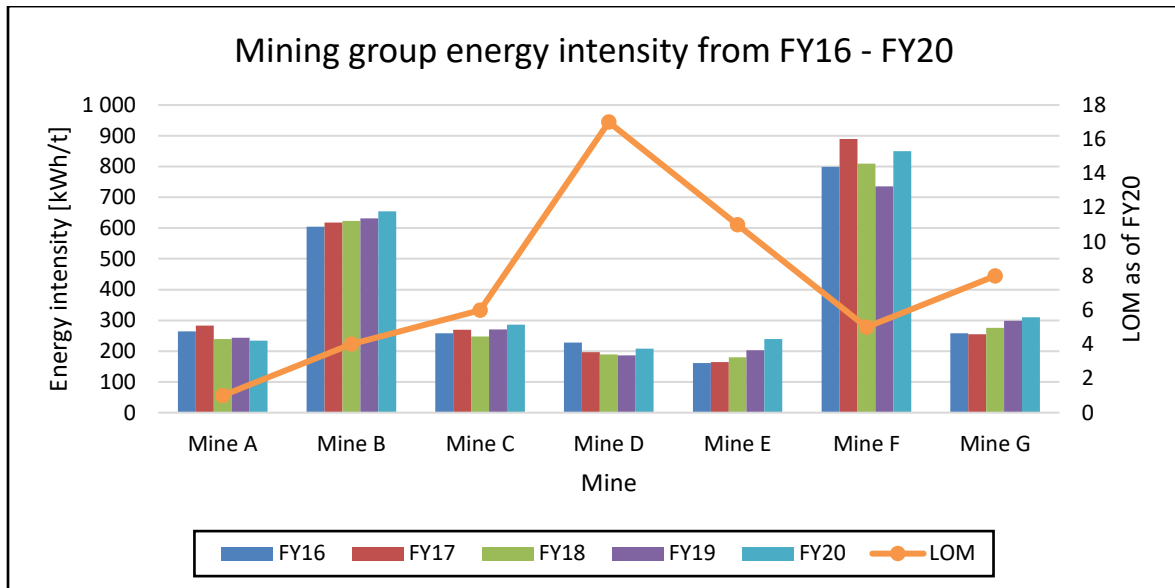


Figure 3-3: Mining group energy intensity

These mines nearing closure have unique trends which can be used to assist with energy management and further reduce energy consumption and overall operating costs. Mine A and Mine B were selected for the case study as they had the shortest LOM, low production with a downtrend in production, and relatively lower CAPEX. Successfully implementing an energy management strategy on Mine A and Mine B will validate the methodology and prove the viability of reducing energy demands on mines nearing closure.

3.4. Case study 1: Energy management of compressed air system on Mine A

3.4.1. Case study 1 introduction

Mine A is a mature, single shaft, deep-level gold mine in the Welkom goldfields area. It is also one of the company's oldest operating mines. This shaft consists of large energy-consuming systems such as compressors, surface fans, dewatering pumps, and refrigeration plants.

This case study focused on reducing the compressor energy demand by reducing wastage on the ageing compressed air system as the mine neared closure. The mine had three installed 2 900 kW centrifugal compressors. Two compressors were continuously run to supply the shaft's compressed air demand, while one compressor was placed on standby as a spare. This shaft had optimised air network (OAN) valves installed on the active underground levels. Ore processing did not take place on site; the unprocessed ore was sent to a central processing plant to be processed. Hence all the

compressed air generated on site was used underground. Therefore, this case study focuses on the compressed air demand of the underground compressed air system and its impact on the energy efficiency of running the compressors. A simplified layout of Mine A is presented in Figure 3-4 below.

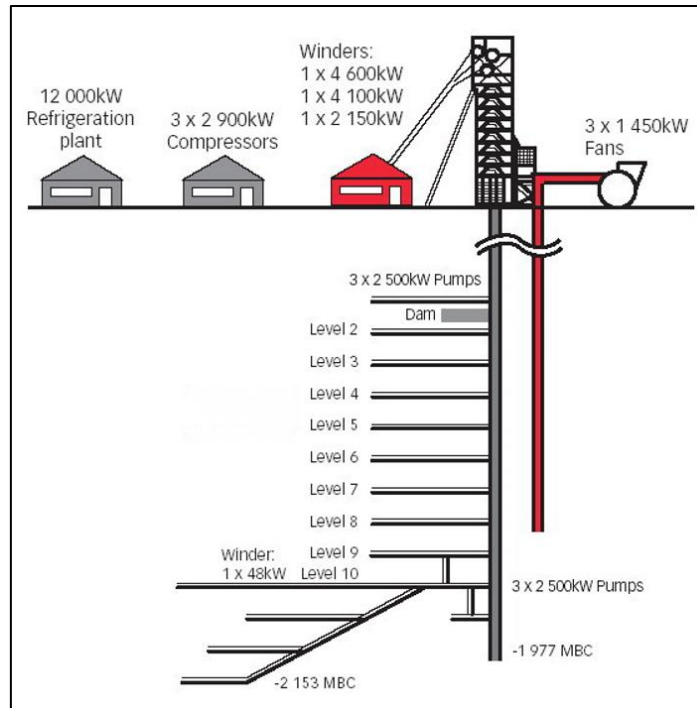


Figure 3-4: Mine A simplified layout

The methodology outlined in Chapter 2 was used to evaluate and implement the energy management framework as follows:

- Step 1: The LOM of mine plan was evaluated.
- Step 2: The zero-waste resource and energy baselines of the compressed air system were developed.
- Step 3: The energy management initiative was selected and implemented based on the required reductions from the zero-waste baselines.
- Step 4: The results from implementing the energy management initiatives over the remaining LOM were evaluated.

3.4.2. Step 1: Quantify planned LOM production

The LOM of Mine A was evaluated based on the mining company's annual report. Available data was evaluated from FY17 to FY21. The gold mining company planned to cease operations at Mine A by FY21. Based on the gold mining company's annual report, Mine A had a LOM of six years in FY17 with a further reduction in the LOM between FY18 and FY19, as presented in Table 3-1.

Table 3-1: Mine A planned LOM

Year	FY17	FY18	FY19	FY20	FY21
LOM (Years)	6	5	2	1	Closed

Aging infrastructure at the shaft has resulted in an increase in engineering stoppages, resulting in decreased production over time. Due to the reduction in production and the ageing infrastructure, a decision was made to reduce the number of workplaces and crew to focus on mining the richer shaft pillar. This change in operation planning ensured mining took place within a smaller area underground. Although planned mining activities were reduced, no initial efforts were made to reduce high energy-consuming services such as compressed air, water, and ventilation. Therefore, these services were still being supplied to inactive areas. This provided an opportunity to implement an energy management strategy that corresponds to the planned downscaling of the operation.

The FY16, FY17, and FY18 production plans were obtained from the mine's planning department. These plans presented sufficient planning information for the mine up to the planned closure date in FY21. The initial values obtained from the plan were the planned number of workplaces, used to determine the number of loaders and bazookas required per level. Figure 3-5 indicates the drop in the number of planned workplaces from 59 in February 2018 to 32 in May 2018.

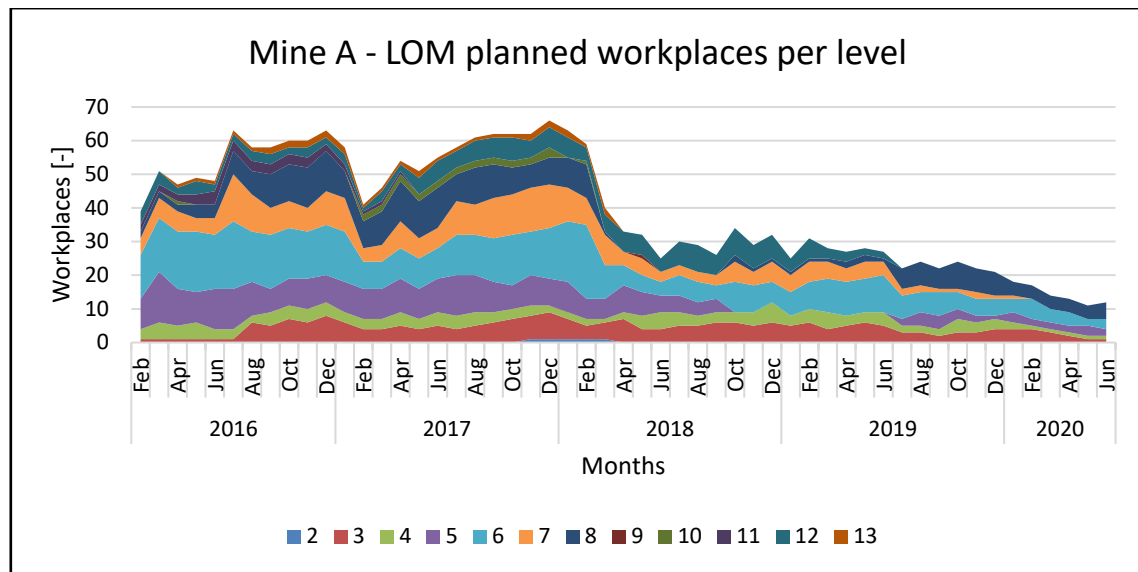


Figure 3-5: Mine A planned workplaces

The second values obtained from the plans were the planned square meters (m^2) to be mined for both stoping and development, as presented in Figure 3-6. This was used to determine the zero-waste compressed air requirements for drilling. Figure 3-6 shows a reduction from $6\,927\text{m}^2$ in February 2018 to $3\,865\text{m}^2$ May 2018 (a reduction of $3\,062\text{m}^2$).

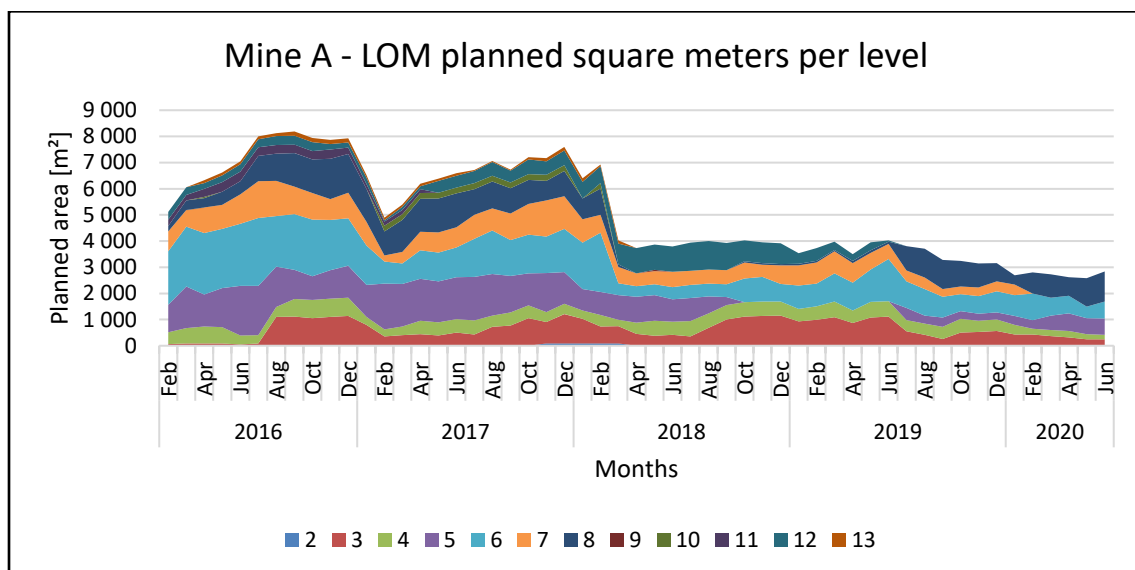


Figure 3-6: Mine A planned square meters

The number of planned levels also decreased by three levels between February and May 2018. There was a subsequent gradual reduction from May 2018 to June 2020, resulting in a further reduction of 18 active places. Overall, the mine planned to downscale by 51 workplaces, resulting in the closure of five levels. This significant decrease in planned production over the remaining LOM provided a sufficient reason to investigate the potential of downscaling the energy demand of the operation as well.

The planned tonnes over the LOM were evaluated using the planned area mined, average face advance of 1.89 m, and gold ore density of 2.73 g/cm³ with Equation 13. The planned monthly production decreased by 18 121 tonnes over the reduction period from 35 907 tonnes in February 2018 to 17 787 tonnes in May 2018, as shown in Figure 3-7.

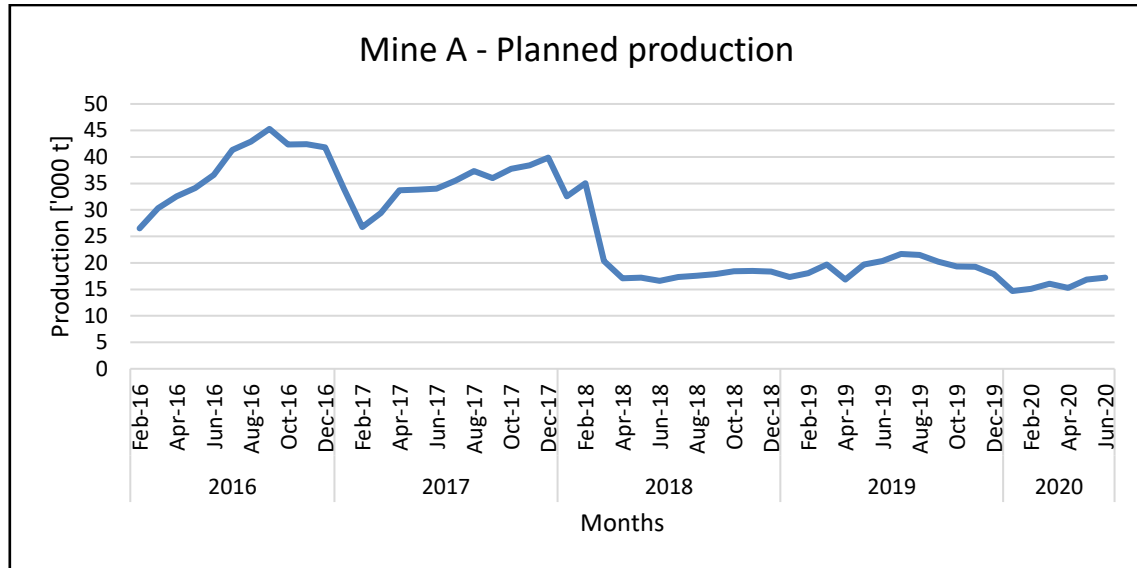


Figure 3-7: Mine A planned production

3.4.3. Step 2: Developing zero-waste baselines

Zero-waste baselines were developed to identify the extent of wastage and allow for effective LOM evaluation and planning. The resource and energy zero-waste baselines were evaluated separately using the same methodology. The compressed air zero-waste baseline was evaluated first to determine the ideal demand and quantify waste. The energy zero-waste baseline was then evaluated to determine the impact of waste reduction on the compressor running efficiency.

Evaluating compressed air zero-waste baseline

The simulation methodology outlined in Section 2.4.4 was followed to develop compressed air zero-waste baselines for Mine A's compressed air system to plan for system downscaling. The most recent and relevant system information was gathered from the operation, including a compressed air flow profile, the quantity of equipment used, the shaft production schedule, and the system layout. Due to limited instrumentation on the operation, only the surface compressed air demand was measured using a mobile flow meter. The flow was measured over a 24-hour period in February 2018 before the planned downscaling took place as presented in Figure 3-8.

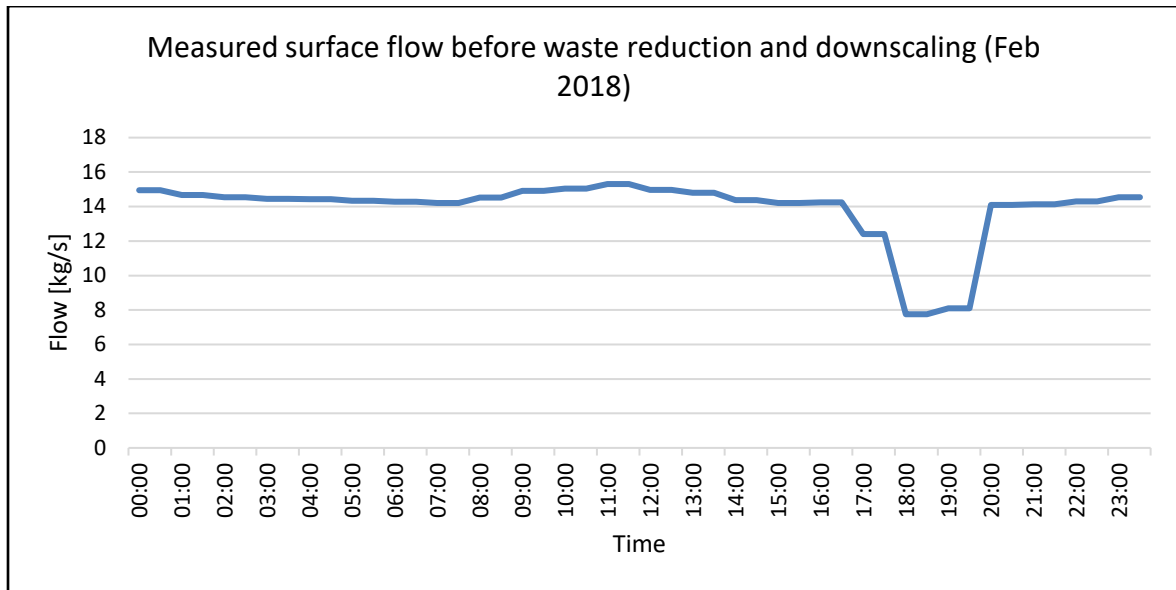


Figure 3-8: Measured surface flow before waste reduction and downscaling

The compressed air demand per level was estimated using actual production data, as presented in Figure 3-9. This gives an indication of the levels with the highest potential demand.

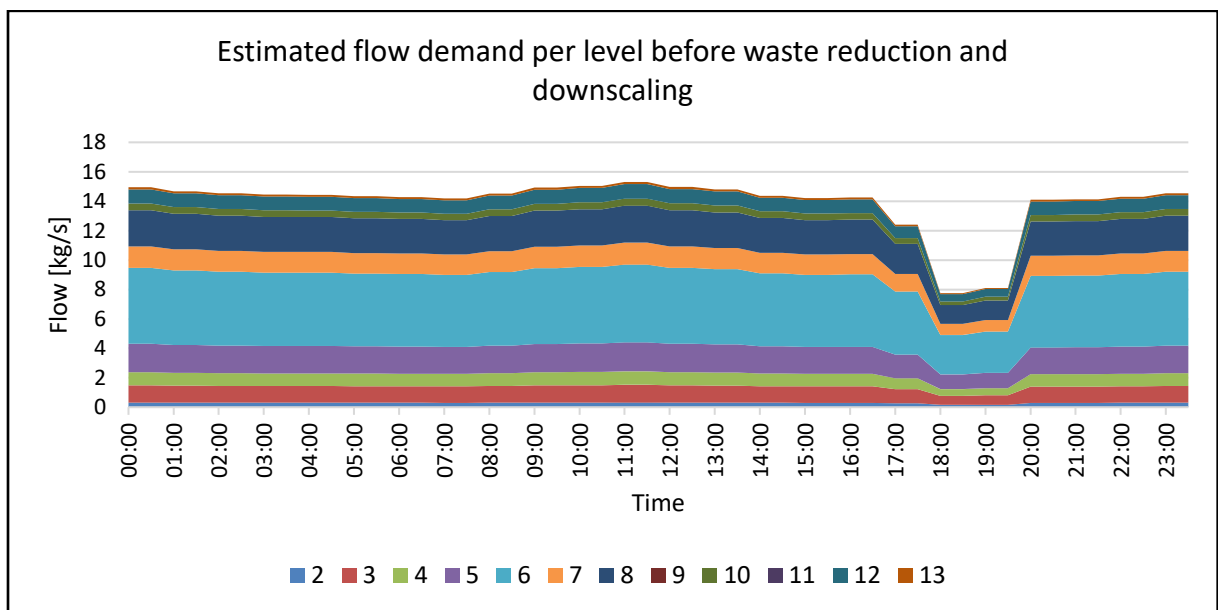


Figure 3-9: Estimated flow demand per level before waste reduction and downscaling

The compressed air consuming equipment was identified from underground audits and the type of workplaces that were planned based on the parameters presented in Table 3-2. Most compressed air was used for drilling and cleaning activity underground, which are subject to the production schedule presented in Table 3-3.

Table 3-2: Mine A compressed air demand calculation parameters

Parameter	Qty
No. advance holes drilled per square meter	4
No. support holes per workplace	14
No. bazookas per workplace	1
No. mechanical loaders per workplace	1
No. refuge bays per level	2
No. loading boxes per workplace	1

Table 3-3: Mine A daily production cycle

Shift	Period
Shift change	03:00 – 08:00
Drilling	08:00 – 17:00
Blasting	17:00 – 20:00
Cleaning	20:00 – 03:00

The compressed air consumer specifications presented in Table 2-6 along with the parameters outlined in Table 3-2 and Table 3-3 were used to develop demand profiles for each level using Equation 14 and Equation 15. A layout of the mine and the levels' depths were obtained from the planning and survey department. Further details are presented in Appendix A.

Once all the shaft and system details were compiled, a viable simulation package was selected. Flonex®, EnviroSim, KYPipe Gas, and ProcessToolbox® were considered for the application. ProcessToolbox® was selected, as it is a dynamic thermal hydraulic-simulation package effective at simultaneously evaluating power, compressed air flow, and pressure within the system. It is also versatile enough to simulate compressed air and water reticulation systems. The simulation was conducted over a 24-hour period with 30-minute time steps.

A simplified underground model was developed since a sufficient digital underground layout for Mine A was not available. The boundary of the model was between the shaft entrance and the demand at each level. This model was sufficient, as the primary focus was determining the impact of the cumulative level demand on the surface air demand. The model included all the levels of the mine with control valves and separate demand nodes for the primary compressed air consumers on each level. An example of a simplified level layout is presented in Figure 3-10.

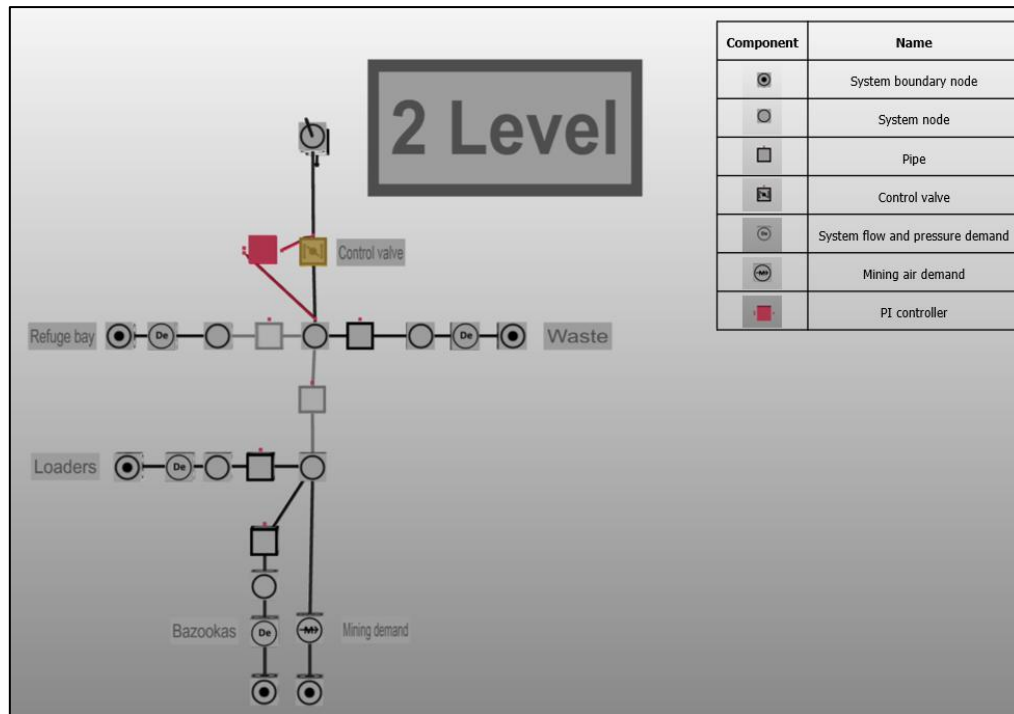


Figure 3-10: Example of simulation level layout

The model was calibrated to the surface flow and pressure measurements taken during the initial audit of the system in February 2018 before the planned downscaling. The simulated pressure and flow values were calibrated within 5% of the measured values by adjusting the integral gain of the control valves on each level. The calibration results can be found in Appendix B.

Three zero-waste scenarios were simulated. This included a zero-waste baseline of the production day before the planned reduction and a production day and non-production day zero-waste baseline after the planned reduction. The parameter for each simulation is presented in Table 3-4.

Table 3-4: Compressed air zero-waste baseline simulation input parameters

Period	Simulation	Parameters		
		Total No. active levels [-]	Total No. workplaces [-]	Total square meters mined [m ²]
Feb 2018	Before planned reduction	10	59	6 927
May 2018	After planned reduction (production day)	5	32	3 865
	After planned reduction (non-production day)	5	-	-

The results of the resource zero-waste baseline are shown in Figure 3-11 with measured flow before waste reduction and downscaling, indicating that there is significant scope for production day waste reduction on Mine A, with additional reduction expected as production downscals. The results indicate a potential daily maximum demand reduction of 7.1 kg/s before downscaling and a further 2.9 kg/s in demand reduction after downscaling over production days, as presented in Table 3-5. The non-production day demand is significantly lower than all the other days, as only the refuge bays on active levels were simulated to run during those periods.

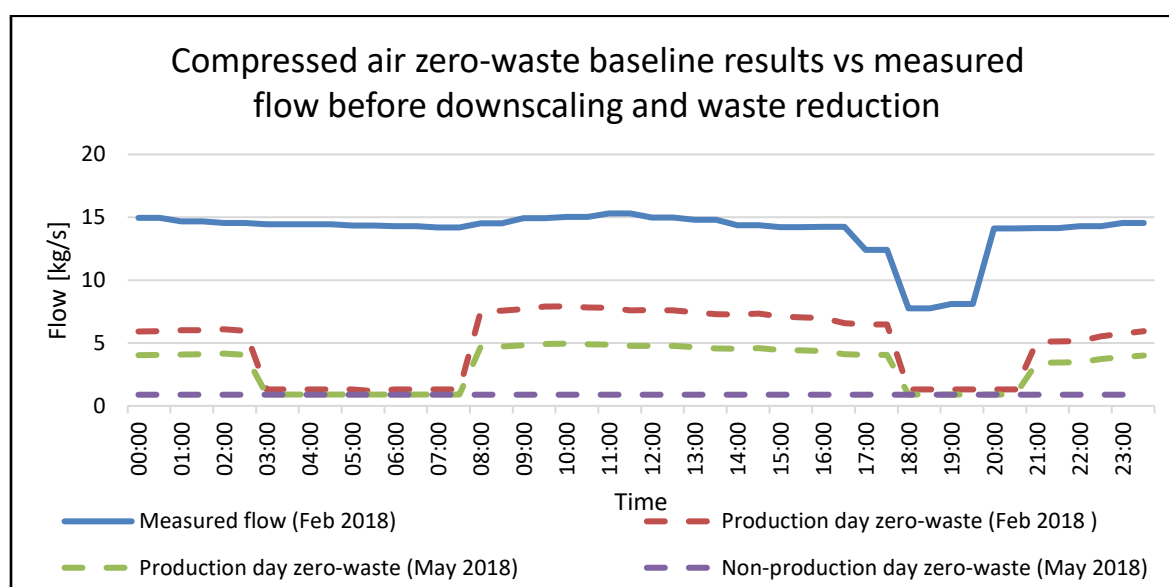


Figure 3-11: Compressed air flow zero-waste baseline vs initial measured demand

Table 3-5: Compressed air demand zero-waste simulation results

Period	Profile	Max flow demand [kg/s]
Feb 2018	Measured flow	15.0
	Production day zero-waste baseline	7.9
May 2018	Production day zero-waste baseline	5.0
	Non - production day zero-waste baseline	0.9

Additionally, the compressed air zero-waste model was evaluated per level as shown in Figure 3-12. This was used to estimate the wastage per level to assist with prioritising audits on levels with the highest flows and potentially the highest wastage.

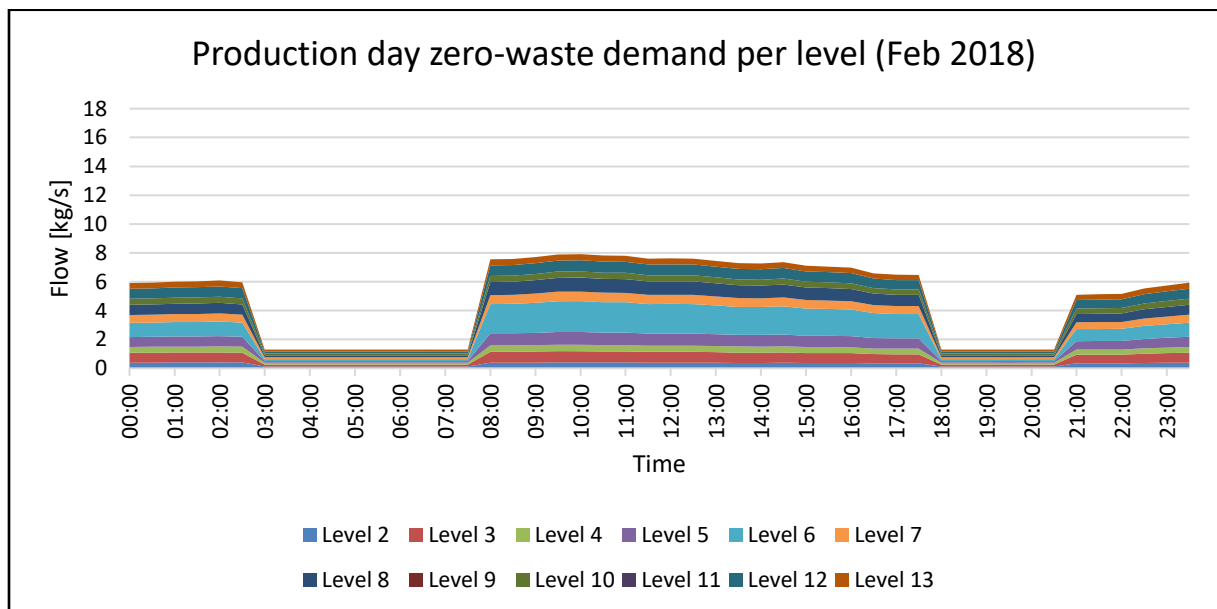


Figure 3-12: Production day compressed air zero-waste baseline per level

The total daily compressed air demand was calculated based on the results presented in Figure 3-12 and subtracted from the estimated daily flow derived from the findings presented in Figure 3-9. This showed that levels 6, 8, and 5 had the highest potential for wastage, as shown in Figure 3-13. It should be noted that levels 2, 9, 10, 11, and 13 had extremely low to no demand and should also be audited to ensure the compressed air to these levels is blanked off.

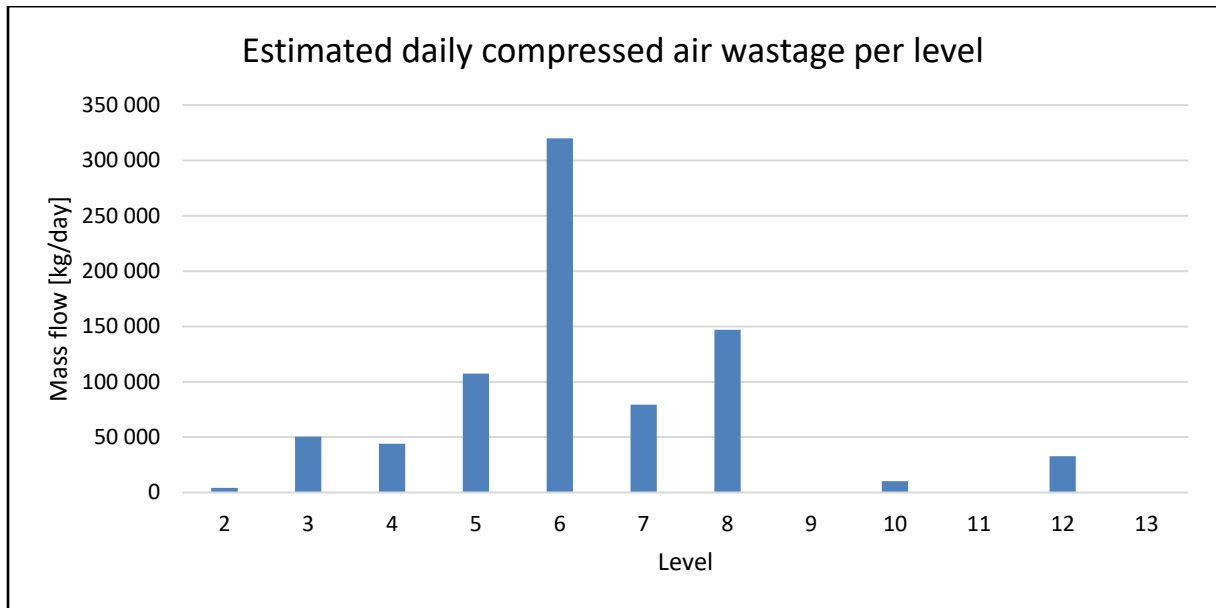


Figure 3-13: Estimated daily compressed air wastage per level

Evaluating energy zero-waste baseline

Mine A had a relatively simple surface compressed air layout with the compressor house being close to the shaft entrance. The compressor house contained three 2 900 kW compressors with a specified flow output of 8.4 kg/s at 550 kPa. The compressor performance and efficiency curves were developed using historic data. The compressor fed a manifold which connected to a 500 mm steel pipe leading into the shaft. Further details on the configuration can be found in Appendix B. The shaft ran two compressors to supply the compressed air demand with one compressor being switched off during the blasting period to ensure energy savings. The compressors had a fixed surface pressure setpoint of 490 kPa. The boundary of the model extended between the air input into the compressors and the demand at the shaft entrance, as presented in Figure 3-14. A dynamic compressor model was used, which allowed for dynamic guide vane and blow off control.

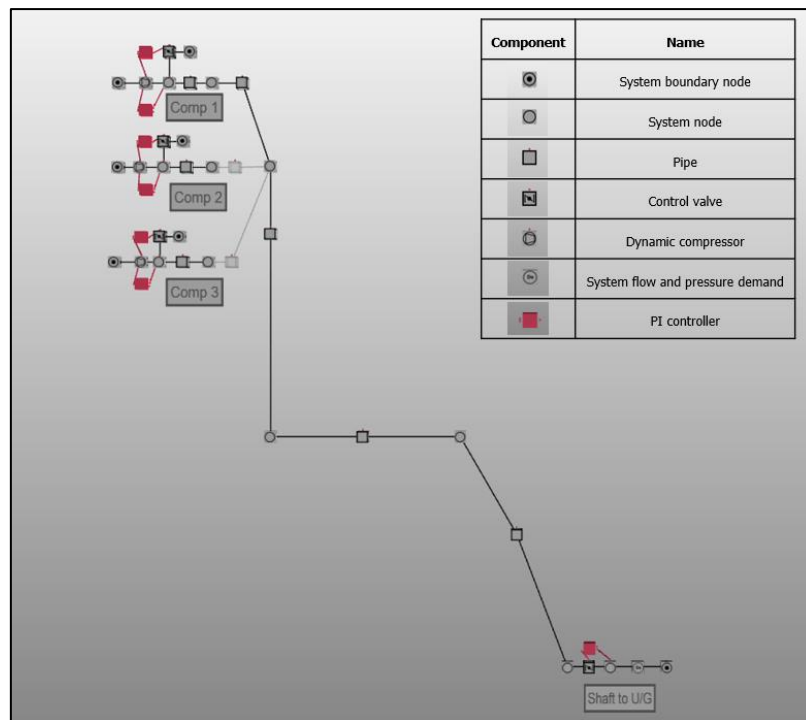


Figure 3-14: Surface compressed air simulation model

The model was calibrated using historic system flow, pressure and energy demand values. A production day before the planned downscaling was selected when one compressor was running. The simulated compressed air surface flow was calibrated within 4.7%. The simulated compressed air surface pressure was calibrated within 4.1% of the measured pressure. The simulated compressor power demand was calibrated within 3.0%. Given these results the simulation model was deemed to be sufficiently calibrated and was used to simulate the zero-waste baseline scenarios. Figures of the model calibration can be found in Appendix B.

The three scenarios presented in Table 3-4 were simulated using the outputs from the compressed air zero-waste baselines presented in Figure 3-11 as inputs. The compressor running statuses and guide vane parameters were adjusted to supply the demand flow at 490 kPa. The results obtained from the zero-waste baseline indicate the potential to significantly reduce the power demand of the compressed air system. Before the planned downscaling, Mine A was running two compressors, with one compressor being switched off during the evening blasting shift. The results in Figure 3-15 indicate that the shaft only requires one compressor to sufficiently supply the shaft's compressed air demands over production days, highlighting the scope to further cut back during the morning shift change and evening blasting period. This represents a potential 61 MWh decrease in daily energy demand before downscaling and a further 2.8 MWh decrease after downscaling over production days, as presented in Table 3-6.

Table 3-6: Compressor supply zero-waste simulation results

Period	Profile	Daily energy demand [MWh]
Feb 2018	Measured energy	117
	Production day zero-waste baseline	55.7
May 2018	Production day zero-waste baseline	52.9
	Non - production day zero-waste baseline	37.5

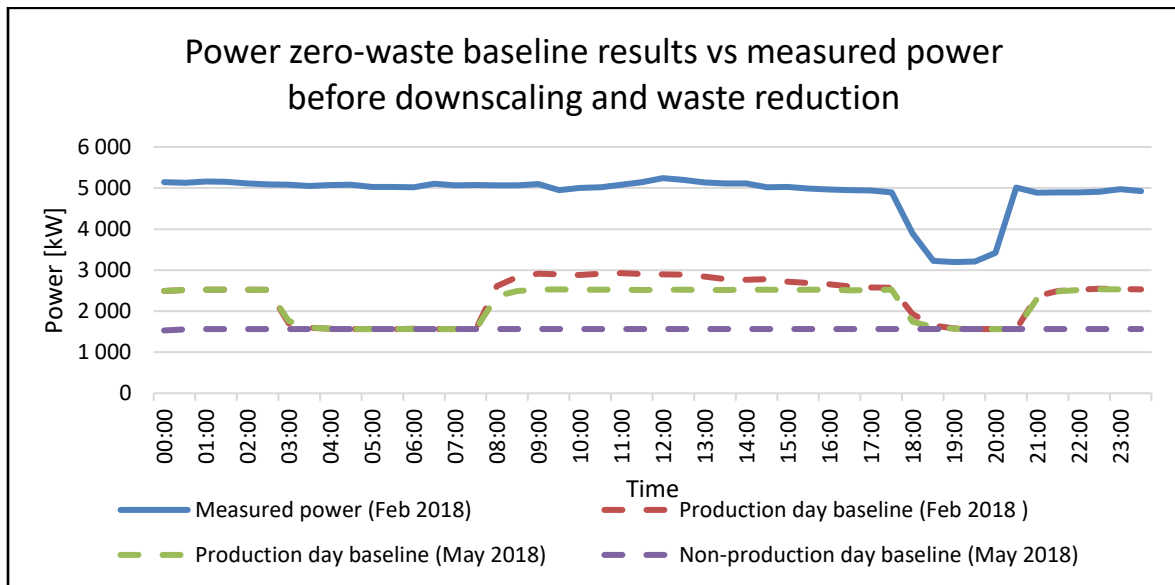


Figure 3-15: Compressor power zero-waste baseline model vs initial measured demand

3.4.4. Step 3: Implementing energy management initiative

Determining energy management initiative

Based on the simulation results, there was a significant discrepancy between the compressed air zero-waste baseline and the measured flow. First, there was a large prevalence of leaks due to ageing infrastructure and compressed air being supplied to inactive areas. Second, two compressors were run throughout the day to compensate for the leaks to supply compressed air at the required flow and pressure for continued production.

There was already an energy management initiative implemented on the compressed air system before the planned downscaling. This energy management initiative consisted of a valve on level 7 being closed during the blasting shift between 17:00 and 20:00, which allowed a compressor to be

switched off over that period. This is indicated by the dip in demand during this period, as shown in Figure 3-15.

Due to reduced capital availability, limited payback period, and limited implementation time, the initiative selection prioritised no cost and short implementation time. A waste reduction approach was chosen, given the planned reduction in number of workplaces and ageing infrastructure. A waste reduction approach also requires no capital cost and can be implemented over the course of a few months.

Three sets of compressed air audits were conducted on the shaft over the span of four months. The aim of these audits was to identify inefficiencies in the underground compressed air network. After each audit was completed, the findings were reported to mine personnel. The mine personnel were responsible for fixing the leaks and blanking off air to unused areas. The shaft compressed air consumption was also measured after every audit.

System analysis

The latest underground layouts were obtained from the planning department. The levels planned for closure as well as the levels with the highest wastages were identified from the LOMP and by using the compressed air zero-waste baseline. Levels 2, 3 and 13 were identified for closure. Levels 5, 6, and 8 were identified to have the highest wastage. Therefore, the planned audits were focused on these levels. Levels 9, 10, and 11 were already blanked before the audit and as such were not prioritised.

Mine A did not have a permanent compressed air flow meter installed on surface. Hence, a mobile thermocouple flow meter was used to measure the surface flow over a 24-hour period before, during, and after the process of implementing the waste reduction strategy. Mine A had power meters installed on the feeders to each of the three compressors which logged data every 30 minutes.

Implementing the waste reduction and energy management initiative

Three sets of audits were conducted over the downscaling period between February 2018 and May 2018. The findings from the audit identified inactive levels which were not blanked off along with multiple large, compressed air leaks. The findings were compiled and reported to the relevant foreman and shift bosses. A template of the audit sheet is presented in Appendix C. The foreman and shift bosses were responsible for ensuring the identified leaks were fixed and compressed air

to the identified levels were blanked off. Once the foremen and shift bosses provided feedback, follow-up audits were conducted to ensure the work was completed sufficiently.

During the initial flow measurement, it was found that the shaft was consuming a maximum of 15 kg/s of compressed air daily. Subsequent surface flow measurements were taken after each audit. There was a clear reduction in compressed air flow after each audit. During the first audit it was found that compressed air was being supplied to inactive levels 2 and 3. During the second audit it was found that compressed air was being supplied to the inactive levels 8 and 13. By the third audit, the compressed air consumption had reached the required target. This saw the maximum compressed air demand reduce by 5.7 kg/s between the second and third audit, resulting in a daily energy demand decrease of 51.1 MWh, as presented in Table 3-7.

Table 3-7: Compressed air leak audit progress

Level shut	Date completed	Associated audit	Maximum CA demand [kg/s]	Daily energy demand [MWh]
-	-	Production day zero-waste baseline	5.0	52.9
-	Feb 2018	First audit	15.0	117.0
2L & 3L	Feb 2018	Second audit	13.0	94.0
8L & 13L	May 2018	Third audit	9.3	65.0

Since the compressed air demand approached the supply threshold of one compressor, one compressor was switched off over a trial period. However, the demand still exceeded the compressed air supply during the drilling shaft. Subsequently, the automatic valve on level 7 was closed. An additional trial test was performed, and it was noted that the average demand had dropped significantly below the 8.4 kg/s limit. Future planning suggests that level 6 will be closed, which will further reduce the demand. The measured compressed air demands after each audit are presented in Figure 3-16.

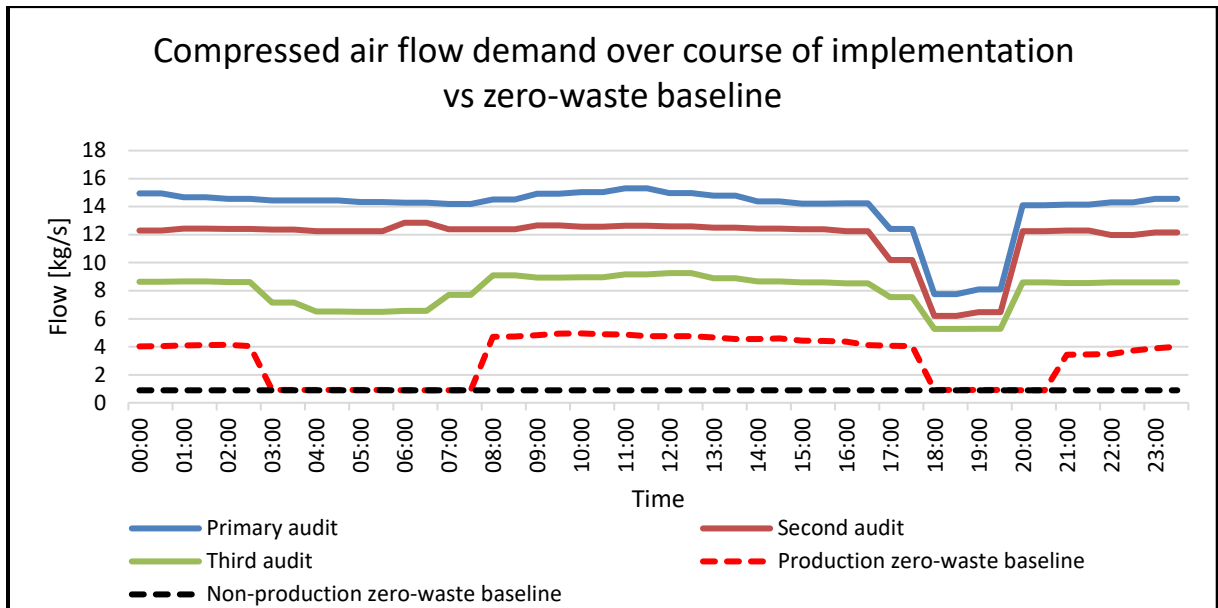


Figure 3-16: Mine A compressed air flow measurements taken between February and May 2018

The compressor power consumption decreased alongside the decrease in flow demand from the implementation of the compressed air initiative. There was an overall decrease of 1 968 kW between the first audit and the third audit, as shown in Figure 3-17. The power profile after the third audit was below the power consumption of a single compressor, indicating that a compressor was switched off and the shaft was sustaining operations with one compressor and using the second and third compressors as standbys.

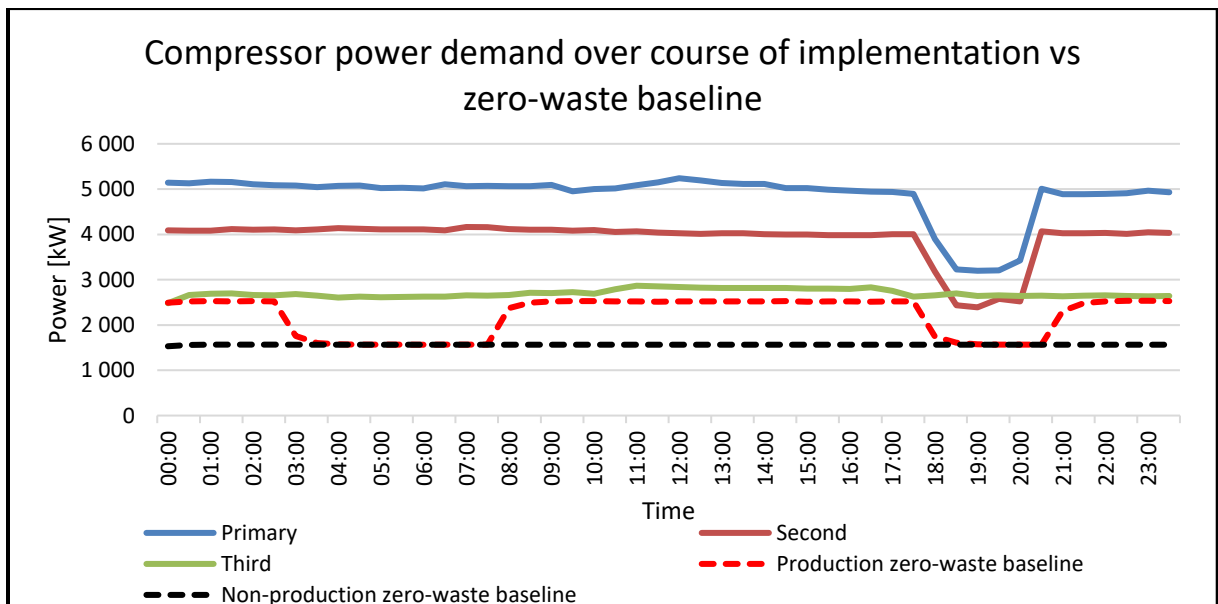


Figure 3-17: Mine A compressor power measurements taken between February and May 2018

3.4.5. Step 4: Evaluating results

The impact of baselining and implementing an energy management initiative on Mine A was evaluated over its remaining LOM. Figure 3-18 shows the energy baseline forecast against the zero-waste forecast and actual demand over the remaining LOM from 2018 to July 2020. In the case of Mine A, the baseline forecast implies that two compressors would have continued to run if a waste reduction plan and energy management strategy were not implemented. However, due to the implementation of an energy management strategy over the downscaling period, a significant energy reduction and cost saving were identified over the remaining LOM. The actual demand reached close to the zero-waste baseline; however, due to unavoidable minor system inefficiencies and the limitations of the compressor, the actual demand did not fully align with the zero-waste baseline. A life of mine energy saving of 32 GWh was achieved out of a potential 38 GWh.

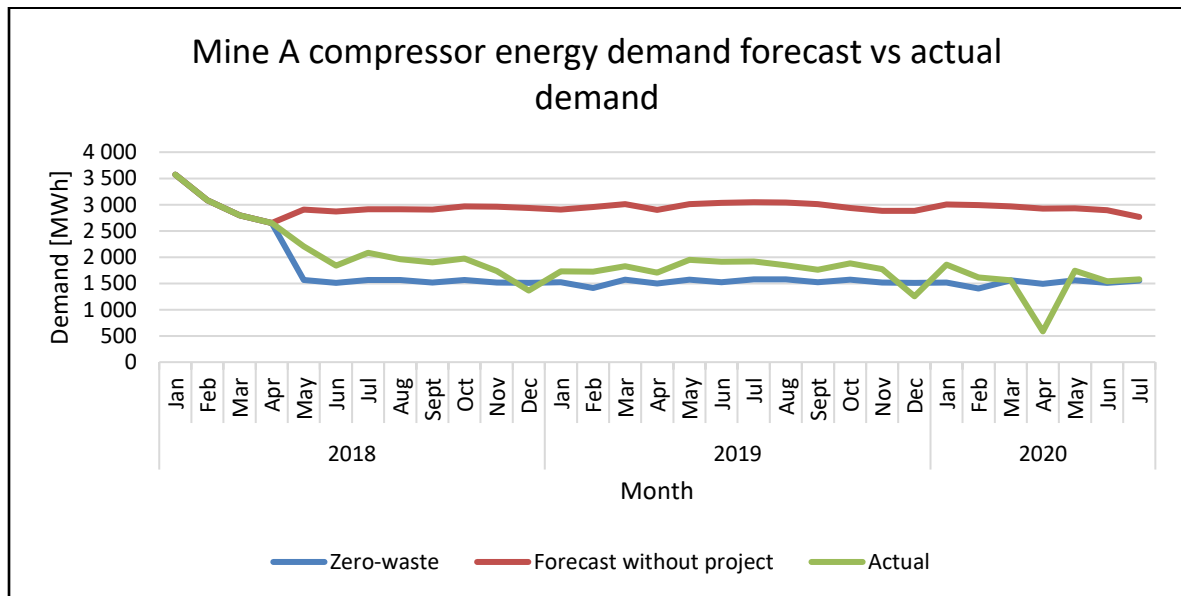


Figure 3-18: Evaluating Mine A compressor energy demand forecast vs actual demand

The energy cost forecast in Figure 3-19 accounts for the change in seasonal and yearly tariffs over the course of Mine A's LOM. The implementation of the project realised an operational cost savings of R32 million out of a potential R38 million.

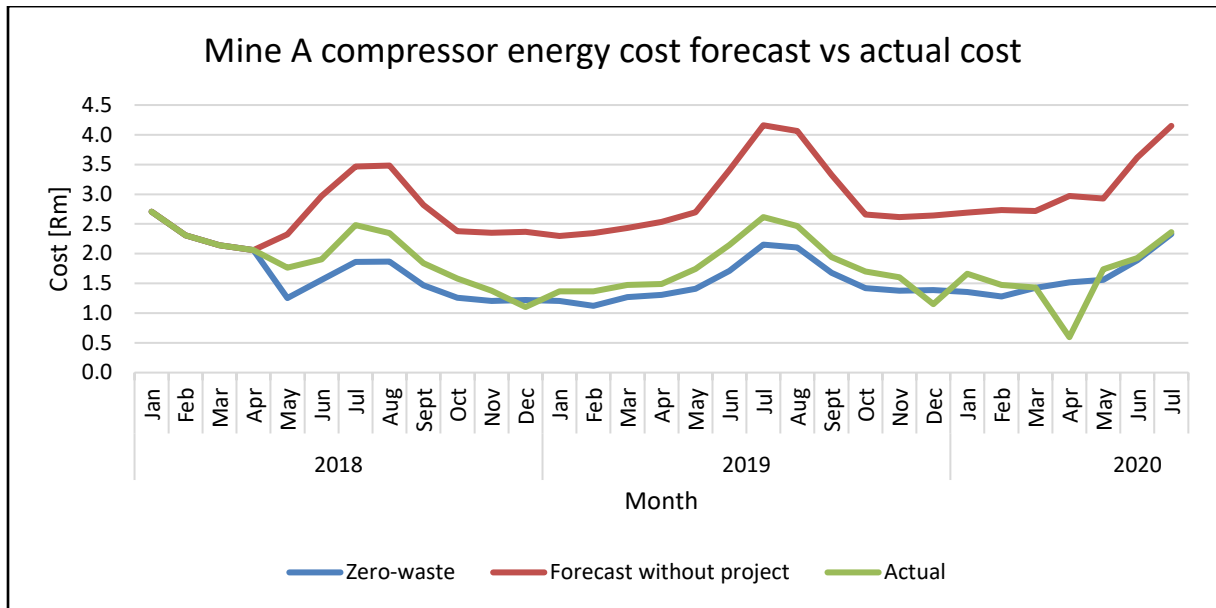


Figure 3-19: Evaluating Mine A compressor energy cost forecast vs actual cost

3.4.6. Case study 1 conclusion

Mine A significantly downscaled operations from February 2018 due to ageing infrastructure and depleting ore reserves with a plan to terminate operations in 2020. This provided an opportunity to evaluate and implement an energy management initiative to reduce compressed air energy demand in line with the planned decrease in production. A cost- and time-efficient waste reduction and energy management initiative was successfully baselined and implemented on Mine A's compressed air system. This resulted in a R32 million energy cost saving over the remaining LOM.

3.5. Case study 2: Energy management of refrigeration system on Mine B

3.5.1. Case study 2 introduction

Mine B is part of the same gold mining company as Mine A and is also located in the Welkom goldfields area. This case study focused on reducing the refrigeration energy demand by reducing wastage on the ageing water reticulation network as the mine neared closure. The mine service water reticulation system operated within a closed loop with only excess fissure water being pumped out. The three fridge plants on 58L were used to cool this water as it recirculated through the system. Two fridge plants were run at any given time as required, with one fridge plant on standby. The fridge plant supplied the chilled water dam, which supplied the service water for

mining and a BAC on 58L which cooled the downcast air entering the lower levels of the shaft. A simplified layout of the refrigeration and water reticulation system is presented in Figure 3-20.

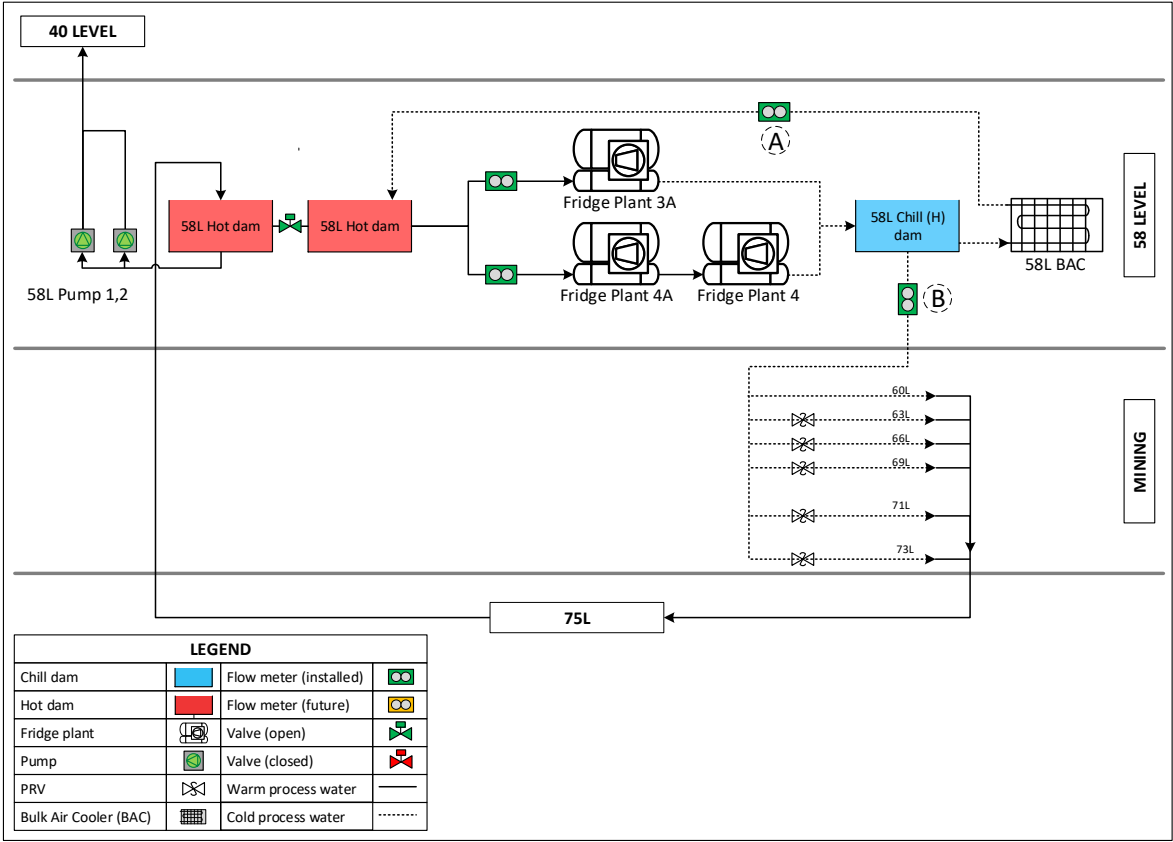


Figure 3-20: Mine B water reticulation system

3.5.2. Step 1: Quantify planned LOM production

Mine B had a two-year LOM remaining as of 2021 and planned to terminate operations in 2023. However, due to a large seismic incident in 2021, the LOM was shortened to June 2022. Since the pillar around the shaft was being mined, all the working places were centralised around one location. Mine B only had four active levels; therefore, analysis was done on a crosscut basis since each active level had approximately two active crosscuts. Mine B planned for a downscale in production from March 2021. This resulted in a reduction of four panels, resulting in a decreased production of 617 m² and a subsequent reduction in 1 500 tonnes of production, as shown in Figure 3-21.

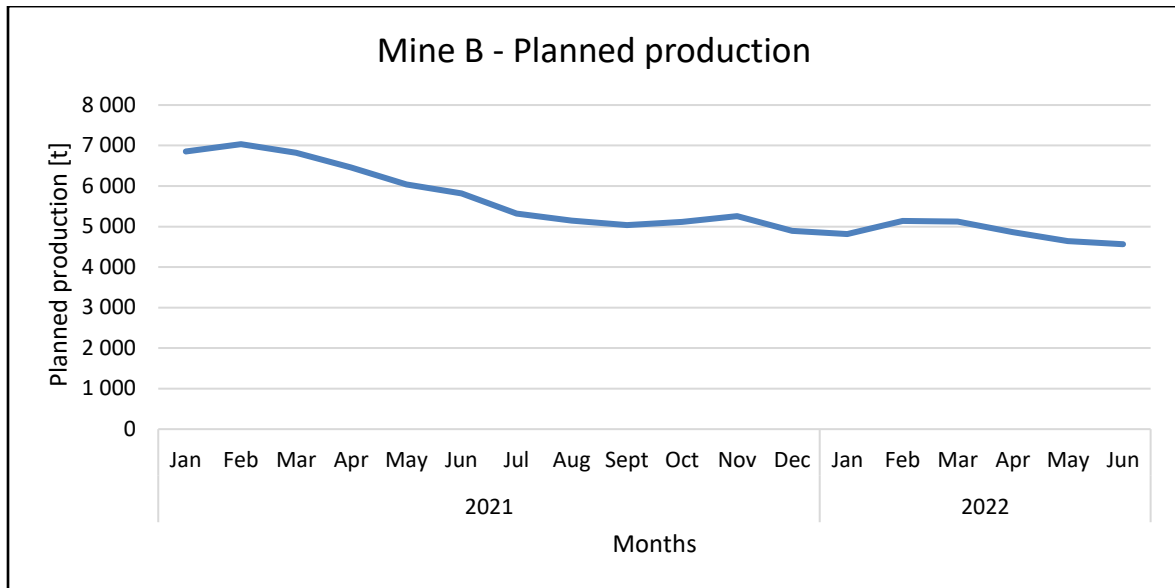


Figure 3-21: Mine B planned production

3.5.3. Step 2: Developing zero-waste baselines

Evaluating resource zero-waste baseline

The simulation methodology presented in Section 2.4.4 was used to develop the resource zero-waste flow baseline. The primary water consuming equipment on this operation was identified as the rock drills and bazookas. This operation did not use any cooling cars on the crosscuts, therefore, there should only be mining water flow demand during the drilling and cleaning shifts.

The zero-waste baseline model for the mining water demand was developed using the same parameters as outlined in the compressed air zero-waste baseline. However, the daily production schedule for Mine B differed slightly, with the cleaning shift taking place alongside the drilling shift, as shown in Table 3-8. The model was simulated using the same simulation package over the same time intervals as in Case Study 1. The model was also calibrated within 5% of the measured flow before being used to develop the zero-waste models. Further details are presented in Appendix B.

Table 3-8: Mine B daily production cycle

Shift	Period
Shift change	21:00 – 08:00
Drilling and cleaning	08:00 – 17:00
Blasting	17:00 – 21:00

Three zero-waste scenarios were simulated similar to the scenarios simulated for the compressed air zero-waste baselines as shown in Table 3-9. The zero-waste baseline model for the non-production day did not have any parameters since there was no expected demand given that the chilled water in this case is used exclusively for production purposes.

Table 3-9: Service water zero-waste baseline simulation input parameters

Period	Simulation	Parameters		
		No. planned Crosscuts [-]	No. planned Workplaces [-]	Planned square meters mined [m ²]
Apr 2021	Before planned reduction	7	29	2 807
Jul 2021	After planned reduction (production day)	5	24	2 190
	After planned reduction (non-production day)	-	-	-

The results from the zero-waste baseline indicates the potential for a 1.7 MI/day reduction in mining water demand before downscaling and a further 0.076 MI/day reduction after downscaling production, as shown in Table 3-10 and Figure 3-22. Significant potential for leaks was also identified on levels 71 and 69.

Table 3-10: Service water zero-waste baseline results

Period	Profile	Max flow demand [MI/day]
Apr 2021	Measured flow	1.93
	Production day zero-waste baseline	0.24
Jul 2021	Production day zero-waste baseline	0.16
	Non - production day zero-waste baseline	0.00

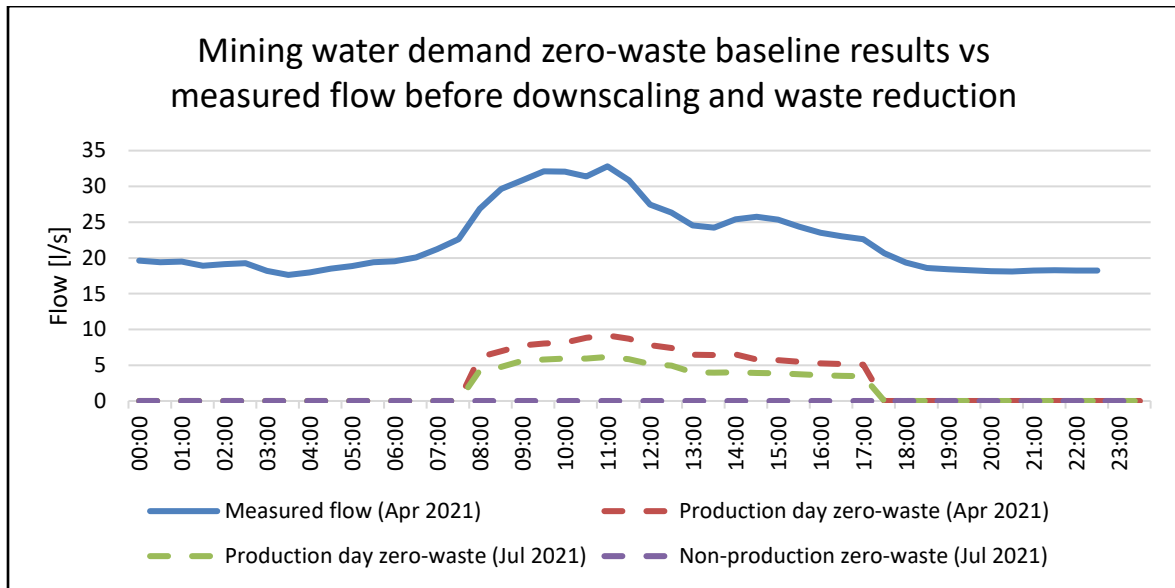


Figure 3-22: Mining water demand zero-waste baseline vs initial measured demand

Evaluating energy zero-waste baseline

The simulation model of the refrigeration system was constructed using the following parameters: the fridge plant coefficient of performance (COP), the fridge plant flows, the number of fridge plants running, the piping layout, the chilled water dam capacities, the connecting pipe sizes, the underground air temperature, the fridge plant running schedule, and the BAC demand profile. These parameters are presented in Appendix B. The boundaries of the model were between the fridge plant water inlet and the chill water dam outlet, which includes the mining service water demand and the BAC demand. The model was calibrated within 5% of the fridge plant running profile and chilled water dam levels.

The zero-waste baseline scenarios were simulated using the outputs from the mining water demand zero-waste baseline. The BAC demand was kept constant throughout the simulations. The simulation results show the significant impact of reducing waste and downscaling operations on the fridge plant running time over a typical day. An expected daily running time reduction of 9.8 MWh was noted between the measured profile and the zero-waste baseline developed for April. A further expected reduction of 1 MW was noted between April and July 2021, as presented in Table 3-11, allowing for more flexibility for the fridge plants to run outside peak Eskom demand hours, as presented in Figure 3-23.

Table 3-11: Frige plant zero-waste simulation results

Period	Profile	Daily energy demand [MWh]	Daily running hours [hr]
Apr 2021	Measured power	32.1	11.0
	Production day zero-waste baseline	10.7	4.0
Jul 2021	Production day zero-waste baseline	8.5	3.0
	Non - production day zero-waste baseline	7.1	2.5

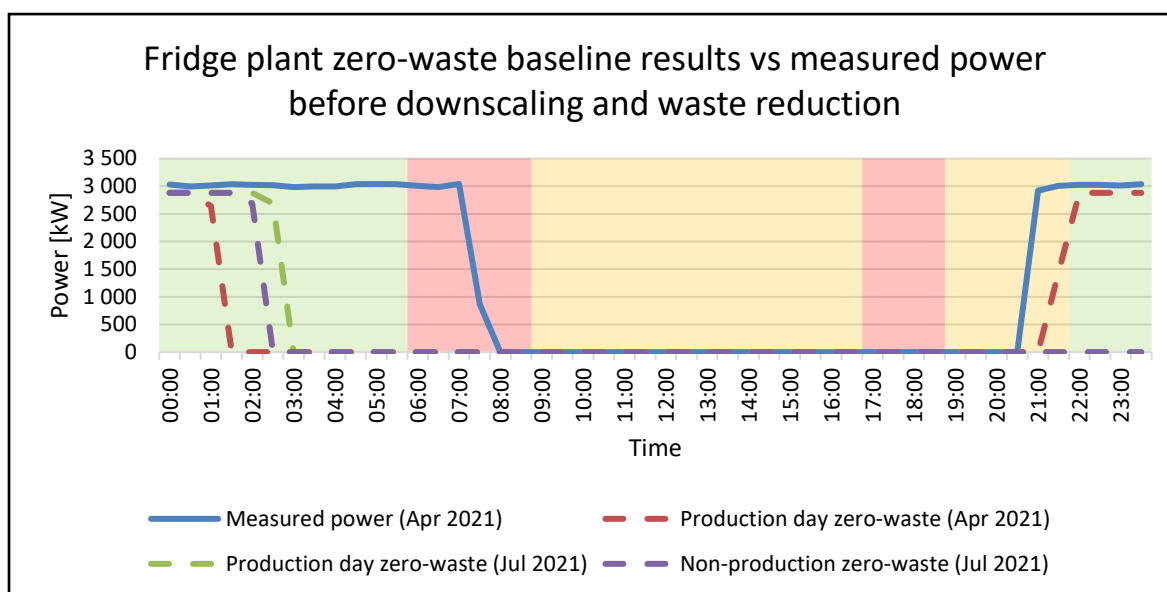


Figure 3-23: Fridge plant power zero-waste baseline model vs initial measured power

3.5.4. Step 3: Implementing energy management initiatives

Two audits were conducted on the water reticulation system between April and July 2021 as the mine gradually downscaled operation, following the same process as on Mine A in Case Study 1. Significant leaks were reported and fixed on levels 71 and 69 and pipes going to levels 69-90x/c and 71-90x/c were blanked off, as those areas had stopped production. This resulted in a significant reduction in the total mining water demand, as presented in Figure 3-24. However, the demand did not reduce to zero-waste baseline simulated values due to large inefficiencies in the stopes and development ends not being addressed. Despite this, the reduction in demand allowed for a reduction in the daily operating hours of the fridge plants, as shown in Figure 3-25. This allowed for the implementation of improved load shifts.

Table 3-12: Fridge plant energy management implementation results

Profile	Daily flow volume [MI]	Daily energy demand [MWh]	Daily running hours [hr]
Production day zero-waste baseline	0.2	8.5	3.0
First audit	1.5	32.1	11
Second audit	1.4	21.5	8
Third audit	1.2	20.3	7

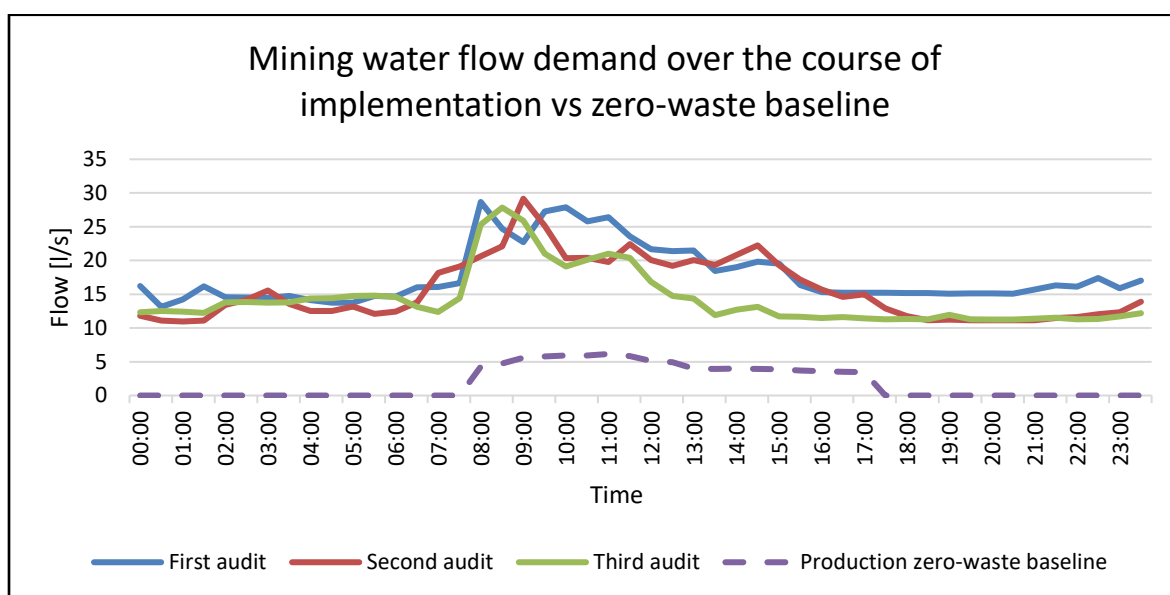


Figure 3-24: Mine B service water flow measurements taken between April and July 2021

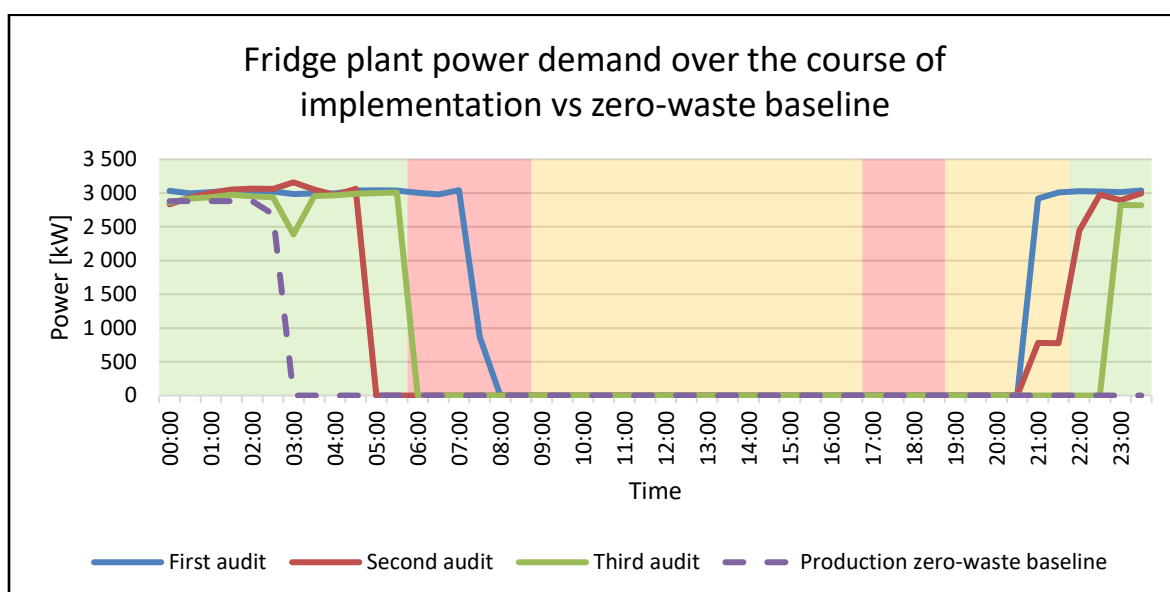


Figure 3-25: Mine B fridge plant power measurements taken between April and July 2021

3.5.5. Step 4: Evaluating results

Implementing the energy management initiative on the fridge plants at Mine B enabled energy savings of 0.89 GWh of a potential LOM savings of 10 GWh to be made between April and December 2021, as shown in Figure 3-26. However, two major factors prevented consistent savings from being realised over the LOM. First, there were constant breakdowns on the level pressure reducing valves (PRVs) which resulted in large quantities of waste over a short period of time. Second, the BAC demand increased due to ventilation system reconfigurations made due to fall of ground incidences. However, if wastage was not reduced over the implementation period, the service water demand would have increased further.

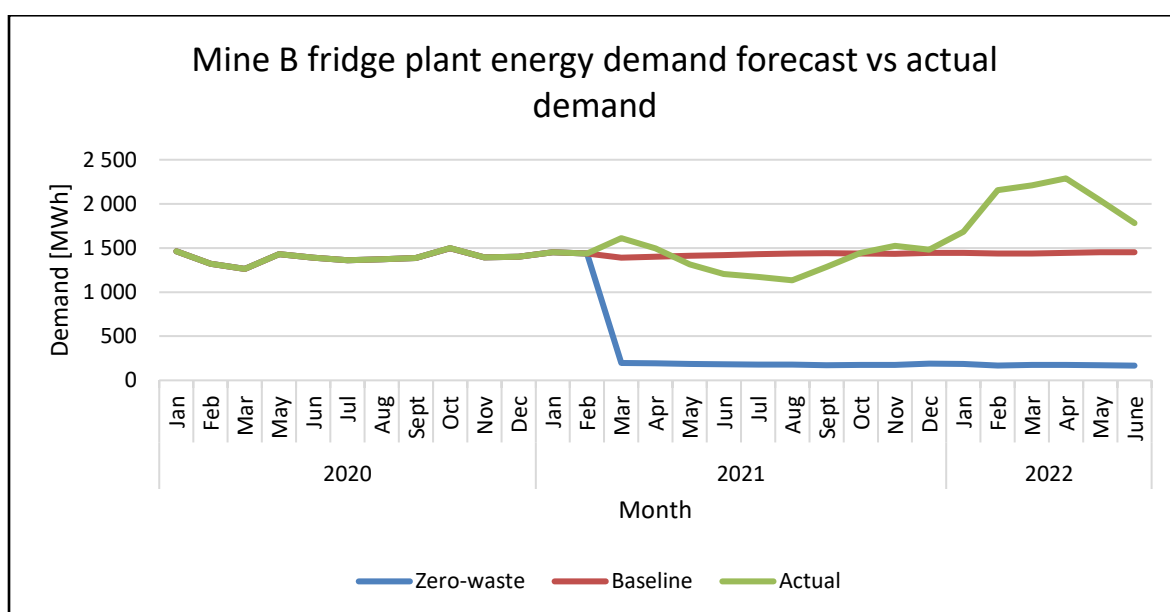


Figure 3-26: Evaluating Mine B fridge plant energy demand forecast vs actual demand

Significant energy cost savings were achieved from April 2021 to February 2022 due to the implementation of the waste reduction and energy management initiatives, as shown in Figure 3-27. Overall, this saved Mine B R2.9 million out of a potential R7.6 million in energy costs over the remaining LOM despite the increase in demand from July 2021. This was primarily due to improved and consistent fridge plant load shifts taking place after the implementation of the waste reduction and energy management initiatives.

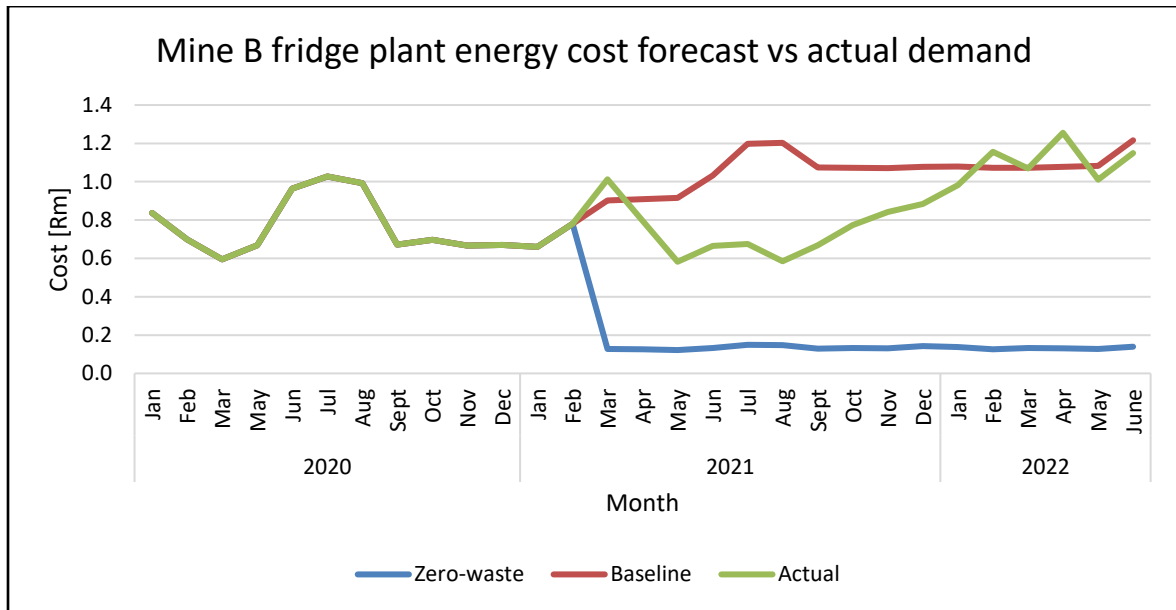


Figure 3-27: Evaluating Mine B fridge plant energy cost forecast vs actual cost

3.5.6. Case study 2 conclusion

Waste reduction and energy management initiatives were successfully implemented on Mine B's water reticulation and refrigeration system in line with the planned downscaling of operations from March 2021 to the end of the LOM in June 2022. However, infrastructure and ground condition challenges limited the potential for further savings. Despite these challenges, the implementation of the methodology presented in this study resulted in a total energy cost saving of R2.9 million over the remaining LOM.

3.6. Discussion

This section discusses the validity of the case study results by critically analysing and evaluating the extent to which they meet the study objectives.

3.6.1. Identify characteristics of mines nearing closure

This study aimed to identify key characteristics of mines nearing closure. This was achieved by evaluating multiple gold mining operations using historic five-year production trends, CAPEX trends, energy intensity trends, and the planned LOM. These were used to determine operations on which to implement specific energy waste reduction and energy management initiatives. Mine A and Mine B were selected for the case studies, as they had low CAPEX allocations relative to the

other operations and a decreasing trend in production. Mine A had a relatively low energy intensity. However, it also had the lowest LOM. Mine B had one of the highest energy intensities of the mines evaluated due to its lower production output. The key characteristics were identified on Mine A and Mine B, and as such they were selected as case studies. These results validate the identification of the key characteristics used to classify mines nearing closure.

3.6.2. Identify changes in planned LOM production trends on mines nearing closure

The LOMPs of both case study mining operations were evaluated. The plans for both operations showed a long-term decreasing trend. There was also a reduction in active workplaces, levels, and crosscuts as the mines neared closure. Despite both case study mines planning to close within the succeeding three years they both ultimately closed for different reasons. Mine A closed due to ageing infrastructure and the unfeasibility of extracting the existing ore. This led to the shaft production being reduced by 3 062 m² between February 2018 and May 2018 and gradually decreasing over the remaining LOM. This resulted in production stopping on five levels and 59 workplaces, with the remaining levels reducing production.

Mine B planned to complete mining the shaft pillar and close by 2023; however, its LOM was reduced by a seismic event due to the shaft pillar being significantly mined out. This resulted in the operation gradually reducing production and closing unfeasible crosscuts from April 2021 to its eventual closure in June 2022. This resulted in a planned production decrease of 617 m² between April 2021 and July 2021, resulting in two crosscuts and 5 workplaces being closed and production being reduced at the remaining crosscuts. These results validate the necessity of identifying changes in production location and output as mines downscale operations and near closure.

3.6.3. Identify resource and energy wastage on mines nearing closure

The simulation results from the resource zero-waste baselines developed for Mine A and Mine B identified a demand reduction of 48% and 85% respectively due to wastage reduction. A total demand reduction of 68% and 90% for Mine A and Mine B respectively was identified due to the planned downscaling as presented in Table 3-13. This indicates that wastage reduction overall has a higher impact on demand than production downscaling. However, including downscale planning in zero-waste baseline development can identify sources of wastage, resulting in further potential for demand reduction, especially if significant downscaling is planned as was done in Case Study 1.

Table 3-13: Resource zero-waste baseline analysis

Period	Case study 1			Case study 2		
	Max. compressed air demand [kg/s]	Demand reduction [kg/s]	Reduction [%]	Mining water demand [MI/day]	Demand reduction [MI/day]	Reduction [%]
Measured demand before planned downscaling	15.31	-	-	1.54	-	-
Zero-waste baseline before planned downscaling	7.91	7.39	48%	0.24	1.30	85%
Zero-waste baseline after planned downscaling	4.95	10.36	68%	0.16	1.38	90%

The simulation results from the energy zero-waste baselines indicated a similar trend to the resource zero-waste baselines for both case studies. This is due to the energy demand of the system being directly impacted by the resource demand. However, energy savings were achieved by different means in both case studies. The energy demand reduction for Case Study 1 was achieved by reducing the number of compressors supplying the zero-waste demand. The energy demand reduction for Case Study 2 was achieved by reducing the running time of the fridge plants over 24 hours given the reduced mining water demand. The energy zero-waste baselines identified the potential to reduce the energy demand by 55% and 73% on Mine A and Mine B respectively, as presented in Table 3-14. These results validate the study's objective of identifying potential wastage.

Table 3-14: Energy zero-waste baseline analysis

Period	Case study 1			Case study 2		
	Energy demand [MWh/day]	Demand reduction [MWh/day]	Reduction [%]	Energy demand [MWh/day]	Demand reduction [MWh/day]	Reduction [%]
Measured demand before planned downscaling	117.0	-	-	32.1	-	-
Zero-waste baseline before planned downscaling	55.7	61.2	52%	10.7	21.4	67%
Zero-waste baseline after planned downscaling	52.9	64.0	55%	8.5	23.5	73%

3.6.4. Implement an energy management strategy to reduce energy demand on mines nearing closure

The systems on the case study mines already had energy management initiatives implemented on them. A relatively fast, low-cost, and high-impact approach was taken to further reduce the energy demand as production downscaling took place. A systematic approach was used to implement waste reduction and energy management initiatives on the case study mines. Measurements were taken before, during, and after the implementation of waste reduction initiatives to determine their impact as well as the viability of implementing energy management initiatives on the respective systems.

Continuous demand reductions were achieved over the planned downscaling period for both case studies. However, better results were achieved in Case Study 1 compared to Case Study 2, as presented in Table 3-15. The implementation of waste reduction in Case Study 1 over the downscaling period resulted in a 40% reduction in demand between the first and third audits, but only a 19% reduction was achieved in Case Study 2. This was due to two factors: first, multiple levels were closed in Case Study 1, allowing for entire levels to be blanked off, resulting in significant demand reduction. Second, all the levels in Case Study 2 remained active; however, the number of crosscuts and workplaces decreased.

Due to the interconnected nature of the water supply in the workplaces, it was more difficult to blank off supply to inactive workplaces. However, large leaks were still identified and the supply to inactive crosscuts blanked off, resulting in an overall demand reduction.

Table 3-15: Implementing energy management strategy

Associated audit	Case study 1			Case study 2		
	Max. CA demand [kg/s]	Demand reduction [kg/s]	Reduction [%]	Mining water demand [MI/day]	Demand reduction [MI/day]	Reduction [%]
First audit	15.31	-	-	1.93	-	-
Second audit	12.85	2.46	16%	1.35	0.18	12%
Third audit	9.26	6.05	40%	1.24	0.29	19%

An overall daily energy reduction of 45% was achieved in Case Study 1 and a 37% reduction was achieved in Case Study 2, as presented in Table 3-16. The reduction in Case Study 1 was due to one compressor being permanently switched due to the decreased flow demand. One compressor was

sufficient to supply the demand for peak drilling. However, during non-drilling periods, the compressor oversupplied the system, leading to a compressor surge and the compressor blowing off to release the excess pressure. This resulted in some wastage; however, the overall energy demand of the system significantly decreased.

Table 3-16: Implementing energy management strategy

Associated audit	Case study 1			Case study 2		
	Daily energy demand [MWh]	Demand reduction [MWh]	Reduction [%]	Daily energy demand [MWh]	Demand reduction [MWh]	Reduction [%]
First audit	117	-	-	32.1	-	-
Second audit	94	23.0	20%	21.5	10.5	33%
Third audit	65	52.1	45%	20.3	11.8	37%

The fridge plant energy demand in Case Study 2 was impacted by the mining water demand and the BAC demand. The BAC demand was not considered in the waste reduction and downscaling audits, as it was a closed-loop system and not directly impacted by changes in production. Any changes to the BAC system would have required a wastage and downscaling audit on the ventilation system which was out of the scope of this study.

The energy reduction in Case Study 2 was due to a reduction in the running time of the fridge plants due to the decreased mining service water demand. This resulted in opportunities for improving the existing load shifts conducted on the fridge plants, leading to further energy cost savings, especially during high-demand periods in the year despite the service water demand not decreasing as significantly as the compressed air demand.

The results show that the energy demands of the compressed air system on Mine A and refrigeration systems on Mine B decreased over the downscaling period. This validates the impact of implementing an energy management strategy on mines downscaling operations and nearing closure.

3.6.5. Quantify the LOM impact of implementing an energy management strategy on mines nearing closure

The LOM impact of implementing the waste reduction and energy management initiatives was evaluated against an energy baseline developed using historic monthly energy and production values. The LOM impact of implementing an energy management strategy is presented in Table

3-17. The results from Case Study 1 shows a 32 GWh energy saving and a R32 million cost saving over the remaining LOM, which is a 41% reduction in demand from the baseline. However, the energy and cost savings were still below the forecast zero-waste reduction of 48% due to minor inefficiencies in the system as well as the compressor blowing off during low-demand periods.

Continuous LOM energy and cost savings were not achieved in Case Study 2. However, an energy saving of 0.89 MWh and a cost saving of R2.9 million were achieved between June 2021 and December 2021. The refrigeration system energy demand significantly increased from December 2021 due to continuous issues with PRV leaks and an increase in BAC demand due to a ventilation system reconfiguration resulting from a fall of ground incident.

This result indicates that continuous monitoring and maintenance are required to maintain energy saving over the remaining LOM even after production downscaling has taken place. The results from both case studies successfully demonstrated the validity of the presented methodology by adequately quantifying the LOM impact of implementing an energy management strategy on mines nearing closure.

Table 3-17: LOM impact of implementing wastage reduction and energy management initiatives

Case study	Period	Profile	Energy savings [GWh]	Energy savings [%]	Cost saving [R million]	Cost savings [%]
Case study 1	May 2018 – Jul 2020	Actual	32	41%	32	41%
		Zero-waste	38	48%	38	48%
Case study 2	Jun 2021 – Dec 2021	Actual	0.89	8%	2.9	34%
		Zero-waste	10	87%	7.6	87%

3.6.6. Study validation

The results presented in the discussion determine that all the study objectives were met, thus proving the validity of the study. A summary of the validation is presented in Table 3-18.

Table 3-18: Study validation

Objective	Validation
Identify characteristics of mines nearing closure.	• The characteristics of mines nearing closure were identified and used to select case study mines.
Identify changes in planned LOM production trends on mines nearing closure.	• Production plans were analysed over the remaining LOM to quantify the extent of downscaling at the operations.
Identify resource and energy wastage on mines nearing closure.	• Simulation models were used to develop zero-waste baselines according to the production downscaling.
Implement an energy management strategy to reduce energy demand on mines nearing closure.	• Waste reduction and energy management initiatives were implemented on the case study operations.
Quantify the LOM impact of implementing an energy management strategy on mines nearing closure.	• Energy and cost savings of implementing the energy management strategy were quantified for the remaining LOM.

3.7. Chapter conclusion

Two case studies were conducted to determine the validity of implementing the methodology presented in this study. The results of the case studies were presented and critically analysed. The results successfully fulfilled the study objectives. The study conclusions and recommendations for future studies are presented in Chapter 4.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

4.1. Chapter introduction

This chapter presents the conclusion and recommendations for further research in this field. The conclusion in Section 4.2. provides an overview of the study with concluding remarks on its success and relevance. Potential study improvements and prospects for further research are presented as recommendations in Section 4.3.

4.2. Conclusion

There has been a constant production decline in the South African gold mining industry, primarily due to deeper ore reserves and increasing energy costs. This contributes to the increased cost of production, leading to the infeasibility of operating many gold mines in South Africa. These increasing costs along with ageing infrastructure have led to the closure of multiple gold mines over the years, with around 77% of existing gold mines planning to close between 2023 – 2040.

Compressed air systems and water reticulation systems form a significant portion of the underground infrastructure on conventional deep-level gold mines. These systems are also the most energy-intensive systems on these mines. The compressed air systems consist of surface compressors and a vast underground reticulation network of pipes supplying underground demands. Water reticulation systems consist of refrigeration plants, dewatering pumps, and a piping network supplying underground demands. The compressors, refrigeration plants, and dewatering pumps are the primary consumers of energy in these systems.

The problems identified on these ageing mines were a result of ageing infrastructure, a lack of maintenance, and inadequate downscale planning. The underground compressed air and water reticulation networks are also prone to significant wastage, leading to a higher energy demand on the compressors, refrigeration plants, and dewatering pumps. A literature study of 16 research papers were conducted to evaluate available research that addressed similar issues across the mining and engineering industries. The evaluated literature was categorised into LOM planning, baseline development, and energy management.

A gap was identified in the available literature between LOM planning as well as baseline development and energy management. This resulted in the need to develop a study to bridge this gap. As such, this study was conducted to develop an energy management strategy for mines

nearing closure. To successfully address the problem statement, the following study objectives were developed:

1. Identify key characteristics of mines nearing closure.
2. Evaluate the LOM production plans to determine changes in production location and output of mines nearing closure.
3. Develop resource- and energy-demand baselines for mines nearing closure.
4. Outline an energy management implementation strategy for mines nearing closure.
5. Evaluate the impact of implementing energy management initiatives on mines nearing closure.

An energy management methodology was developed based on these objectives. The methodology followed a four-step approach based on previous methods developed in the available literature.

Step 1 involved evaluating the LOM characteristics of mines nearing closure to identify key trends of mines nearing closure, including declining production trends, declining CAPEX, increasing energy intensity, and short LOMs. These trends were used to select the case study mines. Mine A and Mine B were selected from a gold mining company, as they were within three years of closure and had decreasing production trends and decreasing CAPEX. Mine A planned to reduce production by 3 062 m³, and Mine B planned to reduce by 617 m³ respectively over the succeeding five months. This resulted in the potential to reduce the energy demand on their high energy-consuming systems. The compressed air system was selected on Mine A and the refrigeration system was selected on Mine B.

Step 2 involved developing a zero-waste baseline for a mine nearing closure. This included simulating compressed air demand and compressor energy zero-waste baselines for Mine A and mining water demand and refrigeration plant energy zero-waste baseline for Mine B. The results of the zero-waste simulation showed the potential to reduce the maximum compressed air demand by 10.36 kg/s and energy demand by 64 MWh/day on Mine A after production downscaling. There was potential to reduce mining water demand by 1.38 ML/day and energy demand by 23.5 MWh/day on Mine B after production downscaling. The zero-waste baselines were used to identify locations with a high potential for wastage and identify the optimised resource and energy demand at the mines. These results were used to guide the implementation of energy management initiatives at the respective mines.

Step 3 involved developing an implementation strategy for energy management initiatives. The implementation focused on identifying workplaces planned for closure and waste reduction. Points of wastage and inactive workplaces were confirmed using underground audits guided by the findings from the zero-waste baselines, LOM production plans, and input from mine personnel. Three sets of audits were conducted iteratively over the downscaling period whilst the resource and energy demands of the systems were monitored and corrective action taken. Over the implementation period, Mine A had a compressed air demand reduction of 6.05 kg/s because of compressed air pipelines to five inactive levels being blanked. This resulted in a compressor being permanently switched off, resulting in an energy reduction of 52 MWh/day. Mine B had a mining water demand reduction of 0.29 ML/day due to two inactive crosscuts being blanked off and multiple leaks being identified and fixed. This resulted in a reduction in the fridge plant running time, resulting in an energy reduction of 11.8 MWh/day.

Step 4 involved evaluating the impact of implementing energy management initiatives on mines nearing closure. An energy forecast baseline was developed for the remaining LOM using historic production and energy data. The zero-waste baseline and actual energy demand were evaluated against the forecast baseline to determine the impact of implementing waste reduction and energy management initiatives on the case study mines. Mine A realised a LOM energy and cost reduction of 32 GWh and R32 million respectively. Mine B realised an energy and cost reduction of 0.89 GWh and R2.9 million, respectively, between June 2021 and December 2021. The full extent of savings was not realised on Mine B due to the impact of seismic activity and infrastructure breakdowns as the mine neared closure.

The energy demand in both case studies decreased over the planned production downscaling period, resulting in energy and cost savings for the mines as they neared closure. However, further savings could have been achieved on Mine B by conducting further investigations after the impact of the seismic activity. However, the results obtained from the case studies validated the methodology and successfully addressed the study objectives.

4.3. Recommendations

This section outlines recommendations for improving and expanding this study. The following recommendations will be expanded on below.

- Expand the scope to develop a holistic energy management strategy that includes all high-energy consuming systems on mines nearing closure.
- Adapt this energy management strategy to be implemented on different types of mining operations nearing closure.
- There is scope to investigate substituting high energy-consuming machinery with more efficient replacements as mines near closure.

This study focused exclusively on implementing a waste reduction and energy management strategy on compressed air and refrigeration systems of gold mines nearing closure. Deep-level mines consist of multiple high energy-consuming systems such as winders and ventilation systems. There is scope to implement and adapt a similar approach to reduce the energy demand on these systems on mines nearing closure. An integrated approach can also be explored to provide a holistic energy management approach to mines downscaling operations or nearing closure. This approach can result in significant energy and cost savings over the remaining LOM.

Deep-level gold mines form a subset of total mining operations. Many other resources are mined in South Africa, including PGMs, coal, and manganese amongst others. Different mining techniques are used when mining these resources. These include decline mining operations and open-cast mining operations amongst others. These operations have infrastructure and equipment that differ from conventional deep-level gold mining, including but not limited to hydro drilling infrastructure, the use of diesel machinery for drilling and ore transport, and the use of smaller compressors and pumping infrastructure. However, many will eventually face the problem of resource depletion and high levels of wastage. Operations will need to eventually downscale before closure due to the nature of the industry. Therefore, there is scope to adapt the methodology presented in this study to these cases.

This study focused on implementing no-cost waste reduction and energy management initiatives. Further research can be conducted to identify viable low-cost energy management initiatives to be implemented on mines nearing closure. There is scope to research the impact of procuring or hiring less energy-intensive equipment for the remaining LOM, particularly in the case of reducing

compressed air demand. In some cases, the compressed air demand may drop below the minimum supply flow specified for large compressors, resulting in the compressors reaching their surge pressure and blowing off, leading to energy wastage. Introducing a cluster of small compressors to the system could reduce this wastage and realise further savings, depending on the ROI.

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Appendix B

This appendix presents supplementary information for Step 2 of the methodologies for both case studies. Figure B-1, B-2 and B-5 present the simulation calibration results for the compressed air zero-waste baseline models. Figure B-3 presents the compressor performance and efficiency curves used to simulate the energy zero-waste baselines developed for Mine A. Figure B-4 presents the surface compressed air configuration for Mine A.

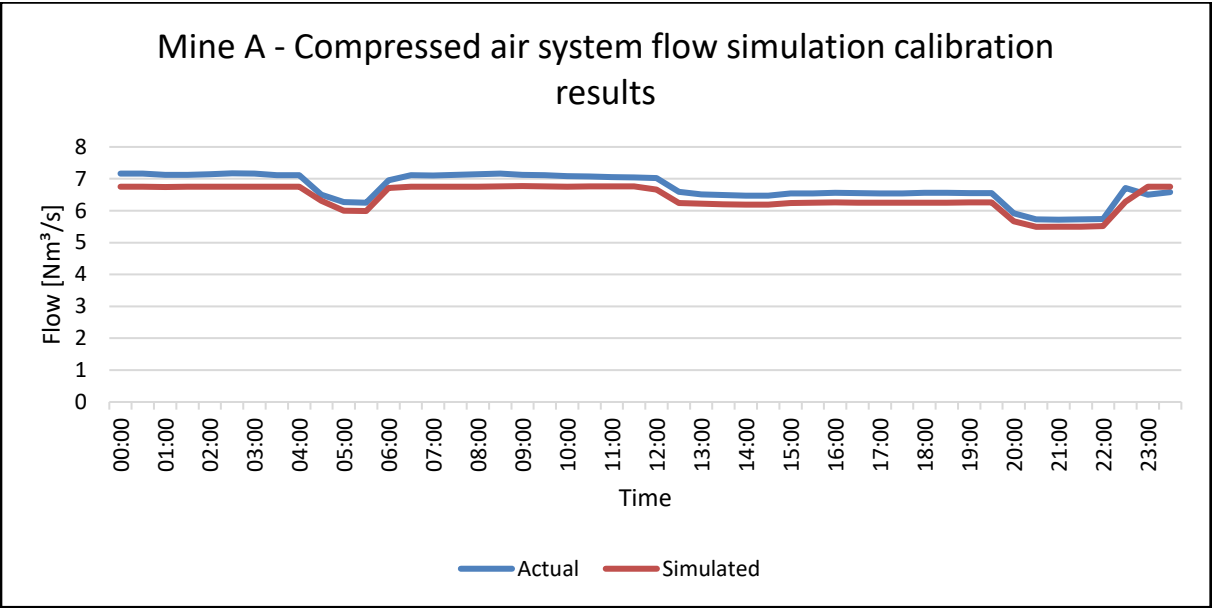


Figure B-1: Mine A - Compressed air system flow calibration results

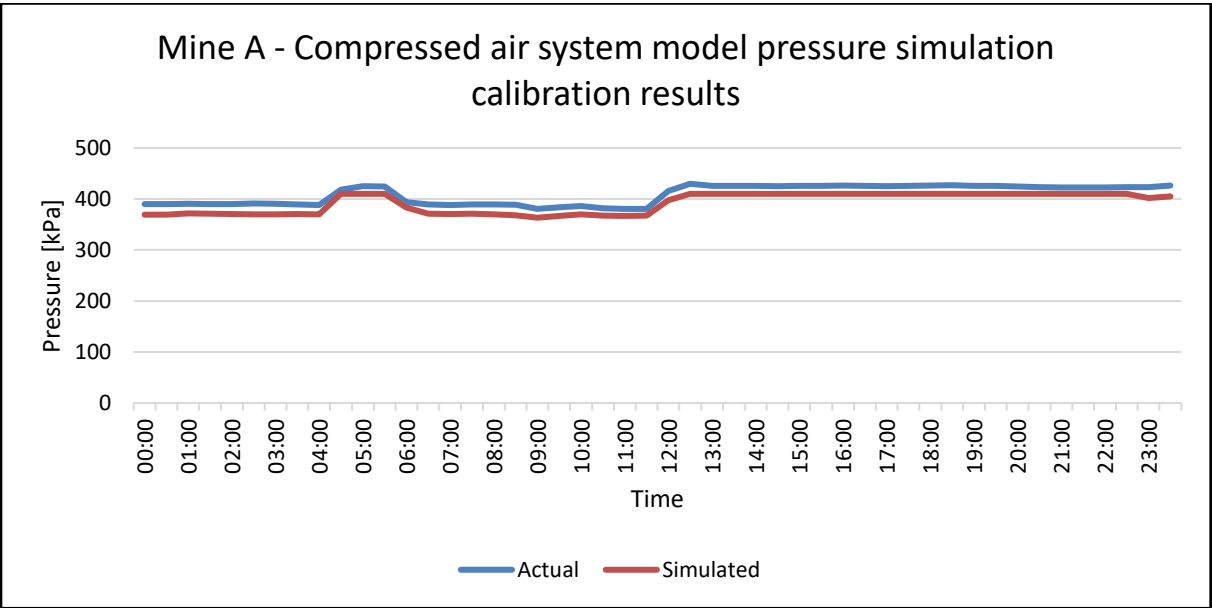


Figure B-2: Mine A - Compressed air system model pressure calibration results

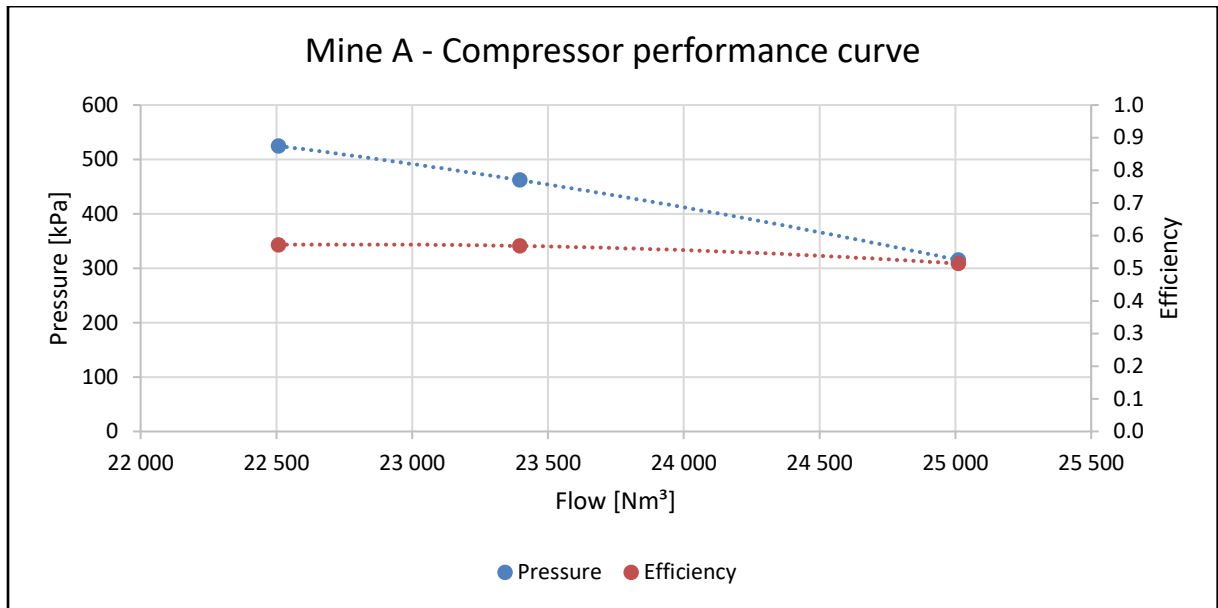


Figure B-3: Mine A compressor performance and efficiency curves

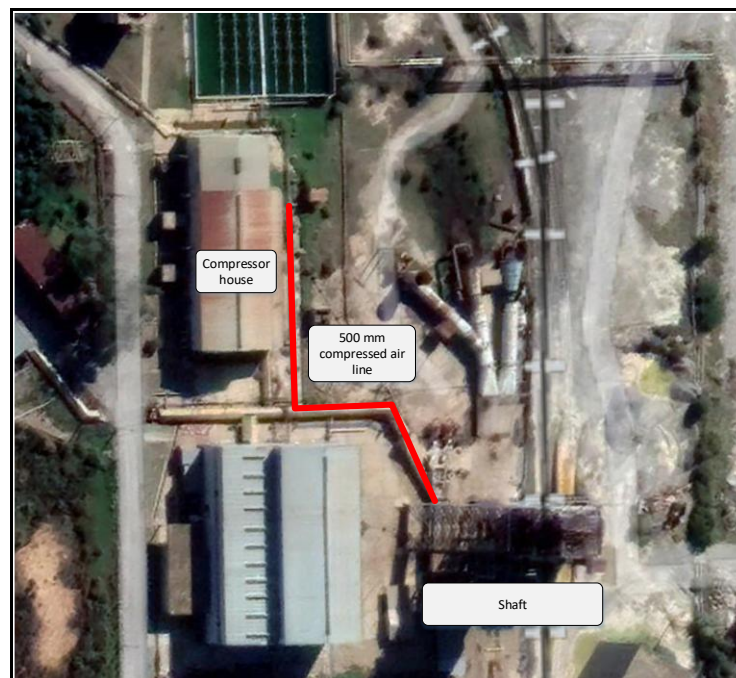


Figure B-4: Surface compressed air layout

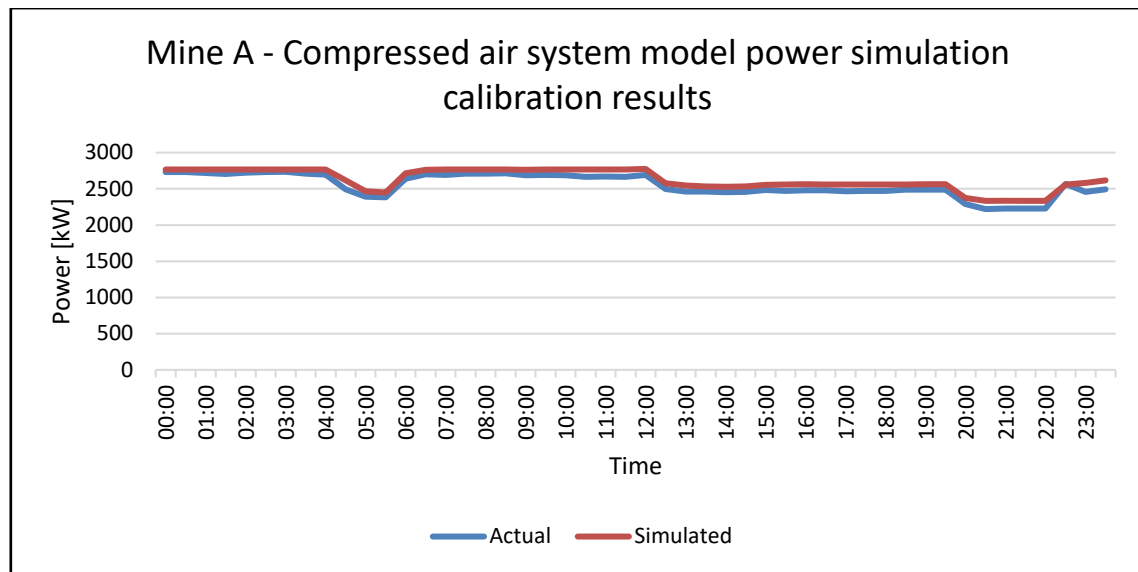


Figure B-5: Mine A - Compressed air system model power calibration results

The zero-waste baseline simulation specifications for Mine B are presented in Table B-1. The fridge plant simulation model layout is presented in Figure B-6. The chill water dam level and fridge plant simulation calibration results are presented in Figures B-7 and B-8.

Table B-1: Fridge plant simulation parameters

Item	Value
Fridge plant COP	2.698
Fridge plant flows	100 kg/s
Number of fridge plants running	2
Chill dam capacity	1 948 m ³
Pipe sizes	300 mm
Underground air temperature	25°C
BAC demand	12 kg/s

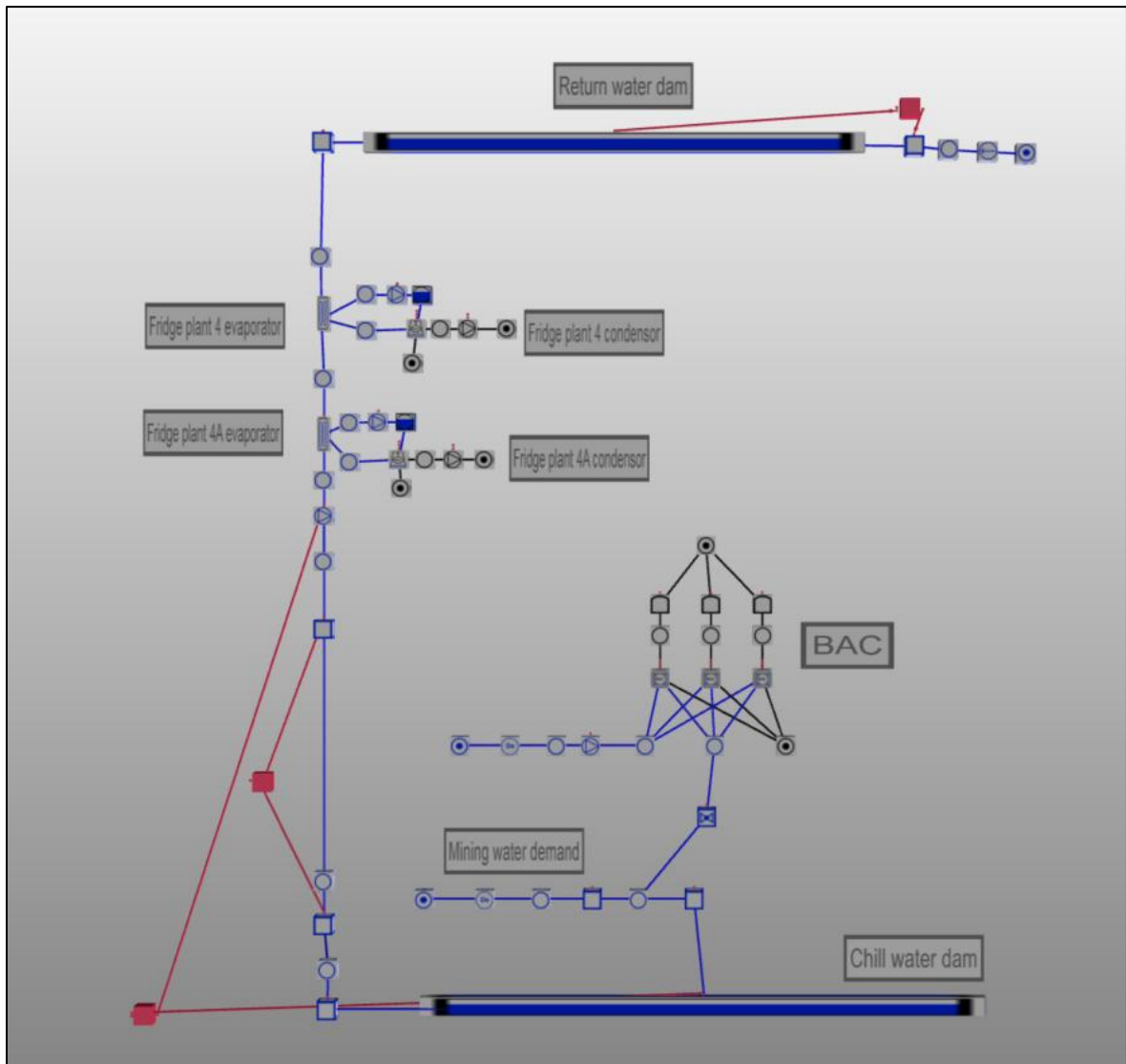


Figure B-6: Fridge plant simulation model layout

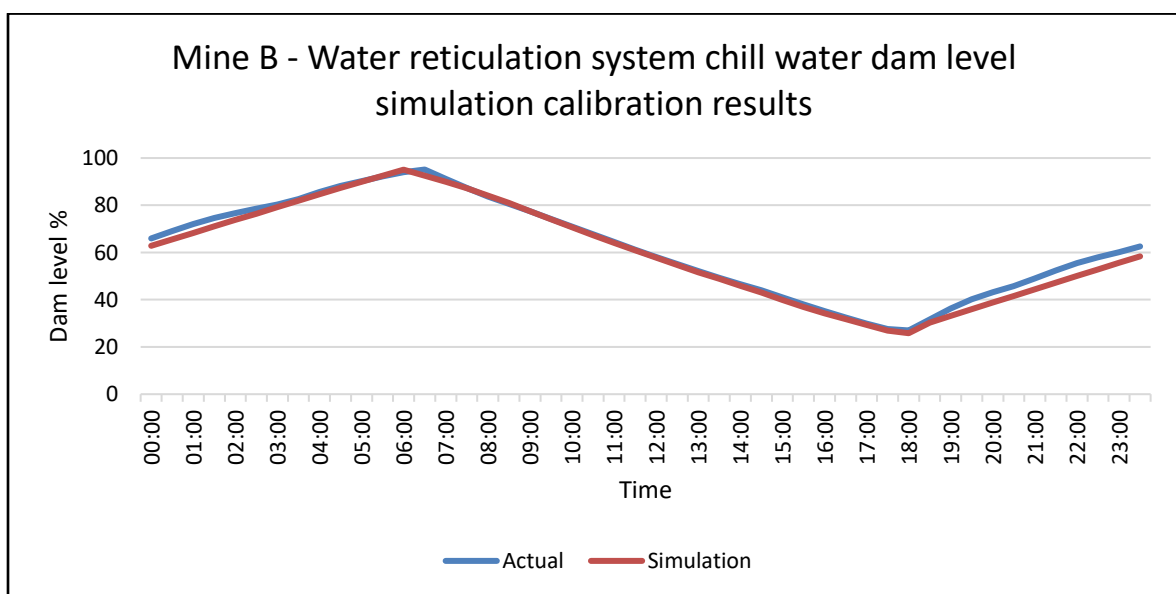


Figure B-7: Mine B - Chill water dam level simulation calibration results

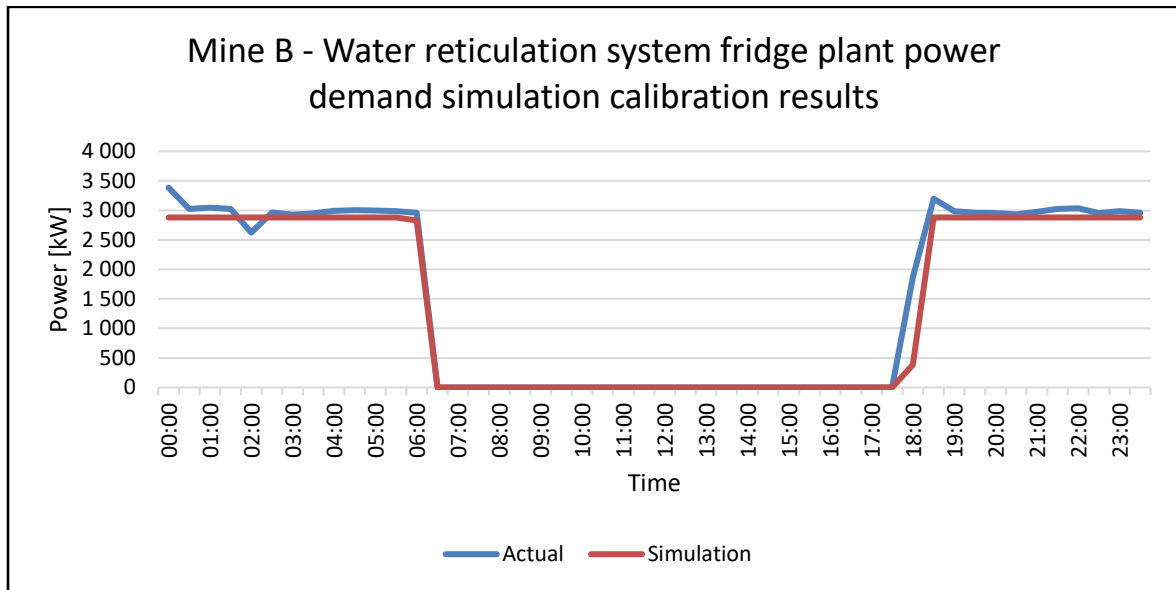


Figure B-8: Mine B - Fridge plant power demand simulation calibration results

Appendix C

This appendix presents supplementary information for Step 3 of the methodology. An example of the underground waste audit sheet is presented in Figure C-1.

Number	Position	Description	Cause	Pipe	Leak size [mm]	Comments
1	39	CA	Gasket	200	2.5	
2	77	W	Hole	200	30	
3	91	CA	Gasket	200	2.5	
4	94	CA	Gasket	200	2.5	
5	95	CA	Gasket	200	2.5	
6	96	CA	Gasket	200	2.5	
7	97	CA	Gasket	200	5	
8	98	CA	Gasket	200	5	
9	107	CA	Gasket	200	2.5	
10	118	CA	Gasket	200	30	Large Gasket Leak
11	124	CA	Gasket	200	5	
12	136	CA	Gasket	200	2.5	
13	149	CA	Gasket	200	2.5	
14	150	CA	Gasket	200	2.5	
15	160	CA	Gasket	200	5	
16	172	CA	Gasket	200	2.5	
17	172	CA	Gasket	200	2.5	
18	211	CA	Gasket	200	2.5	
19	227	CA	Gasket	200	5	
20	232	CA	Gasket	200	5	

Figure C-1: Example of waste audit tracking sheet