

A zero-wastage approach to benchmark energy efficiency on platinum mines

RF Marais

 **orcid.org / 0000-0002-2507-1214**

Thesis accepted in fulfilment of the requirements for the degree
Doctor of Philosophy in Engineering with Development and
Management Engineering at the North-West University

Promoter: Dr HPR Joubert

Co-promoter: Dr JF van Rensburg

Graduation: May 2024

Abstract

Title: A zero-wastage approach to benchmark energy efficiency on platinum mines

Author: Mr R.F. Marais

Supervisor: Dr H.P.R. Joubert

School: North-West University Potchefstroom Campus School of Engineering

Keywords: Benchmarking, zero-wastage, energy efficiency, deep-level mining, platinum mining

The South African mining sector encompasses some of the largest mines in the world. These mines make use of high energy-consuming systems such as compressed air, ventilation, and refrigeration to extract ore from underground. However, the profitability of these mines faces constant threat due to escalating electricity costs and growing pressure from stakeholders to comply with environmental, social, and governance (ESG). Energy efficiency is thus a critical component in reducing energy consumption and producing ‘cleaner’ products. Energy efficiency emerges as a pivotal element in curtailing energy consumption and generating environmentally friendly outputs. Effectively managing energy consumption not only benefits struggling entities like the South African electricity provider Eskom but also aligns with utility cost reduction initiatives and augments ESG scores through the process of decarbonisation. This underscores the imperative role of ongoing research, particularly within the mining industry, in implementing measures to enhance energy efficiency.

Historically, benchmarking methods have been employed to compare analogous systems across different mines with the objective of identifying less efficient systems and components. However, a prominent drawback of this approach lies in its dependence on a multitude of variables inherent in each system. The complexity introduced by these variables, compounded by insufficient available data, can impede the normalisation of diverse systems, rendering the identification of inefficiencies an arduous undertaking. Another critical issue that arises is the dearth of standardised methods for benchmarking a system against itself to discern the wastage within the system.

This study proposes a novel benchmarking method, comprising three novel contributions, for calculating a system’s zero-wastage baseload for optimal efficiency, guided by comprehensive and reliable data considerations. Sub-processes have been developed to calculate zero-wastage baseload either through simulation or a theoretical perspective, depending on the available data. This study’s innovative benchmarking method provides mines with a tangible

target, facilitating a gradual approach towards achieving zero-wastage baseload. Ultimately, this method has the potential to yield substantial cost savings in terms of electricity and resources, advertently also promoting ESG objectives.

The zero-wastage benchmarking process was applied to three case studies involving two compressed air networks and a water reticulation system, respectively the zero-wastage benchmarking process revealed a substantial 49% reduction potential in Case Study A, translating to a noteworthy 72.7 MWh energy efficiency gain over a 24-hour profile. Case studies B and C demonstrated comparable outcomes, with possible reductions of 56% and 25.7%, respectively.

The study's findings underscore the efficacy of the methodology in pinpointing areas with the potential for enhanced efficiency within each case study. Furthermore, the model adeptly identified the least efficient mining levels within a system so that they could be prioritised. This targeted approach provides a more focused approach to energy efficiency projects compared to other efficiency methods.

Acknowledgements

Firstly, I would like to thank God for all the blessings I have received throughout my life. Without it, I would not be where I am today.

Thank you to my wife, Lené Marais, for her continuous support throughout my study.

To my parents and sister, I would like to say thank you for providing me with the necessary support to be able to further my studies.

Thank you to ETA Operations (Pty) Ltd, Enermanage and all the contributors for providing me with the resources needed to complete my studies.

A special thanks to Jean van Laar, Rudi Joubert and Bertie Pascoe for assisting and supporting me throughout my study.

To everyone who has played a part, big or small, in the completion of this thesis, I offer my deepest gratitude. Your support, guidance, and encouragement have been truly invaluable, and I am honoured to have had the opportunity to work on this research project with your unwavering support.

Table of Content

ABSTRACT	I
ACKNOWLEDGEMENTS	III
TABLE OF CONTENT	IV
LIST OF FIGURES.....	VII
LIST OF TABLES	X
LIST OF EQUATIONS	XII
LIST OF ABBREVIATIONS	XII
CHAPTER 1 – INTRODUCTION & LITERATURE REVIEW.....	1
1.1 PREAMBLE	1
1.2 ELECTRICITY GENERATION CAPACITY IN SOUTH AFRICA.....	1
1.3 ENVIRONMENTAL, SOCIAL AND GOVERNANCE IN SOUTH AFRICA	2
1.4 SOUTH AFRICAN PLATINUM MINES	2
1.5 PLATINUM MINE UTILITY SYSTEMS	4
1.5.1 <i>Compressed air</i>	4
1.5.2 <i>Dewatering</i>	8
1.5.3 <i>Ventilation</i>	11
1.5.4 <i>Awareness through system target baselines</i>	13
1.6 SIMULATION IN THE MINING ENVIRONMENT	15
1.7 EFFICIENCY THROUGH BENCHMARKING	15
1.8 PROBLEM STATEMENT.....	17
1.9 OVERVIEW OF EXISTING SOLUTIONS	18
1.10 RESEARCH OBJECTIVES.....	28
1.11 NOVEL CONTRIBUTIONS.....	29
1.12 THESIS LAYOUT	32
1.13 CONCLUSION.....	33
CHAPTER 2 – DEVELOPMENT OF SOLUTION	35
2.1 PREAMBLE	35

2.2	ZERO-WASTAGE BENCHMARKING METHOD	35
2.2.1	<i>Step 1: Establish site parameters</i>	37
2.2.2	<i>Step 2: System identification</i>	39
2.2.3	<i>Step 3: Zero-wastage baseload</i>	40
2.2.4	<i>Step 4: Dynamic achievable target</i>	49
2.3	CONCLUSION	51
3	CHAPTER 3 – PRACTICAL IMPLEMENTATION OF SOLUTION	54
3.1	PREAMBLE	54
3.2	CASE STUDY A	54
3.2.1	<i>Step 1: Establish site parameters</i>	55
3.2.2	<i>Step 2: System identification</i>	56
3.2.3	<i>Step 3A: Theoretical zero-wastage</i>	57
3.2.4	<i>Step 4: Dynamic achievable target</i>	62
3.2.5	<i>Comparison with previous studies</i>	64
3.3	CASE STUDY B	67
3.3.1	<i>Step 3B: Zero-wastage simulation</i>	68
3.3.2	<i>Step 4: Dynamic achievable target</i>	75
3.3.3	<i>Comparison with previous studies</i>	76
3.4	CASE STUDY C	78
3.4.1	<i>Step 1 and Step 2: System identification and establishing site parameters</i>	78
3.4.2	<i>Step 3B: Zero-wastage simulation</i>	80
3.4.3	<i>Step 4: Dynamic achievable target</i>	84
3.4.4	<i>Comparison with previous studies</i>	85
3.5	CROSS-CASE DISCUSSION	86
3.6	ROADMAP TO MITIGATE FUTURE SYSTEM COSTS	87
3.7	CONCLUSION	90
4	CHAPTER 4 – CONCLUSION AND RECOMMENDATIONS	93
4.1	CONCLUSION	93
4.2	RECOMMENDATIONS	95

5	REFERENCES	97
	APPENDIX A – ADDITIONAL INFORMATION	107
	ESKOM TARIFF INCREASE	107
	POWER CALCULATION FORMULAE	107
	APPENDIX B - AUDIT	109
	APPENDIX C - ADDITIONAL CASE STUDY RESULTS	111
	APPENDIX D - ZERO-WASTAGE ARTICLE	113

List of figures

Figure 1: Eskom electricity sales distribution 2019 [5]	1
Figure 2: Location of the Bushveld Igneous Complex [14], [17]	3
Figure 3: Global platinum group metal reserves [18]	3
Figure 4: Platinum energy demand distribution [22]	4
Figure 5: High-level schematic of an underground compressed air system	5
Figure 6: High-level schematic of an underground dewatering system	9
Figure 7: High-level schematic of an underground ventilation system	12
Figure 8: Example of energy target vs actual for a mining group	14
Figure 9: Case study research methodology [101], [102]	29
Figure 10: Proposed zero-wastage benchmarking method	36
Figure 11: Relationship between the solution criteria and the zero-wastage benchmarking method	37
Figure 12: Zero-wastage benchmarking method – establish site parameters	37
Figure 13: Zero-wastage benchmarking method – system identification	39
Figure 14: Step 3A – theoretical zero-wastage	41
Figure 15: Theoretical zero-wastage method [81]	41
Figure 16: Zero-wastage vs actual consumption comparison [81]	42
Figure 17: Zero-wastage benchmarking method – zero-wastage simulation	43
Figure 18: Step 3B – zero-wastage simulation method	45
Figure 19: Example of an underground mine layout	46
Figure 20: Compressed airflow and pressure meter	46
Figure 21: Zero-wastage simulation – mine layout example	47
Figure 22: Zero-wastage simulation – component selection example	48
Figure 23: Zero-wastage simulation – component detail	48
Figure 24: Step 4 – Zero-wastage dynamic achievable target	50
Figure 25: Dynamic achievable target	50

Figure 26: Proposed zero-wastage benchmarking method.....	54
Figure 27: Case study A – high-level mine layout.....	55
Figure 28: Step 3A – theoretical zero-wastage method	57
Figure 29: Mine A's operational schedule.....	58
Figure 30: Case study A – zero-wastage baseload	60
Figure 31: Case study A – actual consumption vs zero-wastage.....	60
Figure 32: Case study A – zero-wastage baseload validation	61
Figure 33: Step 4 – dynamic achievable target.....	63
Figure 34: Case study A – achievable target.....	64
Figure 35: Case study A comparison with previous study – efficiency benchmarking.....	65
Figure 36: Case study A comparison with previous study – baseline comparison	66
Figure 37: Case study A – comparison with previous study concerning valve control	67
Figure 38: Step 3B – zero-wastage simulation method	68
Figure 39: Case study B – compressed air network drawing	69
Figure 40: Case study B – digital twin	70
Figure 41: Case study B – simulation verification (flow)	71
Figure 42: Case study B – simulation verification (pressure).....	71
Figure 43: Case study B – zero-wastage baseload	72
Figure 44: Case study B – zero-wastage baseload vs actual demand.....	73
Figure 45: Case study B – zero-wastage baseload validation	73
Figure 46: Step 4 – dynamic achievable target.....	75
Figure 47: Case study B – achievable target.....	76
Figure 48: Case study B comparison with previous study – all methods.....	77
Figure 49: Case study C – water reticulation network drawing	78
Figure 50: Case study C – year-on-year water increase.....	79
Figure 51: Case study C – water intensity	79
Figure 52: Case study C – digital twin	80
Figure 53: Case study C – simulation verification.....	81

Figure 54: Case study C – zero-wastage baseload	81
Figure 55: Case study C – zero-wastage baseload vs actual demand	82
Figure 56: Case study C – zero-wastage baseload validation	83
Figure 57: Step 4 – dynamic achievable target.....	84
Figure 58: Case study C – achievable target.....	85
Figure 59: Case study C comparison with previous study – all methods	86
Figure 60: Ten-year forecast of case study A – system cost	88
Figure 61: Estimated Case study A roadmap results.....	89
Figure 62: Eskom tariff history.....	107
Figure 63: Operational schedule template.....	110

List of tables

Table 1: Previous compressed air efficiency studies in mining	8
Table 2: Previous water reticulation efficiency studies in mining	11
Table 3: Previous ventilation efficiency studies in mining	13
Table 4: Literature review methodology	19
Table 5: State-of-the-art matrix	27
Table 6: Alignment of Novel contribution & Research objectives	31
Table 7: Relationship between research methodology and thesis layout.....	33
Table 8: System intensities	39
Table 9: Theoretical zero-wastage vs simulated zero-wastage [33], [74], [79], [80]	40
Table 10: Simulation software package comparison	44
Table 11: Zero-wastage simulation – benchmarked example.....	49
Table 12: Assessment of study criteria against proposed method	52
Table 13: Case study A – system intensity data	56
Table 14: Case study A – system intensity results	57
Table 15: Audit results	58
Table 16: Theoretical compressed air consumption on mine A	59
Table 17: Case study A – per-level results	62
Table 18: Case study B – per-level results	74
Table 19: Case study C – per-level results.....	83
Table 20: Estimated road map of compressed air projects for the mine	89
Table 21: Ten-year cost forecast of a mining group	90
Table 22: Study objectives achieved in the thesis	91
Table 23: Instrumentation gap analysis.....	109
Table 24: Simulation checklist.....	109
Table 25: Case study A - dynamic achievable target results	111
Table 26: Case study B - dynamic achievable target results	111

Table 27: Case study C - dynamic achievable target results	112
--	-----

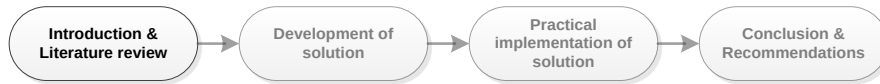
List of equations

Equation 1: System intensity	39
Equation 2: Theoretical consumption	42
Equation 3: System wastage	43
Equation 4: Emissions factor	43
Equation 5: Achievable target scaling factor [109]	51
Equation 6: Dynamic achievable target	51
Equation 7: Power calculation	107
Equation 8: Power calculation from status	108

List of abbreviations

BAC	Bulk air coolers
BEF	Benchmark energy factor
BIC	Bushveld Igneous Complex
CO ₂	Carbon dioxide
DSM	Demand side management
DXF	Drawing exchange format
EPI	Energy performance indicator
ESG	Environmental, social and governance
KPI	Key performance indicator
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
PGM	Platinum group metals
PTB	Process toolbox
SA	South Africa

SCADA	Supervisory control and data acquisition
XC	Crosscut
ZW	Zero-wastage



CHAPTER 1 – INTRODUCTION & LITERATURE REVIEW

1.1 Preamble

This thesis provides a novel approach to identifying energy efficiency potential (wastage) in deep-level mining systems. This chapter begins by offering a background on the problem statement and critically reviews existing efficiency solutions along with their limitations. Subsequently, the research objectives are outlined, along with the unique contributions aimed at addressing the identified problem. A specific research methodology was tailored to meet the study's requirements, aim, and objectives.

1.2 Electricity generation capacity in South Africa

The South African (SA) power utility Eskom accounts for approximately 85% of the total generation capacity [1]. Regrettably, a marked absence of proper maintenance and planning has placed Eskom under enormous pressure to sustain a stable electricity supply since 2010 [2], [3], [4]. By 2019, Eskom's electricity generation capacity had decreased by 4% [5].

The need for additional funding to address maintenance backlogs has led to an annual escalation in electricity tariffs, ranging between 8% and 15% over the last decade [6]. This has directly resulted in rising costs of SA companies [7]. Figure 1 illustrates Eskom's sales distribution for the 2018/2019 financial year. According to the figure, the industrial sector, which includes mining, accounts for 37% of Eskom's total electricity sales [5].

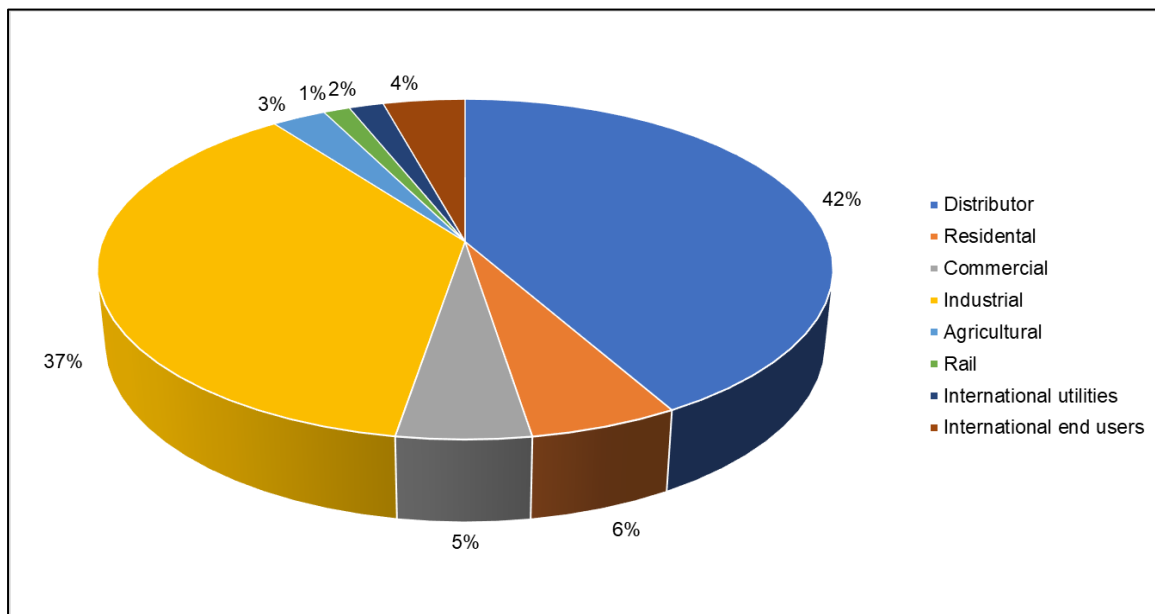
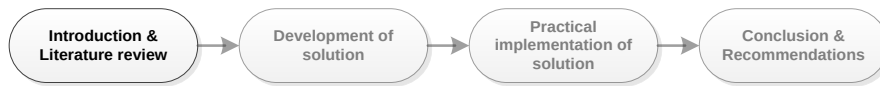


Figure 1: Eskom electricity sales distribution 2019 [5]



1.3 Environmental, social and governance in South Africa

Environmental, social, and governance (ESG) considerations are fast becoming a prominent consideration for companies to thrive in the contemporary market landscape [8]. ESG is one of the compliance measures considered by the market when evaluating a product [9], which entails the following:

- Environmental: Encompassing criteria such as energy source sustainability, energy consumption levels, and the management of resultant waste products.
- Social: Focused on a company's interactions with its employees and entities within its business network.
- Governance: Concerned with the processes adopted to direct the company to apply ethical decision-making to meet the needs of the stakeholders [10].

The benefits of a robust ESG orientation include cost reductions and increased productivity and company value, which make a company more market competitive [10]. Conversely, companies with a weak ESG orientation may be penalised for producing excessive waste in production and face customer and market value losses.

Carbon emissions (CO₂), which fall under the environmental aspect of ESG, have garnered significant attention among larger companies [10]. Investors have begun to compel companies to reduce their carbon footprint, and failure to do so began to influence their portfolio [11]. Consequently, more companies are directing efforts towards the reduction of carbon emissions and offering 'cleaner' products to bolster their corporate image.

The dual challenges of escalating electricity tariffs and ESG compliance place South African mines under strain, necessitating enhanced energy efficiency. This imperative aims to mitigate electricity costs and enhance ESG scores [10], [12].

1.4 South African platinum mines

Mining sectors are dispersed globally, with the SA mining sector containing the largest reserves of platinum group metals (PGM), situated in the Bushveld Igneous Complex (BIC) [13], [14]. The BIC consists of a layered intrusion of magmatic rock located in north-east South Africa [14], [15]. Two major minerals are produced from the BIC, namely platinum and chromium [16]. Refer to Figure 2 for a graphical representation of the BIC's location [17].

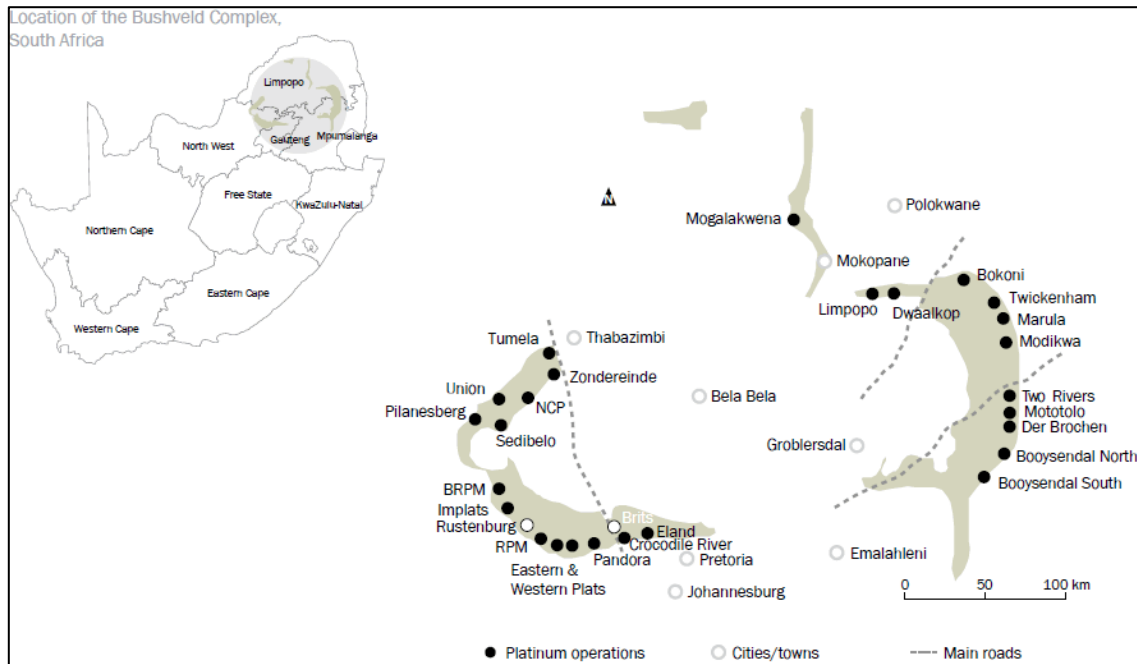
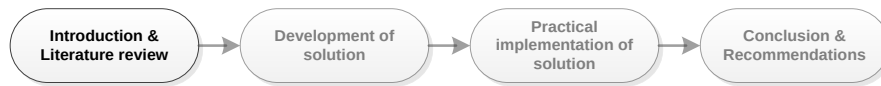


Figure 2: Location of the Bushveld Igneous Complex [14], [17]

As shown in the figure, SA's PGM competes with the likes of Russia, Canada, United States and Zimbabwe in terms of size and exceeds them by far [18].

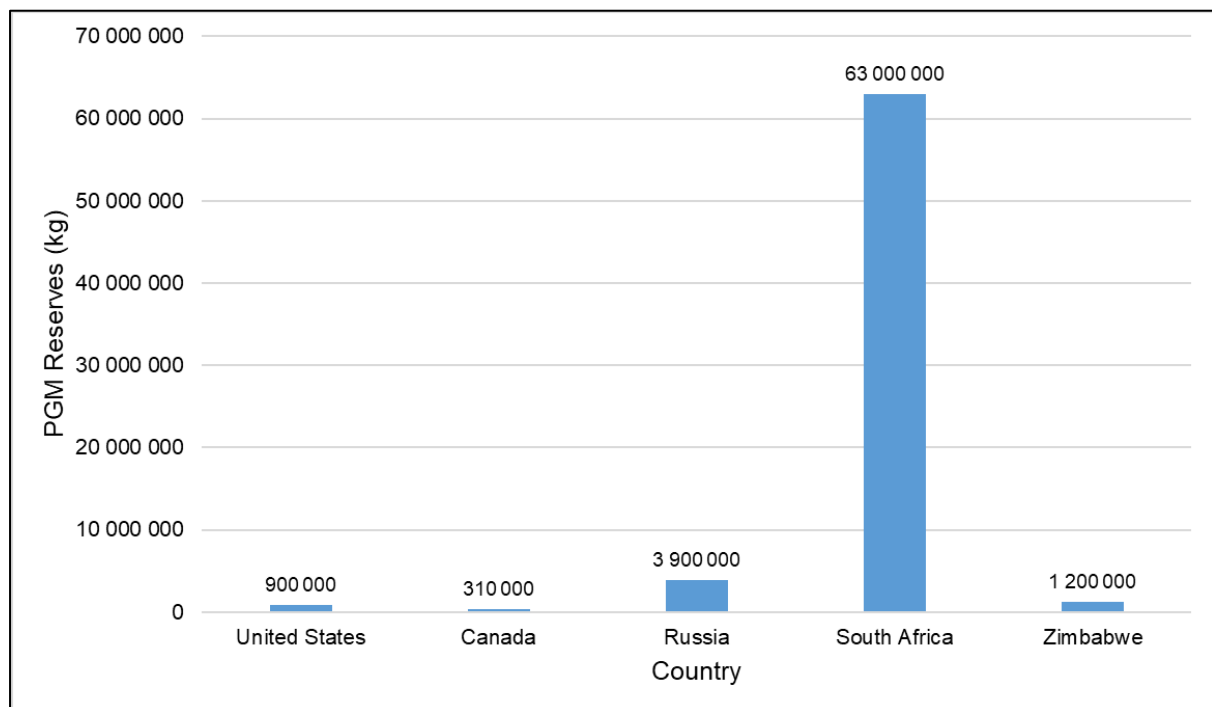
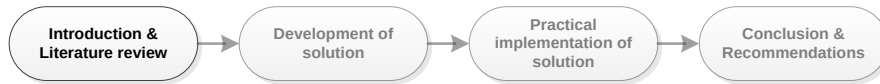


Figure 3: Global platinum group metal reserves [18]

PGMs constitute platinum, rhodium, ruthenium, palladium, iridium, and osmium. The geological and chemical richness of SA's landscape ensures the co-occurrence of multiple PGMs, such as rhodium and palladium, alongside platinum in mining deposits [19]. Given SA's



resource abundance, particularly in ore diversity, platinum mines often yield a combination of PGMs like rhodium and palladium, both highly coveted metals from an economic standpoint. Rhodium, in particular, holds the highest value per ounce [18].

While the contribution of the mining sector to the South African economy has diminished, it remains a substantial player, especially with respect to export value and employment numbers [14], [20], [21]. In 2020, SA emerged as the global leader in PGM production, producing 70% and 41% of the world's platinum and palladium output, respectively [18].

The extraction of these PGMs from underground requires high-energy-consuming mining systems. These systems typically include dewatering, compressed air, refrigeration, and ventilation. Figure 4 illustrates the energy distribution breakdown in a typical SA platinum mine. As displayed, the majority of electricity is consumed by motor-driven systems, particularly compressed air systems, accounting for the highest consumption at 21% [22].

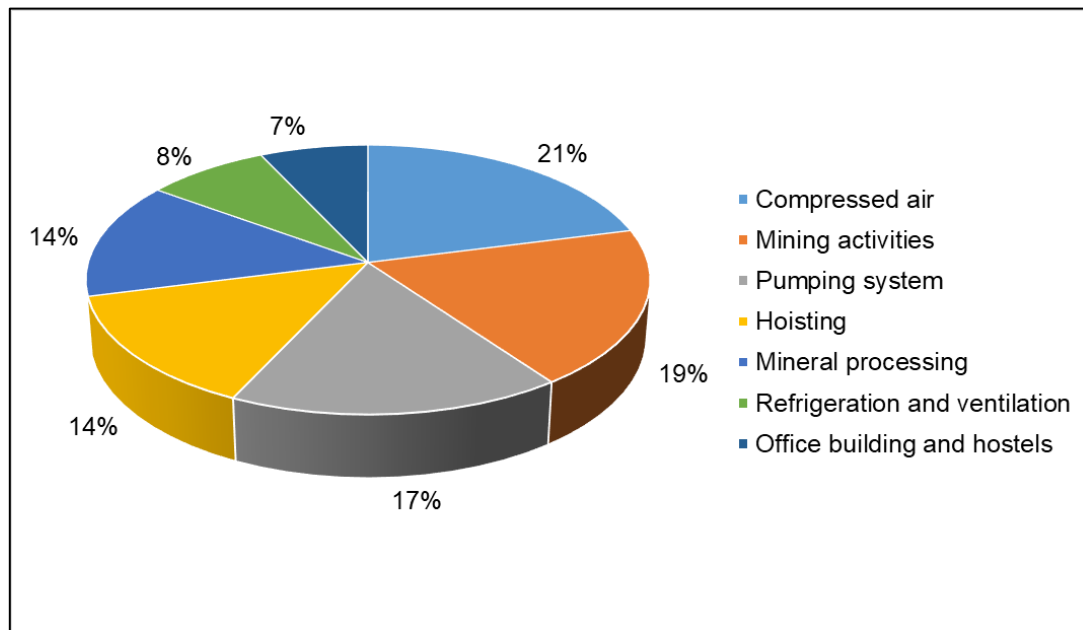
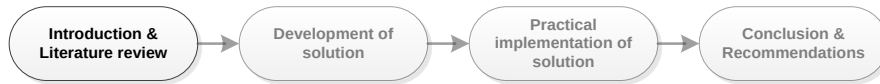


Figure 4: Platinum energy demand distribution [22]

1.5 Platinum mine utility systems

1.5.1 Compressed air

Compressed air is a critical component in the key operations of a conventional mine [23], [24]. Recognised for their safety and expandability, compressed air systems are the preferred energy source for drilling and tramming [23], [24]. A typical compressed air system has a supply side and a demand side.



The supply side consists of compressors and a network of pipes facilitating the transfer of compressed air to the demand side. Deep-level mines in SA favour multistage centrifugal compressors for their capacity to deliver compressed air flow at specified pressure setpoints. An advantageous feature of these compressors is the capability to adjust and control airflow through guide vanes [25]. This is useful when flow optimisation is required for the implementation of energy efficiency initiatives.

The demand side consists of multiple users, including drills, loaders, and refuge chambers [25]. These users typically operate on three different operational schedules in a conventional mine [24]:

- Drilling – Holes are drilled within the rock face to hold explosives set in the next shift.
- Blast – The holes from the previous shift are charged with explosives and detonated.
- Cleaning – This shift consists of cleaning the blasted rock as well as tramming the rock to the loading areas.

Compressed air is fed from the surface to these and various working areas through large steel pipes. Figure 5 displays a high-level schematic of a typical underground compressed air system.

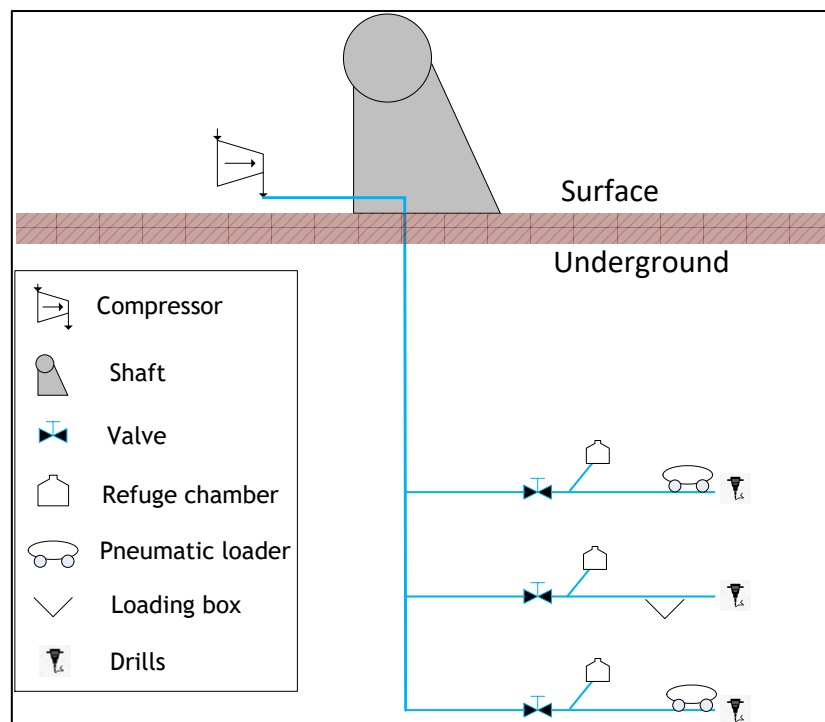
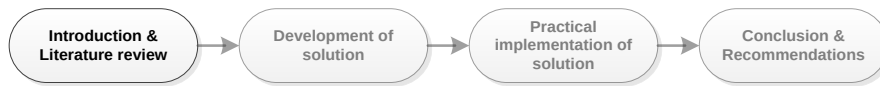


Figure 5: High-level schematic of an underground compressed air system



1.5.1.1 Compressed air components

Rock drills

To extract ore from a mine, the ore must be separated from the surrounding rock through the use of explosives. Rock drills are used to create holes in the rocks for the placement of explosives [23], [24], [26]. Following the completion of the drilling shift, the air supply that feeds the drills is maintained, resulting in compressed air leakage through the drills and within the working areas.

Pneumatic loaders

Pneumatic loaders operate on a track and feature a bucket-like scoop designed for loading ore and waste into hoppers, typically situated at the development end. Once these hoppers reach maximum capacity, they are transported to loading bays. Subsequently, the ore is discharged into a loading box via pneumatic cylinders. According to Marais [25], a pneumatic loader consumes an estimated 1 008 m³/h. However, the propensity for pneumatic loaders to leak due to insufficient maintenance and harsh underground conditions results in wastage during pressurised periods when the loaders are not in use.

Loading boxes

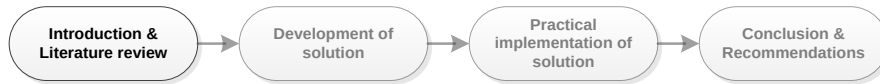
The ore from the loading boxes are loaded into hoppers via a chute regulated by pneumatic cylinders. The ore is transferred to the surface with a winder, with loading boxes strategically located within working sections. Marais [25] states that a loading box consumes between 2.16 m³/h and 50.4 m³/h at 350-600 kPa [25]. The extreme underground conditions cause compressed air systems to form leakages when loading boxes are not maintained regularly.

Agitators

Agitation is a process in which compressed air is released into dams to prevent slurry from settling, ensuring that the slurry-water mixture can be pumped out into waste dams. According to Cilliers (2016), agitation consumes approximately 1 600 m³/h at 400 kPa. In some cases, agitators are left open although the dams are clean [25]. This results in wasted compressed air that is difficult to measure due to a lack of measuring equipment.

Refuge chamber

Refuge chambers are underground chambers with a compressed air feed to ensure positive atmospheric pressure. The positive atmospheric pressure ensures that hazardous fumes are kept from entering the chamber. Refuge chambers are required by law to keep employees safe in case of an underground emergency [23]. In some cases, refuge chambers are supplied



with larger pressures than required and mining employees open bypass valves to create a cooler environment.

Venturi blowers

Due to increasing mining depths, temperatures within underground working areas are increasing. These conditions necessitate mines to place venturi blowers in working sections to ventilate compressed air through these sections. Venturi blowers consume an estimated 327.6 m³/h between operating pressures of 350-600 kPa [23], [25]. In some cases, this consumption is higher due to the unauthorised use of venturi blowers to ventilate working sections with already acceptable temperatures. In addition, this wasted compressed air reduces the pressure available for other processes such as drilling.

Open ends

Open ends are pipes connected to the compressed air supply used by employees to clean dust from development areas. However, this method is highly ineffective in terms of energy management, as it leads to substantial compressed air wastage [23].

Leaks

Leaks are common in an extensive compressed air network. Underground conditions cause compressed air pipes to corrode and form leaks. A substantial number of leaks can cause a pressure drop across a compressed air network [23], leading to overuse and additional energy consumption of compressors to sustain pressure. This is regarded as a considerable waste in compressed air.

1.5.1.2 Compressed air efficiency achieved with previous studies

An estimated 40% to 80% of compressed air is wasted before it reaches consumers [26], [27]. Given the study's focus on system efficiency, it is beneficial to know what system efficiency entails within systems with a high energy demand and the associated constraints within the mining industry. In some cases, capital expenditure is required to implement efficiency projects. Knowledge regarding this can aid the mining industry to make effective decisions to focus on the correct projects as well as systems.

Table 1 provides a list of several efficiency studies that focused on compressed air systems and reducing electricity consumption.

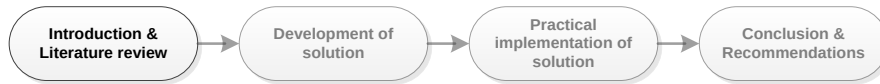


Table 1: Previous compressed air efficiency studies in mining

Reference	Author	Efficiency per annum Cost saving or Energy	Method
[25]	Marais, J.	960 GWh	Identified energy saving techniques to optimise compressed air delivery for demand users.
[28]	Joubert, H.P.R.	2 GWh	Developed cost and time-effective methods to implement demand side management (DSM) projects on mine compressed air systems, focusing on optimising compressed air control and air leaks.
[29]	Venter, J.	2.2 MW	Developed a simulation to implement dynamic compressor selection. The goal of this method is to ensure that the most efficient combination of compressors are operating.
[30]	Van der Linde, S.	R 100 000	Implemented underground valve control on a compressed air system.
[31]	Mathee, G.J.	R 1.6 million	Implemented a method to utilise machine learning for optimised compressed air selection.
[32]	Kriel, C.J.R.	R 4.2 million	Utilised a simulation-based method to showcase the importance of modernising compressed air equipment such as control valves to optimise compressed air usage.
[33]	Du Plooy, D.	R 6.5 million	Used benchmarking techniques to identify underground levels with large, compressed air wastage. Compressed air reduction techniques could then be implemented to realise cost savings.

1.5.2 Dewatering

Dewatering is a critical part of any underground mine. Underground flooding is one of the largest risks factors within a deep-level mine [23], and an estimated 22% to 84% of water is wasted underground [34], [43], [45], [46]. All the water transferred underground needs to be pumped out, including any water released by underground ruptures (fissure water). This is a continuous process to prevent flooding. Figure 6 displays a high-level layout of an underground dewatering system on a deep-level mine.

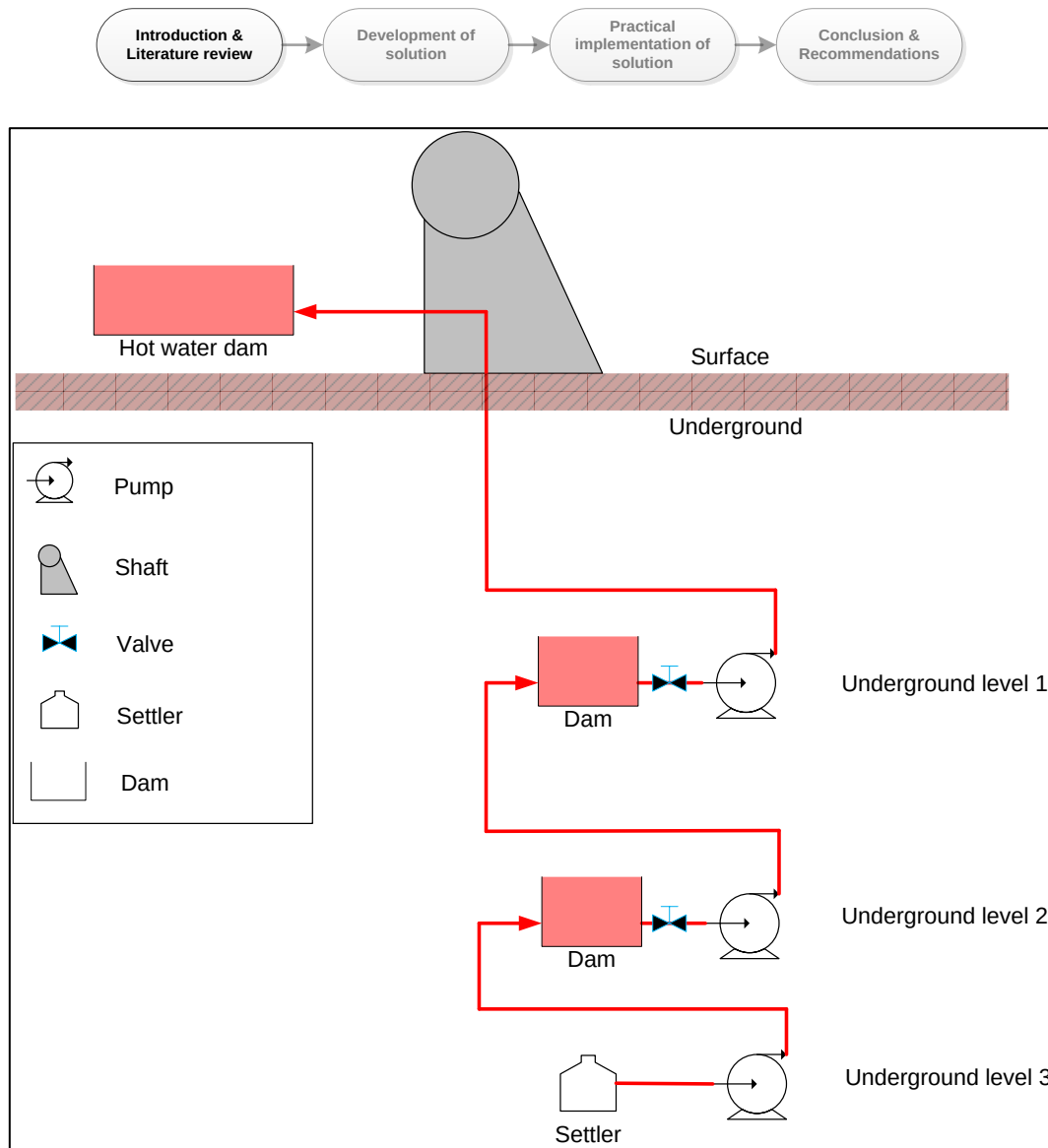


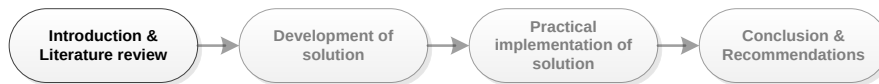
Figure 6: High-level schematic of an underground dewatering system

As seen in Figure 6, there are multiple components involved when extracting water from underground.

1.5.2.1 Dewatering components

Settlers

Settlers are used as a filter for underground service water [23], [35]. The service water used for mining purposes contains ore and small dirt particles that need to be removed before being transferred throughout the mine. A chemical product called flocculant is used to bind small particles to each other to create larger particles (floc) [23], [36]. The floc then settles at the bottom of the settler, allowing the cleaner water to flow into storage dams found underground [37].



Dams

Underground dams are used to store water before transferring the water to the necessary underground locations. The underground dams need to be closely monitored to ensure the dam levels stay within their maximum and minimum limits. This mitigates scenarios of overflowing dams or pumps running dry [38]. A lack of maintenance and harsh underground conditions can cause dams to form leaks that result in more water having to be transferred underground to compensate for the increased water wastage.

Pumps

Dewatering in mining operations is commonly accomplished by circulating heated water extracted from underground dams through the mine network using multistage centrifugal pumps. These pumps, powered by electricity-operated motors, rotate the pump shaft to generate pressure, facilitating the movement of water through the pump's discharge [39]. In larger dewatering setups, pumps are often grouped into pump stations strategically positioned throughout the mine in a cascading configuration to efficiently handle substantial water volumes. These pump stations are located in proximity to underground dams, strategically overcoming significant pressures resulting from elevated pumping heads, which can reach heights of up to 1 100 m [3], [23]. To mitigate inefficiencies and excessive energy consumption, it is crucial to maintain these pumps, as neglecting maintenance can lead to suboptimal performance, requiring more energy to extract the same volume of water.

Valves

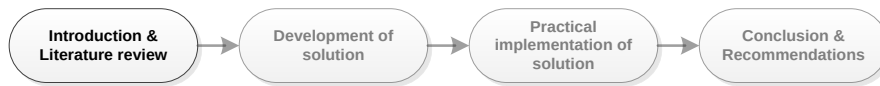
Valves emerge as an optimal solution for regulating water distribution during specific time intervals [40]. They are installed on underground water pipes to control the supply pressure according to the demand. A reduction in water pressure, facilitated by valves, can mitigate water wastage caused by leaks [23].

Leaks

Extreme underground conditions in which large water networks operate often cause leaks. Large leaks can induce a pressure drop throughout a network, demanding additional supplies of water underground to meet the demand and resulting in increased energy consumption [23], [41].

1.5.2.2 Dewatering efficiency achieved with previous studies

Much like the case with compressed air, Table 2 contains a list of past efficiency projects for water reticulation systems in mines. The objective of these initiatives was to reduce electricity



consumption, either through system optimisation for reduced water flow or by operating water reticulation systems outside of Eskom peak periods.

Table 2: Previous water reticulation efficiency studies in mining

Reference	Author	Efficiency per annum Cost saving or Energy	Method
[42]	Oberholzer, P.	R 6 million	Valve control was applied on surface to optimise the mine's dewatering system.
[43]	Van der Wateren, W.	1.5 MW	Integrated hydraulic energy recovery devices into the mine's existing dewatering system.
[44]	Rautenbach, W.J.	R 57 million	Applied pump control on a mine's dewatering system, reducing pumping during Eskom's peak time.
[45]	Smith, T.	R 8.25 million	Applied automation on the mine's pumps. This resulted in the pumps operating more efficiently.
[46]	Deysel, J.A.	R 8.64 million	Multiple DSM studies applicable to platinum mines were identified, providing a summary of the most effective projects and the possible electrical energy impact.

1.5.3 Ventilation

Ventilation systems in underground working areas of deep-level mines are designed with the purpose of supplying these areas with fresh, cooler air, reducing virgin rock temperatures, and managing methane gas released from rock ruptures to ensure safe working conditions for personnel [47].

Typical ventilation systems in SA platinum mines consist of large extraction fans on the surface and booster fans placed strategically underground to sustain optimum airflow throughout the underground mining areas [23]. Figure 7 displays a high-level drawing of a ventilation system.

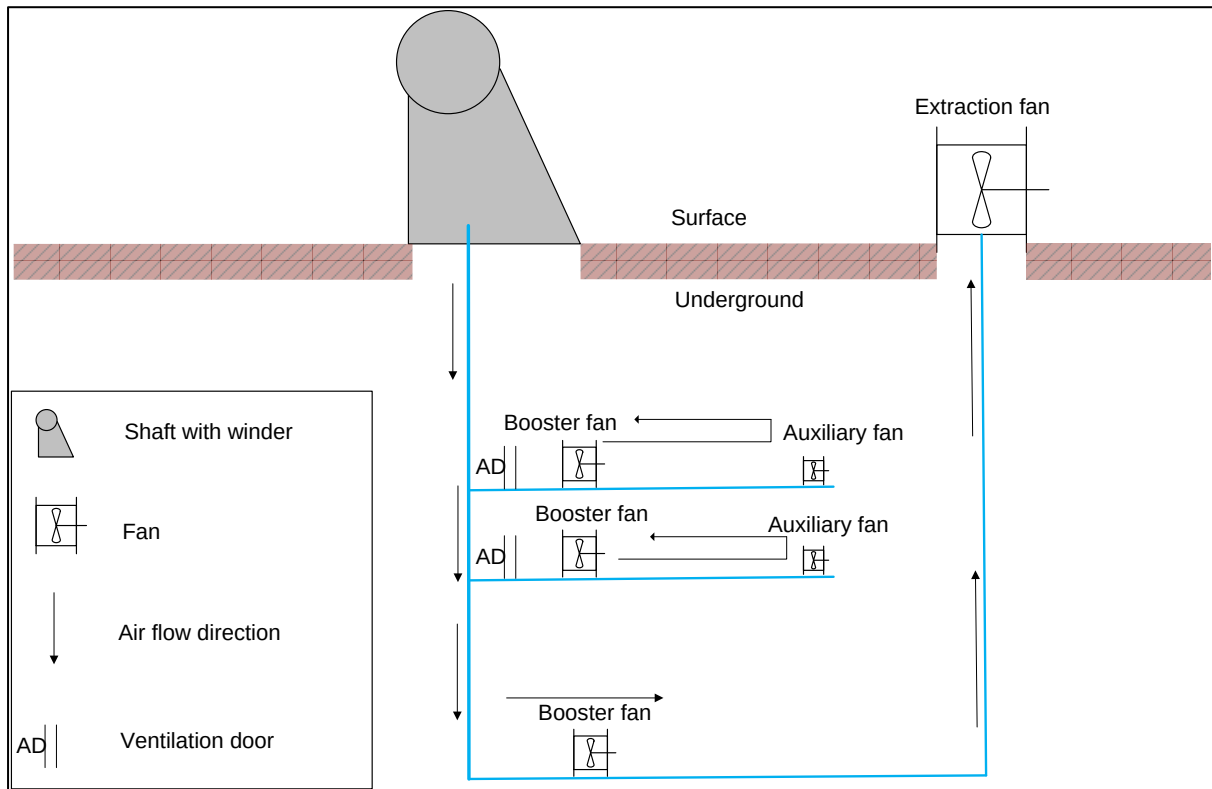
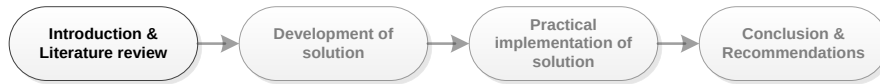


Figure 7: High-level schematic of an underground ventilation system

1.5.3.1 Ventilation components

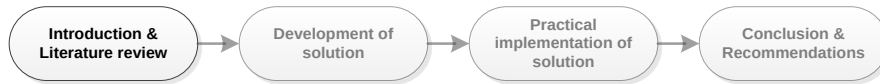
Surface fans

Large surface extraction fans, with capacities ranging from 100 kW to 3 MW, depending on the scale of the underground operation, are important components of ventilation networks [48]. Typically, two or more surface fans are grouped with at least one fan on standby to aid with rising ventilation demand or sudden equipment failure [23].

These surface ventilation fans are crucial for drawing cooler air into the mine and countering the pressure drop caused by the extraction fans. Extraction rates of between 0.05 m³/s and 0.09 m³/s of air are achievable from underground while booster fans circulate the cooler air throughout the mining network [49].

Booster fans and auxiliary fans

The booster fans are designed to be placed in haulages to sustain intake flows throughout the mine. Meanwhile, smaller auxiliary fans are placed to direct cooler incoming air to mining areas with elevated temperature caused by high virgin rock temperatures [23], [50]. The number of booster and auxiliary fans can be adjusted to maintain optimal flow as underground mines expand; however, this may lead to ineffective cooling and increased energy wastage [23].



Ventilation doors

Ventilation doors assist in directing airflow throughout the mining network. They are strategically placed to limit airflow to non-active mining areas and redirect it to active mining areas. This targeted approach aids the system in supplying cleaner, cooler air where needed [51]. Conversely, poorly sealed ventilation doors can cause wastage as cooler air flows to non-operational areas [51].

1.5.3.2 Ventilation efficiency achieved with previous studies

Similar to the case with compressed air, Table 3 contains a list of previously implemented efficiency projects for mining ventilation systems. These projects were aimed at reducing electricity consumption by optimising airflow underground.

Table 3: Previous ventilation efficiency studies in mining

Reference	Author	Efficiency per annum Cost saving or Energy	Method
[52]	Nel, A. J. H.	13.32 GWh	A simulation was developed to identify inefficient areas within the mine's ventilation system.
[53]	Fair, R.	R 1.8 million	Efficiency was realised through a ventilation simulation
[46]	Deysel, J. A.	R 2.5 million	Multiple DSM studies applicable to platinum mines were identified, providing a summary of the most effective projects and the possible electrical energy impact.
[54]	Papar, R.	2.5 GWh	Replaced inefficient equipment with more modern technology.
[55]	De Souza, E.	\$185 080	Multiple leaks were identified and fixed. This resulted in more air being delivered to working stations. Guide vanes could then be adjusted to the reduce energy consumption.

1.5.4 Awareness through system target baselines

Capital is vital to any company in facilitating the expansion of operations and the pursuit of new initiatives [56], [57]. However, realising these goals are contingent upon a well-defined budget or target baseline. A baseline in this context is a pre-determined benchmark against which a system's current operation is compared [58]. Figure 8 provides an example of an actual consumption profile compared to a target baseline. Target baselines assist with planning and forecasting future financial expenditure [59], [58].

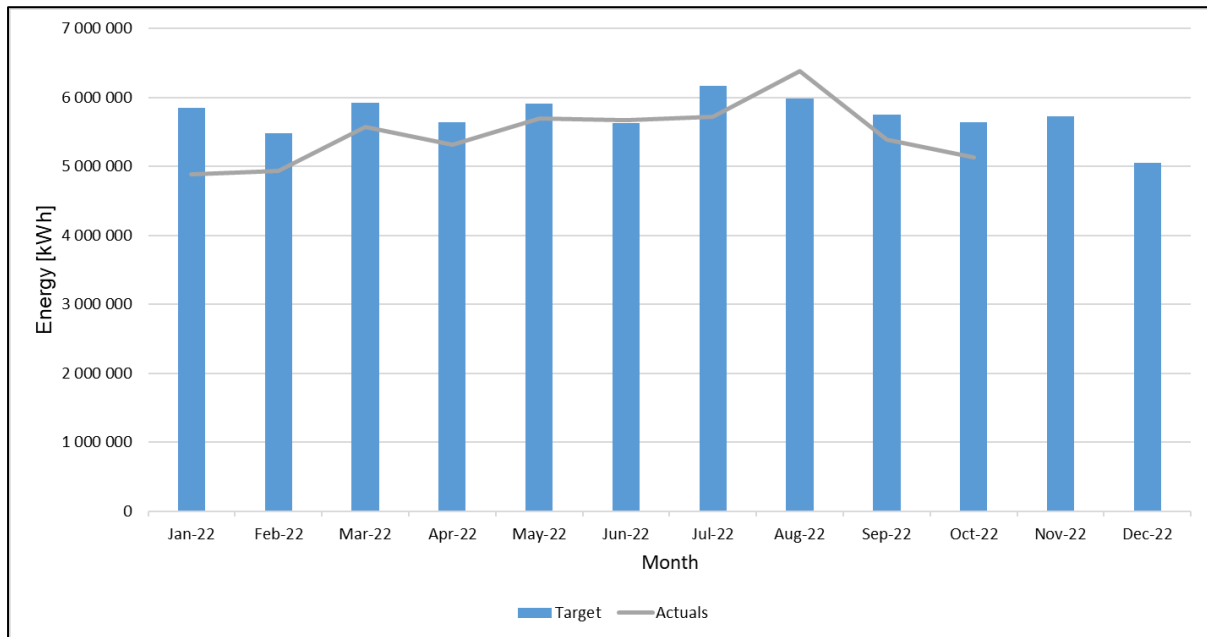
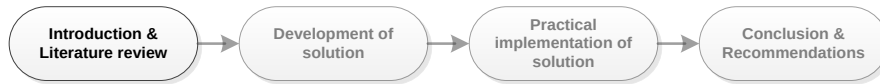


Figure 8: Example of energy target vs actual for a mining group

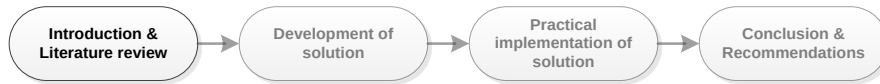
Target baselines serve as valuable tools for setting specific goals and monitoring the performance of initiatives based on those goals, fostering a more manageable system throughout its lifespan [58], [60].

In the mining context, target baselines offer a significant advantage in system management and benchmarking the performance of each system [61]. This critical information empowers managers to formulate corrective measures in response to system performance [62].

While a system target is crucial for a successful mining operation, maintaining its relevance throughout the entire year can be challenging [62], [63]. Despite considerable effort in their development, many targets become outdated. A survey by KPMG [64] revealed that over half of finance professionals acknowledged the limited usefulness of their target baselines at certain points during the year. Relying on an outdated target baseline can lead to unrealistic goals for mine managers and engineers [65].

When a target baseline becomes outdated, it loses its effectiveness as a guide for operational performance and may result in overspending [66]. This can lead to a shortage of funds for ongoing operations, and in severe cases, the closure of mine sections or even entire mines. Therefore, exercising caution in budgeting and ensuring that the budget accurately reflects expectations is crucial to avoid adverse consequences [67].

In numerous cases, mines were found to rarely update their target baselines prior to inflation and tariff changes, assuming that the electricity demand will remain constant [66]. Outdated



data from the previous year may further contribute to inefficiencies, as the mine fails to adapt to the dynamic properties of evolving mining systems [68], [69].

By relying on historical consumption data, mines inadvertently incorporate existing inefficiencies into the established baseline, offering little motivation for improvement. This approach lacks incentives for enhanced efficiency, as mines may hover near the target without experiencing significant improvements. The complexity of multiple variables affecting daily energy demand, such as temperature changes and mine expansion, is often overlooked [58], [70]. Additionally, the target baseline, predominantly comprising engineering information, is sometimes formulated by the financial department, lacking substantial engineering experience. This complexity is further exacerbated by variables considered in previous target baselines, including production changes and increased resource allocation (additional crew members) [58], [71], [72], [73].

1.6 Simulation in the mining environment

Simulation proves to be a valuable tool in conducting energy efficiency audits, facilitating the preparation of these projects [74], [75]. In certain cases within underground mining areas, effective simulation can be achieved through computer modelling [27], [76]. The advantages of simulations encompass:

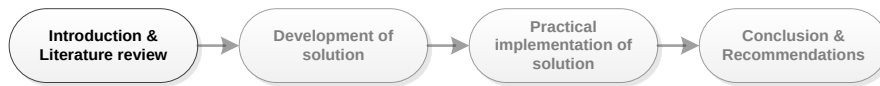
- Scenario testing,
- Identifying additional energy efficiency scope, and
- More cost-effective solution than a trial-and-error approach.

Simulations navigate intricate mathematical equations [77]. Simulation packages amalgamate these mathematical models into a user-friendly platform, simplifying and streamlining system process representations. Various simulation packages are available for simulating deep-level mining systems [24], with further details discussed in Chapter 2. A finely calibrated simulation of a mining system is commonly referred to as a digital twin [78].

However, the creation and utilisation of a digital twin for a deep-level mining system pose certain challenges. Despite the simplification of the construction process by simulation packages, users still need fundamental skills and knowledge [74], [79]. Even with these skills, constructing and calibrating the simulation remains a time-consuming process [33], [80].

1.7 Efficiency through benchmarking

In an ideal world, all systems would operate with zero waste. In the mining environment, achieving a state of zero wastage (ZW) involves eliminating waste and maximising resource



recovery, particularly ore [81]. A strategic approach towards a ZW state involves the reduction of inefficient operations, thereby minimising unnecessary wastage. Benchmarking stands out as a widely employed method for enhancing efficiency [23], [81].

Benchmarking entails the systematic comparison of a facility or process's performance against that of others to identify opportunities for improvement [82]. The process typically involves identifying a set of performance metrics or key performance indicators (KPIs) that are relevant to the facility or process in question and then comparing its performance to that of similar entities [33], [83].

Benchmarking can be applied to a wide variety of industries, including manufacturing, healthcare, finance, and energy, among others. It can be used to identify best practices and areas for improvement, set performance goals, and track progress towards those goals [23].

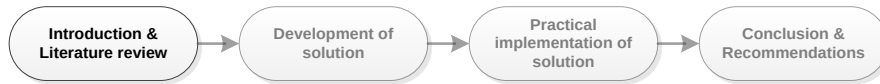
Benchmarking can be executed through internal or external methods. Internal benchmarking involves the comparison of different sections or departments within the same organisation, while external benchmarking compares similar business/industry sectors in the same or different regions. In the realm of energy efficiency, benchmarking aids in identifying and prioritising opportunities to reduce energy consumption and enhance energy performance [23], [84].

Several benchmarking types include [84]:

- Peer benchmarking: This involves comparing the energy performance of a facility to that of similar facilities within the same industry or sector. This can help identify best practices and identify opportunities for improvement.
- Absolute benchmarking: This involves comparing the energy performance of a facility to a predetermined standard or target. This can help a facility set goals for energy performance and track progress towards meeting those goals.
- Normalised benchmarking: This involves comparing the energy performance of a facility to that of a similar facility, taking into account differences in factors such as size, climate, and production levels, thereby identifying improvement opportunities specific to a particular facility.

Similar to KPIs are energy performance indicators (EPIs), which are metrics used to measure and track the energy efficiency of a facility or process. In the context of platinum mining, EPIs can be used to benchmark energy efficiency by comparing the energy consumption of different mines or by tracking changes in energy consumption over time at a single mine [85], [86].

Several types of EPIs can be used in platinum mining, including [86]:



- Energy intensity: This is a measure of the amount of energy consumed per unit of production (e.g. kilowatt-hours per tonne of ore). A lower energy intensity signifies better energy efficiency.
- Specific energy consumption: This is the amount of energy consumed per unit of time (e.g. kilowatt-hours per hour). A lower specific energy consumption indicates greater energy efficiency.

By tracking these and other EPIs, platinum mines can identify opportunities to reduce their energy consumption and improve their energy efficiency. For example, a mine with high energy intensity may improve efficiency by enhancing equipment or processes. Similarly, a mine with a low energy efficiency ratio could invest in more efficient technologies or processes to enhance efficiency [85], [86]. Subsequently, various systems can then be benchmarked against each other based on their EPIs to identify the most efficient systems.

While numerous studies in the industrial and commercial sectors explore energy benchmarking, this section focuses on selected studies within these fields to identify potential shortcomings and points of comparison relevant to the study's focus.

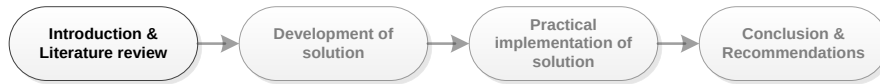
1.8 Problem statement

The mining industry faces mounting pressure to enhance efficiency as a response to escalating electricity tariffs [2], [3], [4]. Moreover, stakeholders are increasingly prioritising the improvement of ESG scores, compelling mines to operate with heightened efficiency [10], [12].

While numerous energy efficiency projects have been implemented in recent years in compressed air, ventilation, and water reticulation systems, the surge in electricity tariffs and the intensification of ESG demands necessitate a more concentrated effort in identifying and realising energy efficiency potential within mines and mining operations [12], [27].

Benchmarking and accurate target baselines are proven methods for promoting energy efficiency [23], [58]. Benchmarking studies in the mining environment primarily concentrated on comparing systems between different mines to identify systems lacking optimal efficiency. More efficient systems often serve as models for best practices that can be implemented in less efficient systems [23].

However, the reliability of this method is directly contingent upon the data collection and normalisation possibilities across diverse mining systems, which may be marked by issues such as outdated information or gaps that neglect existing inefficiencies. The high variability between mines, including the scale of operation, inconsistent data availability, environmental conditions, mine depth, and workforce variations [23], may pose challenges in normalising



these systems and accurately calculating the true energy efficiency potential of a mining system.

In past applications, historical mining data have been employed as target baselines [58]. While this approach can be effective, its success depends on carefully accounting for inefficiencies that may have been discounted or overlooked during the mine's expansion [58].

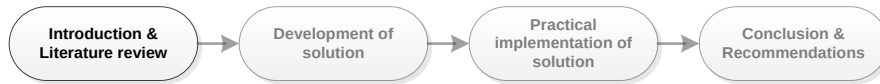
Various benchmarking and efficiency methods exhibit certain limitations, with the foremost challenge being the insufficient availability of historical data. This scarcity makes it difficult to normalise two systems, particularly considering the operational disparities between mines. Moreover, any wastage present in the data used for benchmarking can influence the efficiency potential in another system. In essence, current methods fall short of accurately determining the true efficiency potential of a system.

1.9 Overview of existing solutions

Existing solutions to the problem statement found in section 1.8 were identified through a comprehensive literature review. The study focused on four key categories, shaping both the study's focal points and the foundation for reviewing existing research. These categories include:

- Applicable to deep-level mining
 - Use of existing data
 - Mining systems such as compressed air and water reticulation networks etc.
- Benchmarking
 - Zero-wastage
 - Simulation
- Dynamic target baseline
- Desired outcome
 - Address the problem statement
 - Identify inefficiencies (wastage)
 - Provide a target baseload

The literature review methodology is based on a framework established by Salji and Winchester [87], encompassing six stages. The initial stage involves defining the research topic, as shown in Table 4. The second stage identifies relevant keywords for the study, and subsequently, an analysis of databases is conducted to pinpoint these keywords. In this study,



three databases, namely, Google Scholar, ScienceDirect and Web of Science, were consulted.

The keywords *energy benchmarking* and *deep-level mines* were used for the initial search, which yielded an estimated 910 relevant studies. After including *energy efficiency* and *platinum mines*, the relevant studies decreased to 224. Including the key words *zero-wastage* yielded no relevant results. After screening the relevant studies based on their title, abstract and conclusion, 15 studies were considered. Afterwards, the data from these studies were assessed. The literature methodology is summarised in the following section.

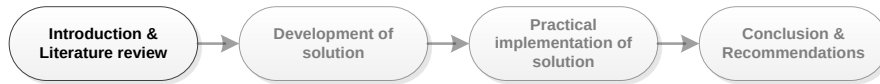
Table 4: Literature review methodology

Stage	Description
Research topic	A zero-wastage approach to benchmark energy efficiency on platinum mines
Keywords	Benchmarking, zero-wastage baseline, energy efficiency, deep-level mining, platinum mining
Source of information	Google Scholar, ScienceDirect, Web of Science
Collection of documents	The information was retrieved from 15 relevant studies.
Systematisation and evaluation	The information extracted from the collection of documents is assessed and compared concerning the topics.
Documentation of literature review	The information analysed is summarised and documented within this study.

Studies on energy efficiency and benchmarking

Cilliers, 2016 [23] – Benchmarked electricity usage

Cilliers conducted a study to benchmark the electricity consumption of deep-level mines, developing models based on data from South African deep-level mines for average and best practice benchmarking. These diverse models were employed as benchmarking methods for comparing high-demand systems. Notably, Cilliers pioneered a technique for prioritising energy efficiency initiatives specifically tailored for high-energy consumption systems. Additionally, a method to establish operational budgets was implemented and used to promote energy efficiency awareness.



The benchmarking method exhibits sensitivity to data availability, necessitating numerous variables for effective implementation. This poses challenges when applying the benchmarking model to mines with limited instrumentation. Furthermore, the method lacks the capability to quantify the existing efficiency potential, specifically in terms of wastage.

Du Plooy, 2018 [33] – Developed a method to identify compressed air wastage

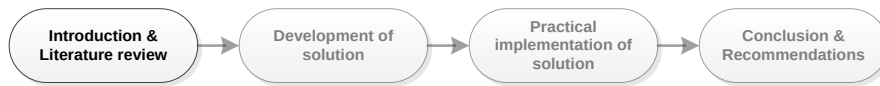
Du Plooy conducted a study to locate wastages within underground compressed air networks. Benchmarking methods were used to identify the relationship between compressed air supply and production, with the goal of detecting wastages within a compressed air network. This approach was specifically applied to the underground compressed air network of a mining operation, leading to the identification of significant wastages. Du Plooy effectively utilised this method to prioritise addressing wastages within the underground compressed air network of the mine.

Relying solely on production as a benchmark for compressed air may yield inaccurate results due to potential mismatches in data. While this method can identify wastage, it lacks the capability to quantify the extent of wastage. Notably, this study did not incorporate simulation as part of its methodology.

Van der Zee, 2013 [88] – Focused on electricity cost risks

Van der Zee conducted a study to model opportunities and electricity cost risks within the gold mining industry. Van der Zee utilised electricity cost data to benchmark multiple gold mines with a focus on their high-demand systems, namely pumping, refrigeration, and compressed air. Consideration was given to various factors, including operation size, technology, depth, production data, and electricity usage, in evaluating these systems. The benchmarking results were then utilised by Van der Zee to prioritise the different mines, enabling the identification of energy efficiency potential.

This model was applied on gold mines. It is important to note that geographical information may vary while the underlying principles remain the same. While this method identifies more efficient systems, it does not have the capacity to quantify wastage.



Ballantyne and Powell, 2014 [89] – Benchmarked electricity use

Ballantyne and Powell conducted a study to rank various mines' energy efficiency based on comminution. This was achieved by benchmarking the energy consumed for gold comminution. The energy intensity was determined by dividing the energy usage by the gold output in ounces.

Relying solely on comminution to benchmark compressed air may yield inaccurate results, as this approach fails to account for all the factors influencing compressed air consumption. Moreover, it's important to note that this method was specifically designed for gold mines, and its application to other mining contexts may impact accuracy. Additionally, the methodology employed in this study did not quantify the wastage within the compressed air system.

Mui, Wong, Law, 2007 [90] – Benchmarked ventilation systems

This study was aimed to benchmark ventilation systems for assessing energy consumption. A fundamental psychrometric analysis was used to design the model used in this study. The study showed a correlation between the average energy consumption and the corresponding CO₂ emissions in the same space. Notably, the model revealed energy efficiency potential when applied to 38 offices.

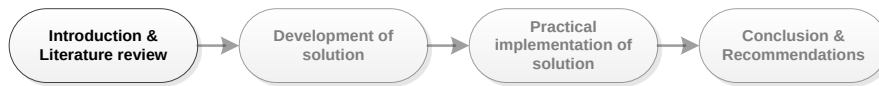
Benchmarking was done without considering relevant external factors such as building ventilation and equipment present inside the building, which may result in inaccurate results. Furthermore, this method was only applied in offices and not in the mining environment.

Chan, 2012 [91] – Benchmarked energy consumption

Chan focused on benchmarking energy consumption for numerous hotels in China through a normalised approach. The goal of this study was to develop a model that would assist with:

- Recommendation of implementation strategies,
- Identification of benchmark challenges, and
- Formulation of the benchmark.

Chan found various factors that affected the overall benchmarking model for hotels in terms of energy efficiency, rendering the model unfeasible for hotels. Factors such as hotel service



types and ranges, room size, ambient temperature, and building quality influence the hotel's total energy consumption.

Chan's study suggests three steps for determining the energy use intensity of the:

- Hotel as a whole,
- Subdivisions such as the various facilities of the hotel, and
- The energy intensity included within the building standards.

Despite the model's limitations, the insights from Chan's research are valuable for hotel managers and owners in emphasising the importance of focusing on energy intensity for improved efficiency in terms of cost and resources. The study's contribution to the body of knowledge is its emphasis on the value of benchmarking as a method to enhance energy efficiency in hotels.

The model in Chan's study may yield less accurate results as it did not account for all the factors influencing energy benchmarking. Additionally, this method failed to quantify the wastage contributed by each hotel.

Filippín, 2000 [92] – Benchmarked energy efficiency in schools

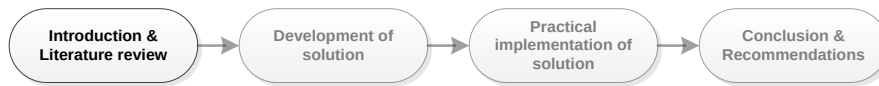
Filippín conducted a study focused on energy benchmarking of schools in Argentina [92]. The primary aim of this study was to assess electricity usage and greenhouse gas emissions in relation to several factors within the schools. Two units of measurement were selected: per pupil and square metre of floor area covered [92].

The study's findings indicated a weak correlation between energy consumption and the number of pupils or floor space [92]. Notably, external factors such as school employee practices, ambient temperatures, and building orientation significantly influenced the outcomes [92]. Unfortunately, these external factors were not normalised, hindering an accurate representation of energy use per unit. Nevertheless, the study did reveal that the schools under examination exhibited high energy consumption [92].

The study lacked consideration for numerous external factors influencing energy consumption, and furthermore, not all the external factors were normalised.

Ke, 2013 [93] – Process-based energy benchmarking

In 2013, Ke conducted a study focusing on the development of a method for process-based energy benchmarking [93]. The study found that process-based benchmarking proved



effective in assessing the complexities arising from interconnections between systems, accurately identifying potential energy savings.

However, while developing a process-based benchmarking method, Ke encountered several challenges. Firstly, breaking down complex systems into subsystems proved challenging due to the observed disassociation between these subsystems. Secondly, actual industrial systems would rarely possess the same processes and parameters for energy consumption. Thirdly, obtaining precise and specific data pertaining to the systems [93].

To address these issues, the study proposed mitigation strategies. It suggested the application of traditional statistical analysis benchmarking methods when process-based benchmarking faced challenges in accurate computation. Former techniques include approximation, linearisation, mathematical transformation, and normalisation [93].

The study also compared process-based benchmarking to the more traditional product-based benchmarking approach. Ke highlighted that while product-based benchmarking is simpler to implement in the industrial context and requires less data collection, its limitation of product-based benchmarking lies in the inability to provide explanations for identified inefficiencies. In contrast, process-based benchmarking allows for a detailed analysis of individual processes, providing a deeper understanding of the inefficiencies identified [93]. Ke recommended that high-quality data and the participation of well-informed staff are required for more accurate benchmarking investigations [93].

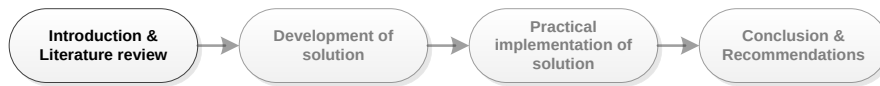
Companies can use internally developed benchmarking methods as a means to protect sensitive data from external entities. Nevertheless, the study was not applied in the mining environment.

Keirstead, 2013 [94] – Benchmarked energy efficiency

Keirstead conducted a study to develop a benchmark model for urban energy efficiency and identify efficient cities. In this study, energy consumption was calculated for 198 urban areas in the United Kingdom. Keirstead compared three methods, namely:

- Ratio measures;
- Regression residuals, and
- Data envelop analysis.

For the first method, Keirstead found that all the areas containing the same energy per capita yielded a relatively accurate comparison of energy efficiency. In the second method the linear regression model allowed consideration of external factors, and the third method allowed for



defining energy efficiency based on urban class. While Keirstead found success in the study, he recommended a more focused benchmarking approach to enhance the accuracy of the model.

A more focussed approach can be implemented, especially when applying this method in the mining environment which includes complex systems.

Nadolski, 2014 [95] – Minimum energy benchmarking

In 2014, Nadolski conducted a study to develop a method determining the minimum practical energy requirements for mineral comminution. This method involved experimentally determining the energy needed to break ore into various particle sizes. The study compared the minimum practical energy intensity, measured in kWh/tonne, to actual data collected for different comminution methods [95].

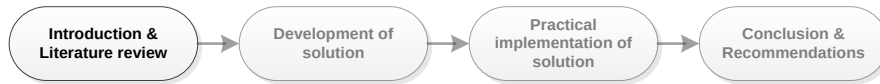
The study's findings introduced a benchmark energy factor (BEF) for each of the comminution methods analysed. The BEF was calculated by dividing the actual energy intensity by the minimum practical energy intensity, both measured in kWh/tonne. A lower BEF indicated a more energy-efficient process, enabling the identification of the most efficient comminution process [95].

Additional research can be done to extend the model's range. Additionally, more tests can be done on the same product size, providing additional normalisation.

Tshisekedi, 2009 [96] – Benchmarking energy usage

Tshisekedi conducted a study examining energy consumption costs and standards in South African gold and platinum mines, with a specific focus on benchmarking energy usage. The study collected data on total annual energy consumption and ore production from various mines. Using this information, Tshisekedi established the energy intensity per tonne of ore mined (kWh/tonne). The study incorporated multiple criteria for benchmarking, including mining depth, mine production, degree of mechanisation, productivity, and environmental impact [96].

The primary aim was to establish kWh/tonne benchmarks based on these set criteria by categorising the mines accordingly. However, the analysis, using average intensity and mining depth as the sole criteria, revealed no correlation between mine depth and energy intensity. This lack of correlation could stem from the fact that the use of total annual energy consumed by the mines and processing plants did not account for the effect of the mine's depth on energy



consumption. Another possibility could have been inefficient processing plants or other systems with a significant contribution to the overall energy consumption, which was not assessed [96].

To achieve clearer outcomes, adopting an approach that benchmarks individual systems within the mines, especially systems exhibiting a clear correlation with depth, would have been beneficial. For instance, assuming all the mines examined in Tshisekedi's study had equally efficient systems (excluding those correlated with depth), the results would have indicated that medium-depth gold mines exhibited lower system efficiency compared to deep or ultradeep mines when correlated with depth [96].

Considering each system individually when conducting benchmarking strategies can yield results with greater accuracy.

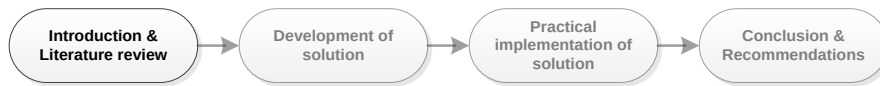
Cai, 2019 [97] – Task-orientated benchmarking

The concept of a "task-oriented energy benchmark" was proposed by Cai's study to enhance the efficiency and performance of energy utilisation in machining systems. An analysis of previous studies on energy benchmarks in machining or production was undertaken, identifying deficiencies in existing approaches. Subsequently, a task-oriented energy benchmark that considers two types of production tasks, namely, certainty production tasks and uncertainty production tasks, was developed [97].

The paper outlines the goal and scope for the task-oriented energy benchmark and presents a method for its development in machining systems. The benchmark's establishment was supported by a database comprising energy-related data, energy-unrelated data, and production data [97].

For certainty production tasks, two types of benchmarks are proposed: one based on historical machining information and one without historical machining information. The paper introduces corresponding benchmark models for each type. The paper introduces two types of benchmarks for certainty production tasks: one based on historical machining information and one without historical machining information. It also proposes a process correlation coefficient for uncertainty production tasks, elucidating the relationships among production tasks and serving as a basis for benchmark establishment. [97].

In conclusion, the study demonstrates the practical application of the task-oriented energy benchmark to a real machining system, showcasing its feasibility for both certainty and uncertainty production tasks. The proven effectiveness of this method contributes significantly to strengthening energy management and fostering energy-efficient production [97].



The study placed a greater focus on the management of the system than the system itself. Although this is an important aspect, system efficiency can play a role in overall efficiency.

Friedenstein, 2018 [72] – Operational improvements on compressed air system

This study's methodology focused on developing a simulation for a compressed air system. Through an audit, the author identified that refuge chambers contributed a large amount of wastage. After adding the audit findings to the developed simulation, the user was able to develop a new baseline for the compressed air system. Afterwards the author converted the compressed air baseline to an energy profile. He then determined that this method can be used to identify wastage equating to a cost saving of R 6.3 million.

The scope of the study was limited to leak identification based only on data from refuge chambers. Additionally, the application was restricted to a compressed air system, limiting the generalisability and applicability of the study's findings to broader contexts or different systems within the mining environment.

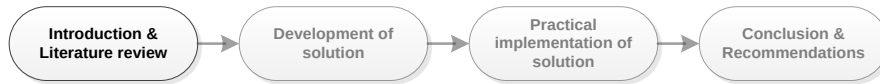
Van Rensburg, Botha and Bolt, 2011 [98] – Optimisation of water reticulation in deep-level mines

The aim of this study was to apply established water conservation methods in order to decrease water consumption at a designated mine, thereby mitigating overall system wastage. Three specific methods were identified:

- Pressure control,
- Stope isolation, and
- Leak identification

Results demonstrated the effectiveness of these techniques in pinpointing and mitigating water wastage. A substantial reduction of 8.6 million litres per day was achieved, equating to a 37% decrease in water consumption compared to the baseline. This led to an annual cost reduction of R 5.6 million based on the 2011 electricity tariff.

One limitation of this study is that the incorporation of a simulation might extend the implementation time for these techniques. However, utilising a simulation could reveal additional instances of wastage.



Saidur, Rahim and Hasanuzzaman, 2010 [99] – A review on compressed air energy use and energy savings

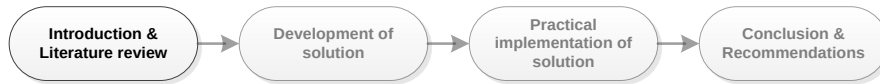
This study examined different energy-saving strategies for plant compressed air systems, with a particular focus on implementing a leak detection measure. The investigation revealed that compressed air leaks incurred additional costs, and larger leaks adversely affected production delivery by impairing the efficient operation of equipment. Ultrasonic equipment was employed to pinpoint leak locations. Subsequently, after addressing the identified leaks, a reduction of 90 m³/h was achieved, effectively eliminating wastage from the system.

The shortcoming with this study is that the solution was not applied on a deep-level mine. Additionally, it can be a time-consuming solution to implement, especially on larger systems such as underground compressed air networks. A simulation package could have been utilised to determine wastage within the compressed air network.

Table 5 summarises the applicable studies and their contributions to the focus areas of this study. Checkmarks denote that the respective study addressed the focus area, while a cross indicates that the study did not fulfil the specified focus area.

Table 5: State-of-the-art matrix

Source	Applied on a deep-level mining system		Benchmarking	Zero-wastage	Used simulation package	Identify efficiency potential	Provide target baseline
	Gold mines	Platinum mines					
[23]	✓	X	✓	X	X	✓	✓
[33]	X	✓	X	X	X	✓	X
[88]	✓	X	✓	X	X	✓	X
[89]	X	X	✓	X	X	✓	X
[90]	X	X	✓	X	X	✓	X
[91]	X	X	✓	X	X	✓	X
[92]	X	X	✓	X	X	✓	X
[93]	X	X	✓	X	X	✓	X
[94]	X	X	✓	X	X	✓	X



[95]	X	X	✓	X	X	✓	X
[96]	✓	✓	✓	X	X	✓	X
[97]	X	X	✓	X	X	X	X
[72]	✓	X	X	X	✓	✓	✓
[98]	✓	X	X	X	X	✓	X
[99]	X	X	X	X	X	✓	X

The matrix evaluates the contribution of each source to the study focus areas, respectively. Work has been done on benchmarking and identifying wastage within the mining environment.

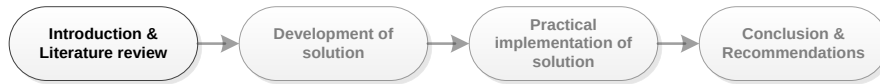
The combination of ZW, simulation, and benchmarking in the mining context revealed significant shortcomings. Additionally, it was observed that many studies lacked the provision of a target baseline for ensuring sustained energy efficiency in the future.

1.10 Research objectives

Determining the available energy efficiency potential of a mining system, as outlined in the literature review, is subject to certain limitations. Notably, there is no standardised method guiding the calculation of a system's ZW baseload within the platinum mining industry. This realisation led to the formulation of the following study objectives:

1. **Use existing and available information to develop a system baseload (ZW) to benchmark the system against itself.** The ZW benchmarking method was implemented on various systems. The method delivered a baseload for each of these systems to identify the most efficient versions.
2. **Use a ZW benchmarking method to identify the available energy efficiency within a system.** The ZW baseload was compared to the actual consumption of the system to expose inefficiencies in addition to identifying areas of wastage.
3. **Develop a system-specific target baseload which is based on the system's ZW baseload.** A dynamic system target was developed from the ZW baseload. This will provide a target representing what is currently achievable with the system.

To achieve these objectives, a solution was devised, and its implementation yielded quantitative data, including cost savings. Ensuring the relevance and applicability of the developed solution across all deep-level mining service systems was crucial. Therefore, a comparative analysis of the outcomes across various mining systems was conducted to validate its effectiveness.



Given the research methodology requirements, the case study methodology emerged as the most suitable approach [100], [101]. This methodology minimised biases during solution validation and required only a few case studies for theoretical generalisation [100], [101], [102].

The research methodology approach not only validated the study but also enhanced the understanding of case study dynamics, ensuring the generic applicability of the solution to various deep-level mines. Figure 9 displays the case study research approach followed in this thesis.

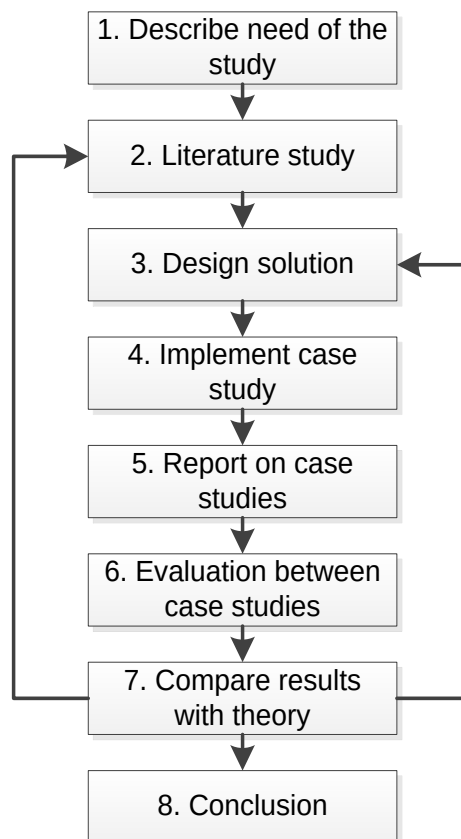


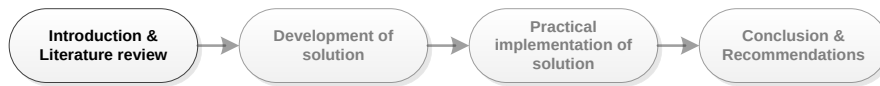
Figure 9: Case study research methodology [101], [102]

1.11 Novel contributions

Novelty 1: Development of a novel benchmarking method for a ZW approach.

How is it currently done?

Presently, various systems undergo benchmarking against each other to pinpoint the one with the highest energy efficiency potential. However, none of the existing methods concentrating on minimising energy consumption provide a quantifiable measure of a system's available energy efficiency potential.



Why are the current methods insufficient?

Current strategies cannot fully normalise systems due to variables such as different mining levels, mining depths, geographical locations as well as a different working schedules. These factors have a direct influence on the benchmarking for comparing different systems.

What needs to be done?

A method is required that compares an accurately and comprehensively derived ideal version of a system to its current version through ZW benchmarking.

How does this study solve the problem?

Within this study, a new method was developed for calculating a system's ZW baseload. A profile was developed illustrating a system's demand without any wastage (ideal efficiency).

Novelty 2: Applying the novel method to identify system-specific inefficiencies through ZW.

How is it currently done?

ZW is a novel approach in the mining environment, with little to no experience within the field regarding implementation. However, from literature, it was found that most systems are either compared to more efficient systems on another mine or compared to a previous year's operational target.

Why are the current methods insufficient?

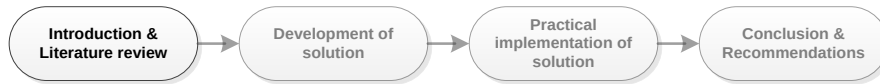
Existing benchmarking methods focus on best-case examples instead of the system's available energy efficiency. Any wastage that is present within the best-case example will be used to identify wastage within the new system.

What needs to be done?

A system needs to be compared against an accurate baseload to identify possible inefficiencies within the system.

How does this study solve the problem?

This study used the ZW baseload developed in the previous contribution to illustrate the system's actual consumption compared to the system's ZW baseload. The ZW baseload can also be used to monitor the performance of the system over a longer period of operation.



Novelty 3: Development of a novel method to calculate a relevant target baseload based on a systems ZW baseload.

How is it currently done?

ZW is a novel approach, especially in creating an operational target from a ZW baseload. However, operational targets within the mining environment have mostly been developed from a previous year's actual consumption.

Why is the current method insufficient?

Using operational targets based on a previous year's consumption can become problematic when compared to a system that underwent changes that remain unaccounted for following the measurement period. This may lead to the system consistently surpassing the target. Moreover, the existing method incorporates inefficiencies into the operational target, offering little incentive for system improvement.

What needs to be done?

A system needs to be compared against a target representing the current system operation.

How does this study solve the problem?

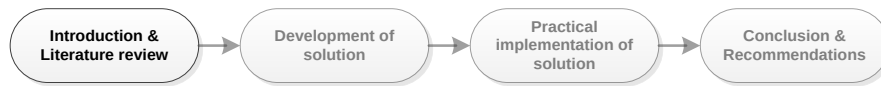
This study employed a system-specific ZW baseload to create a dynamic target baseload. The results showed that comparing the system to this accurate target can enhance the incentive to prioritise efficiency. Additionally, the method enables the identification of an attainable ZW baseload for future initiatives.

Novel contributions aligned with research objectives

The novel contributions discussed above are required to address the research objectives identified in section 1.10. Table 6 provides a summary of the novel contributions and the corresponding research objectives.

Table 6: Alignment of Novel contribution & Research objectives

	Novel contributions	Research objectives
1	Development of a novel benchmarking method for a ZW approach.	1
2	Applying the novel method to identify system-specific inefficiencies through ZW.	2



3	Development of a novel method to calculate a relevant target baseload based on a systems ZW baseload.	3
---	---	---

1.12 Thesis layout

Chapter 1 – Introduction

The introductory chapter delved into the study's background, exploring the impacts of rising electricity tariffs and increasing emphasis on ESG factors in the mining sector. It also outlined existing research and various methods that have been used to identify system (in)efficiencies through benchmarking. This was followed by an evaluation of benchmarking methods used in deep-level mining environments, accompanied by their limitations. These limitations informed the study's research objectives, which brought novel contributions that served as the foundation for developing the method to address the problem statement. Both Step 1 and Step 2 of the research methodology (Figure 9) are executed in this chapter.

Chapter 2 – Development of solution

The second chapter consists of the research methodology and has two parts. The first part consists of the development of the ZW benchmarking method and how it can be used to identify possible efficiencies within a system. The second part of Chapter 2 discusses how to create a system-specific target baseload from a ZW baseload. The methodology is also verified in this chapter. Step 3 of the research methodology (Figure 9) take place in this chapter.

Chapter 3 – Practical implementation of solution

Chapter 3 consists of the results achieved by applying the methodology discussed in Chapter 2 on multiple case study mines in South Africa. The results are used to validate the study. Step 4 to Step 8 of the research methodology (Figure 9) form part of this chapter.

Chapter 4 – Conclusion & Recommendations

Chapter 4 is the conclusion of the study. Recommendations for further development and expansion of the study are also discussed in this chapter.

A visual representation of the relationship between the research methodology and the thesis layout can be found in Table 7. The check marks indicate which step in the research methodology is addressed in each respective thesis chapter.

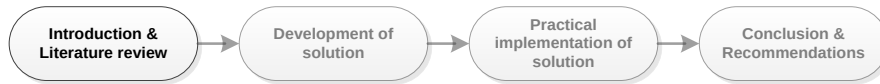


Table 7: Relationship between research methodology and thesis layout

	Chapter 1	Chapter 2	Chapter 3	Chapter 4
1. Describe need of the study	✓	-	-	-
2. Literature study	✓	-	-	-
3. Design solution	-	✓	-	-
4. Implement case study	-	-	✓	-
5. Report on case studies	-	-	✓	-
6. Evaluation between case studies	-	-	✓	-
7. Compare results with theory	-	-	✓	-
8. Adjust methodology if needed	-	-	✓	-

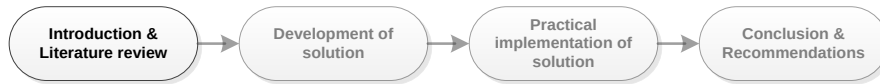
1.13 Conclusion

South Africa hosts some of the world's largest deep-level mines, playing a significant role in contributing to the country's economy. These mines rely on high-energy systems, including compressed air, ventilation, hoisting, and refrigeration, to ensure efficient and safe ore production.

Unfortunately, the mining industry is facing challenges due to escalating Eskom tariff increases and the growing emphasis on ESG considerations. These factors are driving up production costs, impacting the profitability of mines. Despite enduring annual electricity tariff increases ranging from 8% to 15% over the past several years, mines are under increasing pressure to reduce CO₂ emissions. Enhancing energy efficiency in mining processes and operations stands out as one of the most viable approaches to achieve these reductions.

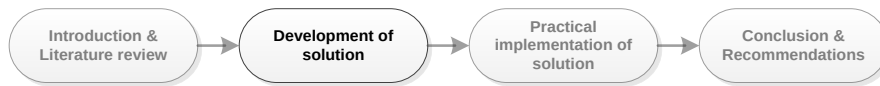
While literature offers various methods to identify energy efficiency potential in mining, each method comes with its own set of limitations. Based on the insights from existing literature, three study objectives were formulated:

1. Use existing and available information to develop a system baseload (ZW) to benchmark the system against itself.



2. Use a ZW benchmarking method to identify the available energy efficiency within a system.
3. Develop a system-specific target baseload which is based on the system's ZW baseload.

Key methods were developed to achieve these objectives, presenting novel contributions to the literature by addressing identified gaps. Chapter 2 provides a detailed discussion of the design solution that effectively tackles the problem statement, as highlighted in Table 7.



CHAPTER 2 – DEVELOPMENT OF SOLUTION

2.1 Preamble

Chapter 1 provided a comprehensive research background focusing on platinum mines and the intricate high-energy systems crucial for extracting PGMs from underground deposits. Essentially, the mining environment faces numerous challenges, notably declining profitability attributed to escalating electricity expenses and growing investor expectations for mining companies to improve their ESG scores. Mines are compelled to adopt efficiency-improving strategies to cut costs, reduce emissions, and minimise waste.

Numerous studies have explored the application of benchmarking to pinpoint areas with energy efficiency potential by comparing different systems. The culmination of the problem statement and existing literature paved the way for the development of innovative methods to address the following objectives:

1. Use existing and available information to develop a system baseload (ZW) to benchmark the system against itself.
2. Use a ZW benchmarking method to identify the available energy efficiency within a system.
3. Develop a system-specific target baseload which is based on the system's ZW baseload.

The remainder of this chapter presents a discussion on the study method, consisting of a four-step method with multiple sub-steps to assist mines in identifying inefficiencies within a system.

2.2 Zero-wastage benchmarking method

Figure 10 displays the ZW benchmarking method. This method is developed to identify a system's most efficient version of itself (ZW baseload) to identify inefficiencies within its ongoing operations. The method comprises four main steps, each featuring sub-steps. These have been designed as a comprehensive guide, offering users a systematic approach to pinpoint inefficiencies within a mining system.

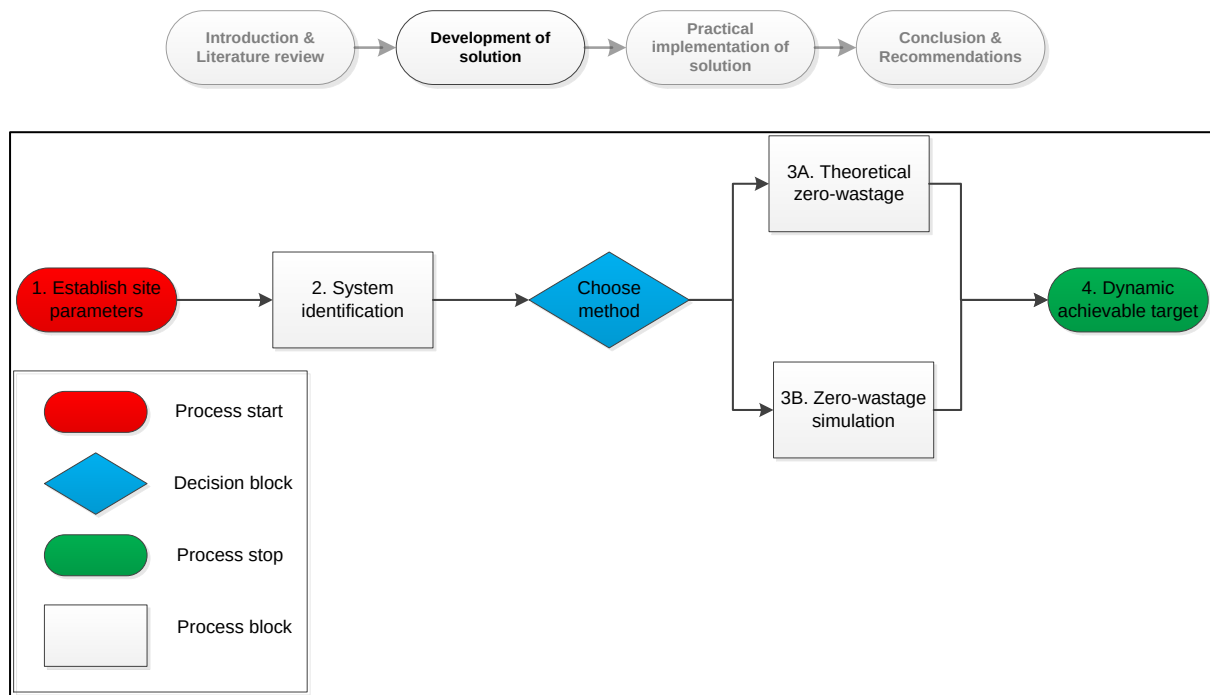


Figure 10: Proposed zero-wastage benchmarking method

Solution criteria were developed from the study focus areas identified within section 1.9. The solution criteria were used to **verify** the ZW benchmarking method. Figure 11 indicates the solution criteria and their relationship with the ZW benchmarking method. Each step in the ZW benchmarking method addresses one or more of the requirements set by the solution criteria. The design of the solution is led by the criteria which are discussed sequentially.

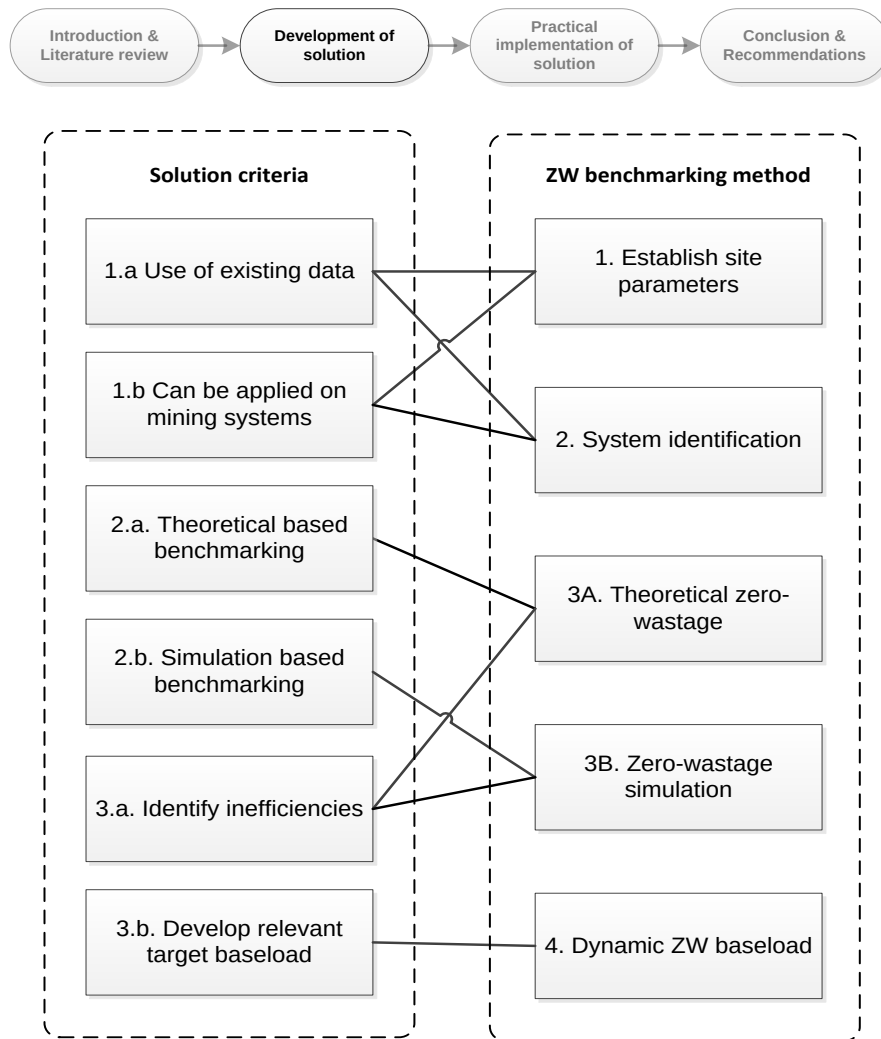


Figure 11: Relationship between the solution criteria and the zero-wastage benchmarking method

2.2.1 Step 1: Establish site parameters

As displayed in Figure 12, the first step in the ZW benchmarking method consists of establishing site parameters. This step was recognised as a requirement from the solution criteria to gain a proper understanding of the site's operational systems, including layouts and data from the mine. This step is dependent on the available data of the mine. To facilitate the ZW benchmarking method, an audit of the mine can be conducted to obtain the necessary information.

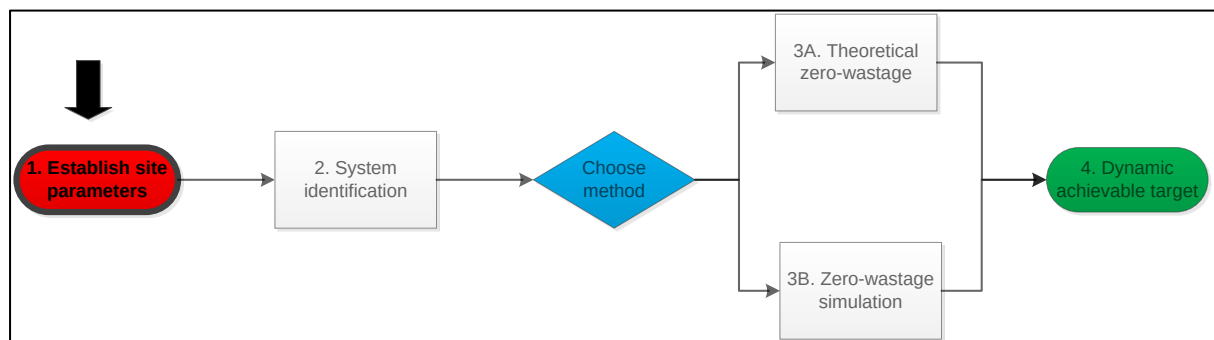
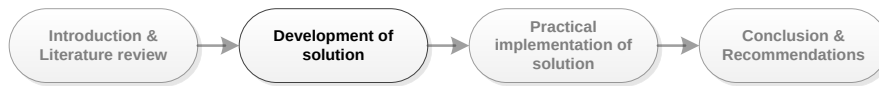


Figure 12: Zero-wastage benchmarking method – establish site parameters



It should be noted that audits can be time-consuming actions that require numerous resources to complete, depending on the size of the mine. Site layouts can be retrieved from the drawing offices on the mine. Additionally, engineers can supply technical drawings of all the operational systems. This information is crucial for conducting audits effectively.

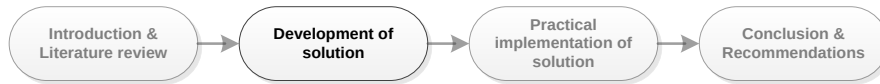
A SCADA (supervisory control and data acquisition) is an information-rich system that plays a vital role in mining operations. It consists of a network of computers and graphical user interfaces that contain a large amount of data. The SCADA system is a mine's primary data interface and enables monitoring and control procedure initiations. Hence, SCADA system and the control room operators are valuable sources for gathering relevant data and operational procedures for audits.

Control room operators are valuable sources of data as they oversee the SCADA system and can provide additional information and clarify any operational procedures that may be necessary for the audit. In summary, the combination of the following data sources, when combined, forms a comprehensive approach for linking the physical infrastructure with the operational aspects of the mine during audits. Ultimately, these data inform the resulting ZW benchmark, which mines can use to identify areas with efficiency potential. The following recommended data requirements were subsequently derived to proceed with the ZW benchmarking method [23]:

- Mine production
- System energy
- System amps
- System power factor
- System status
- Rated power of the system

However, if the energy data is not available, the energy can be calculated with a three-phase power formula. Although not recommended due to possible inaccuracies, equipment status information and the equipment current can be used to calculate the rated power (see Appendix A for Equations 7 and 8 on related power calculations).

In certain scenarios, the mine may opt to pre-select the system, especially when the least efficient system has already been specified. In such instances, the user can commence directly with section 2.2.3. After establishing customised parameters, as discussed in sections 2.2.1 and 2.2.2, the user proceeds to select a mining system for scrutiny through the benchmarking method.



2.2.2 Step 2: System identification

As displayed in Figure 13, in the second step of the ZW benchmarking method, a mining system is selected for which to calculate the ZW baseload, a requirement based on the solution criteria.

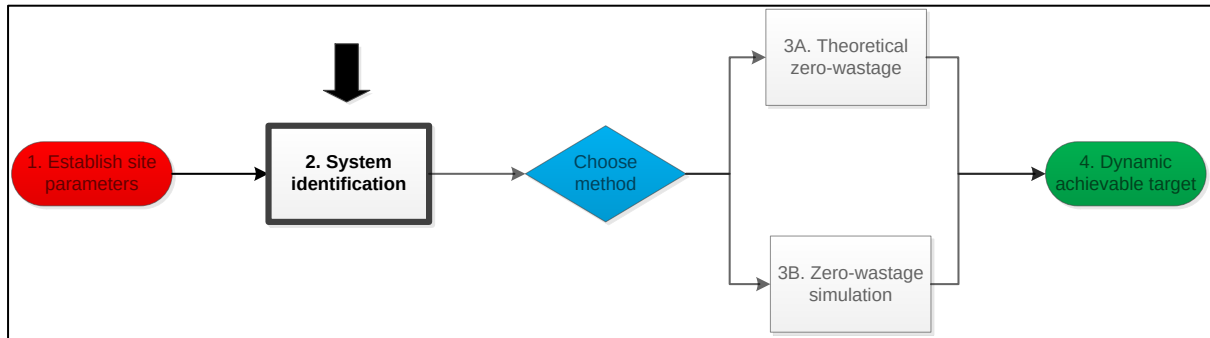


Figure 13: Zero-wastage benchmarking method – system identification

The information gathered during the initial audit will indicate which systems are available and operational on a mine. As found in the literature, intensity calculations can be used to provide a preliminary indication of the system with the lowest-ranked energy contribution. The systems are ranked by efficiency based on energy and production data obtained from the audit, as illustrated in Equation 1:

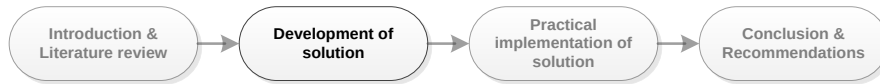
$$\text{System intensity} = \frac{\text{System energy}_{(kWh)}}{\text{Production}_{(tons)}}$$

Equation 1: System intensity

Higher-intensity systems on the mine can have a higher potential for efficiency improvements. However, note that this method is only used to produce a preliminary indication of the system with the highest efficiency potential and needs to be verified with either the theoretical ZW or the ZW simulation step. Table 8 displays an example of the possible results that can be realised with this step.

Table 8: System intensities

System	System intensity
Compressed air	X
Ventilation	X
Dewatering	X
Refrigeration	X
Hoisting	X



The system with the highest energy intensity is used for the next step in the ZW benchmarking method.

2.2.3 Step 3: Zero-wastage baseload

As mentioned in the literature study, the most efficient version of a system will have ZW within the system. This means that the system will run at an optimal baseload without any inefficiencies. Two methods were developed to calculate the ZW baseload of a system:

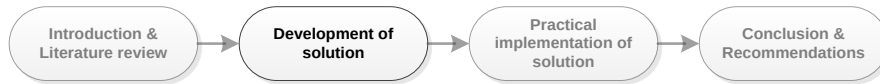
Theoretically based ZW – This method consists of calculating the ZW baseload from a theoretical approach. Using rated and calculated consumption values with operational schedules of each consumer within the system to identify the baseload of the system.

Simulation-based ZW – This method entails auditing the entire system and capturing the results into a simulation package to create a digital twin that can simulate the system's ZW baseload.

As with any method, there are advantages and disadvantages associated with each method that may influence outcomes. Table 9 presents a summary of the advantages and disadvantages associated with using a simulation-based model and a theoretical approach for comparison.

Table 9: Theoretical zero-wastage vs. simulated zero-wastage [33], [74], [79], [80]

Method	Advantages	Disadvantages
Theoretical ZW	Faster implementation time	Less accurate method
	Less information required	Only ZW can be calculated from this method
	No simulation experience required	Basic understanding of the overall system
	Less maintenance required	
ZW simulation	Accurate method	Slower implementation time
	The simulation contains scenario/project testing capabilities	More information required
	A better understanding of the overall system	Simulation experience required
	Real-time data monitoring	More maintenance required



2.2.3.1 Theoretical ZW

This method involves calculating the ZW baseload from a theoretical approach. Specifically, rated and calculated consumption values were used along with the operational schedules of each consumer within the system to identify the baseload of the system. This step is based on the solution criteria as a requirement for the method of benchmarking a mining system.

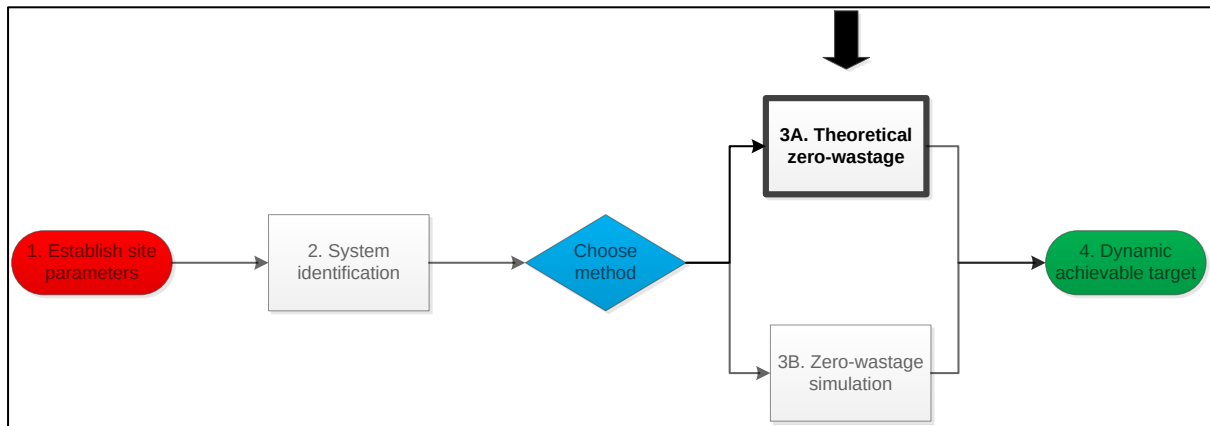


Figure 14: Step 3A – theoretical zero-wastage

Figure 15 displays the method for the theoretical ZW calculation. This method is applied to the system with the highest intensity identified in the previous step.

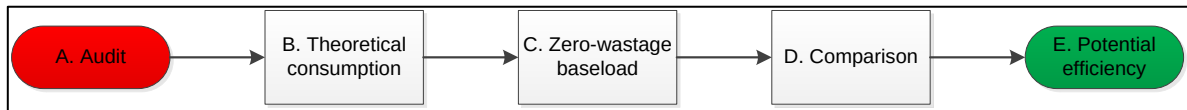
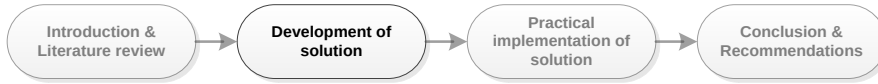


Figure 15: Theoretical zero-wastage method [81]

Step 3A.A – The theoretical ZW method is highly dependent on accurate consumption and operational schedule data of each consumer within the system, as well as actual demand data of the entire system. Therefore, an audit is done on the system to acquire crucial information to understand how the system operates and is used within a mining environment. A typical system audit will entail [81]:

- Meetings and interviews – Scheduling meetings with on-site personnel can supply a substantial amount of information regarding system operations (see template in Appendix B, Figure 63). They can provide details on various system consumers and consumption details of these consumers. On-site personnel are in contact with equipment suppliers for additional information. Most of the details required for the Theoretical ZW method can be retrieved with this method.
- Visual inspections – Remaining information can be retrieved by going underground to visually inspect the system in question. Equipment such as pumps and compressed air equipment can contain name plates with rated consumption details, although it must



be noted that nameplates can be damaged over time due to a harsh underground environment.

- Physical data gathering – Consumption details can also be retrieved with physical measurements such as with flow and pressure measuring equipment on compressed air systems. However, it is advised to inspect name plates or supplier information as leaks can develop due to harsh underground conditions.

Step 3A.B – To calculate the total theoretical consumption of each type of consumer, the rated consumption details identified in step 1 is required. As seen in Equation 2, the total theoretical consumption of each type of consumer can be calculated by multiplying the rated consumption retrieved by the consumer quantity.

$$\text{Theoretical consumption} = f_{\text{rated}} \times \sum_{\text{consumers}}$$

Equation 2: Theoretical consumption

Step 3A.C – Using the theoretical consumption calculated in the previous step and the operational schedule acquired in step 3A.A, the ZW baseload can be calculated. This is done by adding the calculated consumption to the correct operational slot in a 24-hour profile. This will highlight any wastages that may be present due to equipment running while they are not required.

Step 3A.D – With the actual demand data and the ZW baseload can be investigated in more detail. Figure 16 displays an example of a comparison of the ZW baseload profile and the actual demand profile. This highlights inefficiencies throughout the 24-hour profile, indicating wastage as shown in Figure 16. In some cases, multiple iterations might be required to obtain the ZW baseload as accurate as possible.

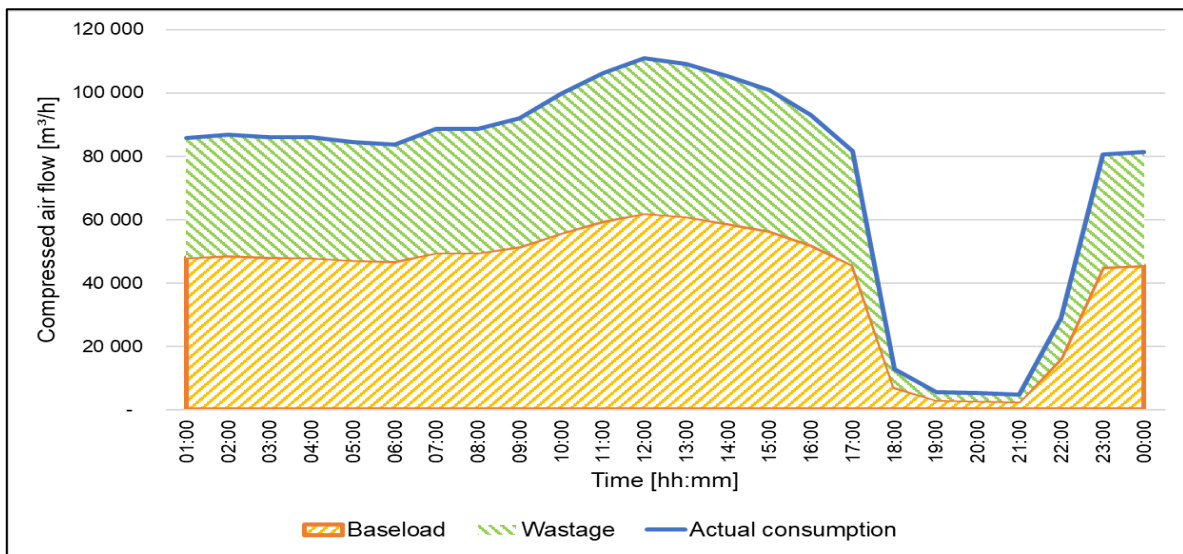
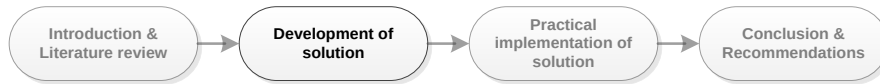


Figure 16: Zero-wastage vs actual consumption comparison [81]



Step 3A.E – The wastage as displayed in Figure 16 is considered a potential saving. Subtracting the baseload from the actual demand will result in wastage. Equation 3 provides a mathematical formula to calculate the wastage [27].

$$Wastage = Actual\ consumption - Baseload$$

Equation 3: System wastage

With the known wastage, the potential energy efficiency can be calculated. This can be system-specific; for example, a 4.3 MW compressor can generate approximately 40 000 m³/h. Resulting in a 4.3 MW efficiency if 40 000 m³ is reduced per hour with the ZW baseload. Additionally, a CO₂ reduction can be achieved based on the energy efficiency improvement. This can be calculated with Equation 4, displaying the ratio between CO₂ emissions and MWh for SA [103].

$$1.08\ ton\ CO_2e = 1\ MWh$$

Equation 4: Emissions factor

2.2.3.2 Zero-wastage simulation

Step 3B in the ZW benchmarking method consists of the ZW simulation method as displayed in Figure 17. This step was recognised as a requirement based on the solution criteria in Figure 11 involving the benchmarking of a mining system through simulating the ZW baseload using a digital twin.

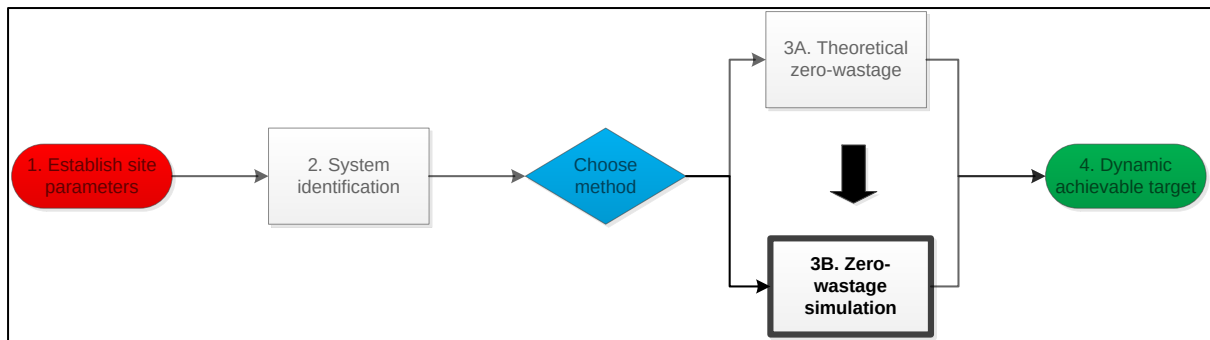
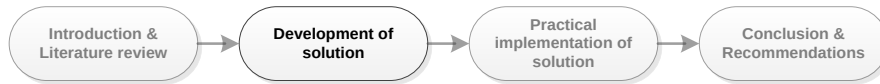


Figure 17: Zero-wastage benchmarking method – zero-wastage simulation

Simulation software is widely used for operational improvements and future developments in various industries. Accurate models can be built for actual and planned systems, making it an intricate part of any field of study, especially engineering [104], [105]. The benefits of simulation software are listed below [105]:

- Project testing – Projects can be tested on a simulation without any capital expenditure included within a real-life implementation.



- Scenario testing – Different scenarios can be tested for system optimisation, reducing turnaround times included with physical tests.
- System understanding – Simulations require an in-depth understanding of a system. This results in a more accurate system simulation and faster problem-solving.

Several simulation packages are available for this method, which are compared under the following categories:

Digital twin – Is it possible to design a digital copy of a system?

Scenario testing – Is it possible to test different scenarios with the simulation package?

System optimising – Does the simulation package provide optimising capabilities?

Full system simulation – Can the simulation package simulate an entire system as a whole?

Real-time data monitoring – Can the simulation package display real-time data?

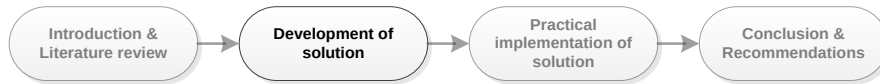
Dynamic simulation – Can the simulation package perform simulations on dynamic scenarios?

Table 10: Simulation software package comparison

Simulation package	Digital twin	Scenario testing	System optimising	Full system simulation	Real-time data monitoring	Dynamic simulation
Solid works [106]	✓	✓	✓	X	X	✓
Kypipe [107]	✓	✓	✓	✓	X	X
Flownex [108]	✓	✓	✓	✓	X	✓
Process Toolbox (PTB™) [109], [46], [110], [72]	✓	✓	✓	✓	✓	✓

VUMA3D and VisualQEC were also considered, however, they focus mostly on ventilation and steady-state simulations, which limits them in the scope of this study [3]. Additionally, the demo versions of Solid Works, Kypipe and Flownex are limited, with the full version costing a hefty price [31]. Although the simulation packages in Table 10 can provide accurate results, PTB™ was chosen as it complied with all the required criteria.

PTB™ is a thermohydraulic-based model that is dependent on prior system knowledge as well as a significant amount of data for the simulation parameters. When modelled correctly, the



system simulation results in improved scenario tests and faster turnaround times [105]. Figure 18 displays the method to develop the ZW simulation.

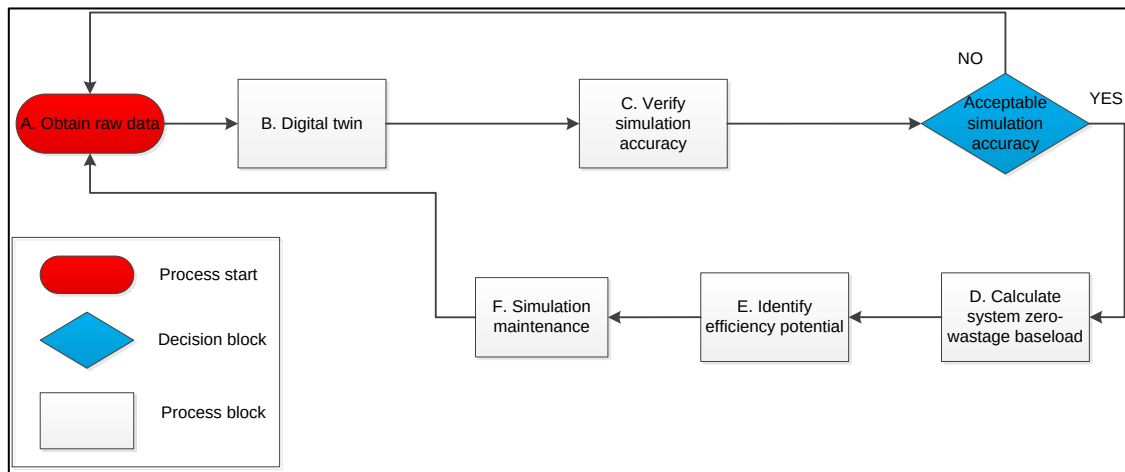


Figure 18: Step 3B – zero-wastage simulation method

Step 3B.A – The first step in the ZW simulation method is to obtain raw data for the identified system to build the digital twin. Multiple variables are required to calibrate a digital twin. Table 24 in Appendix B provides a checklist of the possible information requirements to calibrate the digital twin for a ZW baseload simulation. Obtaining information from underground is generally more complicated than from the surface, as extensive mining networks can stretch over several kilometres [24]. Obtaining the required data can thus be a time-consuming process.

Updated system drawings are required to build the digital twin as accurately as possible. Compressed air and dewatering layouts can usually be retrieved from engineers on site as well as the mine’s drawing office. Ventilation and refrigeration drawings can be retrieved from the ventilation team specialising in underground cooling. Figure 19 displays an example of an underground drawing constructed by a mine surveyor.

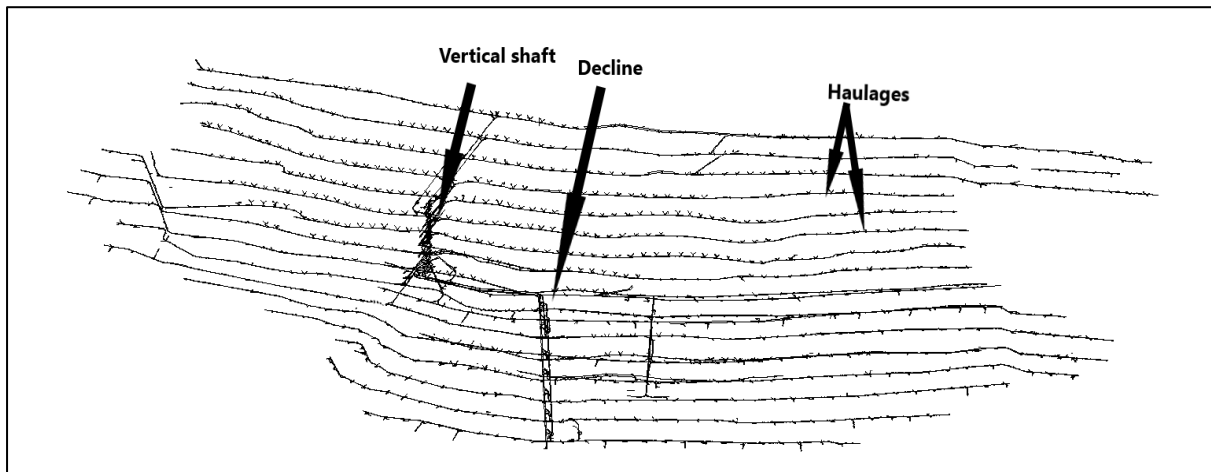
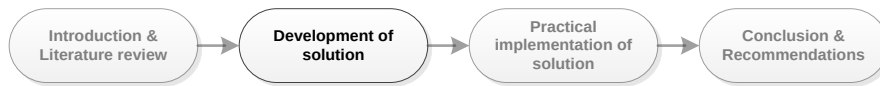


Figure 19: Example of an underground mine layout

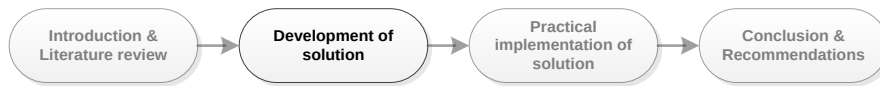
Before conducting the audit, it is important to understand the naming convention used by the surveyors as this will assist with navigating underground as well as making proper audit notes.

Additionally, an instrumentation audit is recommended to identify the location and overall condition of the existing meters and locate lacking metering. The information retrieved from the meters will assist in calibrating the digital twin.

However, in some occurrences, mines contain a limited amount of measurement equipment underground. In that case manual measurements should be taken to gather the required information for the digital twin. Figure 20 displays an example of a compressed airflow meter and pressure meter that can be installed on a compressed air pipe [111]. These meters can also be used to verify existing meters underground [32].



Figure 20: Compressed airflow and pressure meter



Instrumentation audits can also reveal critical locations that require instrumentation equipment. Installing new meters and repairing broken meters will ultimately ensure that mining operations can be accurately monitored. Table 23 in Appendix B provides a template for noting the results retrieved from the instrumentation audit.

Step 3B.B – This step involves the development of a digital twin for the identified system. The data collected in Step 3B.A is imported into PTB to construct the digital twin, commencing with the system's layout. Figure 21 illustrates a drawing exchange format (DXF) drawing of the real system imported into the PTB simulation software. The DXF file is constructed based on precise coordinates, mirroring the genuine layout of the mine. Consequently, all the pathways depicted in the figure below represent the authentic Z, X, and Y coordinates of each haulage and cross-cut (XC) situated underground.

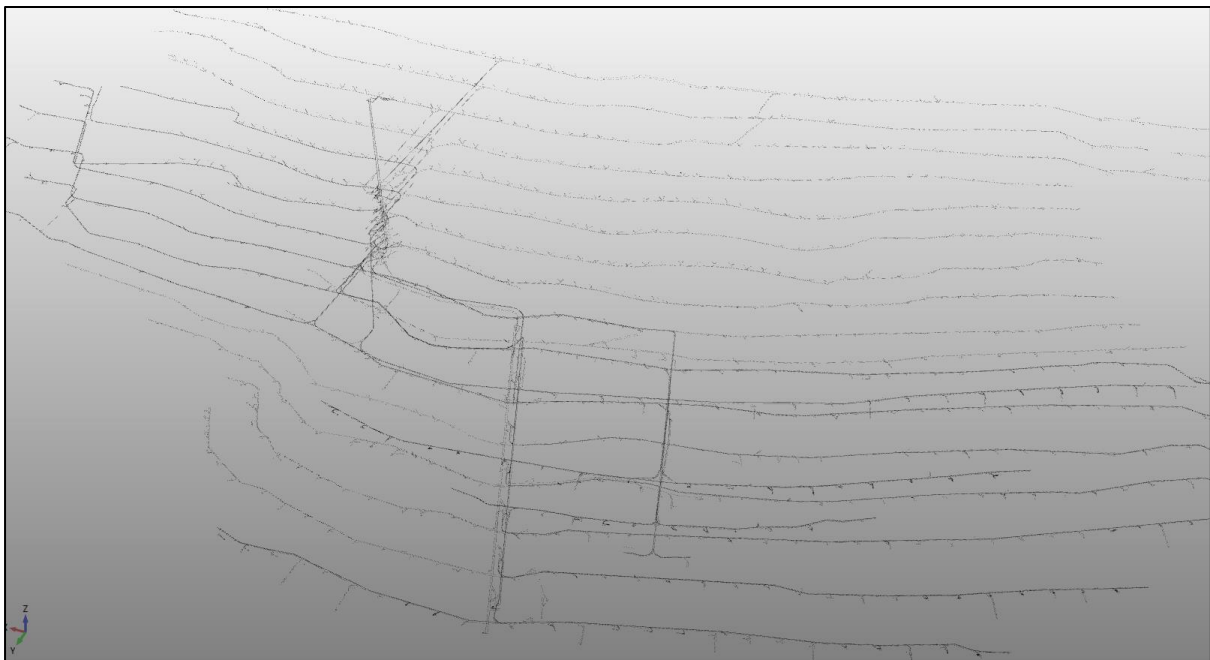


Figure 21: Zero-wastage simulation – mine layout example

After importing the DXF drawing file to PTB, specific system components can be added to the digital twin. The PTB software contains a drag-and-drop feature to add specific components as required. This is illustrated in Figure 22, where a compressed air pipe and an air node were added. PTB contains various built-in components to simulate compressed air, water reticulation, refrigeration, and ventilation networks.

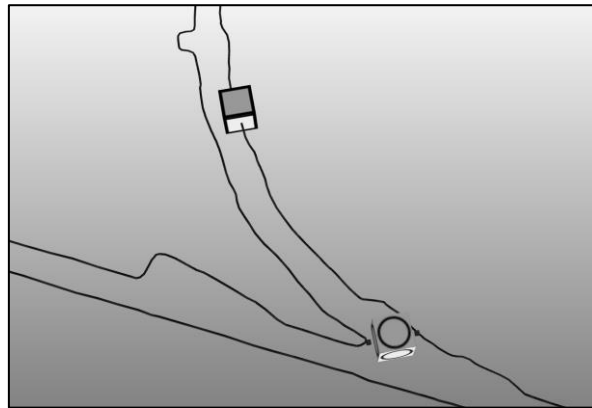
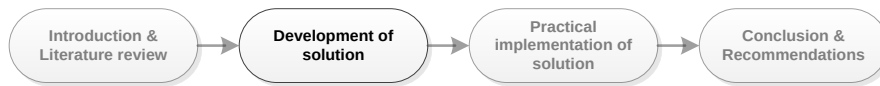


Figure 22: Zero-wastage simulation – component selection example

More detail can be added after the system components have been added and connected. Figure 23 displays an example of pipe alterations that can be added from the built-in PTB library based on the required specifications retrieved from the audit.

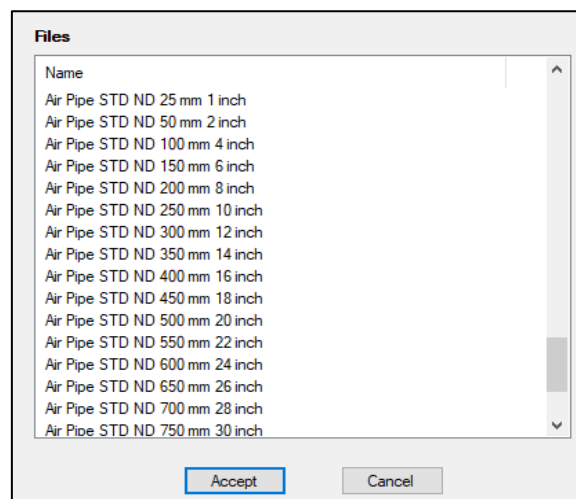
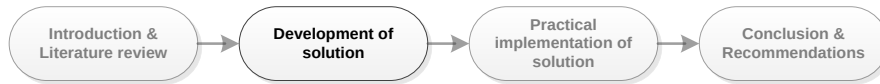


Figure 23: Zero-wastage simulation – component detail

Calibration is required for the digital twin to operate as close to the physical system as possible. This will ensure that all ZW baseloads and scenario tests implemented will be as accurate as possible. PTB has the functionality to add various flow measurements, pump curves, fan curves and refrigeration information etc., to calibrate each component.

Step 3B.C – After the digital twin is calibrated, a test simulation can be done to verify whether the simulation parameters are accurate. A large percentage error will result in a less accurate ZW baseload and affect any scenario simulations in the future. If the percentage error is acceptable, the ZW baseload can be simulated for the system. A root mean squared error above 15% is considered unacceptable [112].

Step 3B.D – With the digital twin it is possible to simulate the ZW baseload of the system. Depending on data availability, the simulation can be used to simulate more focused areas



such as XCs. This will provide a more accurate representation of the actual system's available efficiency.

Step 3B.E – The ZW baseload simulated in the previous step is then compared with the actual data. Inefficient areas and periods can then be located, and the system can be benchmarked based on inefficient working areas. Table 11 provides an example of a mine's working levels benchmarked based on their ZW performance, displaying the levels with the highest efficiency potential.

Table 11: Zero-wastage simulation – benchmarked example

Level	Actual measurement	ZW baseload	Difference
Level 5	X	X	X
Level 3	X	X	X
Level 1	X	X	X
Level 4	X	X	X
Level 2	X	X	X

Step 3B.F – Due to the continuous expansion of the underground mining environment, digital twins must be updated regularly to provide accurate results [105]. Thus, the ZW simulation method needs to be restarted to ensure the information obtained in Step A is still relevant. This is also the case with new project implementations. The method will have to be restarted throughout wherever significant system changes are applied.

2.2.4 Step 4: Dynamic achievable target

As displayed in Figure 24, step 4 in the ZW benchmarking method consists of developing a dynamic target that is based on a system's ZW baseload. This step was recognised as a requirement based on the solution criteria as a method to develop a realistic, attainable target baseload for a mining system.

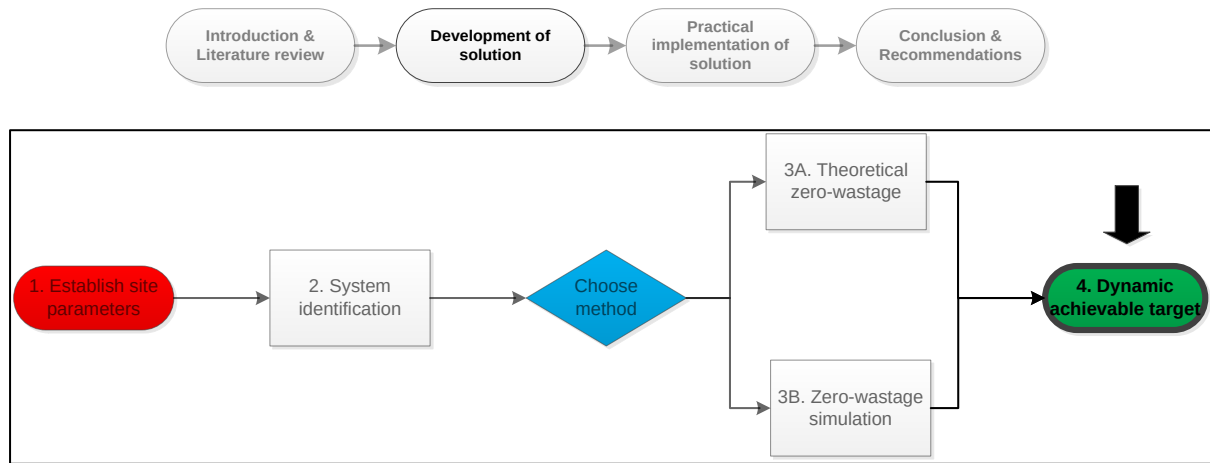


Figure 24: Step 4 – Zero-wastage dynamic achievable target

As indicated in Chapter 1, accurate operational targets may prove invaluable in monitoring and maintaining system performance. This is noted seeing as most mines' adjustments and projections are based solely on energy tariff increases and planned tonnes. The limited scope of considerations in existing methods exclude several other potential inefficiencies that may hinder near-optimal or real measures of potential efficiency.

Figure 25 illustrates a novel method proposed for developing a more achievable target baseload with dynamic properties. The goal of this method is to motivate the mine to gradually decrease wastage while moving closer to the ZW baseload.

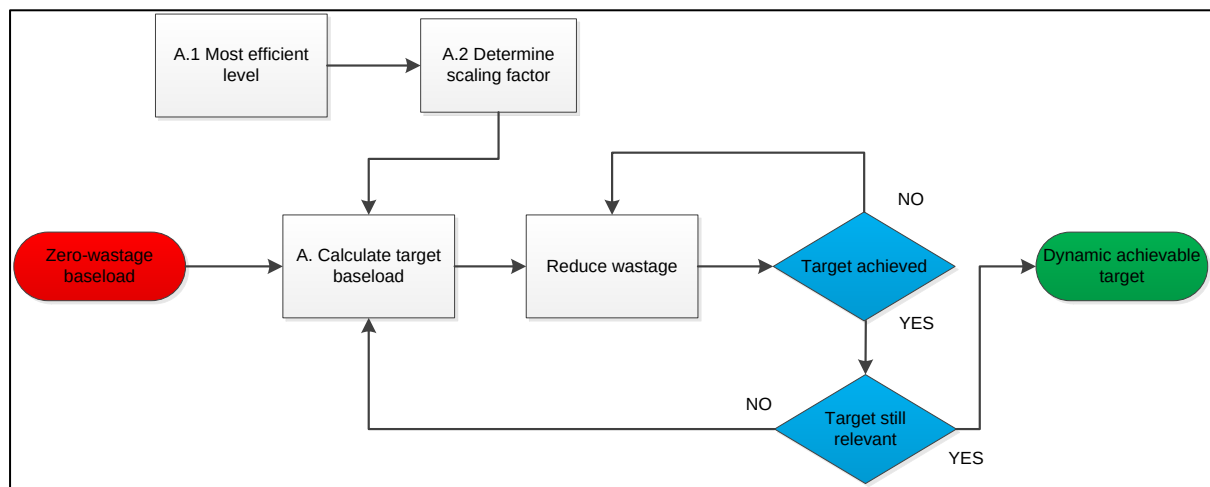
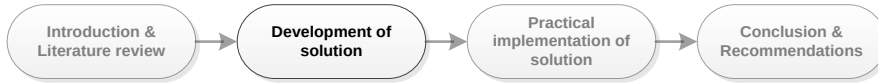


Figure 25: Dynamic achievable target

As mentioned, the ZW baseload is considered the most efficient profile of the system. Although the ZW baseload can assist in identifying and quantifying the potential available efficiency within a system, it is rare that a system will achieve the ZW baseload profile in a real-world scenario. This means that using a ZW baseload as a target profile will result in the system being over-target indefinitely. The solution for this is to scale the ZW baseload. As displayed in Figure 25, this is done with two steps, namely, 4A.1 and 4A.2.



Step 4A.1 is the most efficient level of the mining system identified, that is, the level operating closest to their respective ZW baseload. This level is a realistic indication of what is currently attainable in terms of efficiency within the system.

Step 4A.2 entails calculating the scaling factor by dividing the actual consumption of the level with the ZW baseload of the level for each time stamp as displayed in Equation 5: Achievable target scaling factor [109].

$$Scaling\ factor_n = \frac{Actual\ consumption\ per\ level_n}{ZW\ Level_n}$$

Equation 5: Achievable target scaling factor [109]

The dynamic achievable target can then be calculated by multiplying the scaling factor with the ZW baseload of the system for each time stamp as displayed in Equation 6.

$$Dynamic\ achievable\ target_n = Scaling\ factor_n \times System\ ZW_n$$

Equation 6: Dynamic achievable target

As the system becomes more efficient with time, a new dynamic achievable baseload can be calculated. This leads to a lower achievable target, gradually moving closer to the system's ZW baseload.

2.3 Conclusion

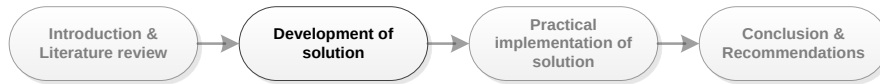
Chapter 2 discussed the methodology that was developed for this study. The methodology proposes a comprehensive four-step ZW benchmarking method accompanied by various sub-steps for identifying areas in various systems with the potential to improve efficiency in terms of operations, resources, and cost. The elements of the proposed method work in conjunction, allowing mines to determine a ZW baseline that considers various systems and factors against which it is measured, thereby guiding enhanced efficiency within the mining operations.

The first step involves conducting an audit to identify the various systems present within the targeted mine with the aim of gaining a comprehensive understanding of the system.

In step two the identified systems are benchmarked based on their energy intensity. This assessment enables mines to identify the system with the highest energy efficiency potential.

The third step illustrates two available sub-methods for calculating the ZW baseload of a system, with the choice of either depending on specified requirements and constraints. These sub-methods were based on the objectives outlined in Chapter 1.

The first sub-method concerns the implementation of the theoretical ZW method, which calculates a system's theoretical baseload. Equation 3 and Equation 4 are used to derive the



potential savings attainable with the ZW baseload. This calculation provides valuable insights into the efficiency that can be achieved within the system.

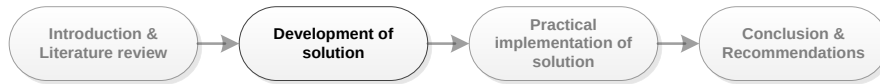
Alternatively, the second sub-method can be used to determine a ZW baseload through the use of a digital twin. This method involves simulating the ZW baseload for the system and comparing it to the actual system data. This comparison can then be used to identify inefficient areas within the system. The digital twin emerges as a valuable tool for project simulation and scenario testing in determining and realising optimal efficiency outcomes.

In the next step, the identified inefficiencies are compared through benchmarking to rank areas according to their highest efficiency potential and develop improvement strategies accordingly. The suggested steps in this approach has the capacity to deliver targeted, realistic efficiency projects for optimising overall system performance.

The outcome of the above measure was a method that was developed to calculate a dynamic achievable target from a system's ZW baseload. The achievable targets and outcomes facilitate a gradual progression towards the ZW baseload as they achieve greater efficiency with the implementation of each new project. Table 12 presents a summary of the solution criteria that was achieved, **verifying** the ZW benchmarking method.

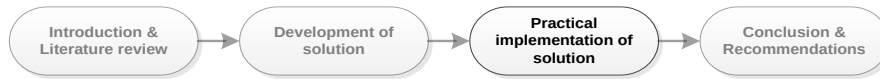
Table 12: Assessment of study criteria against proposed method

Item	Addressed	How?	Section
1. Applicable to deep-level mines	✓	The developed solution considered high energy-consuming mining systems.	2.2
a. Use of existing data	✓	The developed solution uses existing mining data to identify mining systems as well as to calculate a ZW baseload of the identified system.	2.2.1
b. Can be applied to mining systems	✓	The ZW benchmarking method is developed considering mining systems as an input to calculate a ZW baseload for each system.	2.2.2
2. Multiple techniques can be used to develop the solution	✓	Two techniques were developed to calculate a mining system's ZW and a selection guide was provided.	2.2.3
a. Theoretical based	✓	A Theoretical ZW method was developed guiding a user to calculate a system's ZW baseload.	0
b. Simulation based	✓	A simulation-based method was developed guiding a user to calculate a system's ZW baseload.	2.2.3.2



3. Desired study outcome	✓	The implementation of the methodology will identify inefficiencies within a mining system.	2.2
a. Identify inefficiencies	✓	Comparing the ZW baseload with the actual consumption of a mining system identifies inefficiencies within the mining system. Applying the method to deeper mining levels can provide a more focused approach.	2.2.3
b. Develop relevant target baseload	✓	The implementation of the methodology will provide a relevant target baseload which will update as the system's ZW changes.	2.2.4

Chapter 3 discusses the implementation and subsequent results of the ZW benchmarking method in three case studies, after which the method is validated.



CHAPTER 3 – PRACTICAL IMPLEMENTATION OF SOLUTION

3.1 Preamble

Chapter 2 discussed the method developed to address the problem statement identified in Chapter 1. Various novel methods were developed in Chapter 2 to address the shortcomings identified with the previous studies discussed in Chapter 1. These methods culminated in a new benchmarking method for developing a ZW baseload for the comparison of various systems to identify areas with efficiency potential within systems. As per the research methodology, steps 4 to step 8 apply in the following chapter.

The ZW benchmarking method was applied in three case studies – two applied to compressed air systems and one applied to a water reticulation system. The results serve to validate the study methodology. Figure 26 illustrates a flow chart of the ZW benchmarking method, the components of which are subsequently discussed in detail.

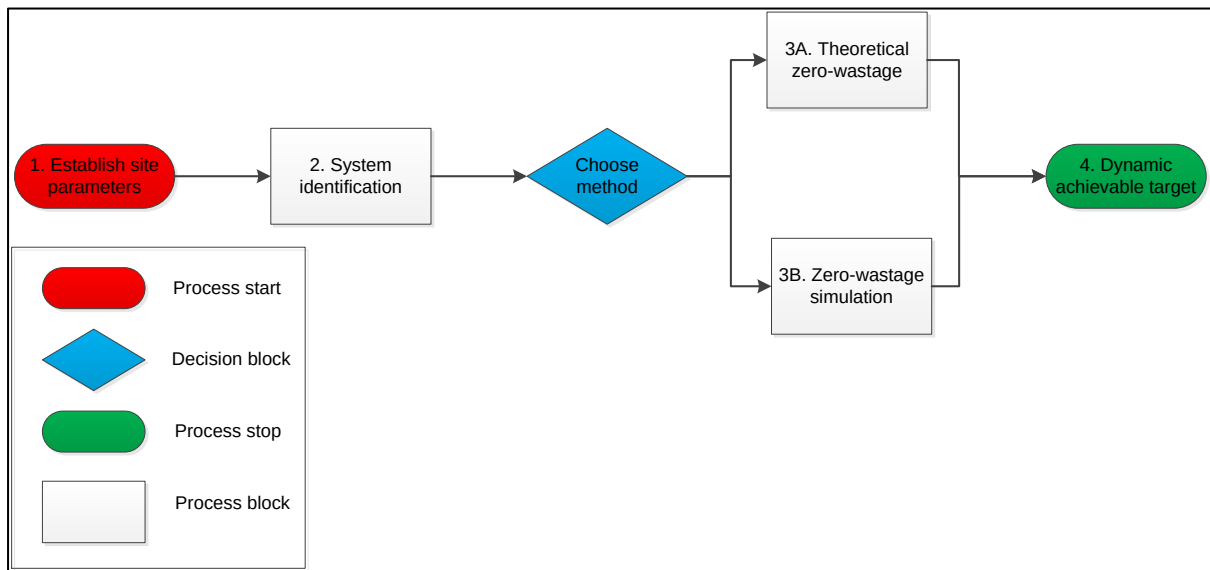
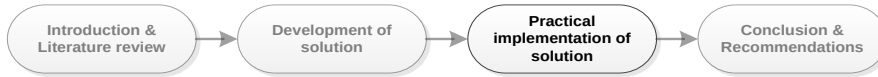


Figure 26: Proposed zero-wastage benchmarking method

3.2 Case study A

In the first case study, the ZW benchmarking method above (Figure 26) was applied in a platinum mine, with the aim of identifying efficiency potential.



3.2.1 Step 1: Establish site parameters

Initial investigation revealed that the mine contains five production levels, as seen in the high-level drawing displayed in Figure 27. Furthermore, it was noted that the mine utilises various high-energy systems as normal operation, namely:

- Ventilation,
- Refrigeration,
- Compressed air, and
- Winders.

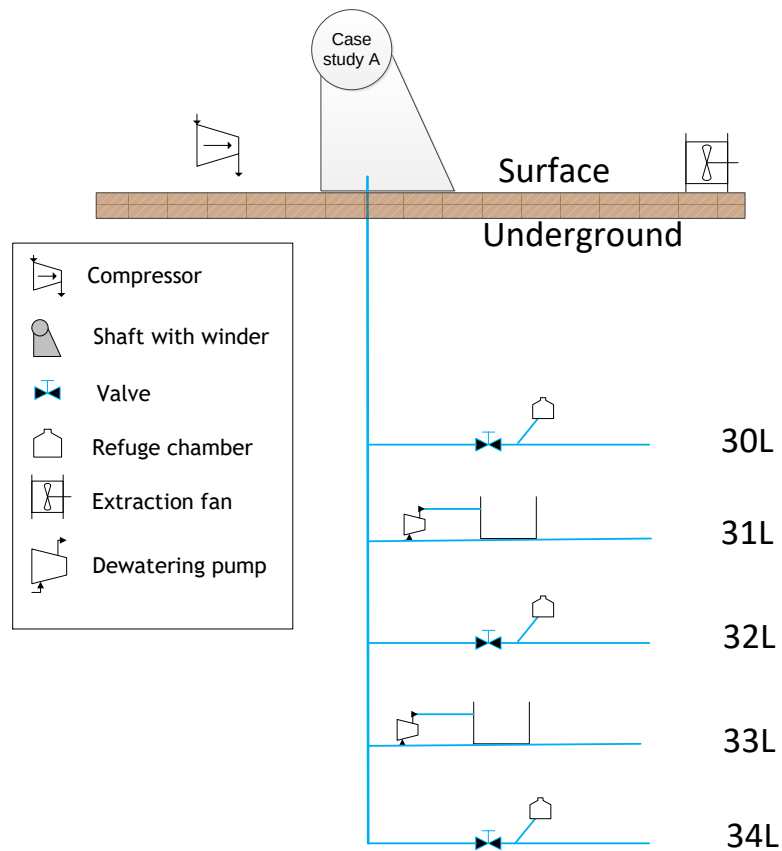


Figure 27: Case study A – high-level mine layout

Energy and production data were retrieved from the mine's SCADA system to apply an intensity study on the mine and thereby identify the least efficient system. The aforementioned data are displayed in Table 13.

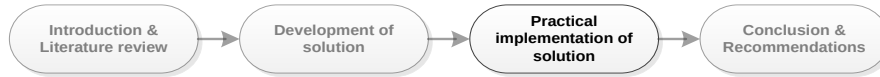


Table 13: Case study A – system intensity data

Month	Refrigeration (kWh)	Ventilation (kWh)	Rock winders (kWh)	Underground (kWh)	Surface (kWh)	Compressed air (kWh)	Production (ton)
Jan-22	1 833 952	3 381 977	289 541	2 144 197	416 201	3 915 339	34 677
Feb-22	1 935 373	2 647 756	347 789	2 008 318	387 511	3 665 788	41 510
Mar-22	2 355 986	3 335 753	426 715	2 248 736	449 376	5 241 377	51 084
Apr-22	1 971 544	2 703 577	320 897	2 272 841	431 619	4 490 646	38 313
May-22	2 111 750	3 515 215	341 421	2 263 988	477 988	4 814 461	41 344
Jun-22	1 513 384	3 267 927	337 071	2 304 871	495 349	3 864 160	38 328
Jul-22	1 585 615	3 222 906	356 956	2 271 624	501 744	4 460 446	42 582
Aug-22	1 531 985	3 181 109	371 785	2 234 534	505 383	4 679 838	43 460
Sep-22	1 401 626	2 657 158	287 820	1 807 357	377 144	4 207 196	-

3.2.2 Step 2: System identification

The intensity of each system is calculated by using Equation 1 in Chapter 2, as displayed below:

$$\text{System intensity} = \frac{\text{System energy}_{(kWh)}}{\text{Production}_{(ton)}}$$

The average energy and production data from February 2022 until September 2022 was used. January 2022 was excluded because the mine was not in normal operation due to the December maintenance shutdown. Substituting the average energy and production data of each system gathered in the previous step into Equation 1 yielded:

$$\text{System intensity} = \frac{\text{Refrigeration}_{kWh}}{\text{Production}_{(tons)}}$$

$$\text{System intensity} = \frac{1\,800\,908}{42\,375}$$

$$\text{System intensity} \approx 42 \frac{\text{kWh}}{\text{t}}$$

Subsequently, the remaining system intensities (from Table 13) were calculated with Equation 1, and the results are displayed in Table 14.

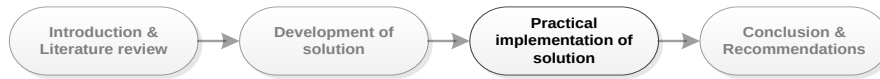


Table 14: Case study A – system intensity results

System	Average Energy (kWh)	Load contribution	Average production (tonnes)	Intensity ($\frac{\text{kWh}}{\text{t}}$)
Refrigeration	1 800 908	15%	42 375	42
Ventilation	3 066 425	25%		72
Rock winders	348 807	3%		8
Underground	2 176 534	18%		51
Surface	453 264	4%		11
Compressed air	4 411 642	36%		104
Total	12 257 580	100%		289

The table indicates that compressed air is the largest energy consumer in terms of production in tons produced. This can be an indication that compressed air has the most energy efficiency potential available.

The compressed air system's ZW baseload was calculated in the next step. Recall from Figure 26 that two options are available for calculating ZW baseloads, namely theoretical ZW and ZW simulation. The researcher opted for the theoretical approach given the limited time frame for project completion and the scope of the information that was supplied (see Table 9).

3.2.3 Step 3A: Theoretical zero-wastage

Figure 28 displays the resulting method that was developed for calculating a theoretical ZW baseload for a system.

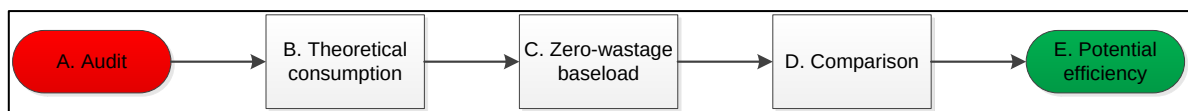


Figure 28: Step 3A – theoretical zero-wastage method

Step 3A.A – Audit

An audit was done of the compressed air network to identify all the compressed air consumers, as illustrated in Table 15 and Figure 29. As seen, five main compressed air consumers were identified, with rock drills accounting for the largest number.

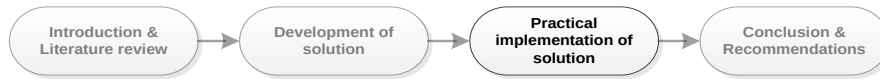


Table 15: Audit results

Consumer	Quantity
Rock drills	76
Refuge chamber	42
Legal venturi blowers	2
Pneumatic loaders	10
Loading boxes	56

The identified consumers in Table 15 were also verified to be typical consumers found underground within a compressed air network [23], [25]. During the audit, operating schedules were determined for each of the consumers identified in Table 15. The identified compressed air consumers and equipment were divided between the three operating shifts of the mine. Figure 29 provides a visual indication of the operational schedule with its corresponding consumers.

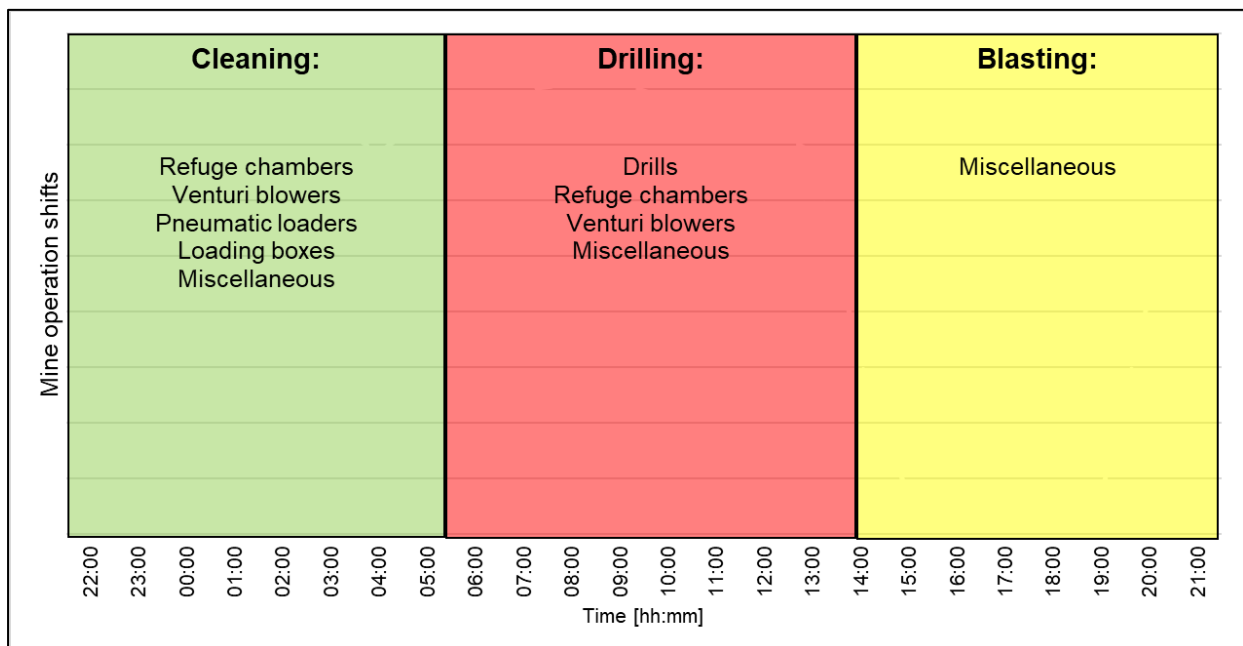
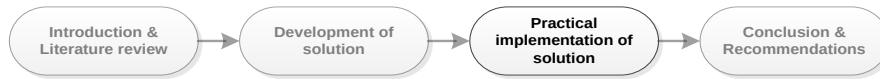


Figure 29: Mine A's operational schedule

Step 3A.B – Theoretical consumption

Rated consumption details were identified for each consumer. This information was gathered through research and direct communication with the equipment suppliers. The total theoretical consumption of the compressed air consumers was calculated using Equation 2, as displayed below:



$$\text{Theoretical consumption} = f_{rated} \times \sum_{consumers}$$

$$\text{Theoretical consumption}_{Refuge\ chambers} = 61.5 \times 42$$

$$\text{Theoretical consumption}_{Refuge\ chambers} = 2\,585\ m^3/h$$

Table 16 provides the results of the total theoretical compressed air consumption of each consumer calculated with Equation 2. Miscellaneous consumers comprise smaller compressed air-consuming equipment such as pneumatic water valves.

Table 16: Theoretical compressed air consumption on mine A

Compressed air consumer	Theoretical consumption (m ³ /h)
Refuge chambers	2 585
Venturi blowers	504
Rock drills	55 018
Loading boxes	1 472
Pneumatic loaders	10 080
Miscellaneous consumers	6 002

Step 3A.C – Zero-wastage baseload

The outcomes obtained in steps 3A.A and 3A.B were employed to compute the ZW baseload. This involved incorporating the compressed air data from Table 16 into the respective operational schedule depicted in Figure 29. Figure 30 illustrates the ZW baseload profile across a 24-hour period for the compressed air network in the case study.

An observation made during the audit revealed that the loaders were solely operational between 22:00 and 01:00 during the cleaning shift, elucidating the surge in compressed air consumption during this specific timeframe.

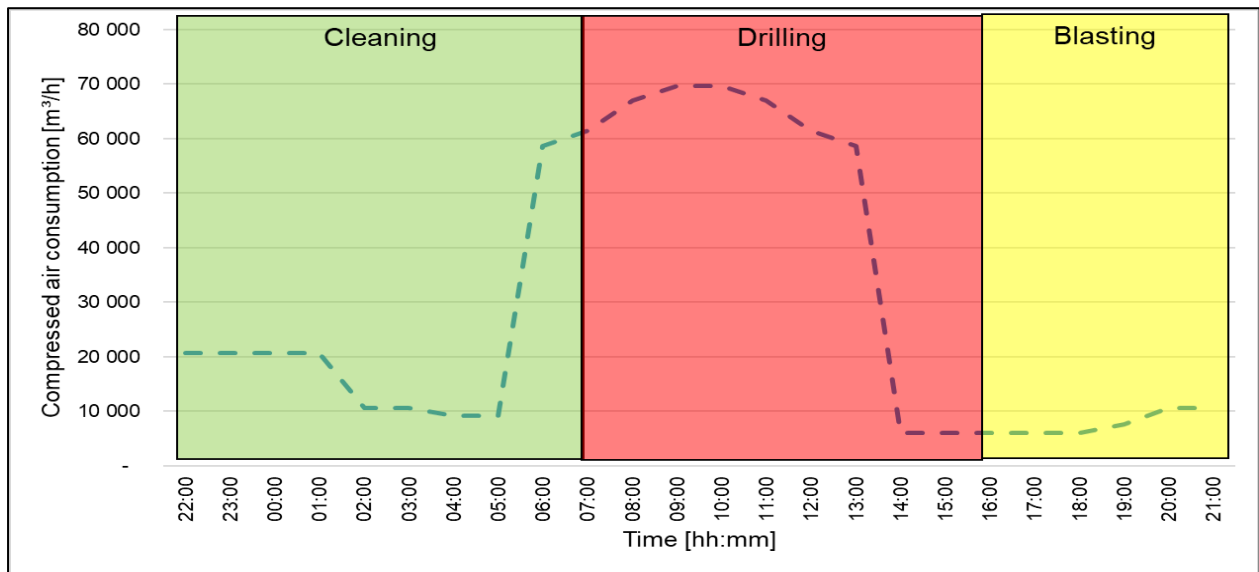
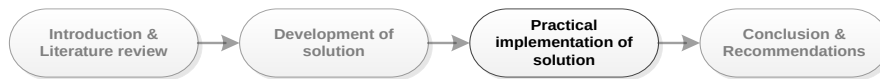


Figure 30: Case study A – zero-wastage baseload

A peak in compressed airflow is noted during drilling shifts in which a large portion of the drills are operational. For comparison, note the significantly lower usage during the cleaning and the blasting shifts due to lower consuming compressed air equipment. With this information, inefficient periods were determined during operational shifts by comparing the ZW baseload to the actual compressed air consumption of the compressed air network in step 3A.D.

Step 3A.D – Comparison

Figure 31 displays the results achieved in Step 3A.D. The actual consumption profile is based on a month's worth of average weekday data.

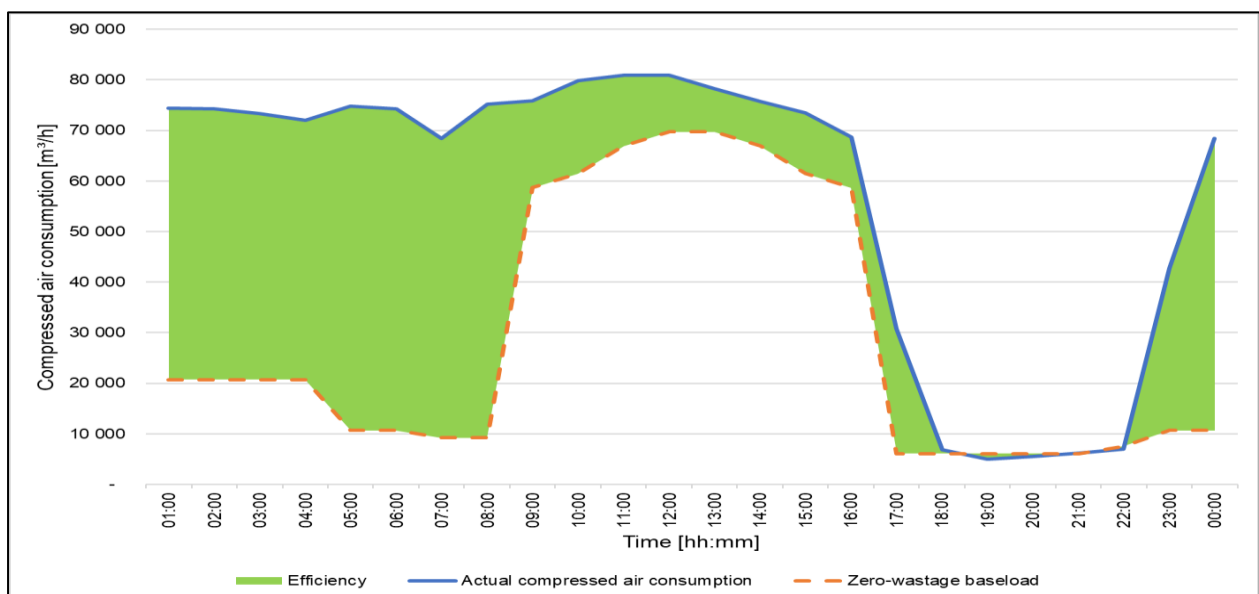
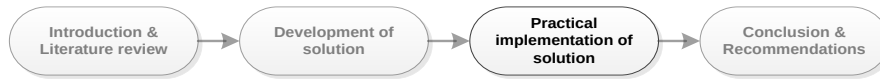


Figure 31: Case study A – actual consumption vs zero-wastage



As seen in Figure 31, the actual consumption profile is substantially higher than that of the ZW baseload profile. The mine in question consumed a total of 1 372 636 m³ over the 24-hour profile compared to the baseload's profile of 676 886 m³.

According to the literature in section 1.5.1.2, an estimated 40% to 80% of generated compressed air goes to waste. This range serves as a validation benchmark, as depicted in Figure 32. The figure illustrates a comparison between the ZW baseload and the validation range. As seen in the figure, the ZW baseload falls outside the designated range during the cleaning and drilling shifts. This is because the validation range, which is based on the specific mine's consumption profile, does not follow the operation schedule which is included in the ZW benchmarking method.

However, when comparing the average wastage (represented by the yellow dots) of the ZW baseload to the validation range, the ZW benchmarking method emerges as capable of identifying the wastage mentioned in the literature, thus **validating** this method.

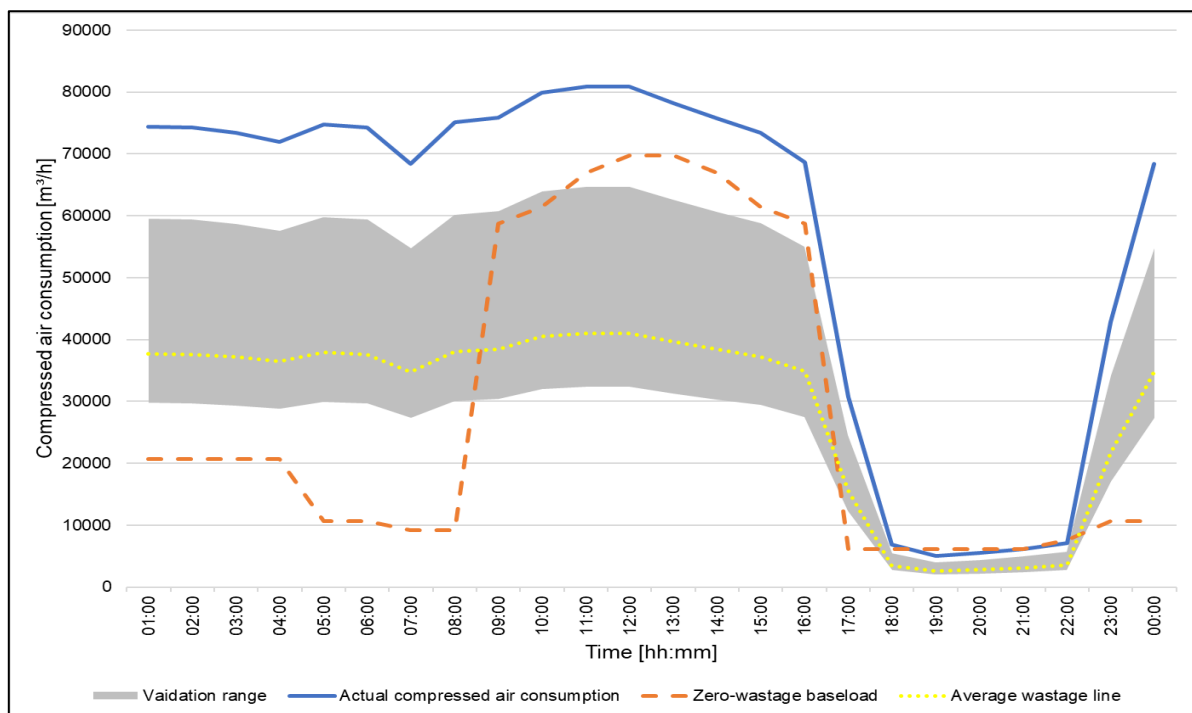
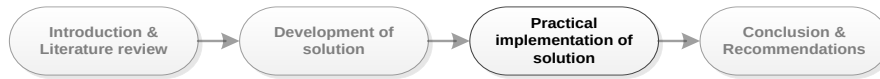


Figure 32: Case study A – zero-wastage baseload validation

The majority of compressed air wastage is found within the cleaning shift, highlighting the misuse of compressed air. As seen, the mine consumed a total of 554 149 m³ during the cleaning shift, compared the benchmarked 153 326 m³. This indicates a potential reduction of 400 822 m³ during the cleaning shift, if the compressed air consumption is managed correctly.



Step 3A.E – Potential efficiency

Using the ratio mentioned in step 3A.E of section 2.2.3, the potential energy efficiency is calculated as 72.7 MWh for the 24-hour profile. This energy saving can also lead to a CO₂ emission benefit. Equation 4 from Chapter 2, as shown below, yields a CO₂ potential reduction of approximately 78.5 tonnes.

$$1.08 \text{ ton } CO_2e = 1 \text{ MWh}$$

$$78.5 \text{ ton } CO_2e = 72.7 \text{ MWh}$$

Additionally, a ZW baseload was calculated for the production levels, providing a more focused solution to identify inefficiencies within the case study mine. Table 17 provides the results achieved for the five production levels. Level 30 (green) was identified as having the most potential, considering that this level has the largest difference between the ZW baseload and the actual compressed air consumption. More information can be found in the written article located in Appendix D [81].

Table 17: Case study A – per-level results

Production level	Level flow per 24-hour (m ³)	ZW baseload per 24-hour (m ³)	Saving (m ³)	Saving (kWh)
30	225 863	54 806	171 057	18 393
31	237 156	76 448	160 708	17 280
32	280 070	151 462	128 608	13 829
34	307 174	209 319	97 855	10 522
33	302 657	208 664	93 993	10 107

3.2.4 Step 4: Dynamic achievable target

Figure 33 displays the dynamic achievable target method discussed in Chapter 2. This method was developed to calculate a target baseline from a system's ZW baseload.

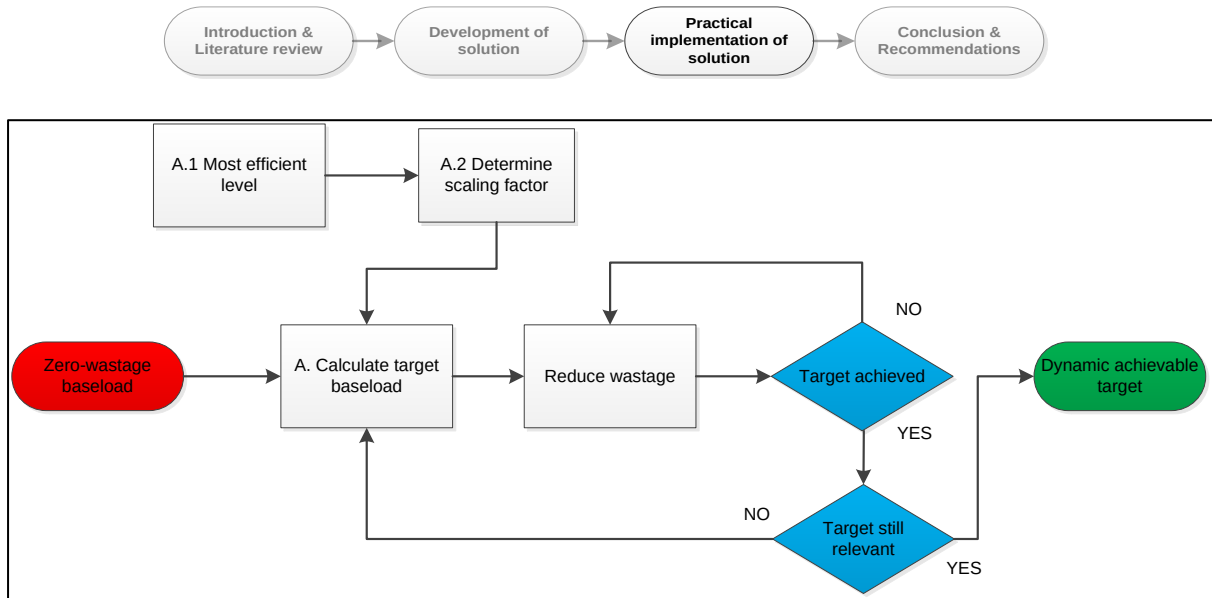


Figure 33: Step 4 – dynamic achievable target

Step 4A.1 – The results achieved in Table 17 designate level 33 as having the smallest variance between its actual compressed airflow and ZW baseload. It is therefore the most efficient.

Step 4A.2 – Equations 5 and 6 were used with the information from step 4A.1 to calculate the scaling factor and corresponding achievable target: Considering the first timestamp 01:00, the calculation is as follows.

$$\begin{aligned}
 \text{Scaling factor}_n &= \frac{\text{Actual consumption per level}_n}{\text{ZW Level}_n} \\
 &= \frac{14\,667.8}{7\,606.5} \\
 &= 193\%
 \end{aligned}$$

$$\begin{aligned}
 \text{Achievable target}_n &= \text{Scaling factor}_n \times \text{System ZW}_n \\
 &= 193\% \times 20\,742 \\
 &= 39\,998 \text{ m}^3/\text{h}
 \end{aligned}$$

Figure 34 displays the ZW baseload and the actual compressed air consumption compared to the achievable target. The calculated results from Equations 5 and 6 are displayed in Table 25 in Appendix C.

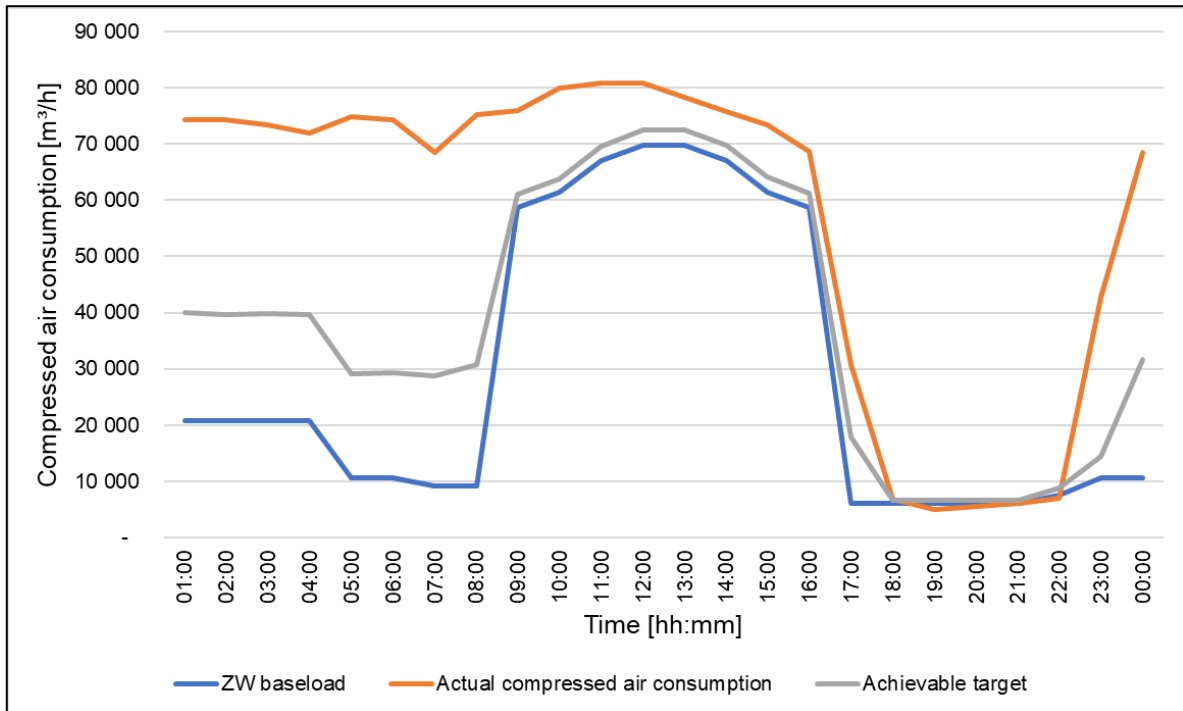
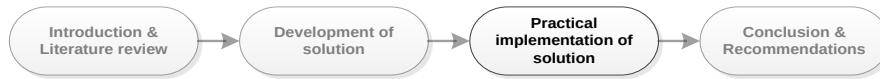


Figure 34: Case study A – achievable target

The target can achieve an estimated compressed air saving of 462 331 m³ within a 24-hour period, equating to a total energy efficiency potential of approximately 49.7 MWh for the same profile. As the compressed air system's efficiency improves, the method can be restarted to calculate a new scaling factor and updated target profile. This measure ensures an updated ZW baseload and target profile that remains relative, even during system adjustments.

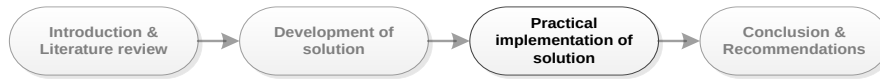
3.2.5 Comparison with previous studies

As reported above, the developed methodology met the requirements for the objectives set for this study. As per the research methodology identified in section 1.10, the next step is to compare the case study results against the theory from Chapter 1 to support the method's validity. Consequently, the results retrieved from the ZW benchmarking study are compared to other methodologies used to identify efficiency potential (wastage) within the mining environment. Three methodologies are singled out:

- Efficiency benchmarking,
- Baseline comparison, and
- Valve control.

Efficiency benchmarking

In most cases, mining systems were compared either to a more efficient system of the same type or to historical data of the same system [23], [81], which provided an indication of the



system's energy efficiency potential. In some cases, the systems were normalised with the objective of increasing the method's accuracy. However, it should be kept in mind that normalisation concerning two systems may be complicated due to system data variations, leading to skewed results.

Figure 35 displays the results of the method modelled on case study A. The actual compressed air consumption of system 2 (previous method) is compared to the ZW baseload for case study A. As seen, although the compressed air line of system 2 provides an indication of potential areas for realising energy efficiency, the ZW baseload provides a much greater efficiency potential between 22:00 and 09:00. The peak drilling shift noted between 10:00 and 16:00 is misleading, as the mine with system 2 operates at a much greater capacity than the one in case study A.

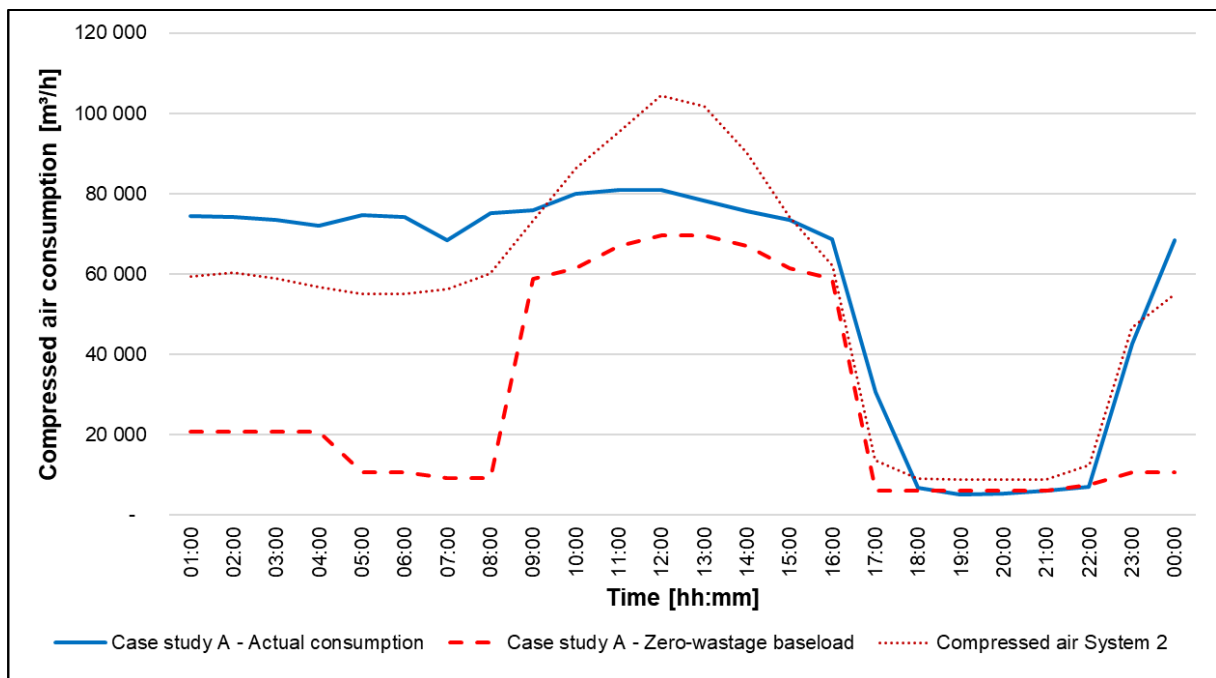


Figure 35: Case study A comparison with previous study – efficiency benchmarking

Baseline comparison

The following method comprised identifying wastage within a mining system by comparing different baselines. Although usually used in studies to calculate the savings resulting from wastage reduction [33], [72], [113], the method can also be used to identify wastage when comparing a system's actual consumption against historical data (baseline) granted that the consumption has increased from the baseline period [27]. Modelling this method in the case study A's compressed air network yielded the results in Figure 36.

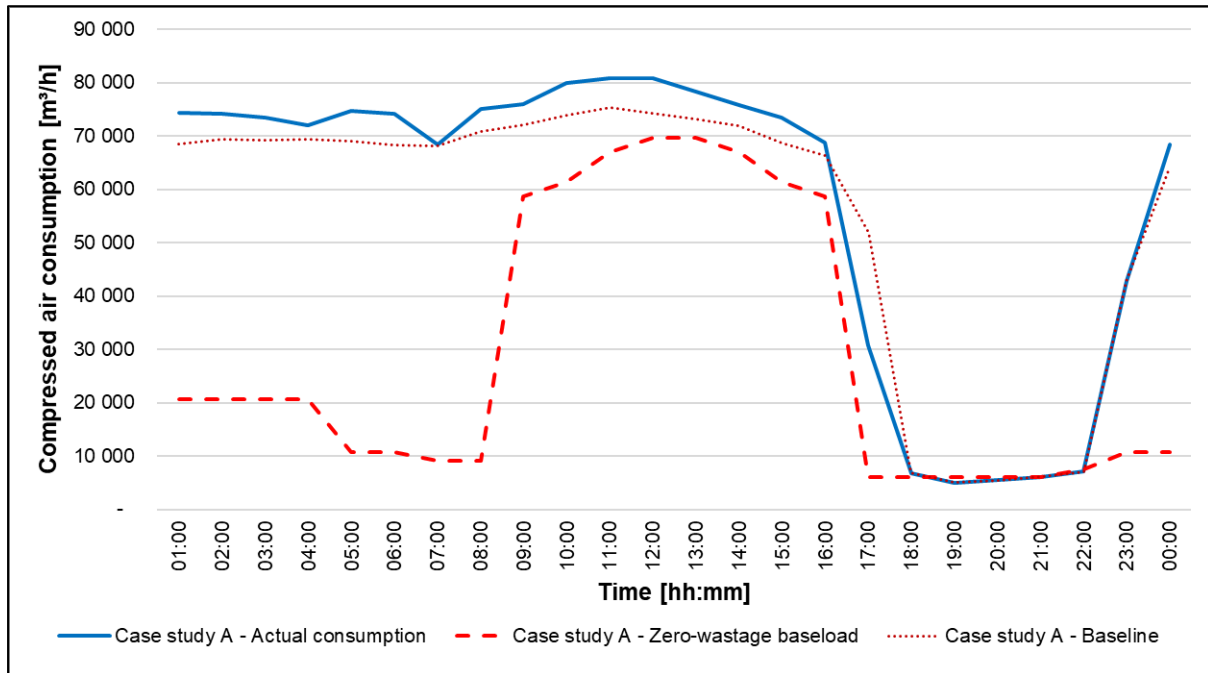
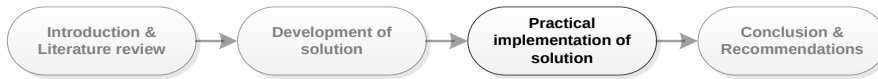


Figure 36: Case study A comparison with previous study – baseline comparison

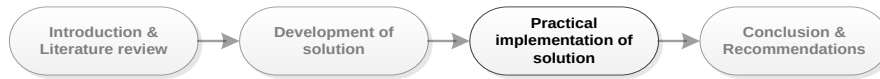
From case study A's baseline it is clear that the consumption increased during the cleaning and drilling shift. The actual consumption profile increased by an average of 2 287 m³/h when compared to the baseline profile, which points to the possible cause of the identified wastage.

However, a comparison between the ZW baseload and baseline profile shows that the baseline comparison method fails to identify most of the wastage during cleaning and drilling shift. Three critical issues were identified as potential causes of the baseline comparison method inaccuracy.

Firstly, the baseline comparison method, using historical data, does not account for any wastage that was present in the compressed air network at the time the baseline was developed. Secondly, the baseline comparison method does not account for any changes that was implemented on the compressed air network. This means that if more compressed air users were to be added to the system, the baseline comparison method would identify them as wastage. Thirdly, if the actual consumption profile is below the baseline profile, this method is rendered irrelevant, and a new baseline profile will be required to identify wastage.

Valve control

Valve control is one of the most utilised methods for optimising a compressed air system. This method usually involves the use of automated control valves controllable from the surface as well as from each mining level [98], [113], [114]. The valves are used to throttle the compressed air supplied to each level, providing the necessary pressure to safely operate pneumatic equipment [27].



The use of valves reduces compressed air oversupply during periods with lower demand for pneumatic equipment, such as the blasting and changeover shift [25], [27]. Figure 37 provides the model results from case study A.

As indicated, the actual flow profile of case study A already incorporates valve control during most of the blasting shift. An opportunity for reduced wastage opens between 05:00 and 06:00 and between 17:00 and 18:00; however, this method does not account for any wastage during the remaining periods, which is a limitation of this method. In addition, if valve control has already been applied on a system, the method will have limited results.

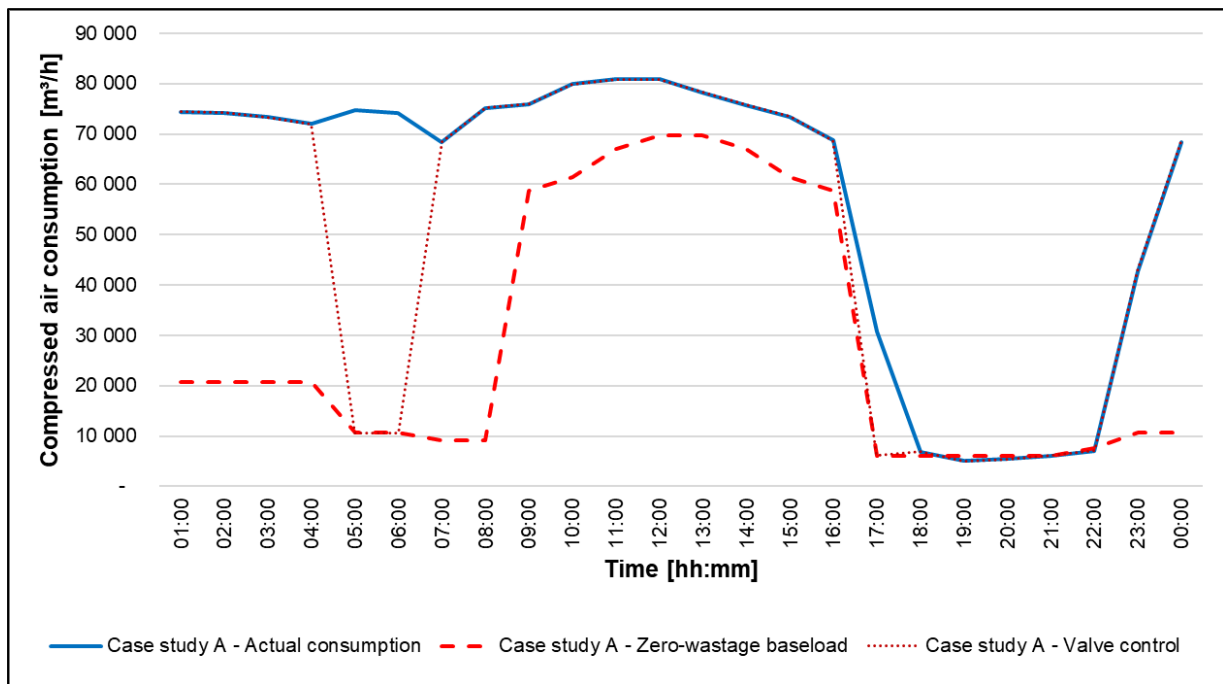


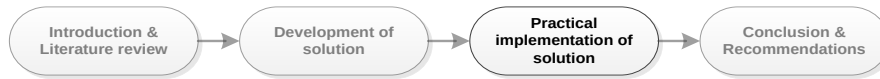
Figure 37: Case study A – comparison with previous study concerning valve control

3.3 Case study B

Case study B involved a platinum mine comprising sixteen underground levels, as displayed in Figure 39, with 10 of the 16 levels used for production and the remaining levels reserved for pumping or being blanked due to low production numbers.

A significant challenge faced by this mine was the provision of adequate compressed air to development ends, particularly at the last active cross cut (XC). The loaders and drills situated at these development ends rely on sufficient compressed air pressure for their operation. Prolonged periods of low supply pressures can adversely impact production, as drills and loaders play a crucial role in ore extraction from underground.

The ZW benchmarking method, outlined in Figure 26 was employed for this mine. In this case study, the objective was to develop a simulation to simulate the ZW baseload and identify



inefficient areas causing pressure drops throughout the compressed air system. Since the compressed air system was the focus of this case study, there was no need to implement steps 1 and 2 in the ZW benchmarking method, given the specific requirements.

3.3.1 Step 3B: Zero-wastage simulation

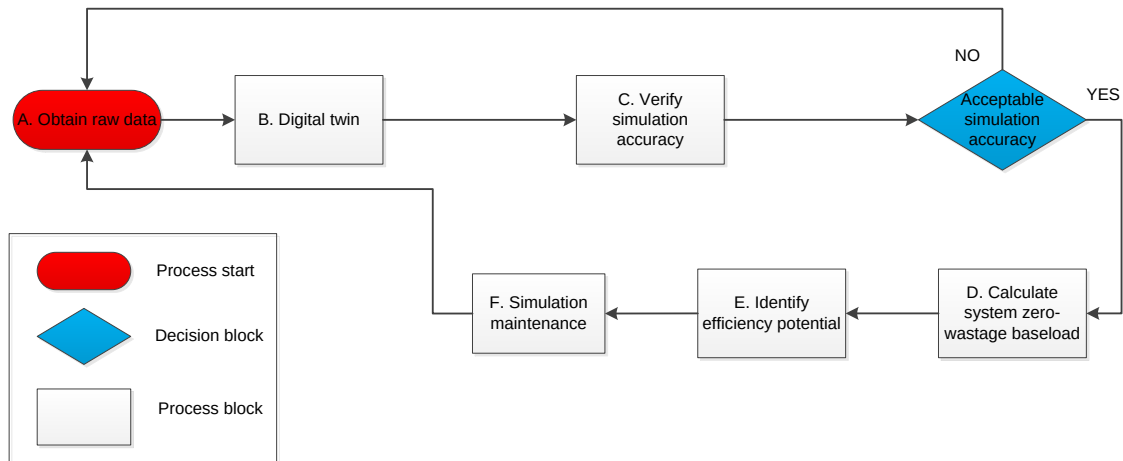


Figure 38: Step 3B – zero-wastage simulation method

Step 3B.A – Obtain raw data

The first step in the ZW simulation method consists of obtaining raw information that will be used to calibrate a simulation of the compressed air network. According to the audit, the mine had 10 production levels with multiple active XCs. Daily production data was obtained from the mine and used to identify the active XCs within the levels.

Underground visits were scheduled to audit the underground compressed air network up until the active XCs. Non-active levels (16L-21L) were monitored to ensure no compressed air was consumed by those levels. Figure 39 displays the compressed air network information retrieved during the audit.

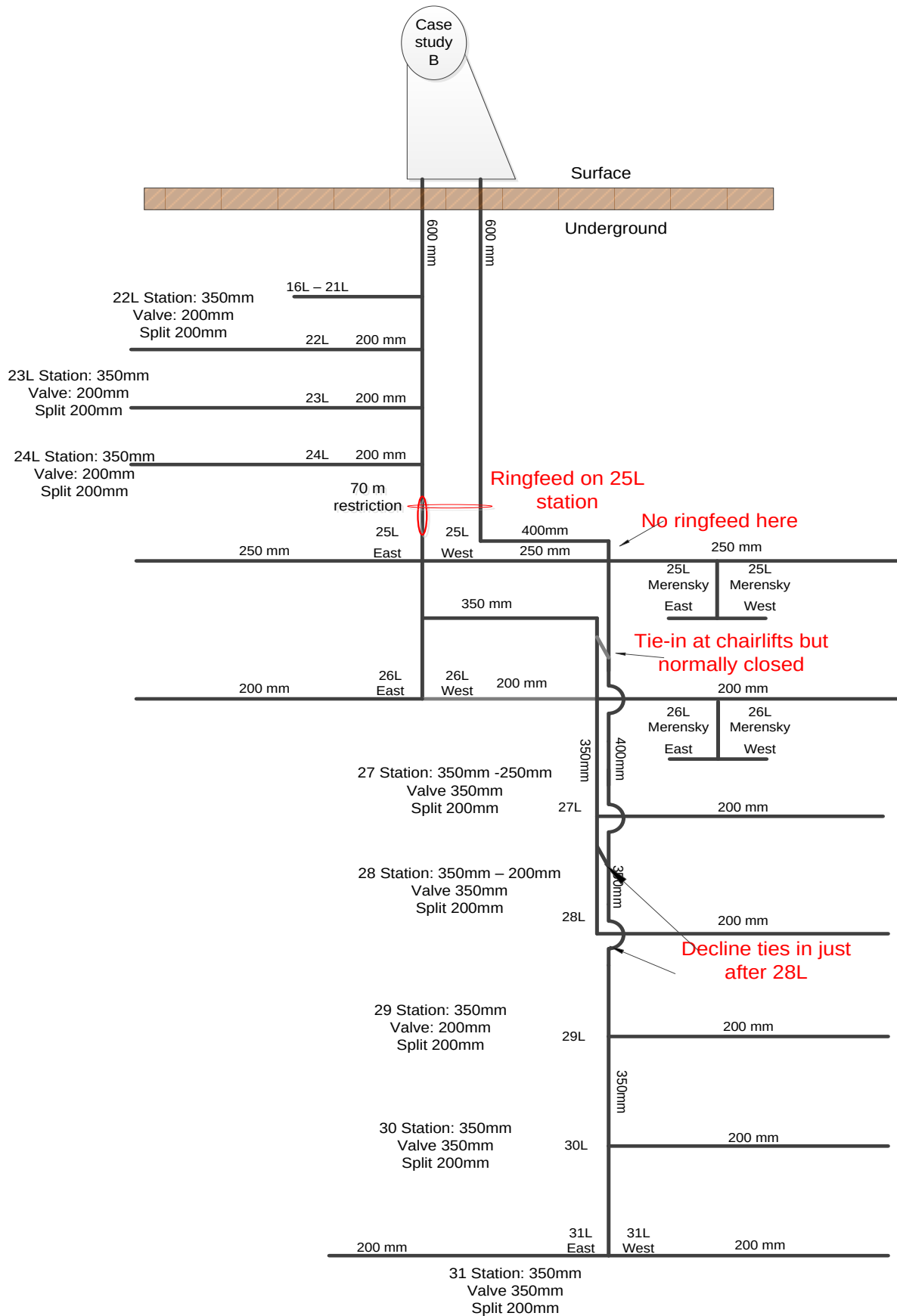
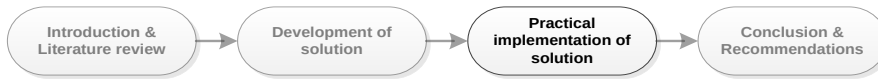
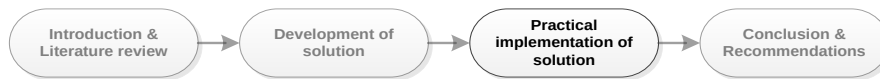


Figure 39: Case study B – compressed air network drawing



The audit template in Appendix B was used during the audit to document the necessary information for the compressed air digital twin. This included the location of all the active refuge chambers, the location of compressed air end consumers, DXF drawings of the mine, pipe layouts (Figure 39), and compressed airflow and pressure measurements. The digital twin was created in step 3B.B.

Step 3B.B – Digital twin

The method discussed in section 2.2.3 was applied to develop a simulation model for the case study compressed air network. The compressed air network was drawn on the DXF as shown in Figure 40, providing the simulation software with information such as component depth.

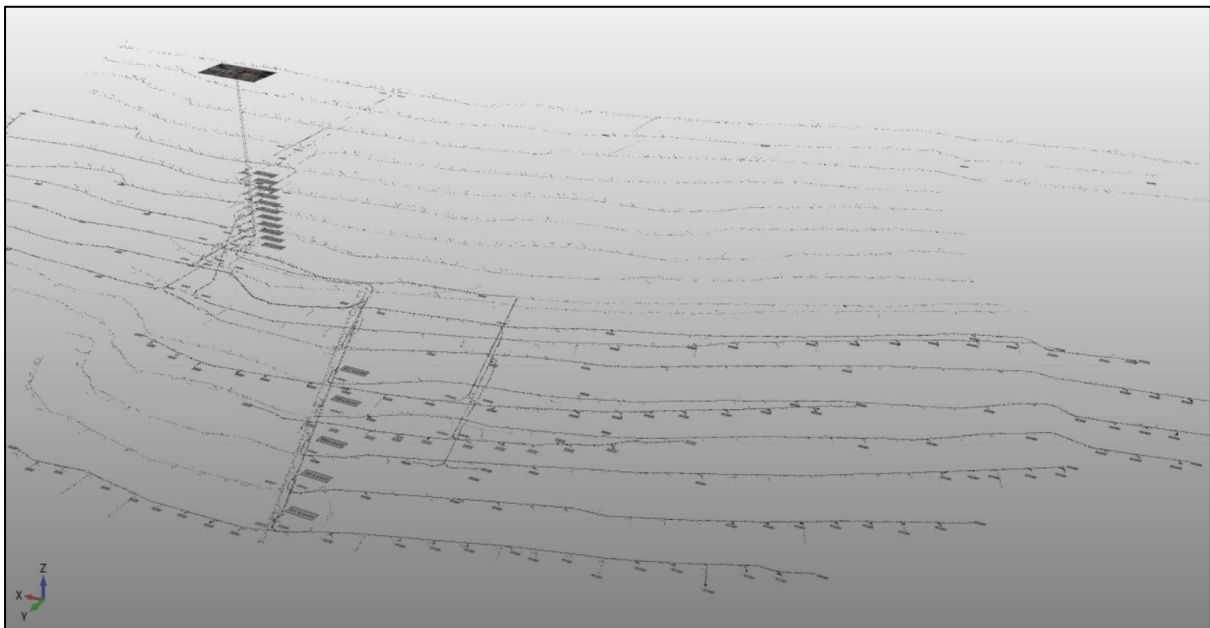


Figure 40: Case study B – digital twin

Step 3B.C – Verify simulation

The digital twin developed in the previous step and used to simulate the compressed air network's ZW baseload was subject to verification. The verification entailed applying the method discussed in Section 2.2.3.2 to ensure the simulated ZW baseload is accurate. Two factors were used to verify the simulation's accuracy, namely, compressed airflow and compressed air pressure. A 24-hour profile of the actual compressed airflow consumption is compared to the simulated compressed air consumption in Figure 41.

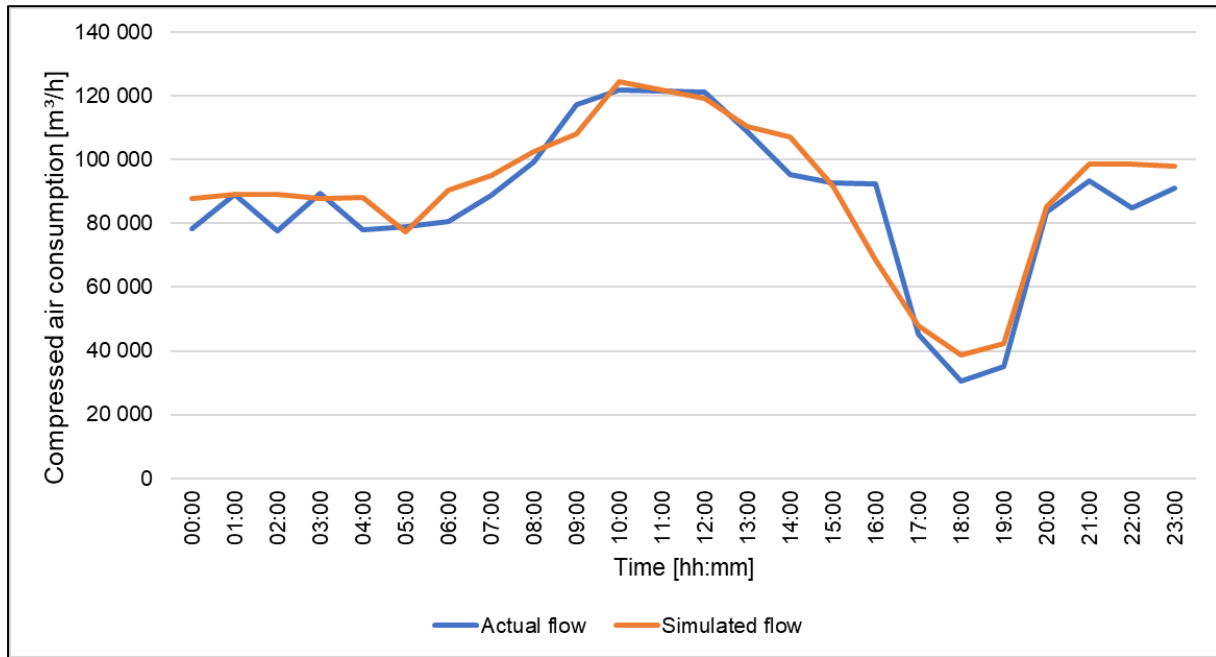
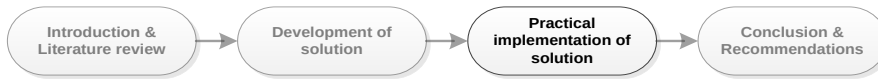


Figure 41: Case study B – simulation verification (flow)

An 8% average percentage error was calculated between the actual compressed airflow and the simulated compressed airflow, which can be seen in Figure 42. Compressed air pressure is an important factor as numerous compressed air consumers required an acceptable pressure range to operate as intended.

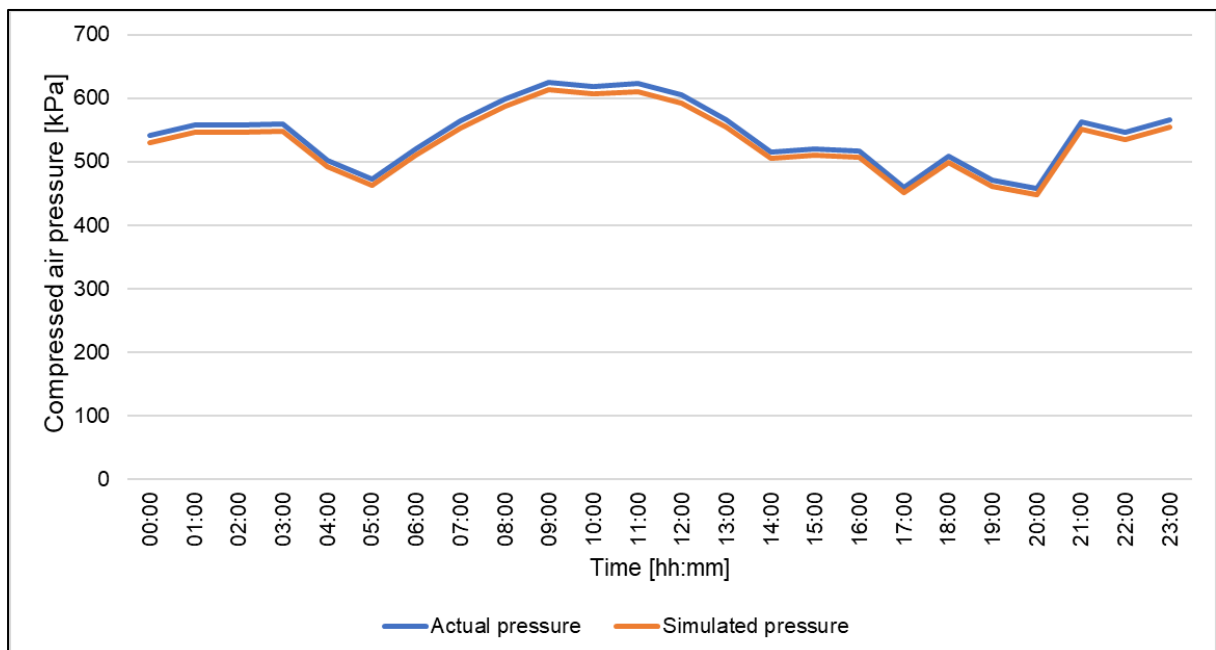
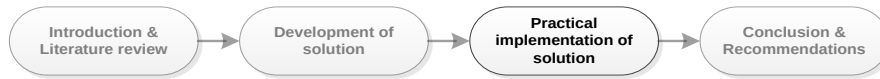


Figure 42: Case study B – simulation verification (pressure)

An average percentage error of 3% was calculated between the actual compressed air pressure and the simulated compressed air pressure. The literature indicates a percentage



error of below 15% as acceptable, implying that the calibration values for the simulation is verified [112]. Repeating this step and adjusting the simulation parameters can increase the simulation's accuracy to acceptable standards.

Step 3B.D – Calculate system zero-wastage baseload

The calibrated digital twin can be used to simulate various compressed air network scenarios. In this step, the calibrated digital twin was used to simulate the ZW baseload of the case study's compressed air network.

Figure 43 presents the simulated ZW baseload for the case study's network, indicating that a total of 930 284 m³ was consumed within the 24-hour profile. This profile represents the most efficient version of the compressed air network (without any wastage).

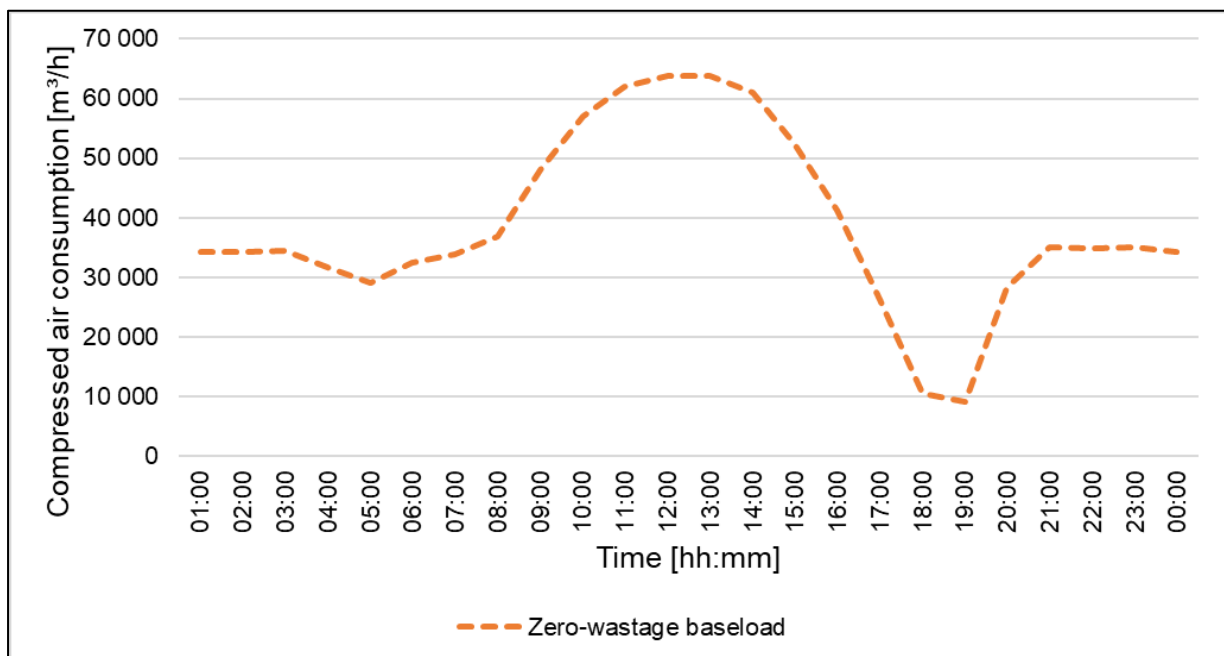


Figure 43: Case study B – zero-wastage baseload

Step 3B.E – Identify efficiency potential

To identify the available efficiency within this network, the ZW baseload simulated in step 3B.D is compared to the actual compressed air consumption in Figure 44. The actual compressed air consumption is represented by the solid blue line with the ZW baseload in a dotted red line. The available efficiency is indicated in green.

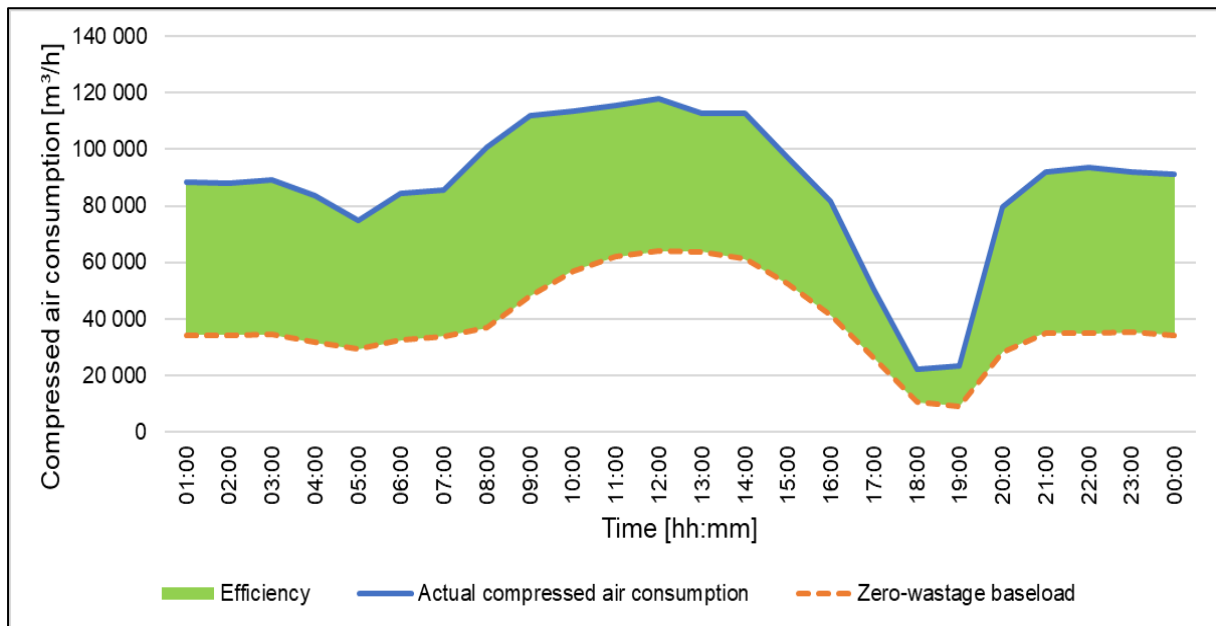
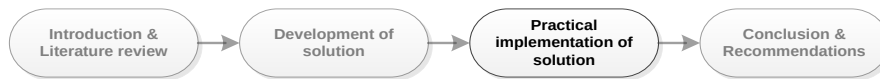


Figure 44: Case study B – zero-wastage baseload vs actual demand

As seen from the figure, the actual consumption profile is substantially higher than the ZW baseload profile. The case study's compressed air network consumed an average total of 2 102 303 m³, compared to the significantly lower consumption of 930 284 m³ for the ZW baseload profile. This translates to a wastage of 56%, or alternatively, an efficiency potential increase of 56%. This falls within the suggested range of 40% to 80% according to the literature as discussed in section 1.2.5.2. This **validates** this method's capacity to identify accurate, reliable instances and levels of wastage within a compressed air network. A visual representation of this can be seen in Figure 45.

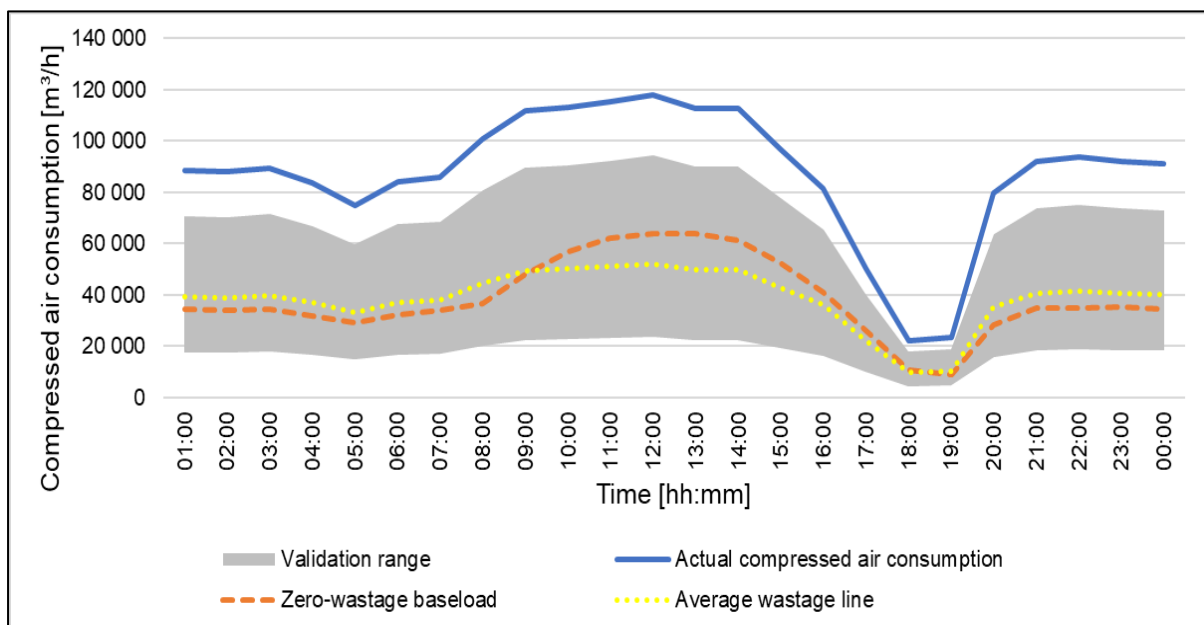
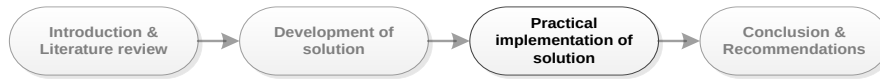


Figure 45: Case study B – zero-wastage baseload validation



The majority of the compressed air wastage is situated within the cleaning shift and drilling shift. Less efficiency is achievable within the blasting shift as the mine closes the compressed air network feeding most of the underground mining areas in this period. This can only be done during the blasting shift as all the mining personnel are out of the mining areas.

The 56% difference between the ZW baseload and the actual compressed air consumption equates to an energy efficiency of approximately 125 MWh for the 24-hour profile. Additionally, this energy saving can also lead to a CO₂ emission benefit. Using Equation 4 in Chapter 2 as shown below results in a CO₂ reduction of approximately 136 tonnes.

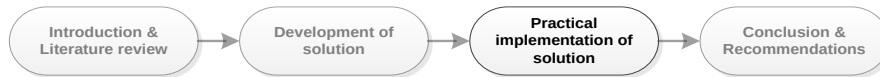
$$1.08 \text{ ton } CO_2e = 1 \text{ MWh}$$

$$136 \text{ ton } CO_2e = 125 \text{ MWh}$$

The simulation made it possible to implement more detailed investigations of the compressed air network by simulating the ZW of different levels to identify inefficient areas. Table 18 displays the results achieved from the simulation. As seen level 31 was identified as the level with the highest efficiency potential as it deviated from the ZW baseload by the most. By contrast, level 22 is the most efficient level, having the smallest difference between its actual compressed air consumption and the ZW baseload. This provides the mine with an indication of where the most compressed air is wasted.

Table 18: Case study B – per-level results

Production level	Level flow per 24-hour (m ³)	ZW baseload per 24-hour (m ³)	Saving (m ³)	Saving (kWh)
22	188 104	69 806	118 298	12 717
23	267 289	110 665	156 624	16 837
24	235 640	94 999	140 641	15 119
25	211 290	165 418	45 872	4 931
26	47 786	35 005	12 780	1 374
27	125 836	105 465	20 372	2 190
28	276 155	134 406	141 749	15 238
29	109 054	33 604	75 450	8 111
30	227 114	85 366	141 748	15 238
31	259 373	90 240	169 133	18 182



3.3.2 Step 4: Dynamic achievable target

Figure 46 displays the dynamic achievable target method discussed in the methodology. As displayed in the figure, the first sub-step is to identify the most efficient mining level in the system, which is followed by calculating the scaling factor to determine the achievable target.

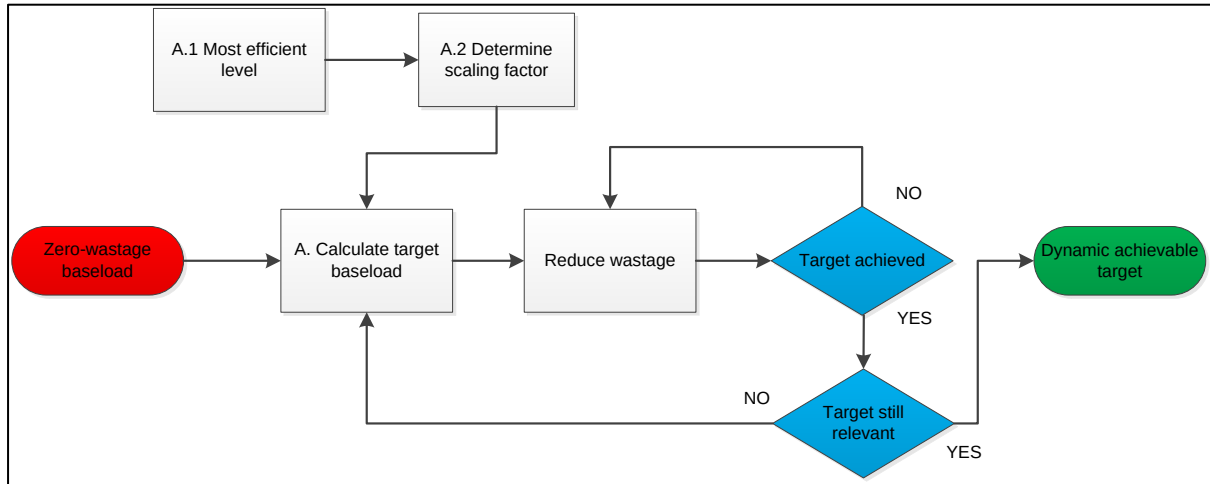


Figure 46: Step 4 – dynamic achievable target

Step 4A.1 - As displayed in Table 18, level 26 is the most efficient level when comparing the level's actual compressed air consumption to the ZW baseload.

Step 4A.2 - Equations 5 and 6 discussed in section 2.2.4 were used to calculate the achievable target. Figure 47 displays the ZW baseload and the actual compressed air consumption compared to the achievable target. More detailed results can be seen in Table 26 of Appendix C.

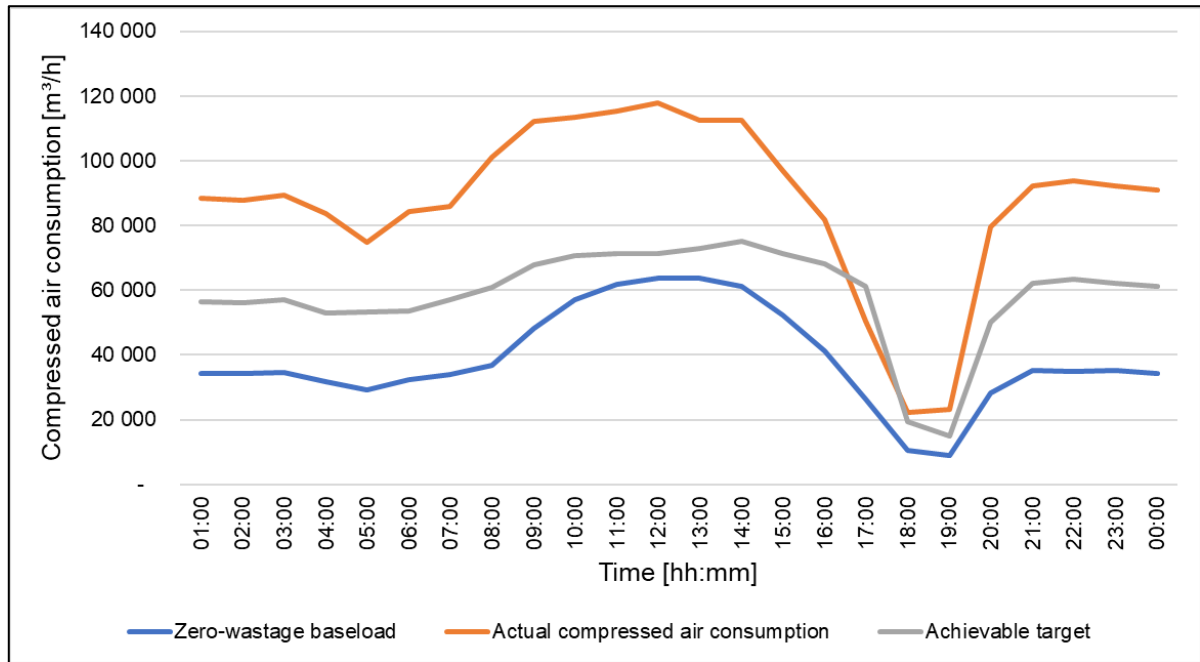
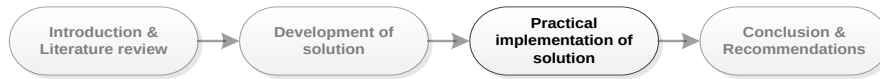


Figure 47: Case study B – achievable target

An estimated reduction of 691 605 m³ can be identified with the achievable target, equating to a total energy efficiency potential of approximately 74.4 MWh for the 24-hour profile.

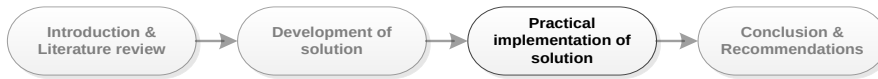
3.3.3 Comparison with previous studies

As per the research methodology identified in section 1.10, the next step was to compare the case study results with theory from Chapter 1. Similarly to case study A in section 3.2.5, case study B is compared to other methodologies used within the mining environment, specifically:

- Efficiency benchmarking,
- Baseline comparison, and
- Valve control.

Figure 48 indicates the results achieved by modelling these methodologies on case study B. All the methods were modelled according to the discussion in section 3.2.5. As seen in Figure 48, the valve control method is only applicable to the blasting shift and the changeover shift between 05:00 and 06:00. Compared to the actual consumption profile of case study B, wastage can be identified as the control valve profile, which is an average of 5 013 m³/h below the actual consumption profile during those periods.

The baseline comparison method was also able to identify wastage during the cleaning and drilling shifts. The baseline comparison consumption profile is 7 205 m³/h below the actual consumption profile. The final comparison method is the efficiency benchmarking method.



This method identified wastage throughout the 24-hour period with a reduction in average consumption of 32 890 m³/h compared to case study B.

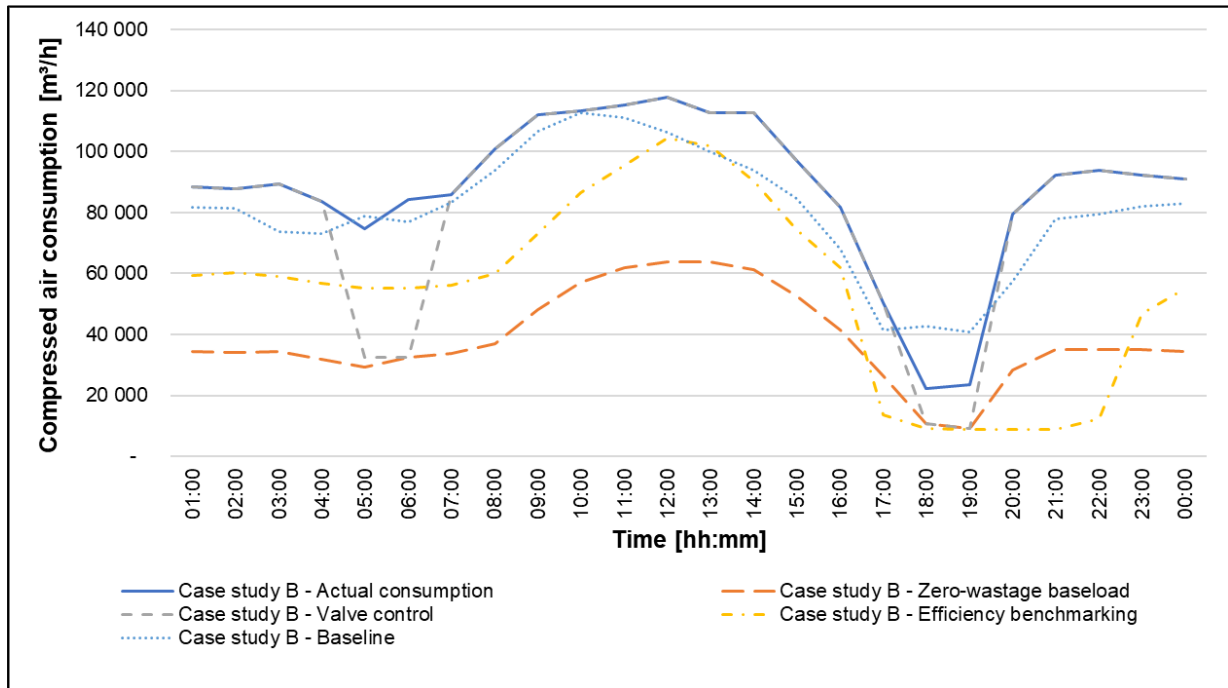
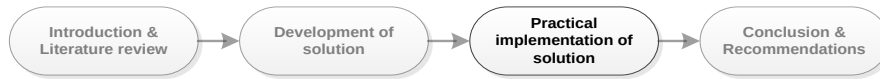


Figure 48: Case study B comparison with previous study – all methods

As indicated in the figure, the previously used methods fail to identify the full spectrum of wastage when using the ZW baseload in comparison. The valve control method is only applicable to the changeover and blasting shifts, provided that this method has not been applied previously. The baseline method can be used to identify wastage; however, this method includes any wastage prior to the baseline.

Compared to the valve control method and the baseline comparison method, the efficiency benchmarking method identifies the highest level of wastage. However, when considering the operational dynamics of case study B, it is important to note that the compressed air network of system 2 remains closed for an extended period during blasting shifts. This extended closure is necessitated by the need for case study B to initiate its ramp-up earlier due to the shortened duration of their blasting shift. As a result, when comparing case study B to a more efficient mining operation, the obtained results can be skewed.

This demonstrates that the ZW benchmarking method is a more accurate method when compared to previous methods for identifying compressed air wastage and thus does not require any modifications.



3.4 Case study C

This case study was derived with permission from an article study conducted by Le Roux [34]. Like case studies A and B, case study C was a deep-level mine in South Africa. A drastic increase in water consumption was observed over the past three years. An investigation was done on the mine in question to verify the drastic increase in water consumption and to identify the available efficiency potential by applying the ZW benchmarking method as displayed in Figure 26.

3.4.1 Step 1 and Step 2: System identification and establishing site parameters

The system was predetermined as the mine asked the energy manager to investigate the water reticulation system as it was presumed that the mine was consuming more water than required. The water reticulation consists of a network of pipes transferring service water through five underground mining levels, as displayed in Figure 49.

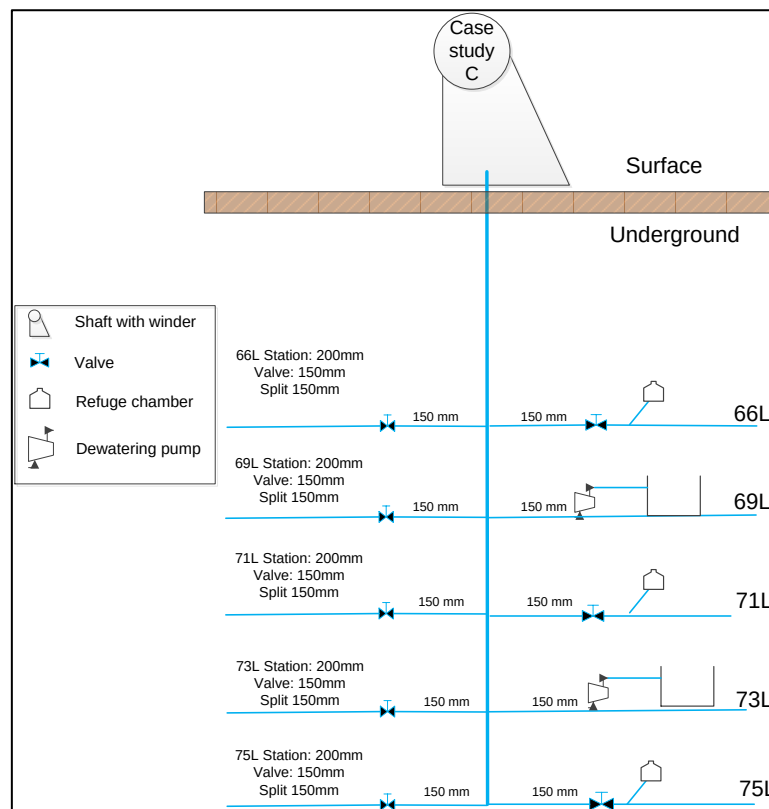


Figure 49: Case study C – water reticulation network drawing

Water flow and production data were retrieved from the mine's SCADA system and used to verify the increase in water consumption. Figure 50 and Figure 51 display the results achieved. An increase in water consumption of 37 L/s is noted between 2019 and 2020. A total increase of 61 L/s is observed between 2019 and 2022.

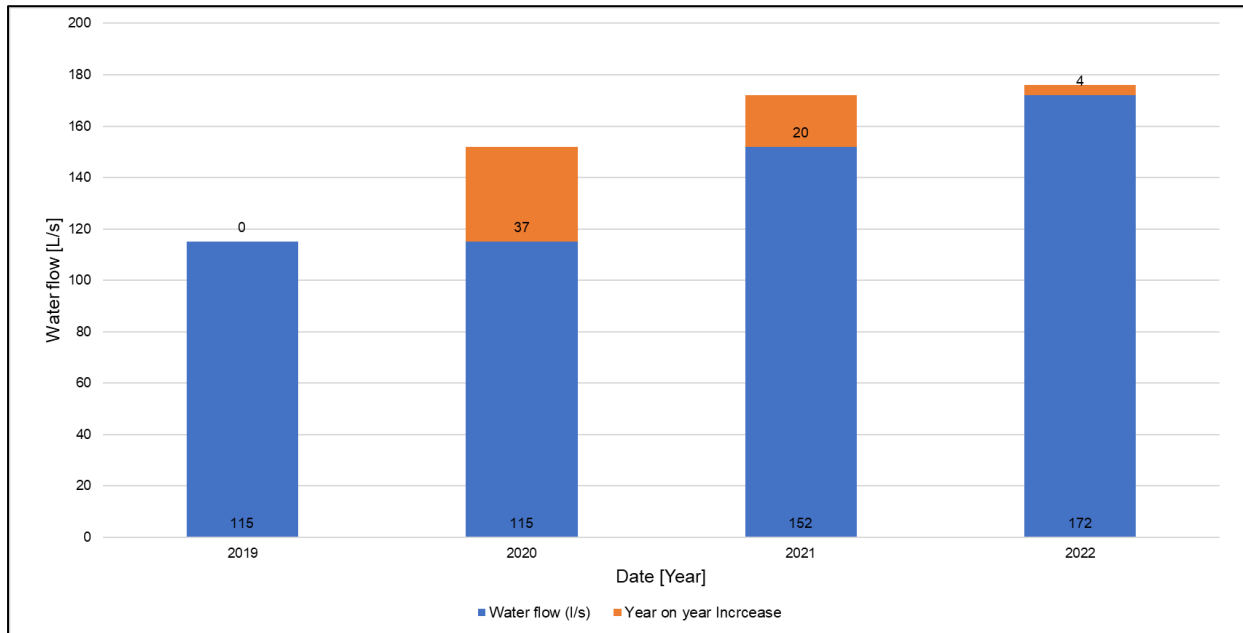
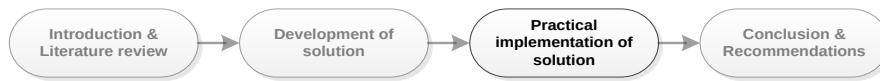


Figure 50: Case study C – year-on-year water increase

Production increases can explain the increase in water consumption [78], [34]. However, the intensity graph (Figure 51) below indicates that the production remained relatively constant apart from 2022, where the production is observed to have decreased while the water consumption increased by 4 L/s [34].

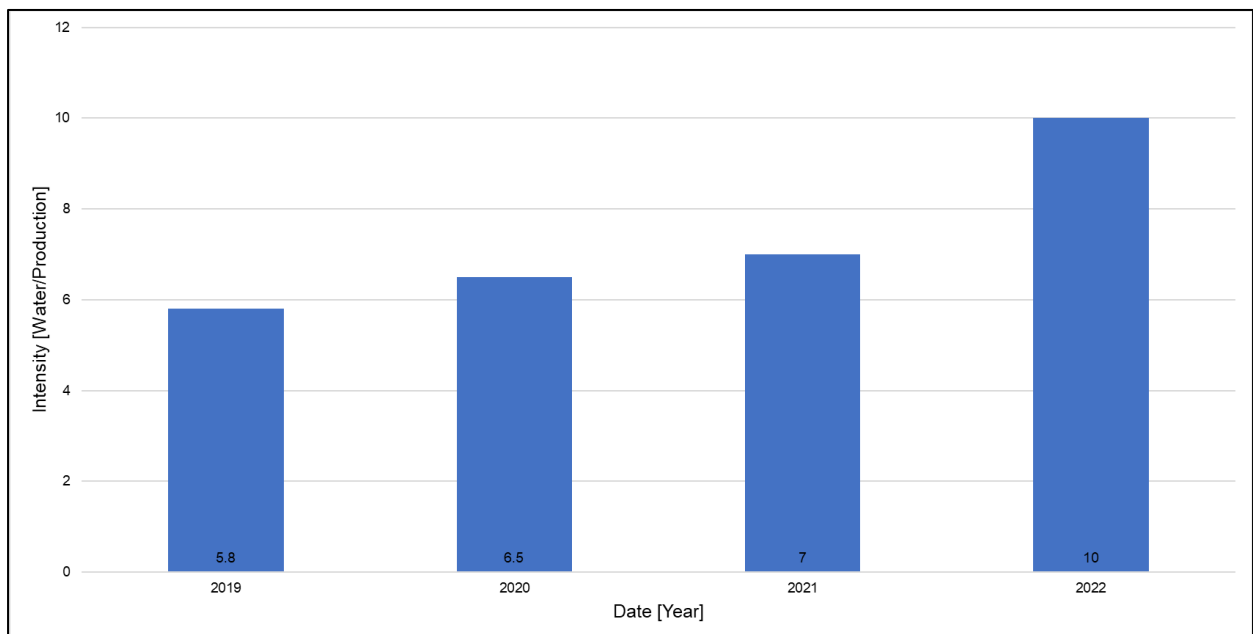
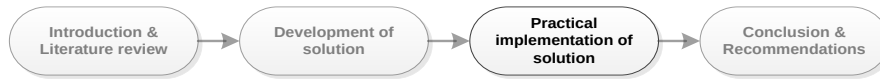


Figure 51: Case study C – water intensity



3.4.2 Step 3B: Zero-wastage simulation

Step 3B.A – Obtain raw data

Following the preliminary results indicating an increase in water consumption, the ZW benchmarking method was applied to the water reticulation network to identify the potential available efficiency. The information acquired from step 1 and step 2 was used to create the digital twin.

Step 3B.B – Digital twin

The methodology discussed in section 2.2.3.2 was applied to case study C. The information displayed in Figure 49 was added to the mine water reticulation network DXF within the PTB simulation software package to create the digital twin displayed in Figure 52.

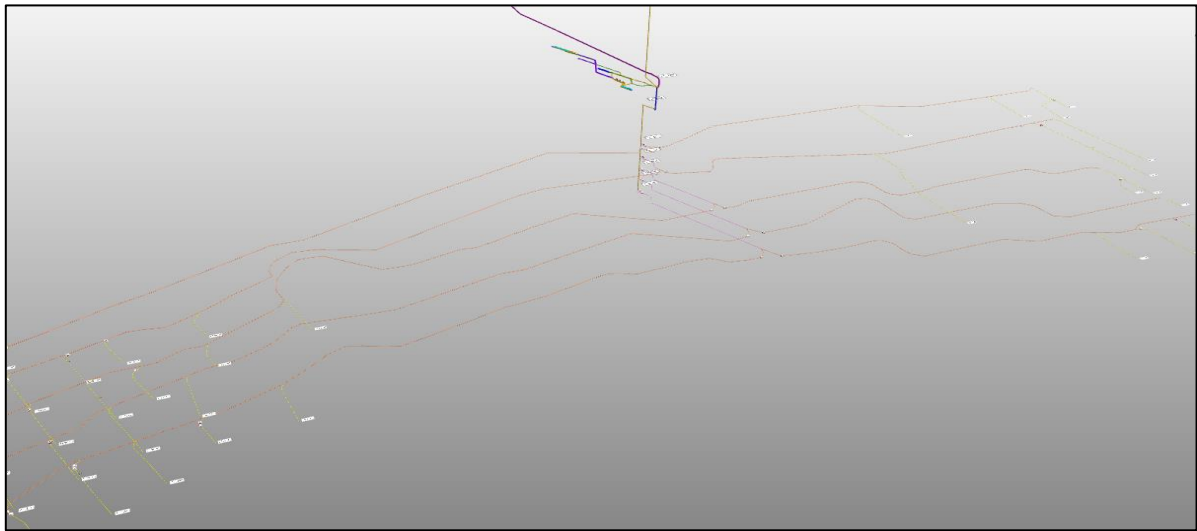


Figure 52: Case study C – digital twin

Step 3B.C – Verify simulation accuracy

Similarly to the previous case studies, the simulation output was verified by applying the method discussed in section 2.2.3.2 to ensure the simulated ZW baseload is accurate. Figure 53 displays the comparison between the actual water consumption and the simulated water consumption. An average difference of 4% was noted between the profiles. This verifies the simulation accuracy, as the percentage error is below the required 15% [112].

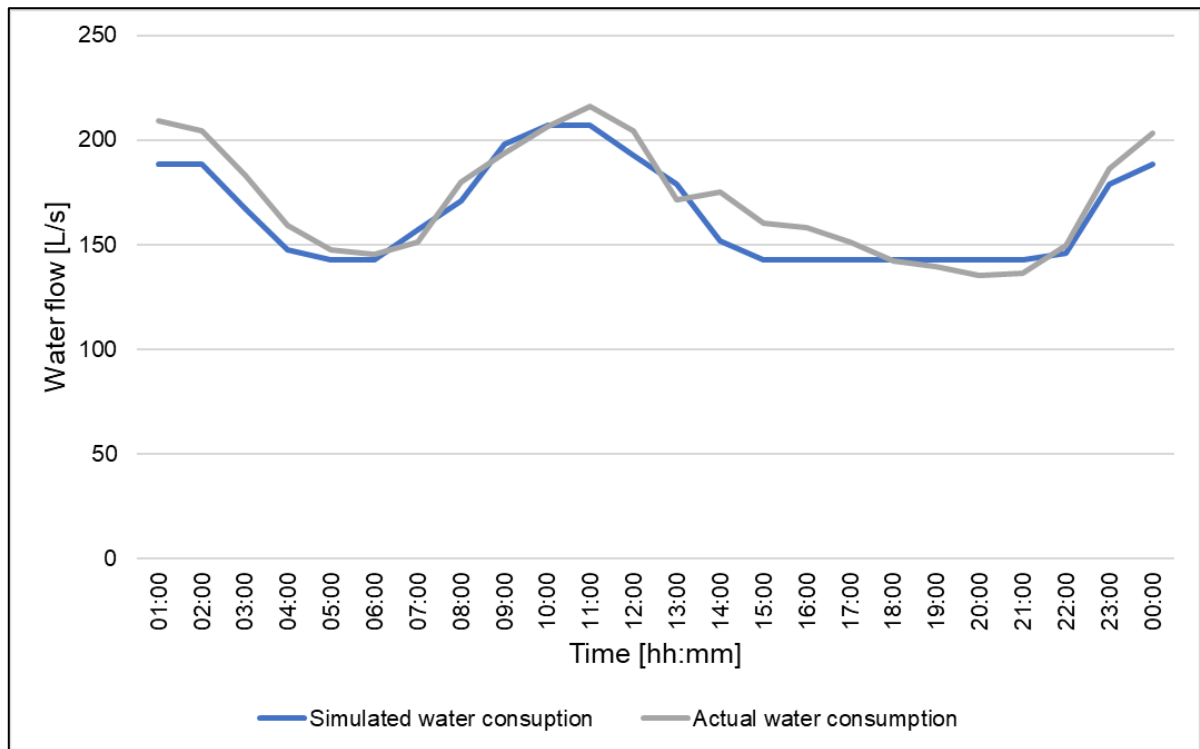
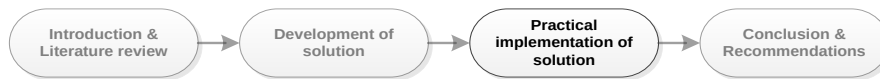


Figure 53: Case study C – simulation verification

Step 3B.D – Calculate system zero-wastage baseload

The ZW baseload of the water reticulation system could be simulated with the digital twin. Figure 54 shows the results achieved. A total of 3 055 L was consumed with the ZW baseload within a 24-hour profile.

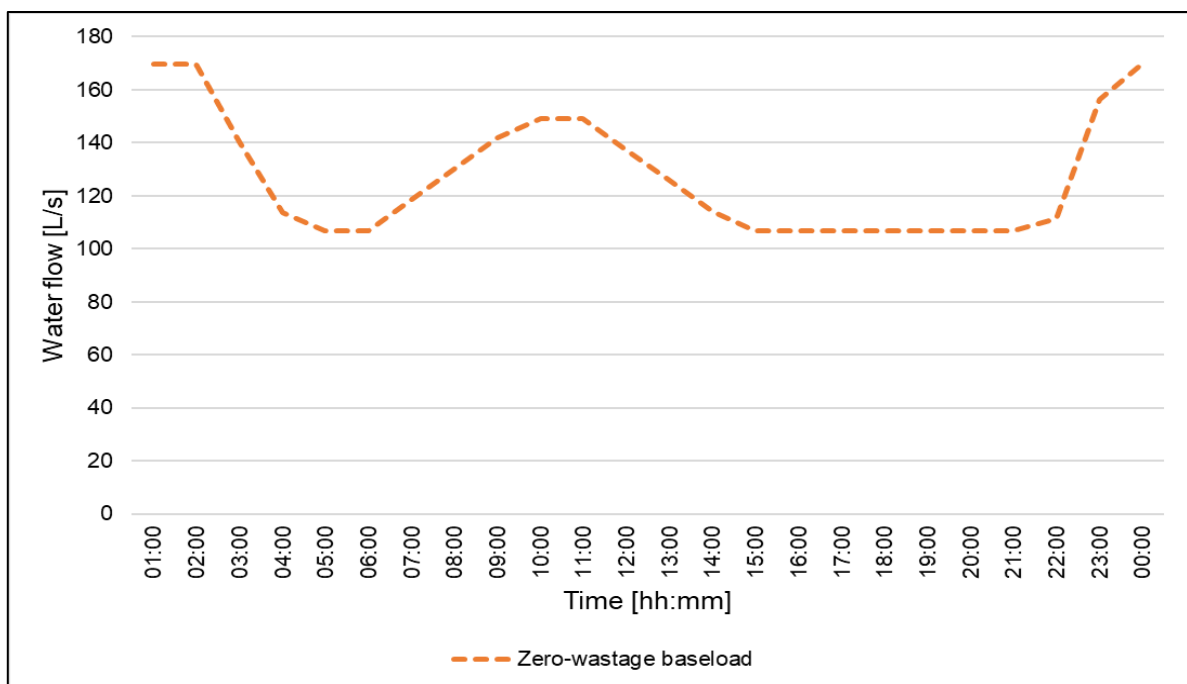
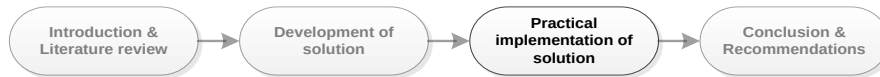


Figure 54: Case study C – zero-wastage baseload



Step 3B.E – Identify efficiency potential

Efficiency can be identified by comparing the actual consumption of the water reticulation network to the ZW baseload as displayed in Figure 55. The actual consumption profile consists of a month's worth of weekday water consumption. An average efficiency of 43.9 L/s can be achieved compared to the ZW baseload, equating to a decrease in water consumption of 25.7% for the specified period.

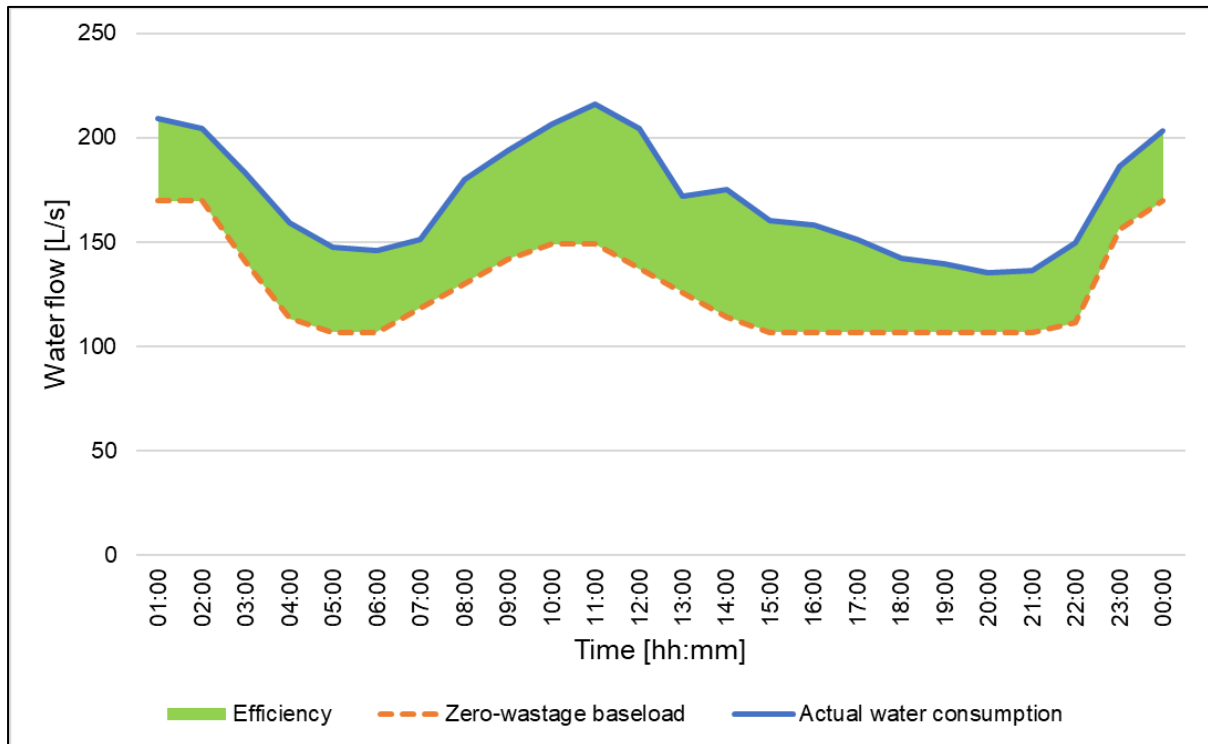


Figure 55: Case study C – zero-wastage baseload vs actual demand

Based on the literature in section 1.5.2.2, it is estimated that 22% to 84% of water used underground is wasted. The 25.7% wastage identified with the ZW baseload falls within this range, **validating** that this method can identify wastage. A visual representation of this can be seen in Figure 56.

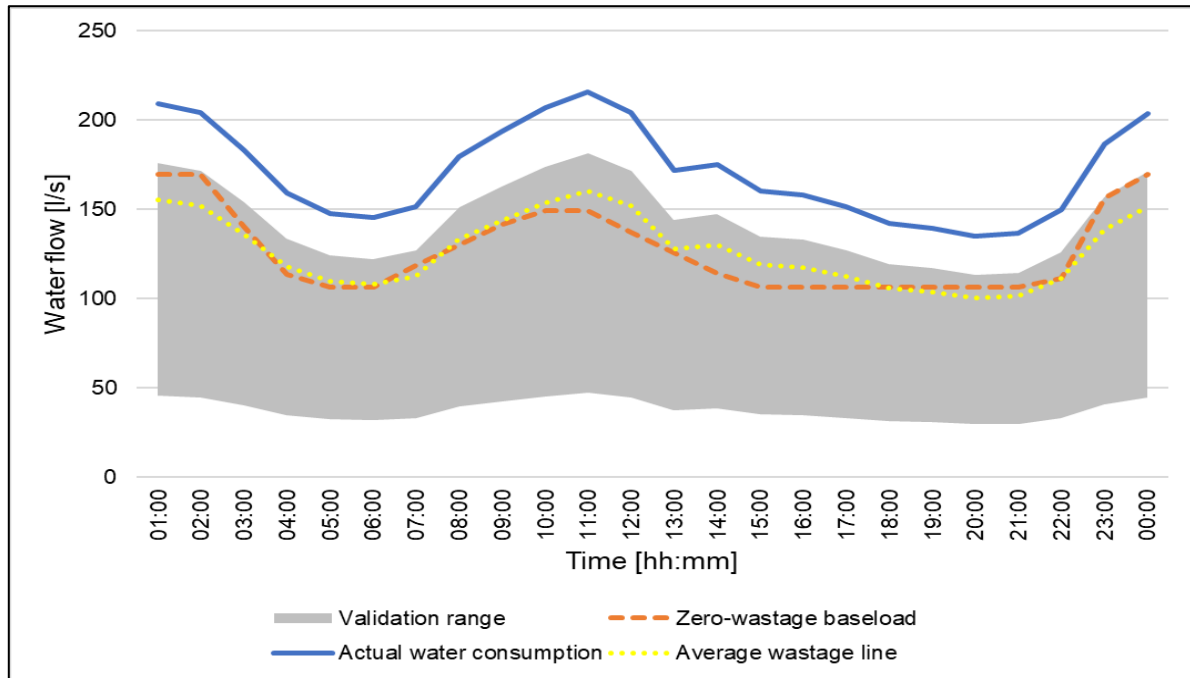
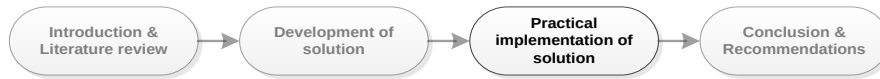


Figure 56: Case study C – zero-wastage baseload validation

The 25.7% reduction in water usage results in an estimated pumping energy reduction of 29 MWh for the 24-hour period. Additionally, this energy saving can also lead to a CO₂ emission benefit. Using Equation 4 in Chapter 2 as shown below, a CO₂ reduction of approximately 29.3 tonnes can be achieved.

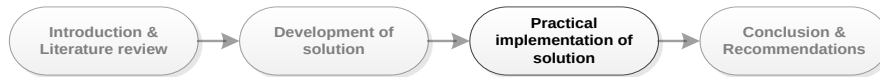
$$1.08 \text{ ton } CO_2e = 1 \text{ MWh}$$

$$30.7 \text{ ton } CO_2e = 29 \text{ MWh}$$

The simulation made it possible to implement more detailed investigations of the water reticulation network by simulating the ZW baseload of different levels to identify inefficient areas. The results of the per-level investigation are displayed in Table 19. As seen from the results, level 73 contained the most wastage and therefore had the highest efficiency potential.

Table 19: Case study C – per-level results

Production Level	Level flow per 24-hour (L/s)	ZW baseload per 24-hour (L/s)	Saving (L/s)	Saving (kWh)
66 L	620	283	373	229
69 L	789	772	14	9
71 L	619	419	200	133
73 L	729	354	375	248
75 L	1350	1 165	185	123
Total	4 058	3 056	1 055	698



3.4.3 Step 4: Dynamic achievable target

Similar to case study A and case study B, the dynamic achievable target method (Figure 57) was applied to this case study to calculate the achievable target for the water reticulation system.

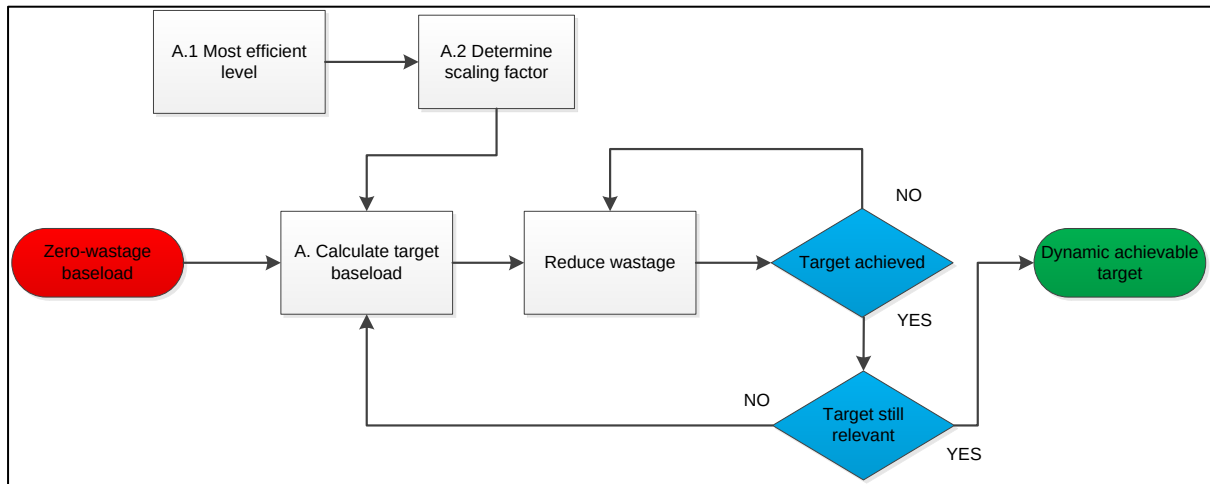


Figure 57: Step 4 – dynamic achievable target

Step 4A.1 - The first sub-step was to identify the most efficient mining level in the water reticulation system. As displayed in Table 19, level 69 is the most efficient level compared to the ZW baseload.

Step 4A.2 – By applying Equation 5 and Equation 6 as discussed in section 2.2.4, the achievable target was calculated. Figure 58 displays the results compared to the ZW baseload and the actual water consumption. As seen from the figure, the achievable target is only slightly scaled upward due to the close resemblance of level 69’s ZW baseload and the level’s actual water consumption. This proves that the ZW baseload can be closely followed by this system. Detailed results can be seen in Table 27 in Appendix C.

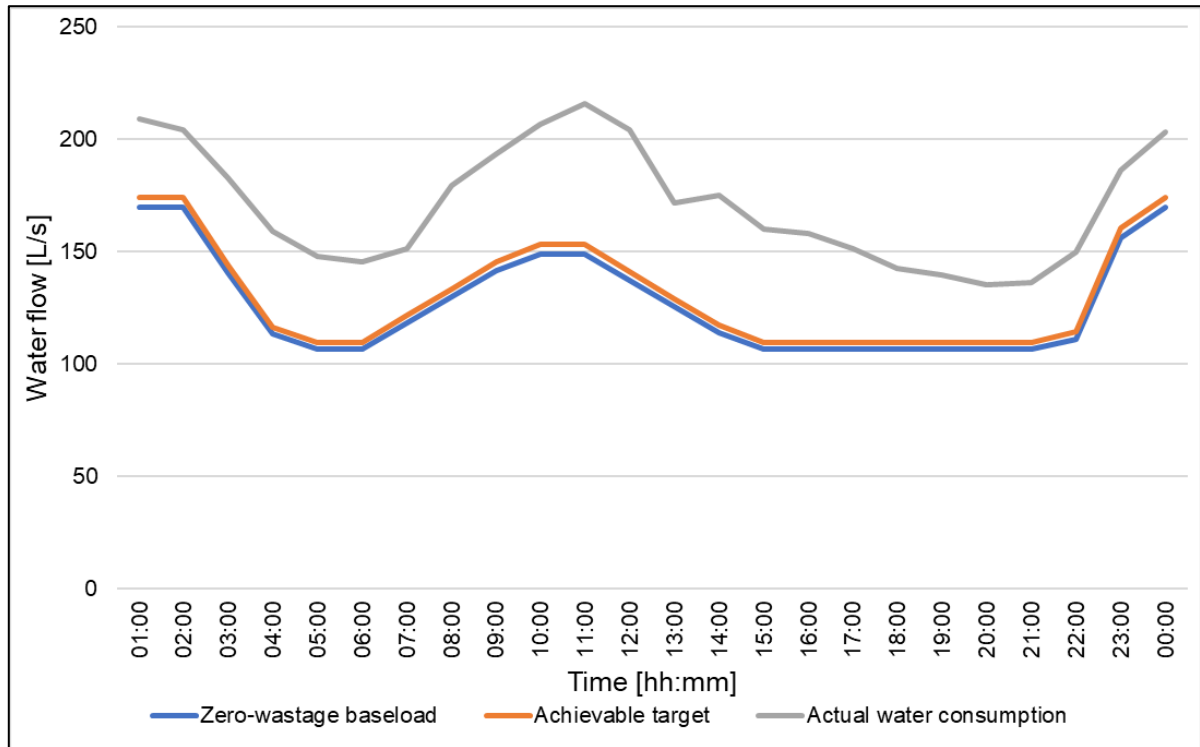
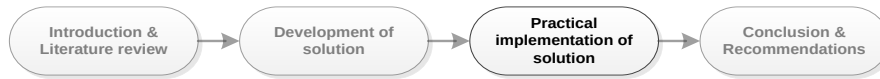


Figure 58: Case study C – achievable target

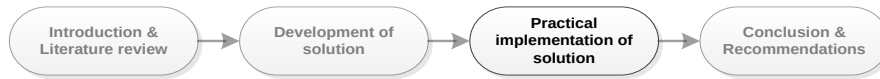
An estimated 40.5 L/s can be reduced by following the achievable target, equating to a total energy efficiency of approximately 26.8 MWh for the 24-hour profile.

3.4.4 Comparison with previous studies

In line with the research methodology identified in section 1.10, the next step entails comparing the case study results with theory depicted from Chapter 1. Methodologies consisting of efficiency benchmarking, baseline comparison and valve control was compared against the results generated with case study C.

Figure 59 indicates the results generated with modelling the previous methodologies against the results generated with case study C. The efficiency benchmarking method was not applied to this case study as no data was available for a water reticulation network within the same mining network. This is a disadvantage of using this method within the mining area, as data is required for two systems on different mines.

The same disadvantages were noted with the valve control method and the baseline comparison method as highlighted in case study B of section 3.3.3. The valve control method was only applicable during blasting and changeover shifts. Comparing this method to the actual consumption profile resulted in an average reduction of 12 L/s. With the baseline method, wastage could be identified through the 24-hour period, in which there was an average water wastage of 10.5 L/s.



An average wastage of 44 L/s was identified when comparing the ZW baseload to the actual consumption profile. This demonstrates that the ZW benchmarking method is a more accurate and reliable method for identifying wastage within a water reticulation system.

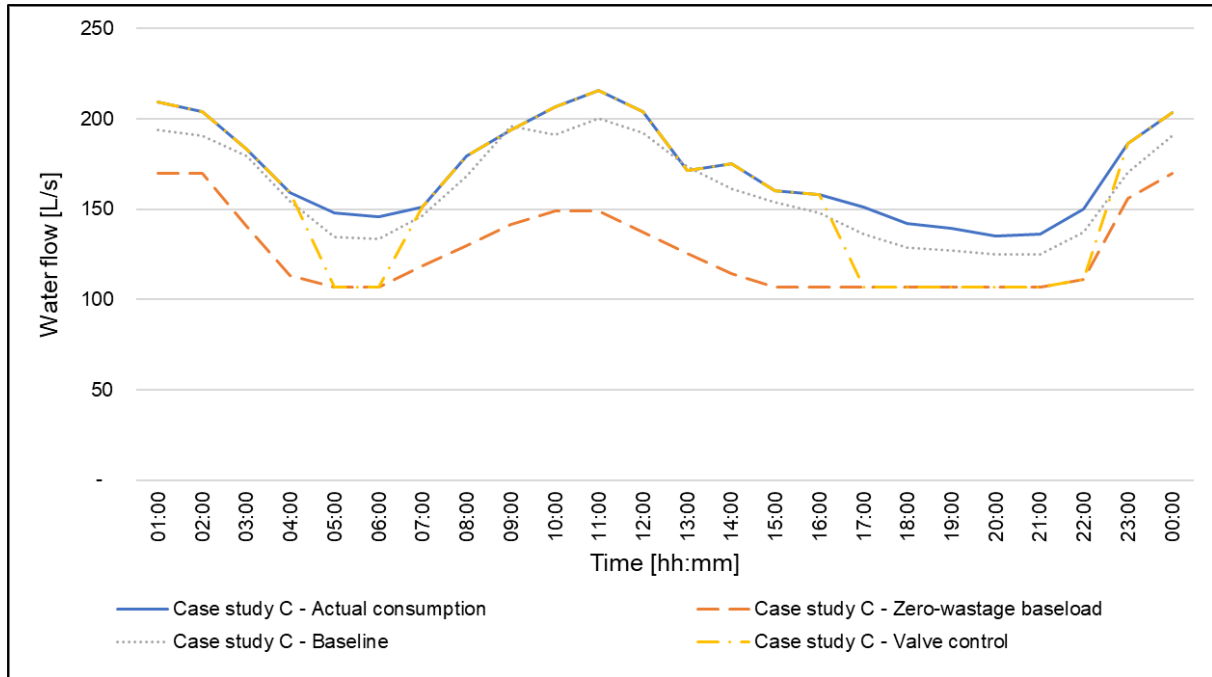


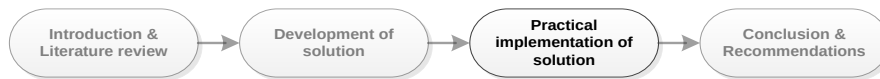
Figure 59: Case study C comparison with previous study – all methods

3.5 Cross-case discussion

The ZW benchmarking method discussed in section 2.2 was applied in three case studies to validate the study solution. Both routes to calculate a ZW baseload namely theoretical ZW and ZW simulation were applied and evaluated. The first case study used the theoretical ZW benchmarking method and the second and third case study used the ZW simulation method to calculate the ZW baseload.

Case study A concerns a compressed air network. The ZW benchmarking method was applied to the case study following the theoretical ZW route. This was implemented successfully, having realised a 51% reduction in compressed air against the ZW baseload. In other words, 51% of the generated compressed air for this mine is wasted according to the data profile. This equates to a potential energy efficiency improvement of 72.7 MWh over a 24-hour period.

Case study B is a compressed air network. The ZW simulation route was followed from the ZW benchmarking method. This was implemented successfully, with a 56% reduction in compressed air realised with the ZW baseload. This equates to an energy efficiency improvement of 125 MWh over a 24-hour period.



Case study C is a water reticulation network in which the ZW simulation route was followed. This was implemented successfully, with a 25.7% reduction in water consumption. This reduction in water usage equates to a potential energy efficiency improvement of 29 MWh over a 24-hour period. Furthermore, a dynamic achievable target was calculated for each case study as an accurate benchmark to ensure that each case study would be compared to an accurate target that will motivate the mine to gradually move closer to the ZW baseload.

The results retrieved from the case studies were **validated** when compared to what was noted from the literature. In case studies A and B, 51% and 56% of the compressed air supplied was being wasted, respectively. This correlates well with the literature, which noted that between 40% and 80% of generated compressed air is wasted (see Figure 32 and Figure 45). Subsequently, case study C identified a wastage of 25.7%. This correlates well with the validation range of 22%-84% (see Figure 56).

Afterwards each case study was compared to previous methodologies applied in the mining environment. Three methods were considered, namely:

- Efficiency benchmarking,
- Baseline comparison, and
- Valve control.

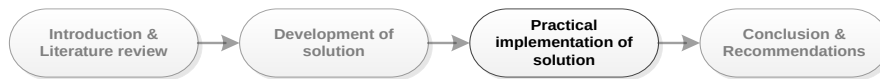
The shortcomings identified in the previous methodologies outweighed that of the ZW benchmarking method. With the ZW benchmarking method, wastage was identified over a 24-hour profile without any of the limitations discussed in the case study sections and literature. Thus, no modifications were required for this methodology.

Additionally, an investigation was done on the possible long-term benefits of this methodology by implementing a 10-year forecast of the potential effects of Eskom tariff increases on the mining environment and the benefit of this study over the forecasted period.

3.6 Roadmap to mitigate future system costs

The current trend in Eskom tariff increases poses a significant risk for mining profitability. Figure 60 in Appendix A displays a year-on-year percentage and cost per kWh amendments Eskom made to their tariff structure from 2003-2022 for the mining sector. On average, a South African mine had to pay 60.44 c/kWh throughout the period displayed in Figure 60 with an average year-on-year tariff increase of 13.1%. This can have a substantial effect on system costs looking 10 years into the future.

Considering the results achieved in case study A, Figure 60 displays the results of the forecasting of current compressed air system costs with a year-on-year tariff increase of



13.1%. During year 10, the mine will pay R121 566 549 more for electricity than in year 0, assuming the compressed air system remains constant. This is a strong incentive for mines to focus on efficiency by reducing unnecessary wastage.

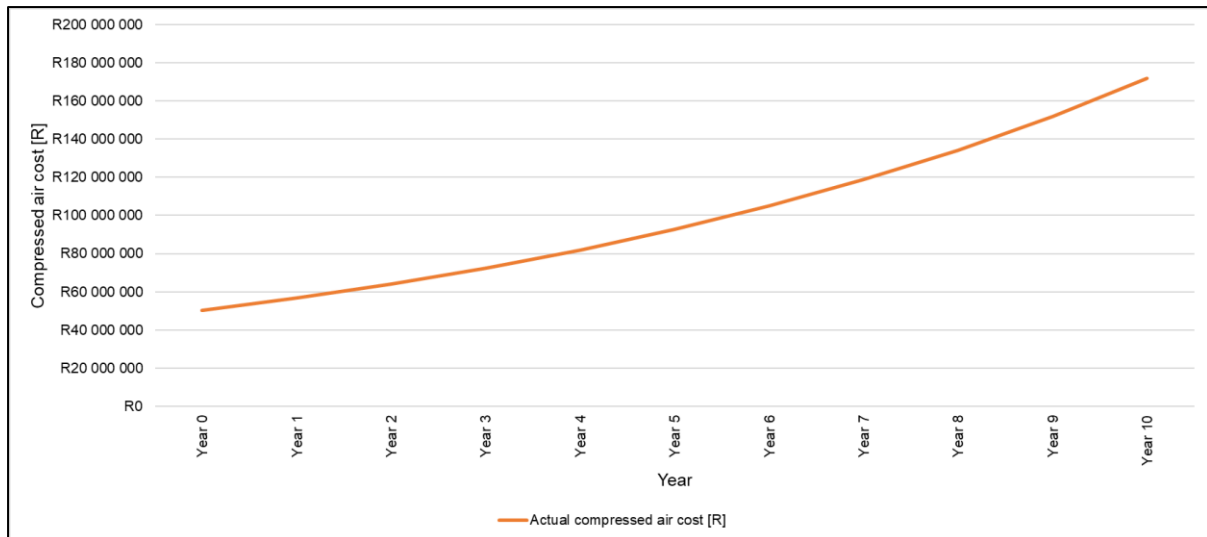


Figure 60: Ten-year forecast of case study A – system cost

Section 1.5 presented multiple studies on projects focusing on mining system efficiency that were identified from the body of knowledge. The information from the studies together with the system-specific information of the compressed air system were used to compile a conceptual roadmap as shown in Table 20. The table is divided into three sections indicating the impact of each project on the total compressed air consumption:

- No Capex projects – These are projects requiring no capital expenditure and are usually the least time-intensive while still bringing a significant improvement in energy efficiency.
- Capex projects – Consisting of projects that require capital expenditure to gain energy efficiency. In most cases, these projects have higher turnaround times while carrying greater risk than projects that require no capital expenditure. However, these projects typically make a greater contribution in terms of energy efficiency than projects containing no capital expenditure.

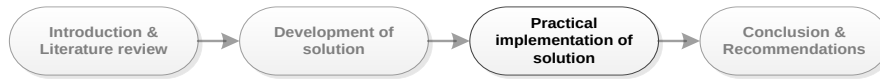


Table 20: Estimated roadmap of compressed air projects for the mine

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
No capex projects	Compressed air consumption	100%	92%	69%	31%	16%	6%	6%	6%	6%	6%	6%
	Operational improvements		3%	5%	10%	15%	15%	15%	15%	15%	15%	15%
	Digitisation		2%	3%	5%	5%	5%	5%	5%	5%	5%	5%
Capex projects	Surface control valve		3%	4%	7%	7%	7%	7%	7%	7%	7%	7%
	Level / Half-level control valves			4%	7%	7%	7%	7%	7%	7%	7%	7%
	Stope isolation valves			5%	10%	15%	15%	15%	15%	15%	15%	15%
	Hydraulic Conversion			10%	20%	20%	20%	20%	20%	20%	20%	20%
	Hydro-powered drilling				10%	15%	25%	25%	25%	25%	25%	25%

With the achievable target profile created from the ZW baseload as shown in Figure 34, the roadmap table can be applied to the system to achieve this profile. As mentioned, at year 10 the current system could cost the mine R121 566 549 more than year 0. Comparing this to the target profile results in a cost reduction of R 57 832 804 for the mine in year 10. Accumulatively, the target profile is R370 397 482 less than the current system cost over the predicted 10-year period. Applying these recommended projects in the case study on a compressed air network could yield the results seen in Figure 61.

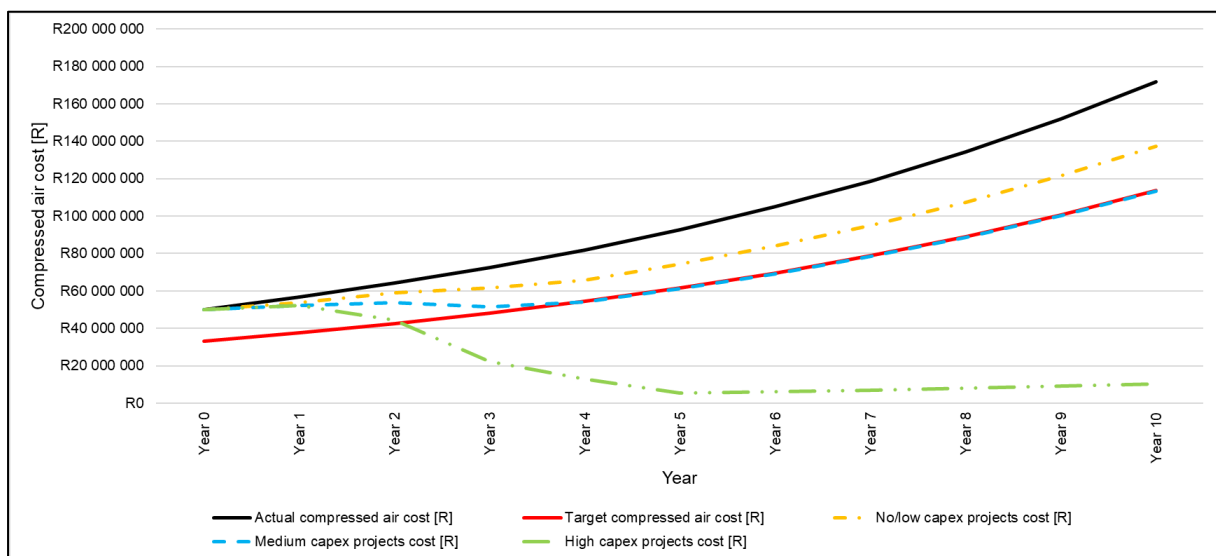
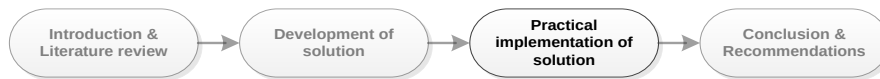


Figure 61: Estimated Case study A roadmap results

As seen in Figure 61, the projects requiring no capital expenditure can still have a significant impact on system cost reduction. It is estimated that the target profile can be achieved by



applying the projects requiring no capital expenditure and the first two Capex projects, assuming that the projects can be launched and conducted in parallel.

The largest compressed air reductions can be realised by implementing the two hydro projects, focusing more on removing compressed air by replacing the equipment. However, it should be noted that these projects require implementation costs and longer implementation periods. Again, assuming the projects can be implemented in parallel, the full benefit can be realised from year 5. An estimated accumulative saving of R871 076 469 can be seen at the end of year 10 compared to the current compressed air system if all the projects are implemented.

Considering the total compressed air cost of a mining group drastically changes the picture looking 10 years into the future. Table 21 considers a mining group consisting of five mines. Like case study A, case study B was forecasted to achieve the results in Table 21 (marked in green as they were derived from actual data). Mines C to D (marked in italics and blue) consist of an average taken between case study A and B to illustrate the projected cost of compressed air for a mining group consisting of similarly sized mines.

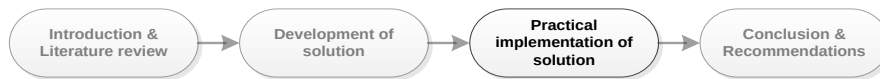
Moreover, applying this model will have positive ESG outcomes. An estimated reduction of 306 110 tonnes and 457 913 tonnes of CO₂ will be realised for case study A and B, respectively. Forecasting this for mine C to E will reduce the mining group's CO₂ footprint by 1.9 million tonnes.

Table 21: Ten-year cost forecast of a mining group

Mining complex	Actual compressed air cost	Target compressed air cost	Total 10-year forecast cost	Forecasted compressed air cost (target)	Cost reduction	ESG contribution (tonne CO ₂)
Case study A	R 50 136 165	R 33 249 332	R 1 099 691 639	R 729 294 167	R 370 397 472	306 110
Case study B	R 76 787 584	R 51 526 410	R 1 684 266 529	R 1 130 185 414	R 554 081 114	457 913
Mine C	R 63 461 875	R 42 387 871	R 1 391 979 084	R 929 739 791	R 462 239 293	382 012
Mine D	R 63 461 875	R 42 387 871	R 1 391 979 084	R 929 739 791	R 462 239 293	382 012
Mine E	R 63 461 875	R 42 387 871	R 1 391 979 084	R 929 739 791	R 462 239 293	382 012
Total mining complex	R 317 309 374	R 211 939 356	R 6 959 895 420	R 4 648 698 955	R 2 311 196 465	1 910 059

3.7 Conclusion

This chapter discussed the **validation** of the method developed in Chapter 2. The ZW benchmarking method was applied to multiple case studies of mines in a SA. A ZW baseload was calculated for each of the case studies by utilising a simulation or a theoretical ZW approach, thus **verifying** that the ZW benchmarking method can deliver a ZW baseload. Each



ZW baseload was then compared to their respective system's actual consumption profile to identify the efficiency potential of each system.

The case studies were investigated in greater detail by applying the ZW benchmarking method in each system's mining level. This provided a more focused approach to identifying inefficiencies in larger systems by prioritising each level based on their performance against the level's respective ZW baseload.

A dynamic achievable target was calculated for each system based on the system's ZW baseload, as the ZW baseload might never be achievable in real-world circumstances. The achievable target allows the system to gradually move closer to the ZW baseload as the system becomes more efficient. This target can also be used as a future benchmark to guide the mine to achieve the ZW baseload.

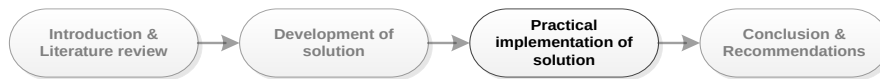
Each case study was compared to various previous methodologies used to identify efficiency potential (wastage). Certain limitations were discovered when the methodologies were modelled on the case studies as discussed in this chapter. This highlighted the accuracy that can be achieved with the ZW benchmarking method.

The chapter concluded by considering the effect Eskom's tariff structure has on the mining environment. R370 397 482 can be reduced over 10 years by reaching the achievable baseload for case study A. A reduction of over R2 billion can be realised for compressed air alone when considering a mining group of five similarly sized mines. This highlights the potential benefits of this method for the mining environment in SA.

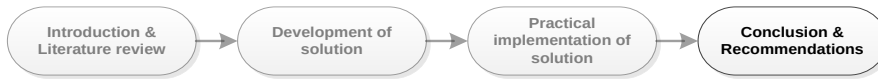
In conclusion, Table 22 provides a summary of how and where each objective was achieved within Chapter 3.

Table 22: Study objectives achieved in the thesis

Study objective	How was the objective solved	Section
1. Use existing and available information to develop a system baseload (ZW) to benchmark the system against itself.	The ZW benchmarking method developed in Chapter 2 was applied to three case studies to calculate the ZW baseload of each, representing the most efficient baseload of the system.	3.2 3.3 3.4
2. Use a ZW benchmarking method to identify available efficiencies within a system.	The ZW baseload of each case study was compared to the actual consumption of each case study. This indicated the time and	3.2.3 3.3.1 3.4.2



	location where efficiencies can be achieved within a 24-hour profile.	
3. Develop dynamic achievable baseload	This was done by scaling the ZW baseload of each case study with the ratio between the most efficient level's actual consumption and its respective ZW baseload.	3.2.4 3.3.2 3.4.3



CHAPTER 4 – CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

South Africa has some of the largest and deepest mining operations in the world. Most mining operations and systems consume high levels of energy to operate continually and ensure optimal production of ore. Such systems include compressed air, ventilation, hoisting, and water reticulation systems.

The high energy requirement of these systems coupled with Eskom tariff hikes and ESG compliance factors places enormous pressure on the mining industry to stay profitable. With increasing pressure from stakeholders on mines to produce cleaner products through reduced CO₂ emissions, it is crucial for mines to develop efforts to increase energy efficiency.

Despite several studies that focused on assisting mines with efficiency, there is room for further improvement in mining systems. Significantly, no general method for benchmarking a system against a more efficient version of itself could be found in the literature. Additionally, system targets may be flawed as many are based on the energy consumption from the previous year.

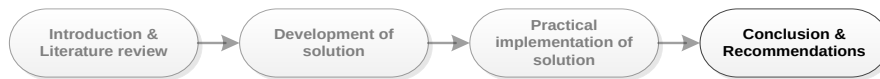
Three study objectives were formulated based on the gaps in the literature, namely:

1. Use existing and available information to develop a system baseload (ZW) to benchmark the system against itself.
2. Use a ZW benchmarking method to identify the available energy efficiency within a system.
3. Develop a system-specific target baseload which is based on the system's ZW baseload.

Three novel contributions were derived from these objectives. The novel contributions are discussed below accompanied by a summary of how they were addressed.

Novelty 1: Development of a novel benchmarking method for a ZW approach.

In section 2.2, a new method was developed to benchmark a mining system against the most efficient version of itself. This was done by applying the ZW benchmarking method. This method uses available system information as inputs to generate a ZW baseload. The ZW baseload is considered the most efficient profile as it excludes any wastage present in the



system. Section 2.2.3 discussed two methods within the ZW benchmarking method for calculating the ZW baseload, namely, ZW simulation and theoretical ZW. Both methods can be used depending on the available information as discussed in section 2.2.3.

In Chapter 3 the results of the study were discussed. The ZW benchmarking method was applied to three case study mines that used a compressed air system and a water reticulation network. The results produced a ZW baseload for each system and its mining levels so that each level can be benchmarked against each other to identify the least efficient level. This provides a more focused approach to identifying the potential efficiency that can be achieved.

Novelty 2: Applying the novel method to identify system-specific inefficiencies through ZW.

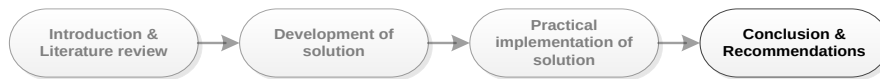
The actual consumption of each system was compared to the ZW baseload of each system. A substantial amount of wastage was noticed within each case study. The ZW benchmarking method indicated that a 49% reduction could be achieved by eliminating wastages within case study A. This reduction could result in a total energy efficiency of 72.7MWh for the 24-hour period, equating to a 78.5-tonne CO₂ reduction.

Subsequently case study B's actual compressed air consumption was compared to the case study's ZW baseload. It was found by eliminating all the wastages, a compressed air demand reduction of 56% could be achieved throughout the 24-hour period. This can result in a 125 MWh efficiency over the 24-hour period, equating to a 136-tonne CO₂ reduction.

Case study C yielded a potential 25.7% reduction in water consumption compared to the system's ZW baseload. This can result in a 29 MWh energy efficiency over a 24-hour period, resulting in a 30.7-tonne CO₂ reduction. This indicates that the results of this method can assist mines to reduce their electricity costs as well as increase their ESG score.

Novelty 3: Development of a novel method to calculate a relevant target baseload based on a systems ZW baseload.

The current method of calculating a system target mostly consists of using historical information. However, historical information may not always offer an accurate representation of the current system, especially if system changes were made due to mine expansion or section closures. Additionally, any wastage present within the previous system will be included in the historical information used to develop the target for the current system.



This led to the development of a new method to calculate a system target from the system's ZW baseload. To achieve this, the system's most efficient section was identified, providing a representation of what is currently achievable with the system relating to efficiency. The ratio between the identified level and the level's ZW baseload was used to scale the system's ZW baseload to a more achievable target. As the system is adjusted with expansion, the ZW baseload will be updated, resulting in a dynamic achievable target. This results in a system target that remains relevant as more initiatives are implemented.

The case study indicates that mines can yield an estimated energy reduction of 49.7 MWh, 74.4 MWh and 26.8 MWh respectively, if the achievable target profile is achieved for each system over a 24-hour period.

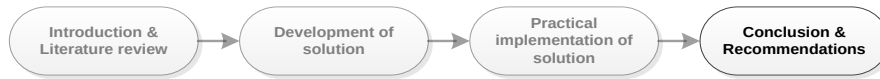
Afterwards, an investigation was done to project the potential effect of Eskom's tariff structure on the case study systems over a 10-year period. According to the investigation, Eskom increased its tariffs by an average of 13.1% from 2003 until 2022. Forecasting the current compressed air system for case study A over the 10-year period can result in the mine paying R121 566 549 more in year 10 than year 0.

By attaining the achievable target, the electricity cost can be reduced by R57 832 804 within year 10; accumulatively over the 10-year period, the achievable target is R370 397 482 less than the current system cost. Multiple Capex and non-Capex projects were identified in the form of a roadmap focused on reducing compressed air consumption. Applying the road map in case study A could result in the mine realising the full benefits of efficient practices by year 5, equating to an accumulative electricity cost reduction of R871 076 469 at the end of year 10. The results of this study hence emphasise the potential benefit this method can realise for the mining environment in SA.

4.2 Recommendations

Several recommendations were identified for future expansion of this study to improve the accuracy of the ZW benchmarking method and expand the application of the existing method. The first recommendation is to implement additional iterations when auditing a mine during the ZW simulation method. This will increase the accuracy of the digital twin, leading to a more realistic simulation. Resultingly, this will increase the accuracy of the ZW baseload calculated for a system, also leading to a more accurate achievable target profile.

In addition to incorporating additional iterations, attention should be directed towards considering the duty cycle of each equipment. It is recommended to expand the ZW benchmarking method to encompass equipment operating on various duty cycles. This will introduce more variability, thereby enhancing the overall accuracy of the method.



As stated in Chapter 1, ventilation and refrigeration are critical components in the mining industry for keeping underground mining areas safe. They account for 19% of the total energy consumption on a typical mine. Forecasting this over a 10-year period with an average tariff increase of 13.1% could result in a mine paying an estimated R109 988 782 more in year 10 than year 0. It is thus recommended that the ZW benchmarking method be applied on these systems to identify any wastage that might be present.

It is also recommended that the ZW benchmarking method be applied on various mining systems to calculate an accurate achievable target profile. This profile can be used to generate an operational budget for the mine that will remain relevant and assist in identifying potential inefficiencies.

Lastly, this study recommends applying the roadmap identified in Table 20 and re-evaluating the study after the 10-year period. This will validate the forecast done on the Eskom tariff increase and the implementation time required to acquire the necessary savings to achieve the achievable target profile.

REFERENCES

- [1] R. Mohanlal, "Power generation, employee and societal well-being," *Journal of Positive Psychology & Wellbeing*, vol. 7, no. 2, pp. 1543–1559, 2023.
- [2] C. J. R. Kriel, "An alternative approach for sustainable industrial DSM in South Africa," Ph.D. dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2016.
- [3] B. Pascoe, "Improved control processes to sustain electricity cost savings on a mine water reticulation system," Ph.D. dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2018.
- [4] W. J. J. Breytenbach, "Framework for operational changes to reduce electricity costs in the South African steel industry," Ph.D. dissertation, Development and Management Engineering, North-West University, Potchefstroom, 2017.
- [5] Eskom Holdings Limited, "Integrated Report – 31 March 2019," *Eskom Holdings Limited*, Johannesburg, Gauteng, Mar. 2019.
- [6] A. B. Sebitosi, "Is the South African electricity tariff model conducive to an energy efficient economy?," *Energy for Sustainable Development*, vol. 14, no. 4, pp. 315–319, 2010.
- [7] M. J. Cameron and R. Rossouw, "Modelling the economic impact of electricity tariff increases on Eskom's top customer segment," *International Journal of Energy Engineering*, vol. 2, no. 6, pp. 315–331, 2012.
- [8] R. Johnson, N. Mans-Kemp, and P. D. Erasmus, "Assessing the business case for environmental, social and corporate governance practices in South Africa," *South African Journal of Economic and Management Sciences*, vol. 22, no. 1, pp. 1–13, 2019.
- [9] W. Masliza, W. Mohammad, and S. Wasiuzzaman, "Environmental, social and governance (ESG) disclosure, competitive advantage and performance of firms in Malaysia," *Cleaner Environmental Systems*, vol. 2, pp. 1-11, 2021.
- [10] W. Henisz, T. Koller, and R. Nuttall, "Five ways that ESG creates value," *McKinsey Quarterly*, 2019.
- [11] J. Azar, M. Duro, I. Kadach, and G. Ormazabal, "The big three and corporate carbon emissions around the world," *Journal of Financial Economics*, vol. 142, no. 2, pp. 674–696, 2021.
- [12] E. Shove, "What is wrong with energy efficiency?," *Building Research and Information*, vol. 46, no. 7, pp. 779–789, 2018.

- [13] M. Taušová et al., "The importance of mining for socio-economic growth of the country," *Acta Montanistica Slovaca*, vol. 22, no. 4, pp. 359–367, 2017.
- [14] H. J. Groenewald, "Developing a framework for managing compressed air in the platinum group metal mining industry in South Africa," M.S. thesis, Business Administration, North-West University, Potchefstroom, 2020.
- [15] E. Keir-sage, "Assessing the extent of local assimilation within the Platreef, Northern Limb of the Bushveld Igneous Complex, using sulfur isotopes and trace element geochemistry," M.S. thesis, Geology, Laurentian University, Sudbury Ontario, 2019.
- [16] A. Hirsikko et al., "Characterisation of sub-micron particle number concentrations and formation events in the western Bushveld Igneous Complex, South Africa," *Atmospheric Chemistry and Physics*, vol. 12, no. 9, pp. 3951–3967, 2012.
- [17] Minerals Council South Africa, "Facts and figures 2017," *MCSA*, Johannesburg, 2018
- [18] U.S. Geological Survey, "Mineral Commodity Summaries 2021," *U.S Geological Survey*, Reston, Virginia, 2021.
- [19] K. Schulz, R. Seal, D. Bradley, and J. Deyoung, "Critical mineral resources of the United States-Economic and environmental geology and prospects for future supply," Reston, USA, 2017.
- [20] B. L. Popovski, G. Soussou, and P. B. Webb, "A brief history of platinum mining with a focus on the Rustenburg region," I Pretoria, South Africa, 2018, pp. 1–20.
- [21] G. Geldenhuys, E. R. Rohwer, Y. Naudé, and P. B. C. Forbes, "Monitoring of atmospheric gaseous and particulate polycyclic aromatic hydrocarbons in South African platinum mines utilising portable denuder sampling with analysis by thermal desorption-comprehensive gas chromatography-mass spectrometry," *Journal of Chromatography*, vol. 1380, pp. 17–28, 2015.
- [22] T. Oelofse, "Using energy balances to evaluate electricity savings projects on platinum mines," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2020.
- [12] C. Cilliers, "Benchmarking electricity use of deep-level mines," Ph.D. dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2016.
- [24] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2017.
- [25] J. H. Marais, "An integrated approach to optimise energy consumption of mine

- compressed air systems,” Ph.D dissertation, Electrical Engineering, North-West University, Potchefstroom, 2012.
- [26] C. J. J. van Zyl, “Practical approach to analyse mine pneumatic drilling performance,” M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2019.
 - [27] L. N. Zietsman, “Novel solutions for compressed air demand management on deep-level mines,” Ph.D. dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2020.
 - [28] R. Joubert, “Cost and time effective DSM on mine compressed air systems,” M.S. thesis, Electrical Engineering, North-West University, Potchefstroom, 2010.
 - [29] G. D. Bolt, J. Venter and J. F. Van Rensburg, “Dynamic compressor selection,” Presented at the 9th Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2012, pp. 1–6.
 - [30] S. N. van Der Linde, “The cost-effectiveness of comprehensive system control on a mine compressed air network,” M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2014.
 - [31] G. J. Matthee, “Improved control of compressed air networks using machine learning,” M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2021.
 - [32] C. J. R. Kriel, “Modernising underground compressed air DSM projects to reduce operating costs,” M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2014.
 - [33] D. du Plooy, P. Maré, J. Marais, and M. J. Mathews, “Local benchmarking in mines to locate inefficient compressed air usage,” *Sustainable Production and Consumption*, vol. 17, pp. 126–135, 2019.
 - [34] G. Lane, K. Mohanarangam, and W. Yang, “Assesment of the flow pattern in a solvent extraction settler,” Presented at the 9th International Conference on CFD in the Minerals and Process Industries CSIRO, Melbourne, Australia, 2012.
 - [35] I. Witham, F. Grabsch, T. Owen, and D. Fawell, “The effect of cations on the activity of anionic polyacrylamide flocculant solutions,” *International Journal of Mineral Processing*, vol. 114-117, pp. 51–62, 2012.
 - [36] J. Bandrowski, J. Hehlmann, H. Merta, and J. Ziolo, “Studies of sedimentation in settlers with packing,” *Chemical Engineering and Processing: Process Intensification*, vol. 36, no. 3, pp. 219–229, 1997.

- [37] A. N. Hasan and B. Twala, "Improving single classifiers prediction accuracy for underground water pump station in a gold mine using ensemble techniques," Presented at the International Conference on Computer as a Tool (EUROCON), Salamanca, Spain, 2015.
- [38] E. W. Bridgwood, R. N. Singh, and A. S. Atkins, "Selection and optimization of mine pumping systems," *International Journal of Mine Water*, vol. 2, no. 2, pp. 1–19, 1983.
- [39] H. Zhang, X. Xia, and J. Zhang, "Optimal sizing and operation of pumping systems to achieve energy efficiency and load shifting," M.S. thesis, Electrical Engineering, University of Pretoria, Pretoria, 2011.
- [40] F. G. Taljaard, "Analytical control valve selection for mine water reticulation systems," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2012.
- [41] P. J. Oberholzer, "Best practices for automation and control of mine dewatering systems," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2015.
- [42] W. van Der Wateren, H. P. R. Joubert, and M. Kleingeld, "Optimising energy recovery in mine dewatering systems," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2018.
- [43] J. W. Rautenbach, "Engineering a novel automated pump control system for the mining environment," Presented at the 5th Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2008.
- [44] T. Smith, "Automated control of mine dewatering pumps," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2014.
- [45] J. A. Deysel, M. Kleingeld, and C. J. R. Kriel, "DSM strategies to reduce electricity costs on platinum mines," Presented at the Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2015.
- [46] G. Xu, J. Huang, B. Nie, D. Chalmers, and Z. Yang, "Calibration of mine ventilation network models using the non-linear optimization algorithm," *Energies*, vol. 11, no. 1, pp. 1–9, 2018.
- [47] A. Chatterjee, "Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff," M.S. thesis, Electrical Engineering, University of Pretoria, Pretoria, 2014.
- [48] A. J. Schutte, "An integrated energy efficiency strategy for deep mine ventilation and refrigeration," Ph.D dissertation, Mechanical Engineering, North-West University,

- Potchefstroom, 2014.
- [49] W. C. Kukard, "Research on reducing costs of underground ventilation networks in South African mines." M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2006.
 - [50] A. Widiatmojo, "Assessment of air dispersion characteristic in underground mine ventilation: Field measurement and numerical evaluation," *Process Safety and Environmental Protection*, vol. 93, pp. 173–181, 2015.
 - [51] A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Evaluating complex mine ventilation operational changes through simulations," *Journal of Energy in Southern Africa*, vol. 29, no. 3, pp. 22–32, 2018.
 - [52] R. Fair, J. H. van Laar, K. Nell, D. Nell, and E. H. Mathews, "Simulating the sensitivity of underground ventilation networks to fluctuating ambient conditions," *South African Journal of Industrial Engineering*, vol. 32, no. 3, pp. 42–51, 2021.
 - [53] R. Papar, A. Szady, V. Martin, and A. Mckane, "Increasing energy efficiency of mine ventilation systems," Proceeding of the 8th US mine ventilation symposium, Washington DC, USA, 1999.
 - [54] E. De Souza and R. M. Buchan, "Cost saving strategies in mine ventilation," *Canadian Institute of Mining*, Montreal, pp. 10–12, 2015.
 - [55] I. E. Tsolas, "Mine performance assessment by means of stochastic frontier analysis," *Mathematical Problems in Engineering*, 2019.
 - [56] S. Goodman, A. Rajagopaul, and Z. Cassim, "Putting the shine back into South African mining," *Applied Energy*, 8(2), pp. 8-16, 2019.
 - [57] C. van Aarde, A. G. S. Gous, and M. Kleingeld, "Improved energy budgeting process for mines using measurement and verification principles," *South African Journal of Industrial Engineering*, vol. 31, no. 3, pp. 58–68, 2020.
 - [58] C. Cilliers, "Cost savings on mine dewatering pumps by reducing preparation- and comeback loads," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2014.
 - [59] H. Nourali and M. Osanloo, "Mining capital cost estimation using support vector regression (SVR)," *Resource Policy*, vol. 62, 2018, pp. 527–540, 2019.
 - [60] M. Shimy, "Fundamentals of Energy Management in Large Industries," *Heat Mass Transfer*, vol. 3, no. 15, 2018.

- [61] M. Mohammadi, P. Rai, and S. Gupta, "Performance measurement of mining equipment," *International Journal of Emerging Technology and Advanced Engineering*, vol. 5, no. 7, pp. 240–248, 2015.
- [62] H. Ruan, X. Gao, and C. Mao, "Empirical study on annual energy-saving performance of energy performance contracting in China," *Sustainability*, vol. 10, no. 5, 2018.
- [63] J. Samuels and K. Sawers, "SRS Educational Supply Company: An Instructional Budget Project," *Accounting Education.*, vol. 32, no. 4, 2017.
- [64] H. Fourie, "Improvement in the overall efficiency of mining equipment: A case study," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 116, no. 3, pp. 275–281, 2016.
- [65] E. Watson and S. Waldorff, "Highlighting trends in the South African mining industry," *Journal of Energy South Africa*, vol. 6, no. 18, pp. 5–9, 2016.
- [66] P. A. Wardhani, "Mining project evaluation process for investment decisions," *Mining journal of Utah*, vol. 62, no. 1, pp. 8–36, 2015.
- [67] N. Akai and M. Sato, "The role of matching grants as a commitment device in the federation model with a repeated soft budget setting," *Economics of Governance*, vol. 20, no. 1, pp. 23–39, 2019.
- [68] A. T. K. Ho, "From performance budgeting to performance budget management: theory and practice," *Journal of Behavioural Finance*, vol. 78, no. 5, pp. 748–758, 2018.
- [69] M. Ali Awan, K. Bletsas, P. F. Souto, B. Akesson, and E. Tovar, "Techniques and analysis for mixed-criticality scheduling with mode-dependent server execution budgets," *ACM Transactions on Embedded Computing Systems*, vol. 18, no. 5, 2019.
- [70] Department of Energy: Republic of South Africa, "Energy Monitoring, Targeting & Reporting," *Industrial Energy Management Training Course*, pp. 1–34, 2015.
- [71] B. M. Friedenstein, C. Cilliers, and J. van Rensburg, "Simulating operational improvements on mine compressed air systems," *South African Journal of Industrial Engineering*, vol. 29, no. 3 Special Edition, pp. 69–81, 2018.
- [72] D. E. Rodríguez, M. S. Sebastian, and A. M. Pulkki-Brännström, "Societal cost savings and budget impact of changing from systemic to intralesional pentavalent antimonials as the first-line treatment for cutaneous leishmaniasis in Bolivia," *Plos Neglected Tropical Diseases*, vol. 13, no. 11, pp. 1–17, 2019.
- [73] A. Kluczek and P. Oleszewski, "Energy audits in industrial processes," *Journal of Cleaner Production*, vol. 10, no. 4, p. 401, 2016.

- [74] K. Bunse, M. Vodicka, P. Schönsleben, and M. Brühlhart, "Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature," *Journal of Cleaner Production*, vol. 19, no. 6-7, p. 667-679, 2011.
- [75] J. H. Marais, M. Kleingeld, and J. F. Van Rensburg, "Simplification of mine compressed air systems," Presented at the 10th Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2013.
- [76] L. Sun, "Mathematical modeling of the flow in a pipeline with a leak," *Mathematical Computer and Simulation*, vol. 82, no. 11, pp. 2253–2267, 2012.
- [77] B. Pascoe, J. H. Van Laar, and J. F. Van Rensburg, "A control strategy to sustain electricity cost savings on a mine water reticulation system in spite of critical component failures." *Mathematical Computer and Simulation*, vol. 82, no. 11, pp. 2253–2267, 2012.
- [78] A. J. M. Van Tonder, "Automation of compressor networks through a dynamic control system," Ph.D. thesis, North-West University, Potchefstroom, South Africa, 2014.
- [79] J. Vermeulen, J. H. Marais, and W. Schoeman, "Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems," Presented at the Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2018.
- [80] R. F. Marais, H. P. R. Joubert, J. F. van Rensburg, and B. Pascoe, "A zero-wastage approach to benchmark compressed air systems on platinum mines," Presented at the Southern, African Institute for Industrial Engineering, KwaZulu-Natal, South Africa, 2022.
- [81] A. Neely, "The performance measurement revolution: Why now and what next?," *International journal of operations and production management*, vol. 19, no. 2, pp. 205–228, 1999.
- [82] B. de Matos, R. Salles, J. Mendes, J. R. Gouveia, A. J. Baptista, and P. Moura, "A review of energy and sustainability KPI-based monitoring and control methodologies on WWTPs," *Mathematics*, vol. 11, no. 1, pp. 1–22, 2023.
- [83] C. Bogan and M. English, "Benchmarking for best practices: Winning through innovative adaptation," New York, NY: McGraw-Hill, 1994.
- [84] K. Awuah-Offei and A. Adekpedjou, "Application of life cycle assessment in the mining industry," *Life Cycle Assess*, vol. 16, no. 1, pp. 82–89, 2011.
- [85] K. Awuah-Offei "Energy efficiency in the minerals industry," *Green Energy and Technology*, January. 2018.

- [86] C. Winchester and M. Salji, "Writing a literature review," Sage, vol. 9, no. 5, pp. 308–312, 2016.
- [87] L. van Der Zee, M. Kleingeld and M.E.H. Mathews, "Electricity cost modelling of the Energy Conservation Scheme (ECS) for the gold mining industry of South Africa", Proceedings of the 9th Conference on the Industrial and Commercial Use of Energy, Cape Town, South Africa, 2012.
- [88] G. R. Ballantyne and M. S. Powell, "Benchmarking comminution energy consumption for the processing of copper and gold ores," *Minerals Engineering*, vol. 65, pp. 109–114, 2014.
- [89] K. W. Mui, L. T. Wong, and L. Y. Law, "An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates," *Applied Energy*, vol. 84, no. 1, pp. 89–98, 2007.
- [90] W. Chan, "Energy benchmarking in support of low carbon hotels: Developments, challenges, and approaches in China," *International Journal of Hospitality Management*, vol. 31, no. 4, pp. 1130–1142, 2012.
- [91] C. Filippín, "Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentina," *Building and Environment*, vol. 35, no. 5, pp. 407–414, 2000.
- [92] J. Ke, L. Price, M. McNeil, N. Z. Khanna, and N. Zhou, "Analysis and practices of energy benchmarking for industry from the perspective of systems engineering," *Energy*, vol. 54, no. March, pp. 32–44, 2013.
- [93] J. Keirstead, "Benchmarking urban energy efficiency in the UK," *Energy Policy*, vol. 63, pp. 575–587, 2013.
- [94] S. Nadolski, B. Klein, A. Kumar, and Z. Davaanyam, "An energy benchmarking model for mineral comminution," *Minerals Engineering*, vol. 65, pp. 178–186, 2014.
- [95] J. R. N. Tshisekedi, "Energy consumption standards and costs in South African gold and platinum mines," M.S. thesis, Mechanical Engineering, University of Witwatersrand, Johannesburg, 2009.
- [96] W. Cai, L. Li, S. Jia, C. Liu, J. Xie, and L. Hu, "Task-oriented energy benchmark of machining systems for energy-efficient production," *International Journal of Precision Engineering and Manufacturing*, vol. 7, no. 1, pp. 205–218, 2020.
- [97] A. Botha, J. van Rensburg, and G. Bolt, "Energy efficiency via optimisation of water reticulation in deep mines," Presented at the 9th Industrial and Commercial Use of

- Energy Conference, Cape Town, South Africa, 2011, pp. 124–132.
- [98] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, “A review on compressed-air energy use and energy savings,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 4, pp. 1135–1153, 2010.
 - [99] R. K. Yin, “Validity and generalization in future case study evaluations,” *Evaluation*, vol. 19, no. 3, pp. 321–332, 2013.
 - [100] S. Teegavarapu, J. D. Summers, and G. M. Mocko, “Case study method for design research: A justification,” *Proceedings of the ASME Design Engineering Technical Conference*, vol. 4, no. May, pp. 495–503, 2008.
 - [101] M. D. Harmse, “A method to apply artificial intelligence techniques to deep-level mine service control systems to realise energy cost savings,” Ph.D. thesis, Electronic Engineering, Stellenbosh University, Stellenbosh, South Africa, 2023.
 - [102] Eskom Holdings Limited, “Integrated Report - 31 March 2021,” *Eskom Holdings Limited*, Johannesburg, Gauteng, Mar. 2021.
 - [103] S. Hoban, “An overview of the utility of population simulation software in molecular ecology,” *Molecular Ecology*, vol. 23, no. 10, pp. 2383–2401, 2014.
 - [104] M. Engineering, “A simulation-based prediction model for coal-fired power plant condenser maintenance,” *Applied Thermal Engineering*, vol. 174, 2020.
 - [105] J. E. Akin, “Finite element analysis concepts: Via solidworks,” *Finite element analysis concepts via Solidworks*, pp. 1–335, 2010.
 - [106] D. Wood, “KYPipe Reference Manual,” *KYPipe LLC*, pp. 1-61, 2010.
 - [107] M. Cregan and D. Flynn, “Condenser maintenance cost optimisation using genetic algorithms,” *IFAC publications*, vol. 36, no. 20, pp. 337–342, 2003.
 - [108] J. Vermeulen, “Cost effective management strategies for platinum mine cooling systems,” M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2015.
 - [109] P. F. H. Peach, M. Kleingeld, and J. I. G. Bredenkamp, “Optimising deep-level mine refrigeration control for sustainable cost savings,” 2017 International Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town, South Africa, 2017.
 - [110] R. Dindorf and P. Wos, “Test of measurement device for the estimation of leakage flow rate in pneumatic pipeline systems,” *Measurement and Control*, vol. 51, pp. 514–527, 2018.

- [111] W. Booysen, "Measurement and verification of industrial DSM projects," Ph.D. thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [112] S. J. Cloete, D. F. le Roux, and R. Buhrmann, "Reducing compressed air wastage by installing new technology in underground mines," Presented at the 10th Industrial and Commercial Use of Energy Conference, Cape Town, South Africa, 2013, pp. 1–6.
- [113] T. C. Mosetlhe, Y. Hamam, S. Du, and E. Monacelli, "Appraising the impact of pressure control on leakage flow in water distribution networks," *Water*, vol. 13, no. 19, pp. 1–13, 2021.
- [114] M. Le Roux, "Identifying Water Wastage in Deep-Level Mines Using a Simulation-Based Zero-Waste Baseline," Presented at the Southern, African Institute for Industrial Engineering, KwaZulu-Natal, South Africa, 2022.

Appendix A – Additional information

Eskom tariff increase

Figure 62 displays Eskom's tariff history from 2003 until 2022. SA mines were subjected to an average 60.44 c/kWh throughout the period displayed, with an average year-on-year tariff increase of 13.1%. Larger increases can be seen from 2008/09 as well as from 2018/19, correlating with when Eskom announced load shedding as a precaution to limit the chances of a national blackout.

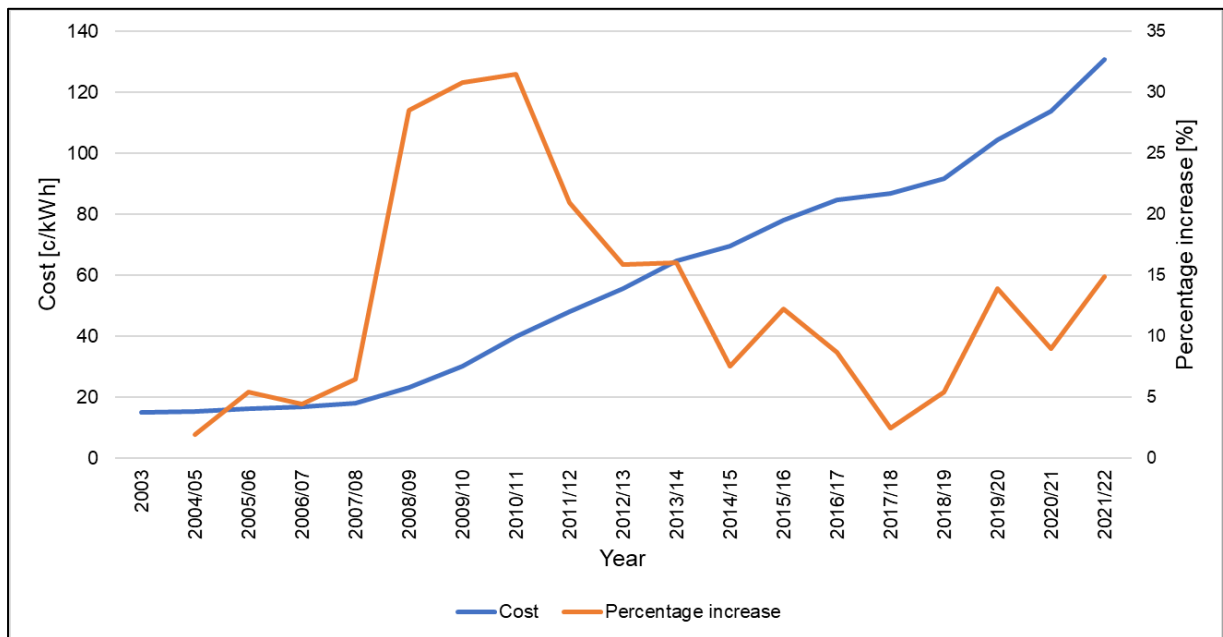


Figure 62: Eskom tariff history

Power calculation formulae

$$P_{kW} = \frac{(I \times V \times PF \times \sqrt{3})}{1000}$$

Equation 7: Power calculation

P_{kW} = Power

I = Current in amps

V = Voltage

PF = Power factor

Power calculation with status tags

$$P_{kW} = \textit{System status} \times \textit{Rated power}$$

Equation 8: Power calculation from status

P_{kW} = Power

System status = System status tags can be retrieved from the SCADA.

Rated power = Can be retrieved from motor name plates

Appendix B - Audit

Audit checklist

The instrumentation gap analysis and the simulation checklist found in Table 23 and Table 24 respectively can be used as a guideline to gather the required information used in the ZW benchmarking method.

Gap analysis

Table 23: Instrumentation gap analysis

Meter type	Metering count	Manufacturer	Part number
Airflow (mass flow)	X	X	X
Air pressure	X	X	X
Potable water flow	X	X	X
Potable water pressure	X	X	X
Water flow	X	X	X

Simulation checklist

Table 24: Simulation checklist

Items required / checked:			
COMPRESSED AIR	Yes	No	NA
Locations of all refuge chambers.			
Locations of other continues users of compressed air, not instrumentation air and pneumatic cylinders (example: mud dam agitation).			
Locations of compressors.			
Compressed air pipe routes (from compressors to users).			
Compressed air valve locations.			
Compressed air pipe sizes (mine standards).			

Compressed air instrumentation locations on SCADA system.			
WATER RETICULATION / DEWATERING			
Location of all dams			
Locations of other continues users of water			
Location of pumps			
Expected water temperature ranges for various areas			
VENTILATION			
Location of fans			
Location of ventilation doors			
REFRIGERATION / CHILLED WATER			
Location of fridge plants			
Location of bulk air coolers (BACs)			
Refrigeration pipe routes			
Refrigeration pipe sizes			

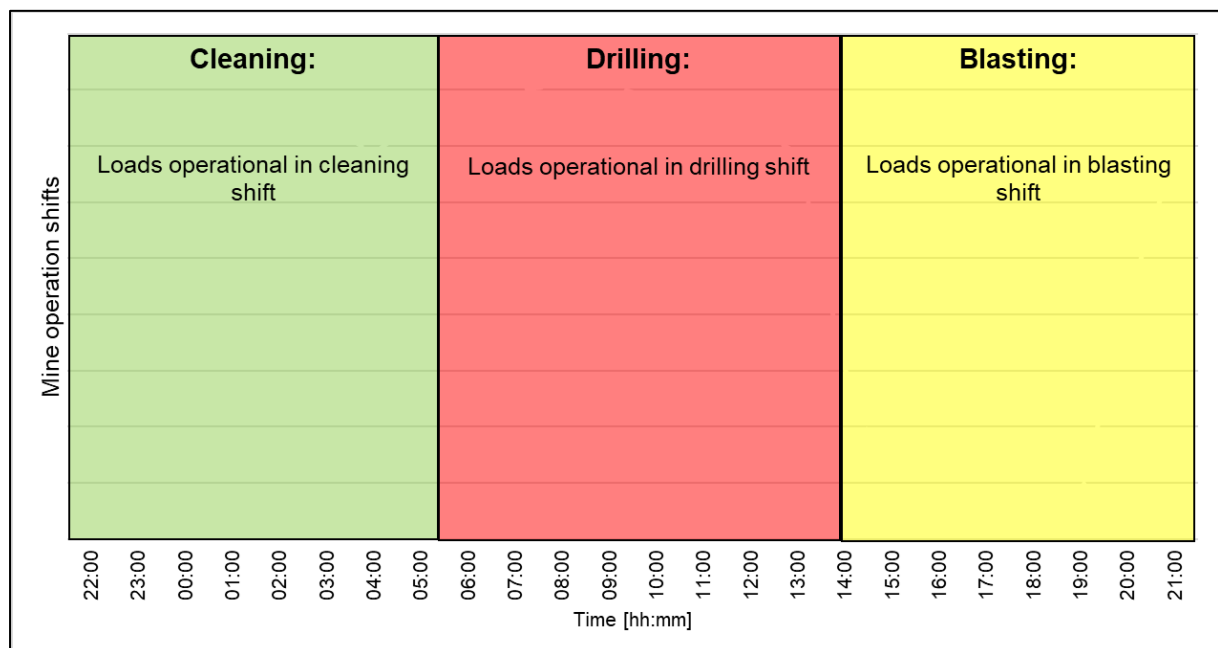


Figure 63: Operational schedule template

Appendix C - Additional case study results

Case study results

Table 25: Case study A - dynamic achievable target results

Time	33L Actual consumption (m³/h)	33L ZW baseload (m³/h)	Scaling factor	ZW baseload (m³/h)	Achievable target (m³/h)
01:00	14 668	7 607	193%	20 742	39 998
02:00	14 534	7 607	191%	20 742	39 633
03:00	14 575	7 607	192%	20 742	39 744
04:00	14 547	7 607	191%	20 742	39 668
05:00	14 702	5 389	273%	10 662	29 089
06:00	14 843	5 389	275%	10 662	29 368
07:00	15 463	4 947	313%	9 191	28 725
08:00	16 567	4 947	335%	9 191	30 776
09:00	17 151	16 501	104%	58 707	61 019
10:00	17 335	16 685	104%	61 457	63 852
11:00	17 526	16 876	104%	66 959	69 538
12:00	17 493	16 843	104%	69 710	72 400
13:00	17 163	16 513	104%	69 710	72 454
14:00	16 611	15 961	104%	66 959	69 686
15:00	15 841	15 191	104%	61 457	64 087
16:00	15 539	14 889	104%	58 707	61 269
17:00	10 853	3 720	292%	6 102	17 800
18:00	2 979	2 720	110%	6 102	6 683
19:00	2 950	2 720	108%	6 102	6 616
20:00	2 911	2 720	107%	6 102	6 529
21:00	2 915	2 720	107%	6 102	6 537
22:00	2 930	2 515	117%	7 574	8 824
23:00	7 651	5 692	134%	10 662	14 332
00:00	14 912	5 019	297%	10 662	31 679

Table 26: Case study B - dynamic achievable target results

Time	26L Actual consumption (m³/h)	26L ZW baseload (m³/h)	Scaling factor	ZW baseload (m³/h)	Achievable target (m³/h)
01:00	1 994	1 212	165%	34 292	56 423
02:00	1 981	1 208	164%	34 186	56 062
03:00	2 016	1 219	165%	34 486	57 047
04:00	1 874	1 122	167%	31 751	53 054
05:00	1 882	1 030	183%	29 171	53 293
06:00	1 890	1 144	165%	32 386	53 490
07:00	2 014	1 196	168%	33 836	57 001
08:00	2 124	1 283	166%	36 823	60 963
09:00	2 450	1 733	141%	48 093	67 991

10:00	2 602	2 099	124%	57 085	70 769
11:00	2 640	2 296	115%	61 957	71 251
12:00	2 657	2 380	112%	63 873	71 289
13:00	2 743	2 406	114%	63 855	72 790
14:00	2 830	2 298	123%	61 079	75 200
15:00	2 666	1 961	136%	52 454	71 304
16:00	2 507	1 516	165%	41 272	68 232
17:00	2 178	933	233%	26 262	61 315
18:00	1 848	1 004	184%	10 592	19 501
19:00	1 615	987	164%	9 104	14 899
20:00	1 861	1 049	177%	28 218	50 073
21:00	2 197	1 240	177%	35 090	62 155
22:00	2 237	1 235	181%	34 931	63 291
23:00	2 193	1 243	176%	35 172	62 058
00:00	2 164	1 213	178%	34 314	61 248

Table 27: Case study C - dynamic achievable target results

Time	69L Actual consumption (l/s)	69L ZW baseload (l/s)	Scaling factor	ZW baseload (l/s)	Achievable target (l/s)
01:00	43	30	145%	170	174
02:00	41	30	139%	170	174
03:00	35	29	124%	140	144
04:00	29	28	105%	113	116
05:00	28	28	101%	107	110
06:00	25	28	91%	107	110
07:00	29	38	78%	118	122
08:00	38	48	80%	130	133
09:00	46	48	96%	142	145
10:00	47	48	98%	149	153
11:00	46	48	95%	149	153
12:00	41	38	108%	137	141
13:00	33	28	119%	126	129
14:00	33	28	119%	114	117
15:00	29	27	106%	107	110
16:00	27	27	98%	107	110
17:00	25	28	92%	107	110
18:00	22	28	79%	107	110
19:00	20	28	72%	107	110
20:00	19	28	69%	107	110
21:00	19	27	71%	107	110
22:00	27	27	96%	111	114
23:00	41	30	137%	156	160
00:00	44	30	147%	170	174

Appendix D - Zero-wastage article



SAIIE33 Proceedings, 3rd - 5th October 2022, KwaZulu-Natal, South Africa © 2022 SAIIE

A ZERO-WASTAGE APPROACH TO BENCHMARK COMPRESSED AIR SYSTEMS ON PLATINUM MINES

R.F. Marais^{1*}, H.P.R. Joubert², J.F. van Rensburg³ and B. Pascoe⁴

¹Centre for Research and Continued Engineering Development (CRCED)
North-West University, South Africa
rmarais@rems2.com

²Centre for Research and Continued Engineering Development (CRCED)
North-West University, South Africa
rjoubert@rems2.com

³Centre for Research and Continued Engineering Development (CRCED)
North-West University, South Africa
jvanrensburg@rems2.com

⁴Centre for Research and Continued Engineering Development (CRCED)
North-West University, South Africa
bpascoe@rems2.com

ABSTRACT

Large industrial systems in deep-level mines contribute to the majority of mining utility costs. Optimising a system's energy efficiency can result in significant cost reduction and energy efficiency. This helps the struggling South African electricity provider, adds saving on utility cost reduction initiatives and improve Environmental, Social and Governance scores through decarbonisation. Optimisation through benchmarking is a common method used to identify inefficiencies by comparing similar systems. One pitfall of this method is the number of variables in each system. Normalising these systems has proven to be problematic due to limited data in the mining environment. This study proposes a new methodology to benchmark a mining system against its theoretical zero-wastage baseload. The proposed methodology was applied on a mine's compressed air system, achieving a theoretical 49% reduction. This resulted in a potential 72.7 MWh saving and a 78.5 ton CO₂ reduction over a 24-hour period.

Keywords: Energy efficiency, Platinum mines, Compressed air, Zero-wastage, Benchmarking

*Corresponding Author



1 INTRODUCTION

The electricity provider Eskom is responsible for approximately 95% of South African's electricity generation [1]. A lack of proper maintenance and planning resulted in Eskom being under enormous pressure to sustain a stable electricity supply since 2010 [2], [3], [4]. The power utility requires additional funds to solve the backlog in maintenance. This resulted in annual 8-15% increases in electricity tariffs over the last decade [5]. A direct result of these increases is the increased costs South African mines have to absorb [6].

In addition to increasing electricity tariffs which increased overhead costs, companies' income also take strain due to competition in the market [7]. Environmental, Social and Governance (ESG) is one of the compliance measures considered by the market when evaluating a company [8]. Lower ESG scores can lead to penalties due to higher CO₂ emissions and a potential loss in customers [9]. The Environmental component of ESG includes criteria such as the energy sources required, the amount of energy consumed, and the management of any waste products produced. Carbon dioxide (CO₂) emissions are included in the Environmental component of ESG and has become a significant focus point within larger companies to produce a cleaner product [9].

Due to the strain and challenges of rising electricity tariffs and ESG compliance, South African mines need to be more energy efficient to reduce electricity cost and improve on ESG scores [9], [10].

1.1 Background of study focus areas

The South African platinum mining industry is the largest in the world, producing 70% of the total annual export [11]. This makes it a very competitive industry, placing focus on components such as ESG scores and clean products.

The mining activity itself requires energy intensive systems such as compressed air, ventilation, dewatering and refrigeration. Error! Reference source not found. displays a breakdown of a typical South African platinum mine's energy distribution [12]. As indicated, the majority of electricity consumption is due to motor driven systems. Compressed air is the highest of these energy consumers, consuming 21% of the mine's total energy [13].

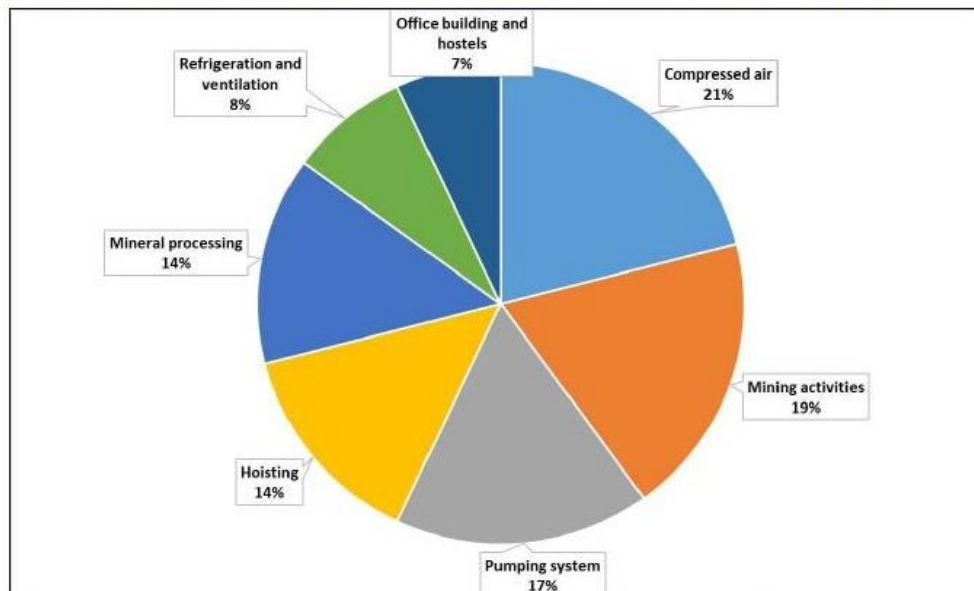


Figure 1: Platinum mining system energy division [13]
[68]-2

Compressed air is a critical component of key operations on a conventional mine [12], [14]. Due to the safety and expandability of a compressed air system, it is the preferable energy source for drilling and tramming [12], [14]. A typical compressed air system consists of a supply- and demand side.

The supply side consist of physical compressors and a network of pipes transferring compressed air to the demand side. South African deep-level mines prefer multistage centrifugal compressors as they can supply high compressed air flow at a required pressure set-point. A benefit to these compressors is the ability to vary air flow through guide vane control [12], [15]. This is useful when flow optimisation is required for the implementation of efficiency initiatives.

The demand side includes multiple users e.g. drills, loaders, refuge chambers, etc. [15]. These users typically operate in three different operational schedules on a conventional mine [14]:

- Drilling - Holes are drilled within the rock face to hold explosives set in the next shift.
- Blast - The holes drilled in the previous shift are charged with explosives and detonated.
- Cleaning - This shift consists of cleaning the blasted rock as well as tramming the rock to the loading areas.

Large steel pipes are used underground to transfer compressed air from surface to working areas. Figure 1 displays a high-level schematic of a typical underground compressed air system.

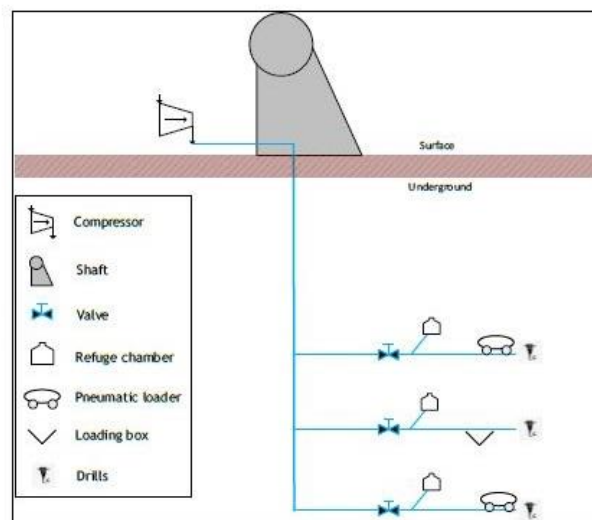


Figure 1: High-level underground compressed air network

Various studies found that compressed air in the mining environment is managed inefficiently [16], [17], [18], [19], [20]. Compressed air systems expand to adapt to ever-growing mining networks underground. Resulting in additional pipe connections and compressed air consumers. Over time this can result in more inefficiencies due to leaks and compressed air flowing in inactive mining areas [21].

Zietsman, found that auditing can assist with the identification of inefficiencies such as leaks [21]. Auditing will also assist in gaining knowledge and understanding of a vast compressed air network [21], [20]. Resulting in managing compressed air more efficiently [21].

Benchmarking techniques is another method that can be used to identify inefficiencies [12], [21]. This is done by identifying a best practice model through comparing inefficient systems to efficient systems, with the goal to identify the best industry practice [22], [23]. Performance indicators are used to compare two or more systems to identify inefficiencies and/or efficiencies within the systems [12].

This method usually requires a lot of accurate data from both systems to execute successfully [12]. This in turn requires sufficient metering and data management that is not always available in the mining environment [12].

In an ideal world the most efficient system will have zero waste. If zero-wastage is considered as a design principle, an entire system can be modelled to operate on its bare requirement [24]. Zero-wastage is then referred to as managing processes to eliminate and avoid any causes of wastage [25]. The information required to achieve this outcome is the total number of equipment used and their rated flow demand. This information is more easily obtainable on a mine than, for example, detailed flow data.

If a zero-waste model can be considered the most efficient version of a system, [24], it stands to reason that an existing system can be benchmarked against the most efficient version. Resulting in only one set of parameters needed and most normalising variables such as geological orientation, mining depth, scale of operation team dynamics and operation scale to be the same.

1.2 Need and Objectives

Considering all the background information, a need exists to improve compressed air efficiency in the platinum mining industry to reduce electricity cost and improve ESG scores. The objectives of this study are as follows:

- Use existing and available information for benchmarking; and
- Develop a zero-wastage benchmarking process that will allow a mine to be measured against the most efficient version of itself.

1.3 Literature linked to benchmarking in industry

Current benchmarking methods used in the mining industry generally compare high demand energy systems with each other to identify energy efficiency opportunities [12], [26], [27]. A challenge typically found with this method involves differences in normalising information between mines. The studies recommended that a normalised approach be followed to mitigate normalising variable requirements, however the methods required an extensive number of variables. As a result, challenges with data availability and accuracy can cause inaccurate benchmarking results [12].

Another benchmarking method common to the mining industry, is production benchmarking. This entails that production is utilized as the normalising variable used to benchmark different mines [28], [29]. The shortcoming with this method is that production is not the only variable affecting energy consumption [12]. Different equipment and normalising information also play a role. This method can result in inaccurate results, especially with larger operations.

Benchmarking in other industries were also considered to identify energy efficiency opportunities within hotels, offices and urban areas [27], [30], [31]. However, normalisation variables and external factors such as temperature had a large impact on these studies. This can lead to inaccurate results, especially with larger systems greatly affected by external factors.

With regards to ESG there is a renewed drive placed on industries to increase their ESG score and in doing so reduce their CO₂ emissions [10]. The CO₂ benefit resulting from energy efficiency can be calculated using the CO₂ /energy equivalent set by each country's energy provider. For South Africa this is Eskom. The national electricity provider stated that in 2021,

[68]-4

1.08 ton CO₂ is generated per MWh produced [32]. As a result, any energy efficiency saving achieved on compressed air will have a significant impact on CO₂ emissions.

With regards to zero-wastage benchmarking, very little literature is available, especially in the mining environment. Databases such as Google Scholar and Science Direct were used in combination with the following keywords: “zero-wastage benchmarking”, “mining” and “compressed air”. Articles published after 2010 found in primary sources were considered as they contain the most relevant information.

1.4 Compressed air in platinum mines

As mentioned, this study focusses on compressed air and demand side utilisation of the pneumatic equipment. The typical components that form a compressed air network are discussed below:

Rock drills

Use: To extract ore from a mine, the ore needs to be separated from the surrounding rock. This is done by inserting explosives within the rock. Rock drills are used to create a hole where the explosives are placed [12], [14], [33].

Misuse: The air supply feeding the drills is kept open after drilling shift is completed. This leads to compressed air leaking through the drills and various leaks within the working areas.

Pneumatic loaders

Use: Pneumatic loaders operate on a track. They contain a bucket-like scoop to load ore and waste into hoppers, usually at development end. The hoppers are transferred to the loading bays as they reach maximum capacity. The ore is then tipped via pneumatic cylinders into a loading box.

Misuse: No misuse of significant size was noticed.

Loading boxes

Use: The ore accumulated in the loading box are loaded into hoppers via a shoot that is controlled with pneumatic cylinders. The ore is transferred to surface with a winder. Loading boxes are located within working sections.

Misuse: No misuse of significant size was noticed

Agitators

Use: Agitation is the process where compressed air is released into dams to keep slurry from settling at the bottom of a dam. This ensure that the slurry water mixture can be pumped out to waste dams.

Misuse: In some cases, agitators are left open although the dams are clean. Resulting in unnecessarily wasting compressed air. Due to lack of measuring equipment, it is difficult to determine the amount of wastage.

Refuge chamber

Use: Refuge chambers are underground chambers with a compressed air feed to ensure positive atmospheric pressure. The positive atmospheric pressure ensures that hazardous fumes are kept from entering the chamber. Refuge chambers are required by law to keep employees safe in case of an underground emergency [12].

Misuse: In some cases, refuge chambers are supplied with larger pressures than required. Personnel open bypass valves to create a cooler environment to sit in.

Venturi blowers

[68]-5

Use: Due to increasing mining depths, temperatures within underground working areas are increasing. Venturi blowers authorised by mine management are placed in working sections to ventilate compressed air through the working sections to comply with ventilation requirements [21].

Misuse: Unauthorized venturi blowers are used to ventilate working sections that already have acceptable temperatures. This leads to lower compressed air pressures for drilling and unnecessary compressed air wastage.

Open ends

Misuse: Open ends are pipes connected to the compressed air supply used by employees to clean dust from development areas. However, this method is very ineffective in terms of energy management, as it leads to substantial compressed air wastage [12].

Leaks

Misuse: Leaks are common in an extensive compressed air network. Underground conditions cause compressed air pipes to corrode and form leaks. A substantial number of leaks can lead to a pressure drop across a compressed air network [12]. This can lead to additional energy consumption as compressors need to work harder to sustain pressure. Leaks can be seen as a misuse of compressed air.

2 ZERO-WASTAGE BENCHMARKING PROCESS

In this section a generic method will be developed that utilise zero-wastage to determine efficiency potential within a compressed air network. Building on the lessons learned from literature, the process shown in Figure 2 was developed.

The goal of this process is to distinguish between the compressed air system's baseload and wastage. The baseload of the compressed air network is the actual consumption excluding wastage (Zero-wastage baseload). The wastage is considered as the inefficient operation which will be identified during the audit phase (efficiency potential).

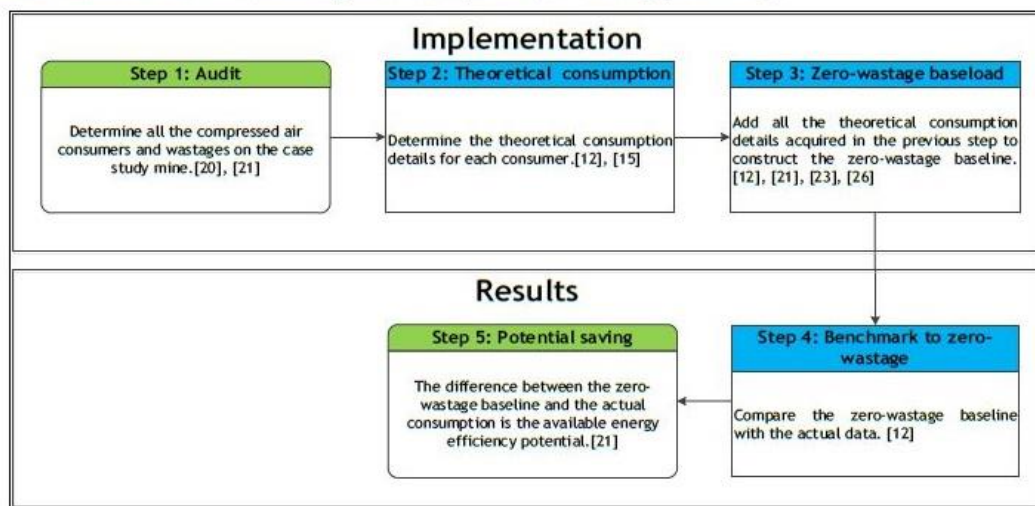


Figure 2: Zero-wastage process

Step 1: Audit - Reliable compressed air data is required. Auditing is a technique used to gather valuable information of a system [21]. Therefore, a detailed audit is conducted on the compressed air network. This verifies which compressed air consumers are operational as well

as the condition of the compressed air network to identify any wastages. A typical audit will entail:

- Meetings and interviews - Meet with on-site personnel for site layouts and preliminary information.
- Visual inspections - Visually inspect the system in question, including underground site visits to identify equipment and infrastructure.
- Physical data gathering - Gather rated consumption details for all consumers identified in the visual inspection as well as operational schedules of each consumer. Pressure and flow measurements are required to identify inefficient areas within the compressed air network.
- Take notes and photos - Take notes of any wastage detected throughout the audit. Photos of wastages and identified consumers can be valuable to mitigate revisits.

Step 2: Theoretical consumption - To calculate the theoretical consumption of each consumer, the rated flow and the quantity of all the compressed air equipment identified in Step 1 is required. The theoretical consumption is calculated by multiplying the rated flow with the quantity of the specific consumer as seen in equation 1.

$$\text{Theoretical consumption} = f_{\text{rated}} \times \sum_{\text{consumers}} \quad (1)$$

Step 3: Zero-wastage baseload - The Zero-wastage baseload is calculated by creating a 24-hour profile consisting of the theoretical consumption details allocated to their respective operational schedule.

Step 4: Benchmark to zero-wastage - Compare the zero-wastage baseload with actual compressed air data found during the audit to locate inefficiencies. This will highlight the waste or potential saving.

Figure 3 displays an example of the variables after typical iteration of the Zero-waste process. As seen in the figure, the additional variable “Unknown” is added for the uncategorised consumption that could not be allocated after the initial audit. The “Unknown” usually result from a lack of accurate data or infrastructure missed during the initial audit. As auditing continue, the “Unknown” areas should become focus areas to reduce “Unknown” data. In an ideal system, the “Unknown” variable will reduce to zero, resulting in the efficiency potential being equal to the identified wastage.

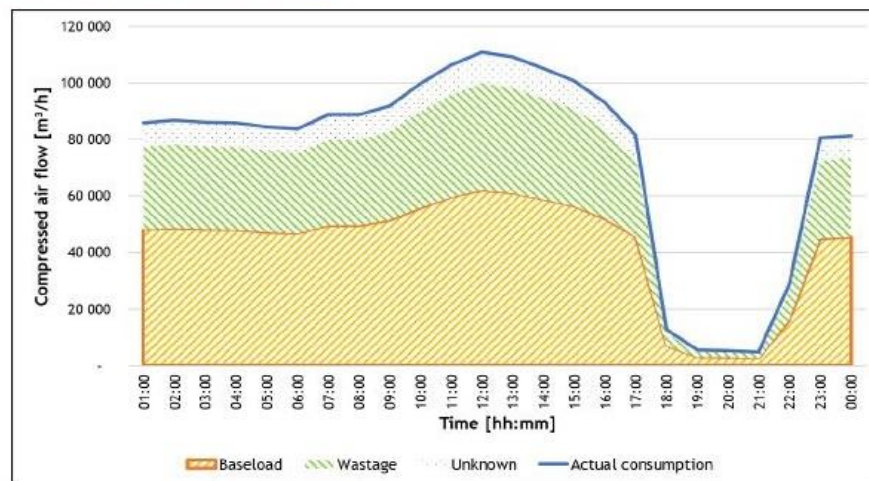


Figure 3: Zero wastage vs actual profile comparison

[68]-7

Step 5: Potential saving - The *Wastage* can be calculated by subtracting the *Baseload* and the *Unknown* from the *Actual consumption* as displayed in equation 2 [21].

$$Wastage = Actual\ consumption - (Baseload + Unknown) \quad (2)$$

The CO₂ reduction due to the energy efficiency improvement can be calculated with Equation 3, displaying the ratio between CO₂ and MWh for South Africa [32].

$$1.08\ ton\ CO_2e = 1\ MWh \quad (3)$$

3 IMPLEMENTATION OF ZERO-WASTAGE PROCESS

The implementation steps (Step 1 - 3) of the zero-wastage process was implemented on a deep-level platinum mine and will be discussed in this section.

Step 1: Audit the system, in this case the compressed air network. Table 1 provides a summary of the audit results.

Table 1: Audit results

Consumer	Quantity
Rock drills	261
Refuge chamber	42
Authorised venturi blowers	2
Pneumatic loaders	10
Loading boxes	56

The identified compressed air consumers and equipment was divided between the three operating shifts of the mine. Figure 4 provides a visual indication of this operational schedule with its consumers.

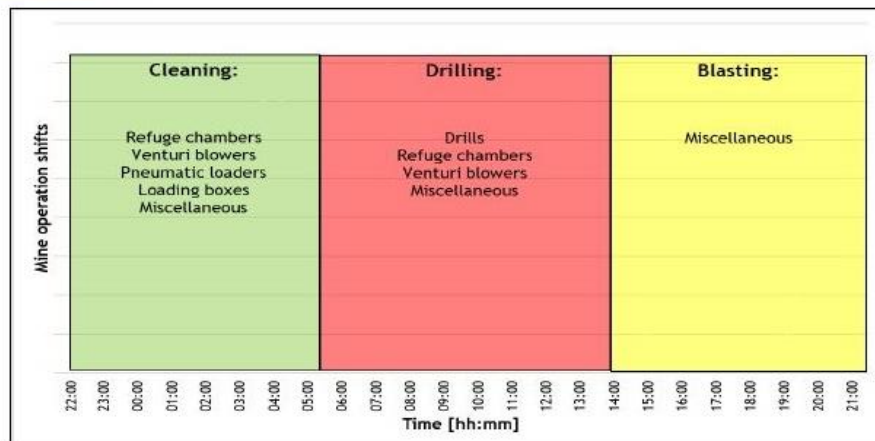


Figure 4: Mine operational schedule

Step 2: Identify the rated consumption details for each consumer. This information was gathered during the audit and direct communication with the equipment suppliers.

Refuge chambers

It was calculated that approximately 61.5 m³/h was consumed by each refuge chamber. The case study contains 42 refuge chambers underground. This entails that 2 585 m³/h are consumed by all the chambers.

Authorised venturi blowers

Venturi blowers consume an estimated 327.6 m³/h. The detailed audit revealed that the case study contains two authorised venturi blowers for cooling purposes. This means a total of 504 m³/h are consumed by authorised venturi blowers.

Rock drills

During the audit it was found that two different drills are used on the mine. The drills used are the S25 and the S215, allocated to development and stopping respectively. Table 2 provides a summary of the number of crews, the rated consumption per drill, the number of allocated drills per crew and the total compressed air consumption.

Table 2: Rock drills compressed air consumption

Crew	Crew number	Drill type	Rated consumption (m ³ /h)	Drills per crew allocated	Total consumption (m ³ /h)
Stopping	48	S215	198	4	38 016
On reef development	13	S25	246	2	6 406
Development	2		246	2	986
Waste development	13		246	3	9 610
Total	76				55 018

As indicated in Table 2, the mine contains 76 crews working in different sections across the mine. A theoretical compressed air consumption of 55 018 m³/h is consumed for drilling purposes.

Loading boxes

The rated flow for the specific loading box is between 2.16-50.4 m³/h at 350-600 kPa [15]. During the audit it was found that the loading boxes on the case study mine operates at 470 kPa. This entails that the loading boxes consumes an estimate total of 1 471 m³/h.

Pneumatic loaders

A pneumatic loader consumes an estimated 1 008 m³/h. The case study mine has ten loaders operating in cleaning shift. Thus, a total of 10 080 m³/h is consumed.

Miscellaneous consumers

During the audit 6 002 m³/h was noticed after the working levels where closed. This consists of miscellaneous underground operations such as compressed air and water pneumatic valves, compressed air leaks and open ends.

Table 3 provides a summary of the total theoretical compressed air consumption of each consumer calculated with equation 1.

Table 3: Theoretical consumption

Compressed air consumer	Theoretical consumption (m ³ /h)
Refuge chambers	2 585
Venturi blowers	504
Rock drills	55 018
Loading boxes	1 472
Pneumatic loaders	10 080
Miscellaneous consumers	6 002

Step 3: Calculate the baseload by adding the results indicated in Table 3 to the mine operations schedule in Figure 4. Figure 5 displays the zero-wastage baseline profile over a 24-hour period for the case study.

It was noticed that the loaders were not operational for the entire cleaning shift. An average operational time of three hours were noticed between 01:00 and 04:00, explaining the increased consumption between the specified period.

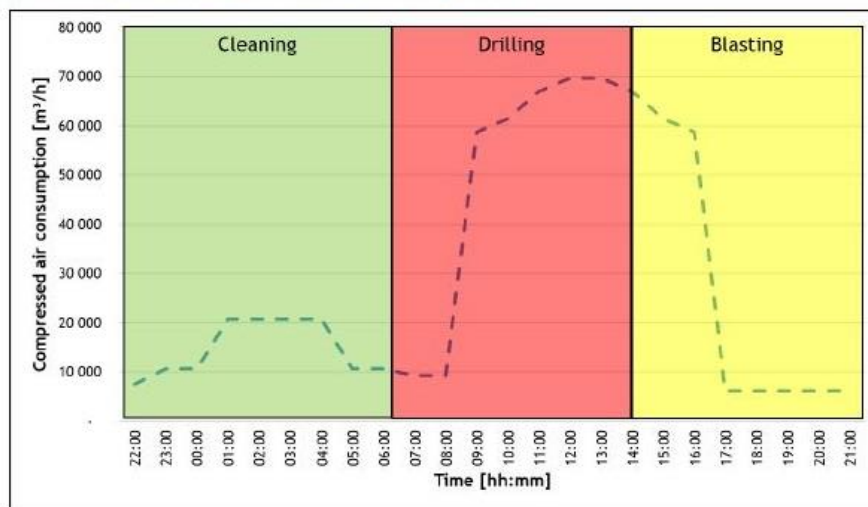


Figure 5: Zero-wastage baseline

The Result part of the zero-wastage process (Step 5 and 6) are discussed in the following section.

4 RESULTS

4.1 Zero-wastage compressed air system

Figure 6 displays the case study mine's actual compressed air consumption compared to the zero-wastage baseline derived in Step 4. The actual consumption profile consists of a month's average weekday data. As seen in the figure, the discrepancy between the cleaning shift (22:00-06:00) and the drilling shift (06:00-14:30) is minor. The majority of the potential is found within the cleaning shift, due to the large difference between the zero-wastage

baseload and the actual consumption. This difference highlights the misuse and inefficiency within these times as pipes deteriorate over time without maintenance, as well as equipment and working areas being left open after use. The compressed air cannot be closed during cleaning shift as numerous equipment and employees underground require the compressed air.

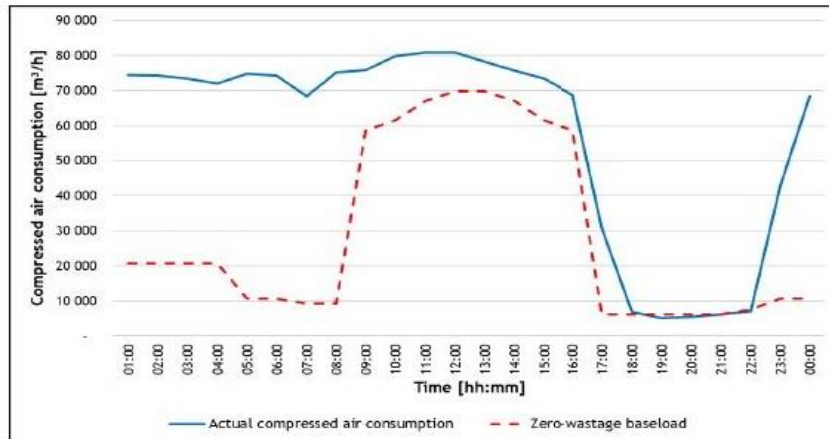


Figure 6: Actual consumption vs zero-wastage

As seen from Figure 6, the actual consumption profile is substantially higher than the zero-wastage profile, especially during cleaning shift. The case study consumed a total of 554 149 m³ during cleaning shift compared to a total of 153 326 m³ for the zero-wastage profile. This indicates that a possible reduction of 400 822 m³ can be achieved during cleaning shift, if the compressed air consumption is managed correctly.

The mine in question consumed a total of 1 372 636 m³ over the 24-hour profile compared to a total of 676 886 m³ for the zero-wastage profile. A reduction of 49% can be achieved with the zero-wastage baseload. It was measured that the case study mine produced 9.3 m³/kW. Meaning, the compressed air reduction is equivalent to a possible energy saving of approximately 72.7 MWh for the 24-hour period. This can result in a CO₂ reduction of approximately 78.5 for the 24-hour period.

4.2 Zero-wastage per-level

The benefit of the zero-wastage benchmarking method is that it is not limited to the overall compressed air system. The zero-wastage method can be applied on one working level, depending on the availability of data. This results in more accurately identifying the compressed air system's available efficiency. The Zero-wastage process was implemented on the case study mine's production levels and benchmarked based on their zero-wastage performance. Table 4 provides the results achieved from the per-level zero wastage implementation.

Table 4: Production level zero-wastage results

Production level	Level flow per 24-hour (m ³)	Zero-wastage baseload per 24-hour (m ³)	Saving (m ³)	Saving (kWh)
30	225 863	54 806	171 057	18 393
31	237 156	76 448	160 708	17 280
32	280 070	151 462	128 608	13 829
34	307 174	209 319	97 855	10 522
33	302 657	208 664	93 993	10 107

As seen in the table above, 30 level was identified with the most efficiency potential available. This is because the level contains the lowest zero-wastage baseload compared to the actual compressed air consumption.

Figure 7 displays 30 level's zero-wastage results compared to the level's actual compressed air consumption. As seen the zero-wastage baseload is lower throughout the entire 24-hour period. A possible efficiency of 171 057 m³ can be achieved in an ideal scenario. Although this network will never reach the zero-wastage baseload, the Zero-wastage process can assist to identify inefficiencies throughout the compressed air network.

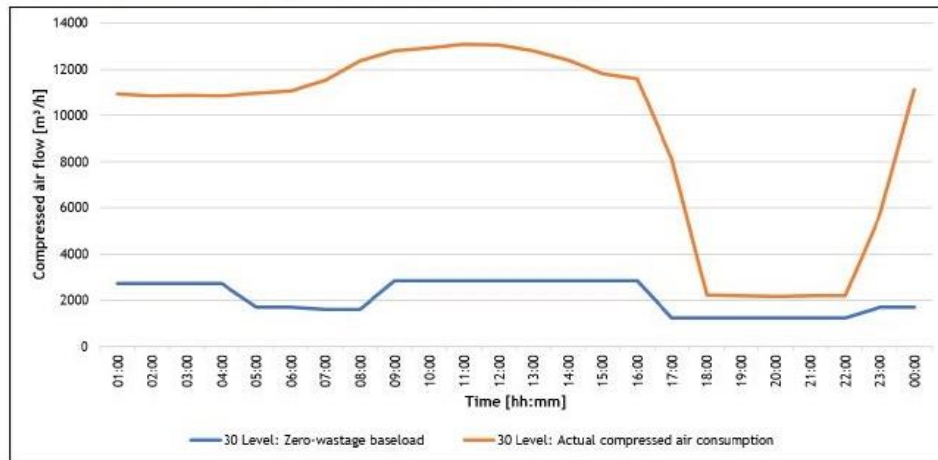


Figure 7: 30 Level Zero-wastage vs actual

5 CONCLUSION

Large industries such as the mining sector is under enormous pressure due to rising electricity tariffs. Additionally, stakeholders have placed more emphasis on ESG scores as it should result in a cleaner product that is more favourable in the markets.

Energy efficiency is a method that can assist industries to mitigate these challenges. Multiple studies focussed on benchmarking methods to identify energy efficiency potential by comparing different systems to each other. The issue with benchmarking mining operations, is that there are inaccuracies when considering numerous variables.

Platinum mines use various high energy consumption systems to extract ore from underground. The focus of this study was the development of a new method to identify available energy efficiency within a compressed air system on a platinum mine. The method consists of creating a zero-wastage baseload to compare a mining operation against its ideal self.

In the case study, a zero-wastage baseload was calculated from theoretical or rated consumption for a mine's compressed air consumers. The baseline indicated that a reduction in compressed air consumption of 49% can be achieved with zero-wastage. This results in a reduction of 72.7 MWh equating to a CO₂ reduction of 78.5 tons for the 24-hour period. From the results, it was seen that additional audits can increase the accuracy of the zero-wastage process.

Compared to the methods researched in the literature study, this method is less variable intensive as it only required data and information from the mine in question. There was no need for any normalisation, as the mine was effectively compared to itself. This greatly reduced the time and effort required to identify savings opportunities with a reduced risk of inaccuracies due to the reduction in required variables.

6 REFERENCES

- [1] H. J. Groenewald, "A performance-centered maintenance strategy for industrial DSM projects," Ph.D dissertation, Computer and Electronic Engineering, North-West University, Potchefstroom, 2015.
- [2] C. J. R. Kriel, "An alternative approach for sustainable industrial DSM in South Africa," Ph.D dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2016.
- [3] B. Pascoe, "Improved control processes to sustain electricity cost savings on a mine water reticulation system," Ph.D dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2018.
- [4] W. J. J. Breytenbach, "Framework for operational changes to reduce electricity costs in the South African steel industry," Ph.D dissertation, Development and Management Engineering, North-West University, Potchefstroom, 2017.
- [5] A. B. Sebitosi, "Is the South African electricity tariff model conducive to an energy efficient economy?," *Energy for Sustainable Development*, vol. 14, no. 4, pp. 315-319, 2010.
- [6] M. J. Cameron and R. Rossouw, "Modelling the Economic Impact of Electricity Tariff Increases on Eskom's Top Customer Segment," *International Journal of Energy Engineering*, vol. 2, no. 6, pp. 315-331, 2012.
- [7] R. Johnson, N. Mans-Kemp, and P. D. Erasmus, "Assessing the business case for environmental, social and corporate governance practices in South Africa," *South African Journal of Economic and Management Sciences*, vol. 22, no. 1, pp. 1-13, 2019.
- [8] W. Masliza, W. Mohammad, and S. Wasiuzzaman, "Environmental , Social and Governance (ESG) disclosure , competitive advantage and performance of fi rms in Malaysia," *Cleaner Environmental Systems*, vol. 2, no. , pp. 1-11, 2021.
- [9] W. Henisz, T. Koller, and R. Nuttall, "Five ways that ESG creates value," *McKinsey Quaterly*, 2019.
- [10] E. Shove, "What is wrong with energy efficiency?," *Building Reserch and Information*, vol. 46, no. 7, pp. 779-789, 2018.
- [11] U.S. Geological Survey, "*Mineral Commodity Summaries 2021*," U.S Geological Survey, Reston, Virginia, 2021.

- [12] C. Cilliers, "Benchmarking electricity use of deep-level mines," Ph.D dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2016.
- [13] T. Oelofse, "Using energy balances to evaluate electricity savings projects on platinum mines," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2020.
- [14] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2017.
- [15] J. H. Marais, "An integrated approach to optimise energy consumption of mine compressed air systems," Ph.D dissertation, Electrical Engineering, North-West University, Potchefstroom, 2012.
- [16] C. J. R. Kriel, "Modernising underground compressed air DSM projects to reduce operating costs," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2014.
- [17] F. W. Schroeder, "Energy efficiency opportunities in mine compressed air systems," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2009.
- [18] A. J. M. Van Tonder, "Automation of compressor networks through a dynamic control system," Ph.D dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2014.
- [19] A. Hassan, K. Ouahada, T. Marwala, and B. Twala, "Optimization of the compressed air-usage in South African mines," in The IEEE AFRICON Conference, 2011.
- [20] A. J. M. van Tonder, "Sustaining compressed air DSM project savings using an air leakage management system," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2011.
- [21] L. N. Zietsman, "Novel solutions for compressed air demand management on deep-level mines," Ph.D dissertation, Mechanical Engineering, North-West University, Potchefstroom, 2020.
- [22] G. Anand and R. Kodali, "Benchmarking the benchmarking models," *Benchmarking: An International Journal*, vol. 15, no. 3, pp. 257-291, 2008.
- [23] B. Y. Tran, "Zero waste lifestyle," B.S. thesis, Energy and Environment Engineering, Tampere University of Applied Sciences, Pirkanmaa, 2019.
- [24] W. Snow and J. Dickinson, "The end of waste: zero waste by 2020," Zero Waste New Zealand Trust, Takapuna, Auckland, 2011.
- [25] A. U. Zaman and M. S. H. Swapan, "Performance evaluation and benchmarking of global waste management systems," *Resource, Conservation and Recycling*, vol. 114, no. , pp. 32-41, 2016.
- [26] L. F. Van der Zee, "Modelling of electricity cost risks and opportunities in the gold mining industry," Ph.D dissertation, Electrical Engineering, North-West University, Potchefstroom, 2013.
- [27] W. Chan, "Energy benchmarking in support of low carbon hotels: Developments, challenges, and approaches in China," *International Journal of Hospitality Management*, vol. 31, no. 4, pp. 1130-1142, 2012.
- [28] D. du Plooy, P. Maré, J. Marais, and M. J. Mathews, "Local benchmarking in mines to locate inefficient compressed air usage," *Sustainable Production and Consumption*, vol. 17, no. ,pp. 126-135, 2019.

[68]-14

- [29] G. R. Ballantyne and M. S. Powell, "Benchmarking comminution energy consumption for the processing of copper and gold ores," *Minerals Engineering*, vol. 65, no. ,pp. 109-114, 2014.
- [30] J. Keirstead, "Benchmarking urban energy efficiency in the UK," *Energy Policy*, vol. 63, no. ,pp. 575-587, 2013.
- [31] K. W. Mui, L. T. Wong, and L. Y. Law, "An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates," *Applied Energy*, vol. 84, no. 1, pp. 89-98, 2007.
- [32] Eskom Holdings Limited, "Integrated Report - 31 March 2021," Eskom Holdings Limited, no. March, Johannesburg, Gauteng, 2021.
- [33] C. J. J. van Zyl, "Practical approach to analyse mine pneumatic drilling performance," M.S. thesis, Mechanical Engineering, North-West University, Potchefstroom, 2019.