



# **A strategy to prioritise compressed air energy-savings initiatives during production stoppages**

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

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Graduation: June 2025

## **ACKNOWLEDGEMENTS**

Thank you to Jesus Christ, my Lord and Saviour, for providing the opportunity and gifting me the ability and capacity to complete this study. All glory to Him.

I would like to thank the following individuals and entities for their contributions:

- My parents, for their sacrifice, support and provision throughout my life. Thank you for all of the prayers.
- Bernie Pretorius, for his continued support and encouragement during the study. Thank you for setting an example.
- Dr Johan Marais, for his guidance as supervisor. Thank you for the time and effort spent throughout the study.
- Dr Jean van Laar, for his guidance and efforts to streamline the academic process.
- My colleagues, for their valuable input and advice related to the study in general. Thank you for your support and encouragement throughout the study.
- The mine personnel, who provided valuable information and assisted during the implementation process. Their quick response and willingness to help is greatly appreciated.
- ETA Operations (Pty) Ltd and its sister companies, for providing the necessary resources, facilities and financial support for this study.

## ABSTRACT

**Title:** A strategy to prioritise compressed air energy-savings initiatives during production stoppages

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**Keywords:** Deep-level gold mining, compressed air systems, energy saving, production stoppages, pressure set points, compressor control.

The cost of electricity in South Africa has increased significantly since 2007. Electricity tariffs increased by 165% over the past decade alone. This negatively affects the profitability of mines with electricity costs forming a large portion of the operational costs. The compressed air system, which is widely regarded as inefficient, is the largest consumer of electricity at a mine.

Energy-saving initiatives are a proven way of reducing electricity costs on the compressed air system of a mine. However, mines face challenges that affect the implementation of energy-saving initiatives. One such challenge is production stoppages. Mines experiencing production stoppages may have limited time, capital and resources available to implement these initiatives.

Previous studies have primarily focused on prioritising and implementing energy-saving initiatives during a typical production period and did not consider production stoppages. The need exists for a strategy that assists mines during a production stoppage by prioritising and filtering energy-saving initiatives.

To address the aforementioned need, a pre-existing prioritisation method was customised specifically for this scenario. By integrating it with a curated checklist of proven compressed air energy-saving initiatives from industry research, a user-friendly tool was created to streamline decision-making. Alongside this, a straightforward four-step energy-saving strategy was developed that integrates the prioritisation method to enable mines to effectively reduce compressed air demand and decrease electricity costs during production stoppages.

The developed strategy was applied to two case study production stoppages. The first case study tested the accuracy and benefit of the prioritisation method and compared it with industry knowledge and experience. This was done by comparing the results of the prioritisation method with the actual initiatives that were implemented, without a guided strategy, during the case study period.

The prioritisation method generated a list of four feasible energy-saving initiatives. These generated initiatives aligned with four out of the six initiatives that were implemented in reality. Unforeseen events resulted in the implementation of two initiatives which were not identified by the strategy. Therefore, the prioritisation method was found to be accurate in determining feasible energy-saving initiatives as well as prioritising these initiatives, except when faced with unforeseen events.

Additionally, results showed that an investigation period of five weeks could have been avoided if the prioritisation method had been used at the start of the case study production stoppage instead of relying on industry knowledge and experience. Usage of the method would have resulted in compressor set-point adjustments being made sooner and a potential saving of 500 MWh (14.3 MWh/day) could have been achieved. This is equivalent to a cost-saving potential of R410 000 with a daily saving of R14 000/day in the summer and R22 300/day in the winter.

The second case study tested the effectiveness of the developed strategy when fully implemented during a production stoppage. Four energy-saving initiatives were identified and successfully implemented according to priority as soon as the production stoppage began. Initiatives were fully reversed on the last day of the production stoppage and production restarted without delays. A total energy saving of 250 MWh (22.7 MWh/day) was achieved during eleven days, equivalent to a cost saving of R200 000 with a daily saving of R22 350/day in the summer and R35 400/day in the winter.

The overall strategy has proven to be an effective tool that may assist mines in reducing costs and saving time during production stoppages by prioritising and filtering energy-saving initiatives.

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## LIST OF ABBREVIATIONS

CAS	Compressed Air System
DCC	Dynamic Compressor Control System
DCS	Dynamic Compressor Selector
DSM	Demand-side Management
EnMS	Energy Management System
ESCo	Energy Services Company
FY	Financial Year
IPMVP	International Performance Measurement and Verification Protocol
ISO	International Organization for Standardization
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
SI	Système Internationale
TOU	Time-of-use
VSD	Variable Speed Drive
ZAR	South African Rand

## NOMENCLATURE

<b>Symbol</b>	<b>Description</b>	<b>Units</b>
<i>d</i>	Distance in metre	m
<i>E</i>	Electrical energy in kilowatt-hour	kWh
<i>m</i>	Mass flow in kilogram per second	kg/s
<i>p</i>	Pressure in kilopascal	kPa
<i>P</i>	Electrical power in megawatts	MW
<i>R</i>	Monetary value in South African rand (ZAR)	R
<i>t</i>	Time in hours	h
<i>T</i>	Temperature in degrees Celsius	°C

## CHAPTER 1: INTRODUCTION AND LITERATURE

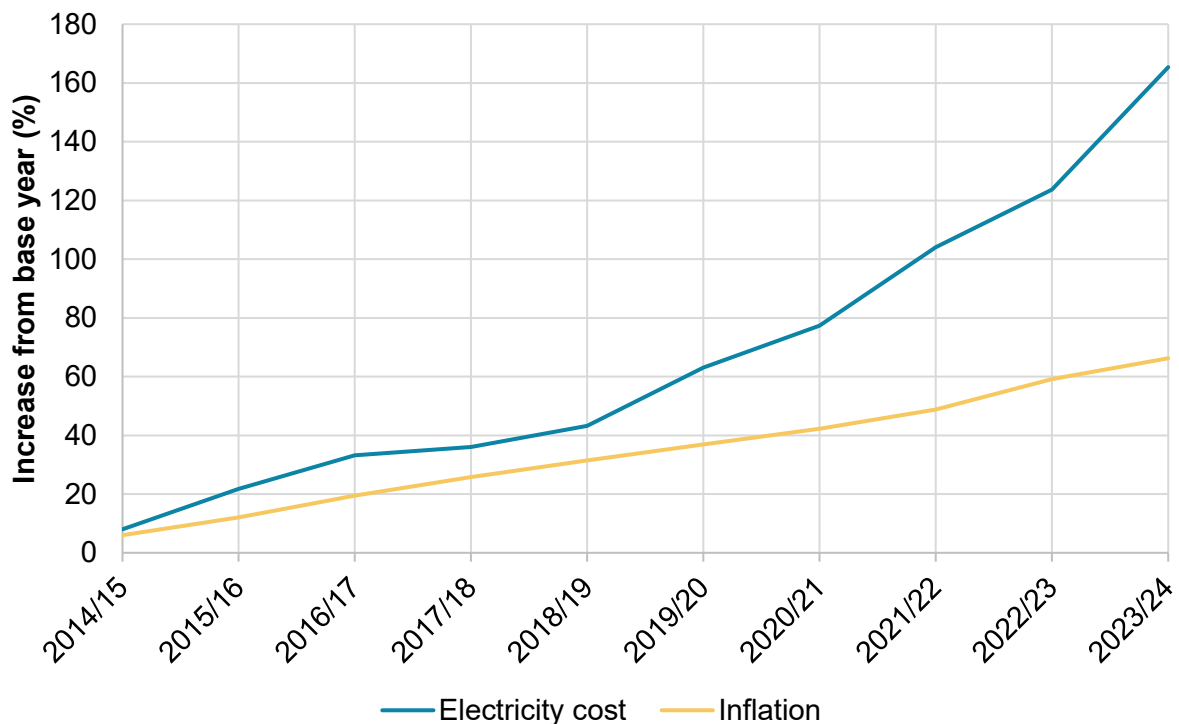


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<sup>1</sup> A. Wannenburg, "Shaft headgear of a gold mine," [Photograph], South Africa, 2022.

## 1.1 Background

South African deep-level mines face various challenges that affect profitability. One such challenge is the cost of electricity, which represents 20% of the total operational cost of a mine [1]. Eskom supplies 90% of South Africa's electricity and 30% of the total electricity used in Africa [2]. The cost of electricity supplied by Eskom has increased significantly since 2007 with tariffs increasing by 165% within the past decade compared with the 66% increase in inflation as shown in Figure 1 [3].



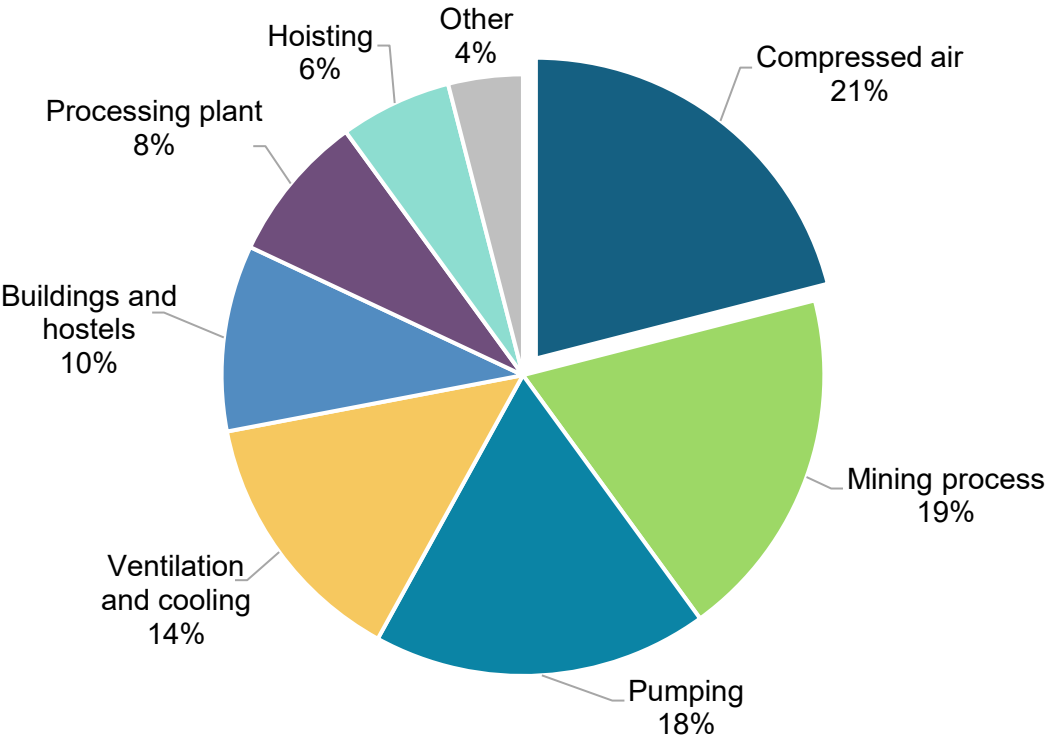
**Figure 1: Eskom electricity tariff increase vs inflation (adapted from [3])**

The profitability of a mine can be improved through a reduction in electricity cost. This is done by shifting electricity demand to lower cost periods (load shifting) or through reducing demand during higher cost periods (peak clipping)<sup>2</sup>. Additionally, costs may be reduced by reducing overall electricity consumption [4]. Implementing energy-saving initiatives is a proven method of reducing the electricity consumption of a mine [5]. Energy-saving initiatives vary depending on the electricity consumer involved. The various electricity consumers at a typical deep-level mine can

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<sup>2</sup> Eskom, "Demand Management Programme". Available: <https://www.eskom.co.za/distribution/demand-management-programme> [Accessed: 9 Feb. 2025].

be grouped by mining section. Figure 2 shows the percentage that each section contributes to the total electricity consumption [6].



**Figure 2: Electricity share per mining section (adapted from [6])**

Compressed air represents 21% of the total electricity consumption of a typical deep-level mine and is the single largest consumer compared to the other sections, as shown in Figure 2. Compressed air systems (CASs) are considered inefficient with estimates indicating that 40% to 80% of the compressed air that is generated is wasted due to system losses such as leaks [4].

**1.2 Compressed air in mining**

**Preamble**

The CAS of a mine consists of a supply side, a demand side, and a distribution network [7]. Equipment that generates compressed air such as compressors form part of the supply side of a CAS [6, 8]. The demand side accounts for all the equipment and processes that require compressed air to operate [6]. The supply and demand sides are connected through a network of pipes known as the distribution network [7]. Figure 3 shows a simplified illustration of a CAS.

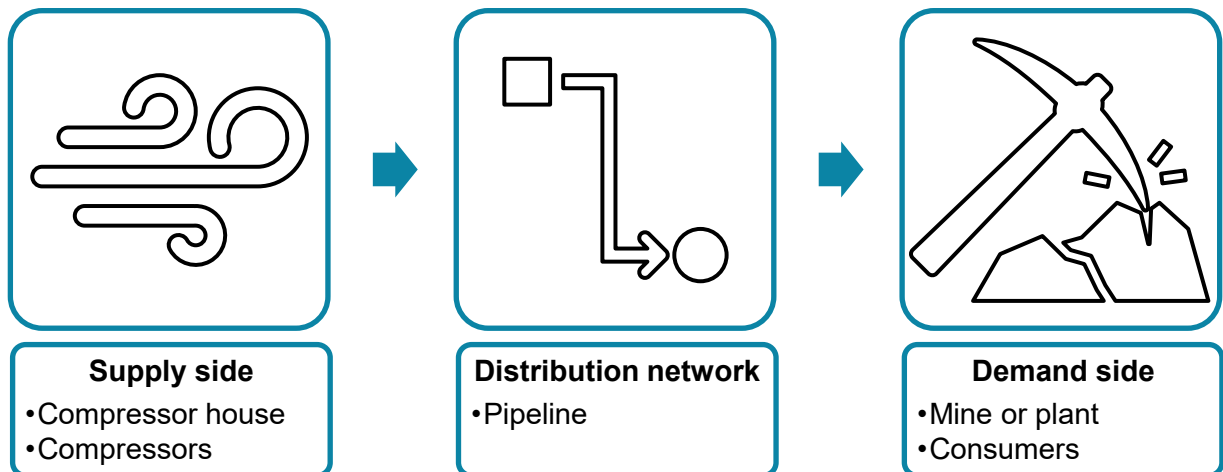


Figure 3: Simplified compressed air system (adapted from [4, 9])

### 1.2.1 Supply side

Compressed air is typically generated by multiple compressors at a mine [4]. These compressors are generally contained in a building referred to as the compressor house [4]. There are many different types of compressors as summarised by Figure 4.

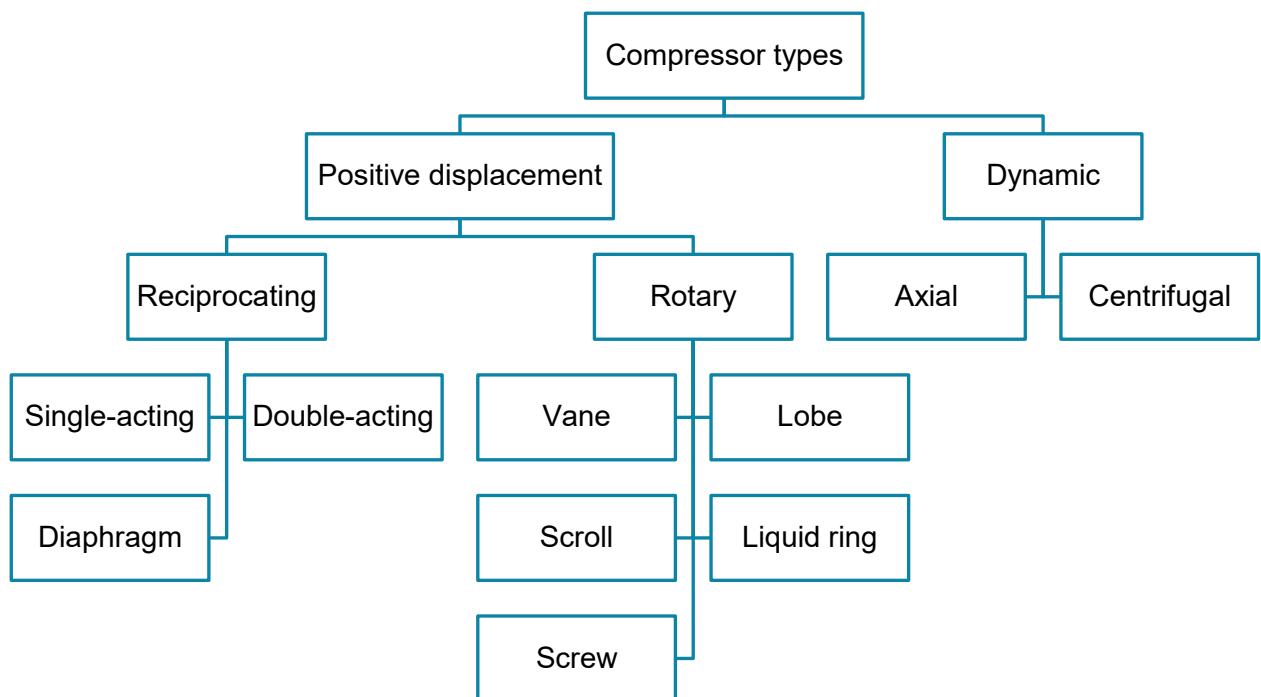


Figure 4: Classification of compressor types (adapted from [10, 11])

Compressed air networks with high flow requirements rely on centrifugal compressors [12]. South African mines typically use the multi-stage centrifugal compressor for its compact size and wide operating range [13]. Additionally, a multi-stage centrifugal compressor is preferred for its capacity to generate compressed air flow at specified pressure set points [14]. The rated power of centrifugal compressor motors could be up to 15 MW for mining applications [4, 15].

Centrifugal compressors have control mechanisms such as inlet guide vanes and blow-off valves that regulate delivery flow [4, 15]. These compressors can also operate in various combinations depending on the flow and pressure requirements of a CAS [4]. Compressor combinations consist of baseload and trimming compressors [4, 16]. Baseload compressors typically operate at maximum capacity to maintain the pressure of a CAS above a specific minimum pressure [4, 16]. Trimming compressors assist baseload compressors during high-demand periods by increasing the supply of compressed air [4, 16].

**1.2.2 Demand side**

*1.2.2.1 Consumers and requirements*

There are various systems and equipment at a mine that are dependent on the supply of compressed air. These will be referred to as consumers. Each consumer has its own pressure and flow requirements, which are summarised in Table 1.

**Table 1: Compressed air consumers at a deep-level mine (adapted from [6, 17, 18])**

<b>Consumer</b>	<b>Flow requirement per unit (kg/s)</b>	<b>Pressure requirement (kPa)</b>
Refuge bay	< 0.06	150–300
Workshop	< 0.0001	200–250
Pneumatic rock drill	Up to 0.12	400–600
Pneumatic cylinder	Up to 0.14	350–600
Mechanical loader	0.80	400–500
Ventilation and cooling	Up to 1.60	100–650
Mud dam agitation	0.56	400
Processing plant	0.82	420–500

## **Refuge bay**

Refuge bays, also known as refuge stations or refuge chambers, are designated safe areas underground where personnel evacuate to in case of an emergency [13]. These areas require a constant flow of compressed air to provide ventilation and to ensure positive pressure inside, preventing smoke and other noxious gases from entering [17, 19].

## **Workshop**

Workshops use compressed air to power pneumatic tools, which do not require a constant supply since these tools are only used briefly when needed [17].

## **Production-related consumers**

Pneumatic rock drills are commonly used for drilling holes into the rockface, allowing the installation and subsequent detonation of explosives to break up the rock [20]. Pneumatic drills release compressed air during drilling, which expands rapidly and provides a limited and localised cooling effect [21]. Pneumatic cylinders control the opening of doors and chutes, while rock is loaded into mine carts using pneumatic loaders [9].

## **Mud dam agitation**

Mines use compressed air to agitate mud dams, which prevents solids from settling at the bottom of the dams [15, 22]. Compressed air is continuously supplied through open-ended pipes; however, mud can clog the pipes if the pressure is insufficient [23].

## **Processing plant**

Compressed air is supplied to gold processing plants in two forms, namely low pressure and high pressure. Low-pressure air is used for aeration of the leach and cyanide destruction circuits, while high-pressure air is used for instrumentation [24]. Processing plants that are located close to a mine are commonly supplied with compressed air from the mine's network. These plants require a constant supply of compressed air due to their continuous operation [25].

### *1.2.2.2 Inefficiencies*

CASs have various inefficiencies and wastages that consume up to 40–80% of the available compressed air [4]. To compensate for inefficiencies, supply pressure and flow are commonly increased, which results in increased electricity costs [17].

The inefficiencies that are commonly found in typical deep-level mine CASs include [25]:

- Improper pipe installation
- Incorrectly sized pipes
- Leaks
- Open pipe ends
- Pipe scaling
- Pressure losses caused by valves or restrictions in the piping
- Sharp bends in pipes

Repairing leaks is often among the first initiatives implemented to reduce energy costs by reducing the demand for compressed air [8].

### 1.2.2.3 Pressure demand profile

The consumers listed in Section 1.2.2.1 are generally connected to the same CAS. The supply pressure of compressed air must always meet the requirements of the consumer with the highest pressure demand [4]. Production and time may be lost if the compressed air pressure is insufficient [4].

Figure 5 shows the daily pressure demand profile of a typical production day. The consumer with the highest pressure demand is listed for each period.

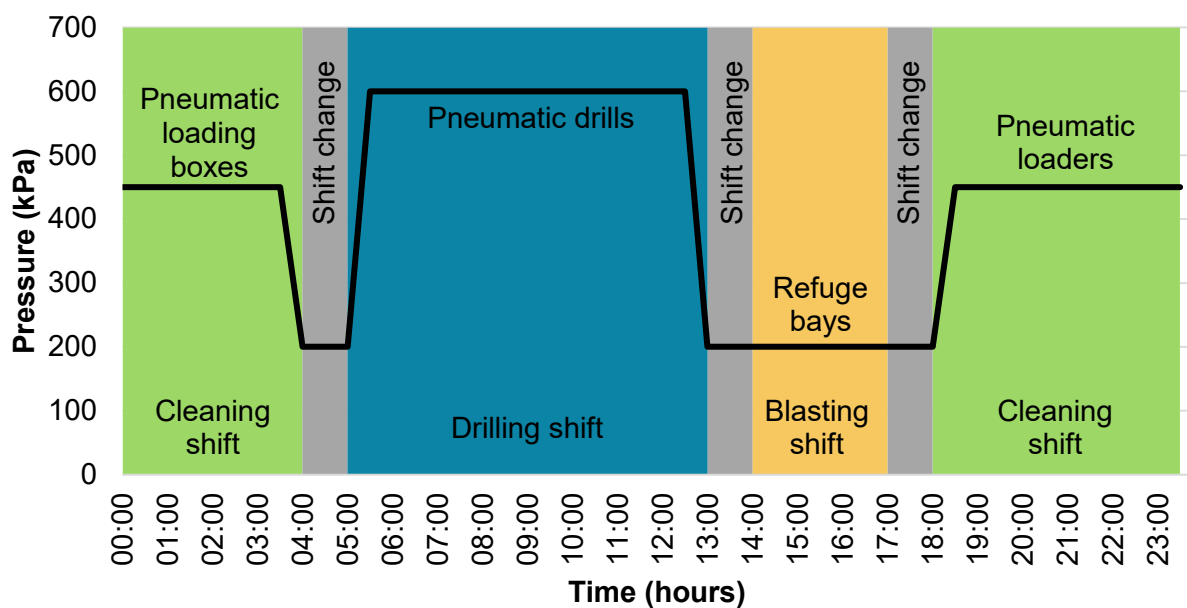


Figure 5: Compressed air pressure demand of a typical production day (adapted from [4])

Miners drill holes in the rockface with pneumatic drills during the drilling shift [6]. The compressed air demand is highest during the drilling shift due to the large number of pneumatic drills in use [6]. Explosives are installed in the holes, and mining personnel evacuate the mining levels before detonation [6]. Blasting takes place during the blasting shift, and compressed air demand is at its lowest during this period due to the evacuation process [6]. Once the blasting process is completed, the ore is collected by pneumatic loaders during the cleaning shift and transported to the processing plant on the surface [6]. There is a high compressed air demand during the cleaning shift because of the pneumatic loaders and cylinders [6].

### **1.2.3 Production stoppage challenges**

Not only is compressed air an essential requirement for production at a mine [13] but the profitability of a mine is also dependent on production [4]. A mine, therefore, benefits from continuous production. However, there are periods of planned and unplanned production stoppages, namely:

- Strikes [26]
- Lockdowns [27, 28]
- Off weekends
- Annual Christmas breaks [29]
- Unforeseen incidents [30]

Production stoppages result in significant costs for industries due to the loss of production output, among other factors [31]. Although no production occurs during production stoppages, mines still require essential services such as refrigeration, ventilation, dewatering and compressed air [27]. These essential services incur an operational cost despite no revenue being generated. Implementing energy-saving initiatives helps to reduce electricity consumption, therefore reducing operational costs as mentioned previously in Section 1.1 [5]. However, the availability of capital for energy-saving initiatives may be limited during a production stoppage. This is evidenced by the limited capital expenditure to preserve cash flow during the 2018/19 strike at Sibanye-Stillwater's gold operations [1].

In addition to limited capital expenditure, labour disputes may lead to the absence of the necessary labour and cause project delays [30]. Employees are required by law to give their employer at least 48 hours' notice before commencing a strike [32]. However, unforeseen incidents that lead to production stoppages such as breakdowns may occur without warning. This

provides mines with limited time to act and prepare for production stoppages, which could affect the implementation of energy-saving initiatives.

### 1.3 Literature review of compressed air energy-saving initiatives

#### Preamble

Cost savings during production stoppages are necessary to ensure that a mine has the best possible chance of recovery after a production stoppage. While compressed air is regarded as inefficient, it is an essential service during a production stoppage [4, 27]. Implementing energy-saving initiatives could lead to a reduction in electricity costs [5]. However, mines have limited capital, labour, and time to prepare during production stoppages, as mentioned in Section 1.2.3. A literature review was conducted to gather existing strategies for reducing the electricity cost of a CAS during production stoppages.

#### 1.3.1 Literature review procedure

The literature review follows the systematic literature review procedure as shown in Figure 6 [33].

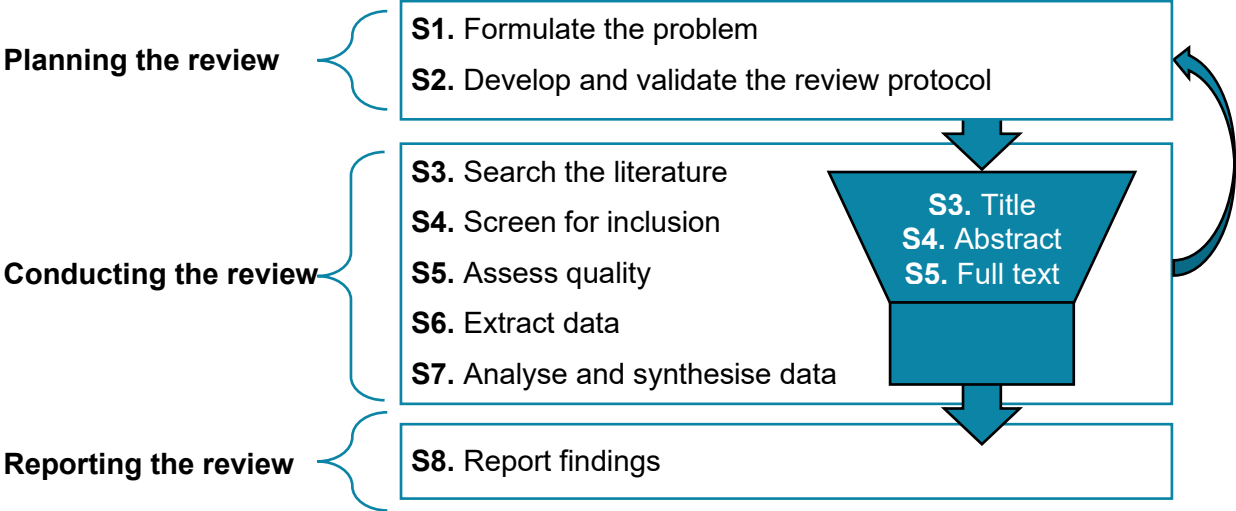


Figure 6: Systematic literature review procedure (adapted from [33])

#### 1.3.2 Planning the review

##### 1.3.2.1 Step 1: Problem

The purpose of the literature review is to explore existing solutions and strategies that can be used or adapted to reduce the electricity cost of a deep-level gold mine’s compressed air network during a production stoppage.

### 1.3.2.2 Step 2: Protocol

The three primary methods of finding literature include electronic database searches, backward searches and forward searches [33]. Although electronic databases are the main source of published literature, no database includes all published materials [33]. A systematic literature search should therefore draw from more than one database [33]. The databases used in this literature search are as follows:

- Google Scholar<sup>3</sup>
- Connected Papers<sup>4</sup>
- IEEE Xplore<sup>5</sup>
- Elsevier<sup>6</sup>
- North-West University Library and Information Service<sup>7</sup>

Google Scholar was used to quickly locate relevant studies in various databases with the aid of the keywords listed in Table 2. The core keywords were based on the problem discussed in Step 1, with some words modified with postmodifiers to refine the search.

**Table 2: Literature search keywords and postmodifiers**

<b>Core keyword</b>	<b>Postmodifier 1</b>	<b>Postmodifier 2</b>
Compressed air	System	Network
Production stoppage	Stop	Break
Energy saving	Management	–
Mine(-ing)	Deep-level	–

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<sup>3</sup> Google Scholar. Available: <https://scholar.google.com> [Accessed: 2023].

<sup>4</sup> Connected Papers. Available: <https://www.connectedpapers.com> [Accessed: 2023].

<sup>5</sup> IEEE Xplore. Available: <https://ieeexplore.ieee.org> [Accessed: 2023].

<sup>6</sup> Elsevier. Available: <https://www.elsevier.com> [Accessed: 2023].

<sup>7</sup> North-West University Library and Information Service. Available: <https://library.nwu.ac.za> [Accessed: 2023].

Connected Papers was used to group similar studies, which enabled easy backward and forward searches. The purpose of backward searches is to obtain a complete list of literature by identifying relevant works cited by a study [33]. This is done by consulting the list of references at the end of an article [33]. Similarly, forward searches are done by finding all articles that have since cited the reviewed article [33]. The search was further refined by limiting the literature to certain inclusion criteria. Included studies had to be:

- Published within the last ten years.
- Written in English.
- Peer-reviewed sources, such as journal articles, dissertations and theses.
- Published by journals accredited by the Department of Higher Education and Training<sup>8</sup> if the study is a journal article.
- Relevant to the topic.

**1.3.3 Conducting the review**

*1.3.3.1 Steps 3 to 5: Literature search*

The literature search was conducted based on the protocol set out in Step 2. Figure 7 summarises the number of studies identified and filtered at each step of the literature search.

Step	Number of records (n)	Criteria
<b>Identification (S3)</b>	Initial search results (n = 262)	Keywords, date range
	Records identified (n = 54)	Title, language
<b>Screening (S4)</b>	Records after duplicates removed (n = 52)	Unique title
	Records screened (n = 30)	Abstract, source quality
<b>Eligibility (S5)</b>	Full text reviewed (n = 28)	Relevance to topic
<b>Inclusion</b>	Total studies included (n = 33)	Additional relevant studies

**Figure 7: Number of studies identified during the literature search**

<sup>8</sup> Department of Higher Education and Training. Available: <https://www.dhet.gov.za> [Accessed: 2023].

At the time of the literature search, the initial keyword searches yielded 262 published results within the last ten years. These results were filtered based on the language and relevance of the title, which resulted in the identification of 54 studies in Step 3.

Two duplicate studies were removed, and each unique study was further filtered based on the source quality to ensure that only accredited journals and peer-reviewed sources were used. The abstracts of the remaining studies were reviewed for relevance to the topic and the number of studies was reduced to 30 in Step 4.

Step 5 consisted of reviewing the full text of each remaining study to determine its relevance to the topic, and the number of studies was subsequently reduced to 28. An additional five studies were identified through forward and backward searching, which were subjected to the same review and filtering process as the initial keyword searches. Therefore, the literature search yielded a total of 33 relevant studies of which 29 studies are associated with the North-West University.

The literature review, however, did not specifically focus on the North-West University and multiple databases were searched for relevant studies. The North-West University aims to develop research initiatives tailored to the South African mining industry [34]. Additionally, the Centre of Research and Continued Engineering Development is a North-West University research institution with focus on energy management in industrial settings such as mines [35]. These factors may explain the prevalence of studies from the North-West University with focus on energy-saving initiatives related to South African mines.

#### *1.3.3.2 Steps 6 and 7: Data*

The most commonly implemented energy-saving initiatives found in the literature are discussed in Section 2.2. A summary of these initiatives is provided in Table 4.

### **1.3.4 Reporting the review**

#### *1.3.4.1 Step 8: Report findings*

#### **Study 1: L. N. Zietsman (2020)**

**Title:** Novel solutions for compressed air demand management on deep-level mines [4]

**Overview:** The objective of Study 1 was to minimise the power consumption of deep-level mine compressors by effectively managing underground wastage. A benchmarking model was devised to prioritise shafts based on their potential to reduce underground demand, showcasing a 57% improvement over other benchmarking models. Furthermore, an accurate savings quantification method was developed to measure the savings resulting from implementing the benchmarking model. An existing leak audit strategy for the potable water distribution industry was modified for use on the CAS of a deep-level mine, which reduced the auditing time by 65%.

Combining the benchmarking model and leak audit strategy created an integrated approach, which was subsequently applied to a deep-level mine. This integration led to an overall pressure increase of 17.7 kPa and a flow reduction of 1.24 kg/s by fixing identified leaks, amounting to a cost reduction of R2.7 million per annum in the financial year (FY) of 2019/20. This saving is equivalent to R4.9 million per annum in FY2024/25 when accounting for Eskom's tariff increases.

**Contribution:** Study 1 highlighted the importance of repairing leaks and managing unauthorised compressed air usage to realise energy savings. Emphasis was placed on the prioritisation of mineshafts based on savings potential to more effectively use the allocated resources. Mines undergoing a production stoppage may benefit from an applicable prioritisation method since resources are limited during such a period.

**Shortcoming:** Study 1 primarily focused on compressed air wastage management without considering other energy-saving initiatives.

### **Study 2: J. Taljaard (2019)**

**Title:** Practical low-cost method to sustain mine compressed air savings [6]

**Overview:** The author developed a methodology to reduce the operational cost of a mine's CAS by accurately matching the compressed air supply to the demand. Matching supply to demand reduces compressed air oversupply, leading to energy savings. The methodology focused on identifying low-cost initiatives that were easy to implement. This methodology was applied to a case study mine, resulting in a saving of R1.1 million per annum in

FY2017/18 (R2.4 million in FY2024/25). The solution included set-point control, compressor selection, and demand prediction using an energy management system (EnMS).

The EnMS notified the control room operators of the compressor running schedule based on the system's demand requirements. This reduced implementation costs by not relying on a fully automated system. Baselines were created to determine the cost savings after implementation.

**Contribution:** Study 2 demonstrated that low-cost solutions can deliver energy savings that are comparative to more resource-intensive initiatives. Additionally, adjusting compressor combinations to match supply and demand proved to be a sustainable energy-saving initiative with no investment required.

**Shortcoming:** The EnMS requires simulation for demand prediction. However, mines that do not already have a calibrated simulation may not have the time to create one during production stoppages.

### **Study 3: S. W. Van Heerden (2016)**

**Title:** A dynamic optimal control system for complex compressed air networks [9]

**Overview:** Study 3 developed a dynamic compressor control system (DCC) to dynamically select compressors and adjust compressor set points based on the current needs of the compressed air network and the proximity of compressors to the consumers.

Two case studies were conducted to test the DCC in different mines. The first case study concluded that implementing the DCC full-time could result in an energy saving of 86 MWh per day, which would be equivalent to a cost saving of R17 million per annum (R47 million in FY2024/25). The second case study involved improving an existing DCC, which resulted in a daily reduction of the mine's energy consumption by 500 kWh. If the enhanced DCC were implemented full-time, this would be equivalent to R650 000 per annum (R1.8 million in FY2024/25).

**Contribution:** Study 3 used compressor set-point adjustment in conjunction with compressor selection to optimally match compressed air supply with demand.

**Shortcoming:** The DCC needs to be integrated into the CAS control system, which enables automatic adjustment of compressor set points and issuance of start/stop commands to the compressors. Therefore, only mines with the necessary automation and remote control to facilitate the DCC stand to benefit.

#### **Study 4: P. De Villiers (2019)**

**Title:** Reducing deep-level mine refuge bay compressed air consumption [13]

**Overview:** Study 4 aimed to optimise the usage of compressed air in a mine's refuge bays to reduce operational costs. The Rapid Re business process re-engineering methodology was adapted to the mining environment and applied to a case study mine. Rapid Re-engineering is a rapid problem-solving approach intended to be used without the assistance of trained consultants.

The proposed solution involved replacing all refuge bay valves with crack valves to ensure sufficient flow during an emergency while reducing consumption during normal operating conditions. A crack valve is a modified ball valve with a hole that allows limited air to pass through while in the closed position. This enables refuge bays to remain ventilated when valves are closed during regular operational periods and become pressurised when valves are fully opened during emergencies.

The implementation of this solution required an investment of R210 000 and a span of two months to replace 49 valves, resulting in a total annual savings of R5.1 million (R10.7 million in FY2024/25).

**Contribution:** The reduction of refuge bay flow would result in savings regardless of the production state due to the constant need for a refuge bay.

**Shortcoming:** Replacing refuge bay valves requires a capital and time investment, which could be limited during a production stoppage.

### **Study 5: B. M. Friedenstein (2018)**

**Title:** Simulating operational improvements on mine compressed air systems [20]

**Overview:** Study 5 developed a simulation methodology to investigate a CAS, create and calibrate simulation models, and implement simulations to obtain results. A proposed benefit of simulation is that it can be used to quantify and prioritise operational changes with minimal risk.

Three case studies were conducted on the CASs of two mines to investigate the potential energy savings and operational improvements from various energy-saving initiatives. The energy-saving initiatives were simulated according to the methodology developed in Study 5. The initiatives investigated included compressor set-point reduction, valve control, valve set-point changes, reduction in flow to refuge bays, and closure of inactive areas. The valve set-point changes were implemented at one mine, which resulted in a compressor power reduction of 1 MW during the Eskom peak period, with an equivalent cost saving of R900 000 per annum (R2 million in FY2024/25).

**Contributions:** Friedenstein proposed that energy-saving initiatives should be prioritised based on the most benefit for the mine. Additionally, each energy-saving initiative's implementation cost and payback period may be considered.

**Shortcoming:** Simulations can accurately model and predict the outcomes of energy-saving initiatives, enabling precise prioritisation based on potential savings. However, creating simulations and thoroughly investigating each energy-saving initiative may consume valuable time during a production stoppage.

### **Study 6: D. Nell (2017)**

**Title:** Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure [25]

**Overview:** Study 6 aimed to reduce drilling time and increase production by addressing inefficiencies in a CAS, including leaks, improper installation,

pipe scaling, sharp bends, pipe restrictions, and incorrect pipe sizing. A method was developed to identify, evaluate, and address these inefficiencies. The method incorporated root cause analysis and guidelines for effective boundary selection procedures.

The method was applied to a case study mine, resulting in a pressure increase of 45 kPa after replacing 400 m of incorrectly sized pipes. This improved efficiency was estimated to lead to a production increase of approximately R11 million per annum. The monetary value of the production increase is dependent on the price of gold.

**Contribution:** Study 6 showed that leaks are not the only source of inefficiencies in a CAS. While an increase in production may not be advantageous during a production stoppage, addressing inefficiencies could effectively reduce energy consumption by minimising wastage.

**Shortcoming:** Study 6's main objective was enhancing production rather than specifically targeting reduction in energy consumption.

#### **Study 7: J. H. Marais (2021)**

**Title:** Evaluating the impact of energy management on deep-level mines during medium-term production stoppages [29]

**Overview:** Study 7 focused on the financial feasibility of a mine using an energy services company (ESCO) to manage energy during a production stoppage. The effect of an integrated energy management approach during a production stoppage was investigated by comparing seven different evaluation strategies. The study also provided general guidelines for evaluating energy-saving initiatives. According to the study, savings are typically calculated by comparing the actual energy usage with the baseline energy usage, but existing baselines are based on normal production periods.

A cost saving of R7 million (R12 million in FY2024/25) was proven during a production stoppage at a case study mine. This saving was compared to the estimated R2 million (R2.5 million in FY2024/25, adjusted for inflation) contracting fees of the ESCo. The ESCo's contracting fees were estimated

based on the project team size and the consultancy fees published by the Department of Public Service and Administration of South Africa. It was determined that it is beneficial for mines to use ESCOs during production stoppages since the savings outweigh the cost.

**Contribution:** Study 7 provides guidance for evaluating the impact of energy-saving initiatives implemented during a production stoppage. It is recommended that the correct measurement boundary be chosen. The measurement boundary has a great impact on the baseline and therefore influences the calculated savings.

**Shortcoming:** Study 7's primary objective was to evaluate the financial impact of energy management and not the implementation of energy-saving initiatives.

#### **Study 8: J. I. G. Bredenkamp, A. J. Schutte, and J. F. van Rensburg (2015)**

**Title:** Challenges faced during implementation of a compressed air energy savings project on a gold mine [30]

**Overview:** Study 8 investigated and addressed the challenges encountered during the implementation of energy-saving initiatives on a CAS. It was determined that significant savings could still be obtained despite difficulties. The study mentioned industrial action and unforeseen incidents as potential challenges.

Actuated control valves with pressure set points were utilised to reduce energy consumption during the mining off-peak periods of a case study mine, which coincided with Eskom's evening peak period. The project resulted in an average weekday power reduction of 2.6 MW during Eskom's evening peak period, with an equivalent saving of R1.5 million per annum (R4 million in FY2024/25).

**Contribution:** Study 8 provided insight into the different challenges that may influence the implementation of energy-saving initiatives. Furthermore, substantial savings were still possible despite the challenges that were faced during the implementation of energy-saving initiatives.

**Shortcoming:** Study 8 mentioned that a strike delayed the implementation of the planned energy-saving initiative. However, Study 8 did not focus on reducing energy consumption during the strike or any other production stoppage. The focus was on reducing energy consumption during the evening peak period of a typical production day.

#### **Study 9: C. J. Oosthuizen (2019)**

**Title:** A compressed air cost savings identification model for deep-level mines [36]

**Overview:** Study 9 aimed to develop a compressed air cost-saving identification model to predict the potential cost savings that could be achieved at deep-level mines. Furthermore, to determine the cost-saving potential of energy-saving initiatives in a short time with limited data.

The model was implemented in two case study mines, resulting in a significant reduction in total investigation time by 86 weeks, and a notable decrease in the number of personnel required, from eight to two. The implemented energy-saving initiatives included compressor set-point control, leak repair, valve control, closure of inactive areas, and optimisation of the compressed air distribution network, such as pipe sizing and configuration. These energy-saving initiatives reduced energy consumption by 1.7 MWh per day for Case Study 1 and 0.72 MWh per day for Case Study 2. The equivalent annual cost saving for Case Study 1 is R7.8 million (R17.5 million in FY2024/25) and R4.4 million (R9.9 million in FY2024/25) for Case Study 2.

**Contribution:** Study 9 highlighted the need for saving time and resources when investigating potential energy-saving initiatives.

**Shortcoming:** The cost-saving identification model focused solely on regular production weekdays.

### **Study 10: J. I. G. Bredenkamp (2016)**

- Title:** An integrated energy management strategy for the deep-level gold mining industry [37]
- Overview:** Study 10 developed an integrated energy management strategy for deep-level mines that aligns with the ISO 50001 energy management standard, providing a structured framework for effective energy management. The research focused on various energy consumers in a mine, including compressed air.
- Contribution:** A sequencing model was devised to determine the optimal order for implementing energy-saving initiatives based on specific criteria. This sequencing model could be adapted to accommodate production stoppages.
- Shortcoming:** The study did not focus on energy management during a production stoppage or the unique challenges faced during such a period.

### **Study 11: W. G. Shaw (2019)**

- Title:** Analysing mine energy management considering utility demand [38]
- Overview:** The first part of Study 11 focused on reducing the utility bill of a deep-level mine by adjusting the schedules of various mining shifts. The adjustment involved arranging mining schedules to minimise energy usage during high-cost peak Eskom time-of-use (TOU) periods and shifting demand to low-cost TOU periods.
- The second part of Study 11 investigated the use of specific energy as a metric to evaluate the performance of CASs. The specific energy of a compressor is defined as the rated energy consumption divided by the supplied compressed air flow at the aforementioned energy consumption. Decreasing specific energy indicates an improvement in efficiency.
- Contribution:** Study 11's case study on specific energy found that a specific compressor was unable to control efficiently during low-demand periods. The compressor was oversized and the blow-off valve was opened during low-demand periods to prevent dangerously high system pressures. This

released excess compressed air to the atmosphere, reducing the supply but not the energy consumption. The need for properly specified compressors to prevent oversupply is evident.

**Shortcoming:** The compressed air demand profile is expected to remain relatively constant during a production stoppage. Adjusting shifts, as investigated in the first part of Study 11, may not be beneficial during production stoppages.

### **Study 12: J. A. Du Preez (2020)**

**Title:** Analysing the influence of compressed air pressure on gold production [39]

**Overview:** Study 12 focused on determining whether fluctuations in compressed air pressure supplied to a gold plant affect the residue in the leaching tanks and whether a constant supply would improve gold production.

A case study was conducted at a gold plant in a mine. The mineshaft supplying the plant was limited by the plant's compressed air pressure requirements. This affected the shaft's ability to lower the compressor set points during low-demand periods. A larger standalone compressor was installed at the plant to ensure a constant flow, isolating it from the broader CAS of the mine. This resulted in a reduction of residue in the gold plant's leaching tanks and an overall electrical cost saving of R3.3 million per annum (R6.9 million in FY2024/25) for the mine.

**Contribution:** Separating two systems with differing demand schedules proved to be beneficial for both parties. Dedicated compressors were found as a viable solution in such a case.

**Shortcoming:** Study 12's main objective was to improve the performance of a gold plant. Although energy savings were obtained, it was not the primary goal of the study.

### **Study 13: J. Kunneke (2022)**

**Title:** Applying a benchmark method to identify utility cost-saving opportunities on a platinum mine [40]

**Overview:** Study 13 employed a benchmarking method to identify areas of potential savings in various utilities, including compressed air. This method utilised multiple correlation factors to establish a benchmark for each utility.

The benchmarking method was applied during a case study at a mine. It was observed that compressed air consumption correlated most with production tonnes. The least efficient shaft, concerning compressed air consumption, was identified. The valve set points were reduced from 550 kPa to 520 kPa during low-demand periods. A further reduction in set points, to 400 kPa, was proposed. The reduction in demand would allow a 4.5 MW compressor to be stopped, with the potential for an annual cost saving of R2.5 million (R4.7 million in FY2024/25). However, this required the replacement of pneumatic loaders with electro-hydraulic loaders.

**Contribution:** Study 13 showed that significant energy savings are achievable by replacing pneumatic equipment with more efficient alternatives.

**Shortcoming:** The benchmark for compressed air primarily relies on production data to identify inefficient systems. However, this correlation cannot be utilised during a production stoppage due to the absence of production during this period.

### **Study 14: J. Jonker (2016)**

**Title:** Automated mine compressed air control for sustainable savings [41]

**Overview:** Study 14 developed an improved and more stable version of an existing dynamic compressor selector (DCS), which considers autocompression, flow loss, and pressure drops. The DCS accurately matched the demand of the CAS and reduced oversupply. Using a DCS was proven to be more efficient than manually selecting compressor combinations and adjusting set points.

The DCS was implemented in a case study mine, optimising compressor power usage during the day and resulting in a power reduction of 3.3 MW during the evening peak period.

**Contributions:** Manually operated compressed air networks are typically maintained at higher pressures than required, according to Study 14. Automatic control proved to be more efficient. Therefore, energy savings were achieved by changing the control strategy of a CAS to be more automated.

**Shortcoming:** The DCS is dependent on infrastructure and the ability to interface with multiple control systems at once. Mines that do not have this system would need to invest capital and time to implement it, which may not be feasible during a production stoppage.

#### **Study 15: A. J. M. Van Tonder (2014)**

**Title:** Automation of compressor networks through a dynamic control system [42]

**Overview:** Study 15 developed a DCS to automatically manage a CAS based on real-time data from instrumentation to prevent missed savings due to static inputs and delays.

Two case studies were conducted in different mines to evaluate the impact of the DCS on the CAS of the mines. An average energy saving of 5%, equivalent to R11 million per annum (R31 million in FY2024/25), was realised after the successful implementation of the DCS.

**Contributions:** Automatic control of compressors led to increased stopping and starting. This, in turn, increased the maintenance that compressor motors require. However, the savings realised through automatic control far outweighed the increase in maintenance costs.

**Shortcoming:** The complete DCS could not be utilised in all of the intended mines during the case study due to time and hardware limitations. Mines without an existing DCS are unlikely to acquire the necessary infrastructure in time to realise the benefits during a production stoppage.

### **Study 16: C. Cilliers (2016)**

- Title:** Benchmarking electricity use of deep-level mines [43]
- Overview:** Study 16 developed models to benchmark the electricity usage of deep-level mines, aiming to highlight inefficiencies across various utilities, including compressed air. The benchmark considered real data from multiple South African mines to formulate precise models. Additionally, the study incorporated a novel technique to determine the priorities of energy-saving initiatives for high-demand systems.
- Contribution:** Study 16 used the benchmark score to determine the priority of energy-saving initiatives by identifying inefficient systems. The goal of the prioritisation was to assist mines with decision-making when it came to implementing energy-saving initiatives. Using a similar approach to assist mines in making decisions during production stoppages may prove to be advantageous.
- Shortcoming:** The benchmarking model for compressed air is dependent on tonnes of ore produced, which is not a viable variable during a production stoppage since no ore is produced.

### **Study 17: J. Vermeulen, C. Cilliers, and J. H. Marais (2017)**

- Title:** Cost-effective compressor control to reduce oversupply of compressed air [44]
- Overview:** Study 17 aimed to identify and implement a cost-effective approach by using existing throttle control strategies and infrastructure. The existing guide vane control for a case study compressor was inefficient. A square open/close butterfly valve was converted to act as a variable throttle control by installing an actuator and positioner. This approach resulted in a reduction in implementation costs. The utilisation of variable throttle control achieved a flow reduction, which realised energy savings of 650 kWh per weekday, equivalent to R3.4 million per annum (R7.6 million in FY2024/25).

**Contribution:** Study 17 demonstrated that savings can still be achieved if capital is limited. Creative use of existing infrastructure can reduce implementation costs.

**Shortcoming:** Study 17 did not consider production stoppages or the challenges related to such periods.

**Study 18: S. W. Van Heerden, R. Pelzer, and J. H. Marais (2014)**

**Title:** Developing a dynamic control system for mine compressed air networks [45]

**Overview:** The study developed a DCS that worked in conjunction with a standard compressor controller to automatically select the optimal compressor combination and adjust compressor set points based on network demand. The purpose of the DCS was to reduce energy consumption, minimise compressor cycling, and stabilise the compressed air delivery to the network. The DCS was implemented at a case study mine and achieved a power reduction of 1.8 MW during the test period. This could result in an equivalent cost saving of R3.7 million per annum (R11 million in FY2024/25) if implemented permanently.

**Contribution:** When calculating optimal compressor set points, testing showed that the results were influenced by set points on the demand side. If set points on the end user's side are selected incorrectly, it may result in a higher compressor set point than required.

**Shortcoming:** The DCS experienced stability issues during its implementation in the case study and was operational for only one day. This occurred because the DCS relies on data from multiple sensors and yields inaccurate calculations when a sensor fails or provides a false reading.

**Study 19: R. Maneschijn (2017)**

**Title:** Developing a dynamic operational energy management strategy for energy intensive industries [46]

**Overview:** The author developed a system-based approach for energy management in a complex industrial facility. This approach encompassed multiple

electricity consumers, including compressed air. Additionally, a methodology for implementing energy measurement was devised to ensure accurate measurement of important energy streams. A method to manage measurement quality was also created to guarantee the accuracy of measurements. Furthermore, a methodology for providing feedback on operational energy management was developed to incorporate all relevant stakeholders.

The methodology was implemented during a case study at a gold mining group. The implementation resulted in a total cost saving of R42 million (R94 million in FY2024/25) in specific, isolated cases within one year. Moreover, the improved operational control achieved an annual cost saving of R25 million (R56 million in FY2024/25) on the group's total bill.

**Contribution:** Study 19 emphasises the need for accurate and reliable energy measurement when determining the energy performance of a system.

**Shortcoming:** The comprehensive methodology did not specify the initiatives to be implemented to achieve energy savings but instead offered guidance on how to implement energy management in a mine.

#### **Study 20: D. L. Du Plooy (2019)**

**Title:** Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines [47]

**Overview:** Study 20 developed a localised benchmarking methodology to identify and manage factors contributing to inefficiencies in the CAS. The developed methodology was applied to a mine as part of a case study, revealing 80% of operational improvement opportunities compared to manual audits of the entire underground network, and it took only 20% of the time. This implementation resulted in an electricity cost saving of R7.4 million per annum (R15.5 million in FY2024/25) and a 19% increase in production. Some of the energy-saving initiatives implemented included isolating inactive sections and valve control. While leak repair was recommended, it was not implemented due to ventilation concerns.

**Contribution:** Study 20 found that compressed air supplied to inactive sections, where no mining took place, was a major contributor to wastage. A significant reduction in compressed air demand was achieved when inactive sections were isolated.

**Shortcoming:** Benchmarking relies on production data to determine which levels consume more compressed air than is typically required. It would not be effective for identifying inefficient sections during a production stoppage due to the lack of production.

**Study 21: P. Maré, J. I. G. Bredenkamp, and J. H. Marais (2017)**

**Title:** Evaluating compressed air operational improvements on a deep-level mine through simulations [48]

**Overview:** The authors developed an easy-to-use simulation method for evaluating the operational improvements of CASs. In-depth studies of operational improvements were found to be economically unfeasible; therefore, a simulation-based approach was presented. The method can be used to evaluate solutions that improve production and/or energy saving.

Simulation results of a case study indicated a potential improvement of 51 kPa during peak drilling shifts and an electricity cost saving of up to R1.5 million per annum (R3.4 million in FY2024/25) if implemented. The simulation was used to determine which operational improvements were feasible and credible. The proposed solution included changing the compressed air network by interconnecting two shafts and switching to a more efficient compressor combination.

**Contribution:** Study 21 evaluated the feasibility of energy-saving initiatives and removed unfeasible initiatives from the list of proposed solutions before investigating further. It stated that the infrastructure costs, effect on service delivery, impact on electricity cost, implementation time, and any advantages or disadvantages must be considered as part of the evaluation.

**Shortcoming:** The simulation method requires the construction and calibration of a compressed air network simulation before the feasibility and performance

of energy-saving initiatives can be evaluated. Study 21 mentioned a total of 104 hours spent on evaluation in the case study. Mines without pre-existing or calibrated simulations may not have the required labour and time for constructing a simulation during a production stoppage.

#### **Study 22: F. J. L. Mathee (2021)**

**Title:** Evaluating the feasibility of integrating mine compressed air systems for energy savings [49]

**Overview:** Study 22 evaluated the feasibility of integrating CASs to form a larger interconnected system. The purpose was to reduce compressed air wastage by enabling large or over-specified compressors to redirect excess compressed air to additional consumers instead of releasing it through blow-off valves. This approach has the potential to decrease the total number of required compressors due to the efficient utilisation of excess compressed air, resulting in compressor energy savings.

Two shafts were interconnected, and other energy-saving initiatives were implemented as part of a case study. This implementation resulted in a daily average power reduction of 1.45 MW and a cost saving of R11 million per annum (R18.6 million in FY 2024/25). The additional energy-saving initiatives, including isolating inactive sections and valve control, were achieved by using an actuator that operated based on pressure set points and a predefined schedule.

**Contribution:** Study 22 demonstrated that energy savings may be achieved by interconnecting compressed air networks. This allows a network with excess compressed air to share with other networks that can utilise the supply instead of releasing excess through a blow-off valve.

**Shortcoming:** Seven people were required to make the necessary adjustments to the case study network, which may be a limiting factor during a production stoppage. Mines that do not have pre-existing pipelines connecting multiple shafts would require a significant amount of time and capital investment to implement this solution, which may not be feasible during a production stoppage.

### **Study 23: L. Zhong, Y. Liu, J. Zhao, and W. Wang (2023)**

**Title:** Hierarchical reinforcement learning based operational optimization for compressed air system [50]

**Overview:** Study 23 used artificial intelligence and hierarchical reinforcement learning to optimise and control a complex CAS to reduce energy consumption. The control method included two parts: an adaptive parameter controller and a coordinated optimisation control system with a built-in feedback correction strategy to mitigate the negative effects of errors. Energy savings were achieved by effectively matching the compressed air supply with the demand by adjusting the compressor motor speed.

The control method was tested in an industrial park. Comparative experiments showed that hierarchical reinforcement learning achieved the best trade-off between model complexity and time consumption when compared to other scheduling strategies.

**Contribution:** Study 23 demonstrated that accurately adjusting the compressor motor speed through variable speed control improves efficiency and realises energy savings.

**Shortcoming:** The control method relies on sufficient data to train the artificial intelligence, which may be limited or incorrect due to potential operational differences between a typical production period and a production stoppage.

### **Study 24: A. Trianni, D. Accordini, and E. Cagno (2020)**

**Title:** Identification and categorization of factors affecting the adoption of energy efficiency measures within compressed air systems [51]

**Overview:** Study 24 aimed to support companies in the decision-making process when selecting compressed air energy-saving initiatives. This is done by developing a framework that takes the most relevant factors related to the implementation of compressed air energy-saving initiatives into account. These factors include the impact on production, operations, and energy. Additionally, the cost, complexity, compatibility, and observability of these

initiatives are considered. The framework was designed with decision-makers in mind and was validated theoretically and empirically.

**Contribution:** Study 24's decision-making framework provided multiple criteria that could be considered when selecting energy-saving initiatives. This could be adapted for use during a production stoppage.

**Shortcoming:** The decision-making framework for implementing energy-saving initiatives is limited to the industrial sector, which does not include mining.

### **Study 25: S. J. Fouché (2017)**

**Title:** Improving efficiency of a mine compressed air system [52]

**Overview:** The purpose of Study 25 was to improve the energy efficiency of a mine's CAS to reduce the annual operating cost. An efficient approach to leak auditing was developed in this study, and additional energy-saving initiatives were investigated, including replacing compressors, selecting the appropriate compressor, and replacing the inlet air filters of a compressor. A control philosophy was developed to maximise energy savings when offloading a compressor.

The initiatives that provided the largest improvement in energy efficiency at a case study mine were leak repair, pressure set-point adjustment, and valve control. A total power reduction of 1.35 MW was achieved by implementing the aforementioned initiatives, which is equivalent to an annual cost saving of R8 million (R18 million in FY 2024/25).

**Contribution:** Study 25 suggested that replacing old compressors and inlet air filters may improve the efficiency of a CAS.

**Shortcoming:** The study focused on improving efficiency during a typical production period and was constrained by the demand of the drilling shift.

### **Study 26: D. L. Du Plooy *et al.* (2019)**

**Title:** Local benchmarking in mines to locate inefficient compressed air usage [53]

**Overview:** A practical method to identify localised compressed air inefficiencies with limited time and resource investment was developed in Study 26. Local benchmarking based on compressed air consumption and production data was used to pinpoint areas of inefficiency in an underground compressed air network by comparing different sections of a mine.

The method was implemented in a platinum mine. It was determined that 80% of the total compressed air wastage occurred within the top three prioritised mining sections.

**Contribution:** Study 26 stated that local efficiency improvements that improve the total system efficiency should be prioritised. Investigating areas with low efficiency but also a low compressed air consumption would not be beneficial compared with higher demand areas since the potential improvement on the overall system would be less.

**Shortcoming:** The benchmarking method relied on production data to determine areas of inefficiency. It would not be possible to use during a production stoppage due to the absence of production.

### **Study 27: A. J. A. Visagie (2021)**

**Title:** Modelling the effect of changes in mining compressed air networks on refuge chambers [54]

**Overview:** Study 27 investigated the effect that changes to existing CASs have on the compressed air supplied to refuge bays. The primary concern was the health and safety of miners when the need for evacuation to a refuge bay arose. Before implementing changes to the system, a simulation-based method was developed to simulate complex CASs, including all refuge bays, to ensure that each refuge bay met the minimum safety requirements.

**Contribution:** Study 27 provides the minimum requirements for refuge bays in detail. Before any changes are implemented, it was noted in the study that any changes made to a CAS must be checked to ensure that the requirements of refuge bays are met.

**Shortcoming:** Study 27 was limited to refuge bays and did not focus on energy savings for the rest of the compressed air network.

**Study 28: C. J. R. Kriel, J. H. Marais, and M. Kleingeld (2014)**

**Title:** Modernising underground compressed air DSM projects to reduce operating costs [55]

**Overview:** Study 28 developed a solution to reduce the energy consumption and operating costs of a mine's CAS by improving and updating existing demand-side management (DSM) projects. The solution was implemented in a case study mine, which resulted in a total saving of 1.2 MW during working days, equivalent to R4.2 million per annum (R12.6 million in FY2024/25).

The existing DSM project involved automatic valve control through actuated valves on the main supply to the shaft and on each level to regulate the compressed air supply. Improvements to the existing project included using globe valves instead of butterfly valves to control the supply with greater accuracy and reduce maintenance costs. Pressure set points were updated and reduced during low-demand periods, thereby reducing the energy consumption of the CAS. The study concluded that existing DSM saving strategies need continuous maintenance and updates to ensure optimal energy savings are achieved.

**Contribution:** One of the problems that Study 28 found during the case study was that the set points of the actuated control valves were out of date. The solution involved enabling remote set-point adjustment from surface. This allowed the mine to keep the set points up to date whenever changes were made to the CAS. Study 28 showed that regular evaluation of pressure set points on the demand side is required.

**Shortcoming:** Study 28 focused on a typical production period, and valve control was limited to low-demand periods to avoid affecting production.

**Study 29: F. Bonfá et al. (2019)**

**Title:** New efficiency opportunities arising from intelligent real time control tools applications: The case of compressed air systems' energy efficiency in production and use [56]

**Overview:** Study 29 developed a methodology to reduce energy consumption in industrial plants through monitoring and control. Statistical regression was used to establish an energy consumption baseline for the system based on historical data. The actual consumption data was compared regularly with the baseline to identify any changes in the system or degradation in its performance.

The solution was applied to a pharmaceutical manufacturing plant, and an inefficient activation sequence of compressors was identified and improved, resulting in a 10% reduction in energy consumption.

**Contribution:** Monitoring a system's energy consumption and comparing its actual performance to an established baseline has the potential for energy savings. This is done by identifying areas of inefficiency.

**Shortcoming:** The developed solution requires the end user to determine what needs to be done to improve the performance of the system.

**Study 30: J. Vermeulen (2018)**

**Title:** Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems [57]

**Overview:** The primary goal of Study 30 was to develop a single-variable benchmarking model to simplify the benchmarking of a mine's CAS. The model ranked CASs based on energy usage data. Additionally, the study aimed to simplify the quantification of potential savings from energy-saving initiatives. An integrated investigation methodology was created by

combining the developed benchmarking model with a savings quantification tool.

The methodology was applied to two case study mines and delivered accurate results within a brief period. The energy-saving initiatives implemented included stopping a compressor during the low-demand period, repairing leaks, ensuring optimal compressor selection, and controlling valves. These energy-saving initiatives resulted in a combined power reduction of 6.2 MW.

**Contribution:** The investigation methodology emphasised the development of tools that could be applied with limited data, time and resources. This approach to solution development could also be applied to production stoppages due to the limitations of such an event.

**Shortcoming:** The benchmarking model utilised energy consumption data from the blasting and drilling shifts in a mine to evaluate a CAS. However, this approach would not be viable during a production stoppage, as there are no drilling shifts during this period.

#### **Study 31: J. Galvão *et al.* (2013)**

**Title:** Sustainable energy for plastic industry plant [58]

**Overview:** The purpose of Study 31 was to reduce the energy consumption of a company in the industrial sector. An energy model that focused on self-renewable energy production and energy management for lighting and CASs was developed.

A case study was conducted on a plastic film industrial unit. Various energy-saving initiatives were suggested. It was determined that repairing leaks and employing variable speed drives (VSDs) on compressors were the most viable solutions for the CAS, with a combined potential energy saving of 19.8%.

**Contribution:** The energy-saving initiatives identified during the case study were evaluated based on applicability and expected annual savings. Each criterion received a percentage score and the product of these scores

provided a contribution potential. Recommendations were made based on the calculated contribution potential. The financial return, advantages, limitations and design of initiatives were also taken into consideration.

**Shortcoming:** The energy management of the CAS was limited due to production requirements. Energy-saving initiatives were not permitted to interfere with production output, which would not be a limitation during a production stoppage.

**Study 32: M. H. P. Van Niekerk, S. W. van Heerden, and J. F. van Rensburg (2015)**

**Title:** The implementation of a dynamic air compressor selector system in mines [59]

**Overview:** The purpose of Study 32 was to determine whether a DCS could be implemented successfully in a mine's CAS. A case study was conducted on a platinum mine where the DCS was implemented. It accurately matched the compressed air supply to the demand, reducing compressed air usage. The DCS additionally improved compressor scheduling and control, resulting in a power reduction of 3.5 MW during the Eskom evening peak period. This is equivalent to an annual cost saving of R940 000 (R2.6 million in FY2024/25). The CAS of the case study mine required upgrades such as the installation of isolation valves and automatic control valves to enable control of the compressed air supply.

**Contribution:** During the case study, actuated valves were installed on the main supply line on surface, which supplies compressed air to the shaft. The valves were controlled based on pressure set points according to a schedule. During low-demand periods, the compressed air supply was reduced, contributing to energy savings.

**Shortcoming:** The DCS system is dependent on infrastructure that enables automatic control of compressors and the compressed air supply. Mines lacking the necessary infrastructure would be unable to implement the solution during a production stoppage due to the capital and time investment required. The DCS can only realise its full potential if it is granted complete control over the scheduling of compressors and control valves. This will enable the DCS to cycle compressors and adjust set points based on the demand of the end user.

**Study 33: W. G. Shaw, M. J. Mathews, and J. H. Marais (2019)**

**Title:** Using specific energy as a metric to characterise compressor system performance [60]

**Overview:** Study 33 used specific energy to determine the performance of compressors and CASs based on energy consumption and compressed air flow. The specific energy was compared with a baseline that showed when a system decreased in efficiency over time or to gauge the effect of energy-saving initiatives and operational improvements.

A case study was conducted on the CAS of a platinum mine where specific energy was used to characterise and prioritise each compressor. This was done based on the difference between the ideal baseline specific energy and actual specific energy. The compressor set points were reduced, along with improved scheduling and control. These measures reduced the oversupply of compressed air, resulting in a total improvement of 6% in the average total specific energy.

**Contribution:** A scoring method was used to prioritise compressors based on multiple criteria. The priority indicated which compressor required intervention to improve performance. A similar scoring philosophy could be used to prioritise energy-saving initiatives based on relevant criteria.

**Shortcoming:** The specific energy baseline was based on a typical production period. A new baseline would be required for production stoppage periods if data is available.

### 1.3.5 State-of-the-art summary

A wide variety of compressed air energy-saving initiatives were found in the literature. A study filtered unfeasible initiatives before further investigation [48], while other studies provided methods of prioritising energy-saving initiatives [20, 37, 43]. In the context of this study, filter refers to removing unfeasible energy saving initiatives from the list of initiatives being considered for implementation.

Du Toit [61] states that facilities with limited time and human resources must prioritise feasible projects. Prioritisation of energy-saving initiatives may assist mines during production stoppages since there is limited time to prepare, as mentioned in Section 1.2.3. However, most studies focused on a typical production period and did not consider production stoppages. This indicates a gap in the literature.

The literature review is summarised in Table 3 as a state-of-the-art matrix that highlights the identified gap in the literature. The criteria for the state-of-the-art matrix were chosen based on the four core keywords used during the literature search. Prioritisation of energy-saving initiatives was identified as a potential method to assist mines during a production stoppage and was added to the list of criteria.

#### The criteria for the solution to the problem included:

1. Compressed air
2. Energy saving
3. Production stoppage
4. Prioritisation of saving initiatives
5. Mining

**Table 3: State-of-the-art matrix**

Study number	Reference	Compressed air	Energy saving	Production stoppage	Prioritising saving initiatives	Mining
1	[4]					
2	[6]					
3	[9]					
4	[13]					
5	[20]					
6	[25]					
7	[29]					
8	[30]					

Study number	Reference	Compressed air	Energy saving	Production stoppage	Prioritising saving initiatives	Mining
9	[36]					
10	[37]					
11	[38]					
12	[39]					
13	[40]					
14	[41]					
15	[42]					
16	[43]					
17	[44]					
18	[45]					
19	[46]					
20	[47]					
21	[48]					
22	[49]					
23	[50]					
24	[51]					
25	[52]					
26	[53]					
27	[54]					
28	[55]					
29	[56]					
30	[57]					
31	[58]					
32	[59]					
33	[60]					

Legend	
	Included in the reference
	Not included in the reference
	Gaps in the literature

## 1.4 Purpose of the study

### 1.4.1 Need for the study

Based on Table 3, there is a need for a strategy to prioritise and filter energy-saving initiatives during a production stoppage to assist with lowering the compressed air demand and reducing electricity costs.

### 1.4.2 Aim of the study

The study aims to develop a generic energy-saving strategy to identify energy-saving initiatives that could be implemented on a mine's compressed air network in the case of a production stoppage. This strategy needs to assist the end user with deciding which energy-saving initiatives are feasible and then determine the priority of each initiative in order to realise compressed air savings.

### 1.4.3 Objectives

To achieve the aim, the envisioned strategy must meet the following objectives:

**Objective 1:** Compile a generalised list of at least 15 possible compressed air energy-saving initiatives based on the literature. This will form the basis for the prioritisation method to work from.

**Objective 2:** Adapt an existing method that can filter and prioritise the generalised list of compressed air energy-saving initiatives based on specific criteria. This method will form part of the developed strategy. The method will be validated based on the accuracy of the method when compared to a case study.

**Objective 3:** Develop an energy-saving strategy to reduce compressed air energy usage during a production stoppage at a mine. Thereafter, validation will be done by applying the developed strategy to a case study production stoppage and comparing the savings with previous studies. Verification will be done by evaluating whether the strategy was correctly applied during the case study.

## 1.5 Research methodology

All the studies included in the literature review used a case study approach when testing developed solutions [36]–[60] to gain an in-depth understanding of an issue or phenomenon in a bounded system [62]. This study will also be approached via a case study methodology.

The developed strategy will be applied to two case study production stoppages at a mine. The first case study will be applied retrospectively to test the accuracy and benefit of the prioritisation method compared with industry knowledge and experience. The results will be compared to the actual events that occurred during that period as part of the review process. A second case study will test the performance of the developed strategy when fully implemented during a production stoppage. Figure 8 summarises the steps of the research methodology.

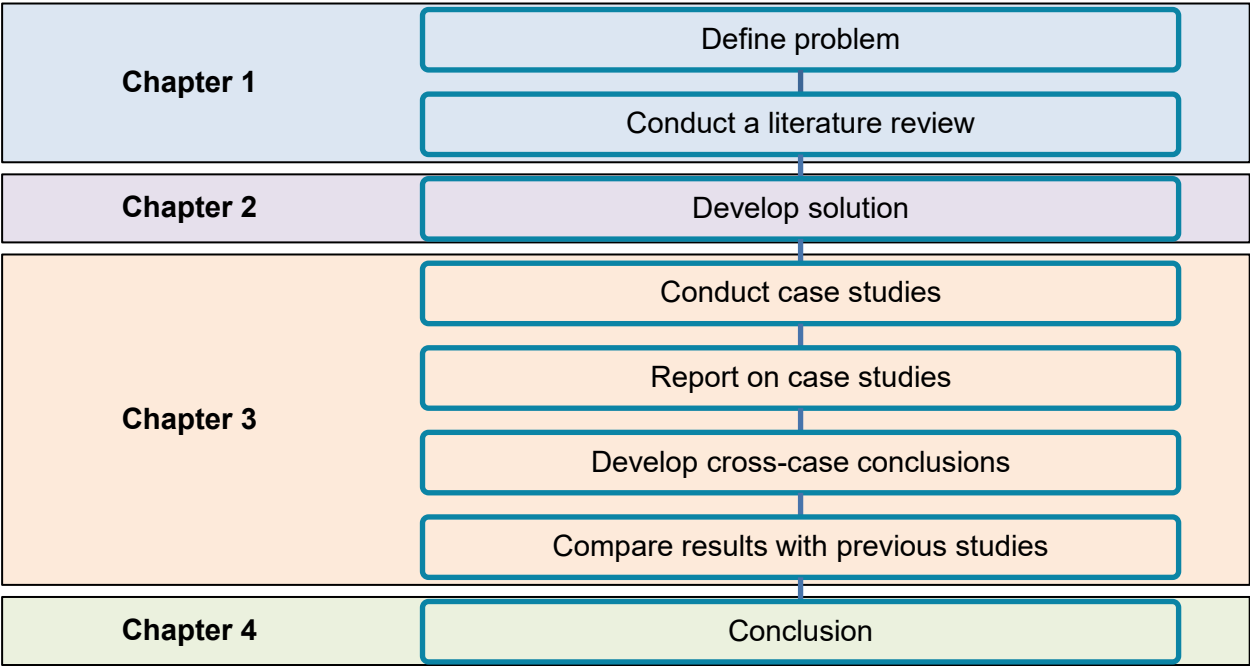


Figure 8: Case study methodology (adapted from [14, 63])

**1.6 Dissertation overview**

**Chapter 1**

A brief background of the increasing cost of electricity and compressed air inefficiency is given. The usage of compressed air in the context of mining is explored along with challenges faced during production stoppages. A literature review is conducted to gather possible methods for reducing the electricity cost at a mine during production stoppages. Thereafter, the purpose of this study and research methodology are explained.

**Chapter 2**

A strategy to prioritise energy-saving initiatives during production stoppages is developed with the focus on CASs at mines. An existing prioritisation method is adapted and combined with a list of compressed air energy-saving initiatives from the literature to form the initial step of the strategy. Each step of the strategy is discussed along with data collection and verification.

### **Chapter 3**

The strategy developed in Chapter 2 is applied to a case study mine that experienced two separate production stoppages. The first case study is used to test the accuracy and benefit of the prioritisation method. Thereafter, the second case study tests the effectiveness of the developed strategy when fully implemented. Finally, the developed strategy is reviewed and the shortcomings are discussed.

### **Chapter 4**

A summary of this study is provided and the chapter concludes with recommendations for further study.

## CHAPTER 2: DEVELOPMENT OF A NEW STRATEGY



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<sup>9</sup> C.A. Monteiro, "Centrifugal compressor at a gold mine," [Photograph], South Africa, 2023.

## **2.1 Preamble**

This chapter discusses the development of a solution as part of the research methodology summarised in Figure 8. The developed solution is in the form of a strategy to reduce the electricity cost of a mine's CAS during a production stoppage. The strategy aims to assist the end user during the decision-making process by identifying feasible energy-saving initiatives and determining the priority of each initiative.

## **2.2 Compressed air energy-saving initiatives**

Before prioritising or filtering energy-saving initiatives, it is necessary to know what initiatives exist. The literature review conducted in Section 1.3 provided insight into the various compressed air energy-saving initiatives that were found in the literature. These energy-saving initiatives will be divided into four groups based on the area of focus, namely: compressor control, valve control, wastage reduction and system changes.

### **2.2.1 Compressor control**

Compressor control involves various initiatives that reduce compressor energy consumption by adjusting how existing compressors operate.

#### **Compressor selection**

The optimal compressor combination is chosen to efficiently match the compressed air supply with the demand [37]. This involves running the minimum number of compressors necessary [6]. Compressor selection can be done manually or automatically through a DCS [36].

#### **Guide vane control**

The inlet guide vanes of a compressor adjust the angle of the air entering the compressor to regulate the compressed air flow [41]. Reducing the flow rate also reduces strain on the compressor motor, which lowers energy consumption [47, 64]. By automatically controlling the inlet guide vanes, the compressor is able to adjust to changes in demand while still maintaining compressor efficiency [6, 37]. This is achieved through a controller that adjusts the inlet guide vanes according to the compressor's pressure set point [15, 41].

## **Load sharing**

Compressed air networks typically have various compressors that differ in size and efficiency [47]. These networks can achieve energy savings by sharing the load of the compressed air demand between the most efficient compressors [47].

## **Load-unload**

Unloaded compressors operate under no load, and guide vanes are set to the minimum position [52]. The blow-off valve is opened, and the compressor is isolated from the network by closing the delivery valve [6]. The unloaded compressor only consumes energy to overcome basic friction [6]. Unloading a compressor provides 40–80% less energy savings than stopping the machine [37].

## **Pressure set-point reduction**

Inlet guide vanes are controlled by the set points of a compressor [41]. Reducing the pressure in the compressed air network reduces energy consumption since the compressor requires less work [20]. Van Heerden [9] used pressure set-point reduction in conjunction with compressor selection to optimally match compressed air supply with demand.

## **Regular maintenance**

Regular maintenance involves replacing air inlet filters, cleaning and lubricating motors and compressors, as well as inspecting auxiliaries and moisture traps [6, 37]. Generally, the power consumption of a compressor increases by 2% for every 2.45 kPa increase in pressure drop at the compressor inlet [65]. Pressure drops can be caused by blocked filters [65].

## **Stop-start**

The stopping and starting of compressors is considered as one of the most basic control strategies [6]. Energy savings are obtained by stopping unnecessary compressors during low-demand periods and only restarting compressors when the compressed air demand increases [42]. Some mines do not allow frequent stopping and starting of compressors [57]. Van Tonder [42] noted that an increase in the frequency of stopping and starting compressors resulted in an increase in the maintenance that compressor motors require. However, the savings outweighed the increase in maintenance costs [42].

## **Variable speed drives**

A VSD regulates the motor speed of a compressor, which allows the compressed air supply to be matched with the demand [37]. However, VSDs are considered expensive and are mostly not considered as a viable option for energy-savings initiatives [6, 37].

### **2.2.2 Control valves**

The control valve category includes energy-saving initiatives that aim to regulate the compressed air supply and demand through control valves.

#### **Surface and underground valve control**

Compressed air demand can be regulated with control valves by adjusting the valve openings [47]. These valves can be situated on surface or underground [47]. Underground valve control is implemented on the demand side to reduce compressed air usage, while surface valve control is used to reduce the system pressure and compressor output [37].

#### **Set-point control**

Valves can be controlled automatically using an actuator [52]. The control valve regulates the downstream pressure by following a predetermined pressure set-point schedule [41]. An actuator is used to adjust the valve position to match the pressure set point [52]. Kriel *et al.* [55] state that the pressure set points on the demand side have to be evaluated regularly. Pressure set points are determined by the pressure requirements of the compressed air consumers [41].

#### **Peak-clipping**

Peak-clipping is similar to set-point control but focuses on peak demand periods only. The pressure set points of compressed air control valves are reduced during Eskom's peak demand periods [36]. Refer to Annexure E for more information on demand periods.

#### **Stope isolation**

Stope isolation involves closing the manual isolation valves located near the stopes [55]. Isolation is done after the drilling shift to mitigate compressed air wastage [55, 66]. Automatic isolation valves can be used to remove reliance on personnel, which improves sustainability and energy savings [66].

### **2.2.3 Wastage reduction**

Wastage reduction includes energy-saving initiatives that target compressed air wastage and the reduction thereof.

#### **Close inactive sections**

This energy-saving initiative involves closing the valves that supply inactive sections to reduce compressed air wastage [36]. A section of an underground level is considered inactive if there is no production, development, or any other active operation that requires compressed air [53]. This is distinct from valve control since these valves typically remain closed.

#### **Eliminate or reduce unauthorised use**

Unauthorised use of compressed air includes activities such as cooling bearings, cooling rock faces where mining takes place, and using open-ended hoses for additional ventilation [67]. Additionally, compressed air may also be used for personal cooling [51]. Unauthorised use can be reduced by restricting the compressed air supply to match the requirements of production activities, thereby reducing the availability of compressed air for other purposes [67].

#### **Repair leaks**

Leaks contribute significantly to compressed air wastage. Up to 50% of compressed air consumption is attributed to leaks in poorly maintained systems [47, 68]. Leakage can be reduced by repairing damaged compressed air piping, tightening connections, or replacing faulty equipment [36, 69]. Repairing leaks is considered one of the most impactful methods of improving energy efficiency [70, 71]. However, Zietsman [4] states that repairing all compressed air leaks is not feasible, but maintaining a leakage rate of 10% to 15% is acceptable.

### **2.2.4 System changes**

System changes refer to any energy-saving initiatives that achieve savings by adjusting the existing structure of a CAS.

#### **Adjust mining shifts**

The initiative entails adjusting mining shifts so that the mine's low-demand periods align with Eskom's higher cost, peak demand periods to save on electricity costs [38]. Adjusting shifts does not deliver energy savings on its own.

### **Use dedicated compressors**

Consumers such as processing plants require high compressed air pressure and low flow [72]. If a processing plant is connected to a compressed air network, the entire network must operate at a higher pressure [72]. By separating these consumers and installing dedicated compressors, the network can operate at a lower pressure, leading to energy savings [72].

### **Eliminate/reduce pneumatic equipment**

Alternative solutions to pneumatic equipment such as electric or hydropowered equipment could remove an operation's dependence on compressed air [37]. Kunneke [40] found that pressure set points could be reduced if pneumatic loaders were replaced with electro-hydraulic loaders, which would lead to a reduction in compressed air consumption.

### **Integrate smaller CASs**

Integrating networks consists of connecting two or more compressed air networks with a pipeline [49]. This allows consumers to be supplied from any connected compressor house [49]. In cases where compressors oversupply a network, integration may allow an oversized compressor to be switched with a smaller one in the network [49].

### **Use optimally sized compressors**

Oversizing of compressors is one of the major issues on the supply side of a CAS [51]. Over-specified compressors can oversupply compressed air networks, which leads to the discharging of excess air into the atmosphere [49]. It is important to use compressors that can efficiently supply the demand of the system at any time [51].

### **Reconfigure pipes**

Pressure losses occur in pipe sections due to pipe friction [47]. Multiple factors such as bends, blockages, corrosion, or varying diameters contribute to these losses [47]. Pressure losses due to an inefficient piping network can only be rectified through reconfiguration [47]. If pressure losses are too great, more work is required by the compressors to meet the requirements of the consumers.

### **Reduce compressor inlet temperatures**

Higher air inlet temperatures result in lower volumetric efficiency and higher power consumption [65]. Generally, the compressor energy consumption increases by 1% for every 4°C

increase in air inlet temperature for an equivalent output [65]. Therefore, it is beneficial to reduce a compressor's air inlet temperature by relocating the air intake to the coolest location or by cooling the air with a heat exchanger [51].

### Reduce refuge bay flow

Refuge bays require a constant supply of compressed air as discussed in Section 1.2.2.1. Friedenstein [20] found that an average power reduction of 1 MW and a pressure improvement of 15 kPa could be achieved if the refuge bay demand was reduced. De Villiers [13] realised a power reduction of 960 kW after replacing the valves of 42 refuge bays with crack valves.

### 2.2.5 Summary

Table 4 summarises the energy-saving initiatives for mine CASs found in the literature. The table serves as a generalised list for all mines using compressed air. Additionally, Table 4 will serve as a prioritisation method to work from in Section 2.3, accomplishing **Objective 1** listed in Section 1.4.3.

**Table 4: Summary of compressed air energy-saving initiatives**

Strategy	Initiatives	Reference
Compressor control	Compressor selection	[6, 9, 36, 37, 41, 42, 45, 47, 48, 52, 57, 59, 60]
	Guide vane control	[6, 37, 41, 44, 47]
	Load sharing	[30, 47, 51]
	Load-unload	[6, 37, 52]
	Pressure set-point reduction	[9, 20, 36, 41, 45, 51, 59, 60]
	Regular maintenance	[37, 51, 52, 58]
	Stop-start	[6, 37, 42, 57]
	VSD	[6, 37, 50, 58]

Strategy	Initiatives	Reference
Control valves	Peak-clipping	[20, 30, 36, 55]
	Set-point control	[6, 20, 30, 40, 52, 55]
	Stope isolation	[36]
	Surface valve control	[36, 37, 47, 55]
	Underground valve control	[20, 30, 37, 47, 55]
Wastage reduction	Close inactive sections	[20, 36, 47, 51, 53]
	Eliminate/reduce unauthorised use	[20, 51, 67]
	Repair leaks	[4, 25, 36, 47, 51, 52, 57, 58]
System changes	Adjust mining shifts	[38]
	Use dedicated compressors	[36, 39, 72]
	Eliminate/reduce pneumatic equipment	[37, 40, 51]
	Integrate smaller CASs	[48, 49]
	Use optimally sized compressors	[49, 51]
	Reconfigure pipes	[25, 36, 47, 48]
	Reduce compressor inlet temperatures	[51, 65]
	Reduce refuge bay flow	[13, 20]

## 2.3 Step 1: Prioritising and filtering energy-saving initiatives

### 2.3.1 Existing energy-saving prioritisation method

It is important to determine which energy-saving initiatives are feasible and the appropriate order to implement them in a specific scenario. Bredenkamp [37] developed a generic energy-saving initiative sequencing model applicable to all systems in mines, which is not limited to compressed air. The purpose of the sequencing model is to identify and implement the energy-saving initiatives with the lowest risk and highest cost-saving potential first. Thereafter, the remaining energy-saving initiatives are prioritised for maximum cost savings [37]. Table 5 shows an example of the sequencing model and the criteria used to evaluate the energy-saving initiatives.

**Table 5: Example of an energy-saving initiative sequence analysis [37]**

Energy Savings Initiative Sequence Analysis				
Implementation Criteria	Old Initiative Maintenance	System Inefficiencies	New Initiatives	Reconfiguring Designs
Cost	Low	Moderate–High	Moderate–High	High
Time	Low	Low	Moderate–High	High
Complexity	Moderate	Moderate–High	Moderate–High	Moderate–High
Difficulty	Low	Low	Moderate–High	Moderate–High
Benefits	Moderate–High	Moderate–High	Moderate–High	Moderate–High
<b>Sequence (Low Risk–High Risk)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>

Key				
Cost	R0–R100 000	R100 000–R1 000 000	R100 000–R5 000 000	R5 000 000 +
Time	1 month	1–3 months	1–6 months	6 months +
Complexity	Low	Moderate	Moderate–High	High
Difficulty	Low	Moderate	Moderate–High	High
Benefits (MW)	0–0.5	0.5–1	0.5–5	5 +
	<b>Low</b>	<b>Moderate</b>	<b>Moderate–High</b>	<b>High</b>

Each energy-saving initiative is rated based on the key in Table 5 and subsequently prioritised from low to high risk. Initiatives are implemented chronologically according to the determined sequence. The criteria used for evaluating each energy-saving initiative are as follows [37]:

1. **Cost:** The cost required to implement the energy-saving initiative.
2. **Time:** The time required to implement the energy-saving initiative.
3. **Complexity:** The complexity of designing solutions.
4. **Difficulty:** The difficulty of implementing the energy-saving initiative.
5. **Benefits:** The benefits, potential energy and cost savings of implementing the energy-saving initiative.

### 2.3.2 Adapting the existing energy-saving prioritisation method

The existing method by Bredenkamp [37] partially addresses the need for a prioritisation method for energy-saving initiatives but falls short when applied in the context of production stoppages. The following changes are proposed to address the shortcomings and adapt the existing prioritisation method to work with production stoppages:

#### 2.3.2.1 Reversibility of energy-saving initiatives

Certain energy-saving initiatives implemented during a production stoppage may reduce the compressed air supply below the requirement for a typical production period. Therefore, these

initiatives may need to be reversed before normal operations can be restarted after a production stoppage. An example of such an energy-saving initiative is stopping a compressor during low-demand periods to reduce oversupply [44]. However, major system changes may be difficult or unfeasible to reverse. It may take over a year to reconfigure a distribution network, which may cost up to R15 million if new equipment is required [18].

According to previous studies, the implementation time of a particular energy-saving initiative needs to be considered as part of the prioritisation process [5, 37, 61]. Similarly, it is expected that each initiative has a time requirement for reversal, if at all possible, which should be considered as well. Bredenkamp's method, mentioned in Section 2.3.1, does not account for reversal time or reversibility of energy-saving initiatives. The following changes to Bredenkamp's method are proposed to address the aforementioned shortcomings:

- **Change the Difficulty criterion to include reversibility if the initiative is a temporary solution.**

The Difficulty criterion is an indication of how difficult it is to implement an energy-saving solution [37]. Similarly, the difficulty of reversing an energy-saving initiative could also be incorporated into this criterion.

- **Change the Time criterion to include the reversal time of temporary solutions.**

The Time criterion considers the implementation time of an energy-saving initiative [37]. Similarly, the time to reverse temporary energy-saving initiatives could also be considered as part of this criterion.

### *2.3.2.2 Labour and resource availability*

Labour may be limited during a production stoppage as mentioned in Section 1.2.3. Du Toit [61] also lists limited human resources as one of the barriers to the implementation of energy-saving initiatives. Other resources may also be limited due to the possibility of limited capital expenditure during periods of non-production as seen during the 2018/19 strike at Sibanye-Stillwater's gold operations [1]. Although costs can be reduced by using salvaged equipment, this is also limited by the availability of such resources [18].

Bredenkamp's method does not consider the availability of labour and resources. The following changes to the existing method are proposed:

- **Change the Complexity criterion to include the labour required.**

The Complexity criterion is based on the complexity of designing solutions [37]. Additionally, Du Toit [61] includes availability of knowledge and skills to implement and maintain an energy-saving initiative as part of complexity. Therefore, the criterion can be adjusted to also consider the availability of sufficient labourers with the required skill level to implement a given energy-saving initiative.

- **Change the Cost criterion to include the resources required.**

The Cost criterion includes the cost to implement an energy-saving initiative [37]. However, there may be resources, such as equipment or materials, which need to be acquired or salvaged. The availability of these resources during a production stoppage should also be considered when evaluating cost.

### 2.3.2.3 *Scoring method*

The scoring method used by Bredenkamp rates criteria from high to low [37]. However, it may be difficult to determine the sequence based on a mix of low and high ratings. The exact sequence of energy-saving initiatives is not immediately apparent.

De Jager [5] employs a Likert scale to assign scores from 1 to 5 to criteria when determining the priority of energy-saving initiatives. These criteria scores are multiplied by a weight factor and summed to determine a final implementation score for each initiative [5]. The final scores are ordered from highest to lowest to generate a prioritised list [5]. Thereafter, the implementation order is the same as the list order [5].

Similarly, Du Toit [61] ranks the implementation order of energy-saving initiatives from highest to lowest based on the final scores. According to Du Toit [61], a higher rating on a rating scale should reflect greater convenience for the end user. Preferably, a high value for a benefit should correspond to a high rating or score [61]. This is in contrast to a criterion such as cost where a low value is preferable and, therefore, corresponds to a high rating or score [61]. The following change to Bredenkamp's [37] scoring method is proposed based on those used by De Jager [5] and Du Toit [61]:

- **Change the scoring method to a number-based scale.**

Simplify the scoring and prioritising of initiatives to make the sequence more obvious. This can be done by replacing the low to high scores with a number-based score from 1 to 5, which is similar to De Jager's method [5]. However, the low to high scores only constitute four values namely: low, moderate, moderate-high, and high.

Rating scales can be symmetrical by having an equal number of positive and negative positions, with a neutral point included [73]. Otherwise, rating scales can be nonsymmetric, typically starting at the lowest positive point and advancing to the highest positive point while excluding the neutral option [73]. A fifth option will be added below low to represent very low, which will extend the unsymmetrical scale toward the more positive direction. The numbered scale corresponds to the low to high scores as shown in Table 6.

**Table 6: Adjusted rating scale for prioritisation method**

<b>Rating scale</b>	<b>Individual scores</b>				
<b>Number-based</b>	1	2	3	4	5
<b>Very low to high</b>	High	Moderate-high	Moderate	Low	Very low

Similar to Du Toit’s method, higher ratings on the scale are associated with greater convenience [61]. Therefore, high is given a low rating of 1 since four out of five of Bredenkamp’s criteria are less convenient when values are high. The exception is the Benefits criterion, where higher values are preferable and will therefore be scored higher.

When prioritising energy-saving initiatives, each criterion receives a number-based score. Thereafter, the scores are added together to calculate a total score for each energy-saving initiative. The weight factor for each criterion may differ depending on the end user and will be excluded for the purpose of this study. Lastly, the energy-saving initiatives are ordered from highest to lowest total score and implemented chronologically according to the order.

*2.3.2.4 Score key time intervals*

The goal of the Time criterion is to score energy-saving initiatives based on the time it takes to implement the initiative [37]. However, short production stoppages may not provide sufficient time to implement projects that may require months of preparation. Production stoppages could last from a few days, such as during an off weekend, to weeks as with the 21-day shutdown in 2020 [27]. There were also cases where strikes led to production stoppages that lasted for multiple months. One such event occurred in 2014 when three major platinum producers experienced a five-month long strike during which all production ceased [26]. The intervals for the Time criterion in Table 5 are based on a typical production period and may not be appropriate for production stoppages that require savings within a short period. The following change to Bredenkamp’s score key is proposed:

- **Shorten time intervals to accommodate the timelines of production stoppages.**

The Time criterion's intervals must be adjusted to better suit a production stoppage. Table 7 lists the proposed time periods.

**Table 7: Adjusted time interval for prioritisation method**

<b>Number-based score</b>	<b>Previous interval [37]</b>	<b>Proposed interval</b>
1	> 6 months	> 1 month
2	1–6 month(s)	1 week–1 month
3	1–3 month(s)	< 1 week
4	1 month	1–3 days
5	–	< 1 day

As seen in Table 7, the maximum time interval was changed from more than six months to one month while the minimum time interval was changed from one month to less than a day. These changes accommodate short production stoppages that require the implementation of energy-saving initiatives within a short period. Additionally, longer production stoppages lasting a month or more with enough time to implement larger projects are also accounted for.

#### *2.3.2.5 Filtering unfeasible energy-saving initiatives*

Bredenkamp's method does not filter out solutions that are not feasible but simply moves them to the end of the sequence. This is because the maximum score is allocated to a given criterion if the requirements are too high, but there is no built-in condition for disqualifying an energy-saving initiative.

Du Toit [61] evaluates the feasibility of each energy-saving initiative based on multiple criteria and places an initiative on hold if it fails any feasibility checks. Maré *et al.* [48] conduct preliminary feasibility studies and exclude unfeasible energy-saving initiatives before continuing to a deeper analysis of each initiative. The following change to the existing method is proposed:

- **Add the possibility to exclude unfeasible energy-saving initiatives from the final sequence.**

The existing method does not filter out energy-saving initiatives. It is proposed that an additional option be added to the scoring method that indicates that an energy-saving initiative is unfeasible,

is impossible to implement, or provides no benefit during a specific production stoppage. This can be achieved by adding an X instead of a number when scoring a particular criterion. Energy-saving initiatives that receive one or more Xs are not considered when implementing solutions or determining the sequence of energy-saving initiatives.

**2.3.3 Energy-saving initiative sequencing method for production stoppages**

The shortcomings of the existing energy-saving initiative prioritisation method and proposed changes are discussed in Section 2.3.2. Bredenkamp’s prioritisation method was adapted for use during production stoppages by applying the proposed changes to Table 5 as well as the criteria descriptions. Table 8 contains the modified key for scoring an energy-saving initiative during a production stoppage.

**Table 8: Energy-saving initiative sequencing method for production stoppages**

Criteria	Key					
<b>Cost (R million)</b>	Capital or resources unavailable.	> 5	1–5	0.1–1	< 0.1	No cost
<b>Time</b>	Longer than available time.	> 1 month	1 week–1 month	< 1 week	1–3 days	< 1 day
<b>Complexity</b>	Labour unavailable.	High	Moderate–high	Moderate	Low	Pre-existing solution
<b>Difficulty</b>	Temporary solution irreversible.	High	Moderate–high	Moderate	Low	Very low
<b>Benefits (MW)</b>	Negative or none.	Non-energy	0–0.5	0.5–1	1–5	> 5
<b>Score</b>	<b>X</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

If a requirement for implementing an energy-saving initiative cannot be met, a score of X is given for the specific criterion instead of a numerical score.

**Criteria description:**

1. **Cost:** The capital cost and resources required to implement the energy-saving initiative.
2. **Time:** The time required to implement and reverse (in the case of a temporary solution) the energy-saving initiative.

3. **Complexity:** The complexity of designing solutions and the availability of sufficient labour of the necessary skill level.
4. **Difficulty:** The difficulty of implementing and reversing (in the case of a temporary solution) the energy-saving initiative.
5. **Benefits:** The benefits, in terms of potential energy and cost savings, associated with implementing the energy-saving initiative. This criterion is primarily scored based on the expected reduction in compressor power measured in megawatts (MW). Non-energy benefits such as a direct monetary saving or improved system performance may be considered but are allocated a lower score. Higher benefits receive a higher score.

#### **2.3.4 Energy-saving initiative checklist for production stoppages**

The list of common compressed air energy-saving initiatives from Section 2.2 is combined with the adapted sequencing method from Section 2.3.3 to create the checklist as shown in Table 9. This checklist can be used during a production stoppage to quickly filter and prioritise energy-saving initiatives. A printable template of Table 9 is included in Annexure A for ease of use during a production stoppage.

Each criterion receives a number-based score according to the key in Table 8, and the scores are added together in the Total column. The energy-saving initiatives are implemented chronologically from highest to lowest total score. Energy-saving initiatives that receive one or more Xs are considered unfeasible and removed from the sequence.

The checklist in Table 9 and the key in Table 8 form a method for prioritising and filtering a list of compressed air energy-saving initiatives during a production stoppage. This accomplishes **Objective 2** as listed in Section 1.4.3.

**Table 9: Energy-saving initiative checklist for production stoppages**

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Compressor control	Compressor selection						
	Guide vane control						
	Load sharing						
	Load-unload						
	Pressure set point reduction						
	Regular maintenance						
	Stop-start						
	VSD						
Control valves	Peak-clipping						
	Set-point control						
	Stope isolation						
	Surface valve control						
	Underground valve control						
Wastage reduction	Close inactive sections						
	Eliminate/reduce unauthorised use						
	Repair leaks						
System changes	Adjust mining shifts						
	Use dedicated compressors						
	Eliminate/reduce pneumatic equipment						
	Integrate smaller CASs						
	Use optimally sized compressors						
	Reconfigure pipes						
	Reduce compressor inlet temperatures						
	Reduce refuge bay flow						

### 2.4 Step 2: Implementing energy-saving initiatives

After identifying feasible energy-saving initiatives, it is necessary to implement these initiatives. The purpose of implementing energy-saving initiatives is to realise the energy-saving potential of each initiative and reduce electricity costs. Previous studies have included implementation as part of energy-saving strategies [40, 74].

Kunneke [40] used an inefficiency identification strategy, shown in Figure 9, to identify mineshafts with potential for energy savings. The bulk of the process focuses on developing a benchmark for each shaft that can be used to identify areas of inefficiency, which is outlined in green.

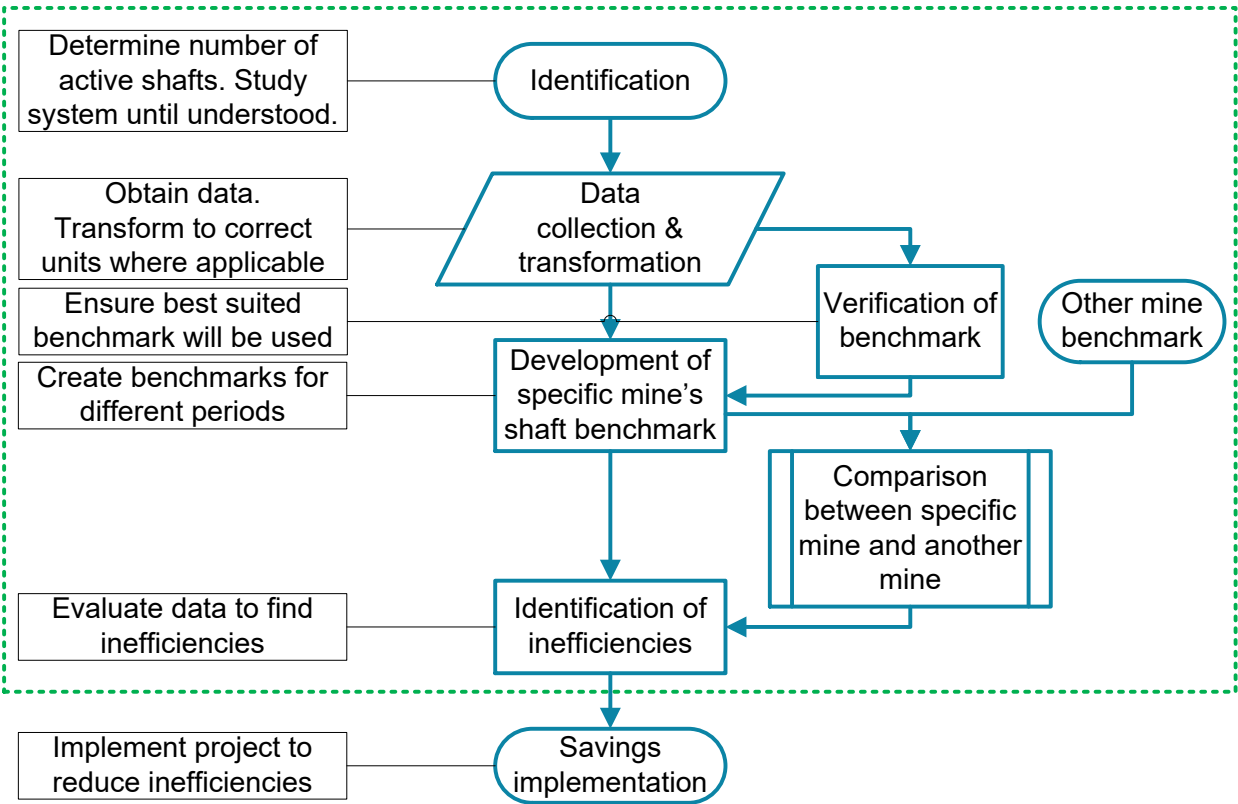
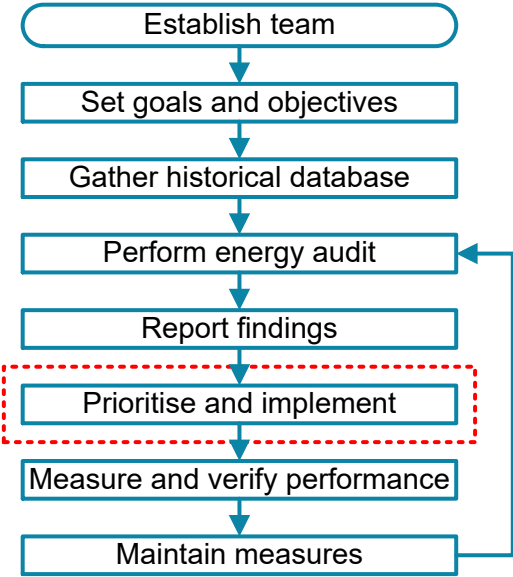


Figure 9: Inefficiency identification strategy flow chart (adapted from [40])

The benchmarking and inefficiency identification process helps the end user to decide where to focus resources and efforts [40]. This serves a similar purpose to the prioritising and filtering of energy-saving initiatives discussed in Section 2.3. According to the inefficiency identification strategy, once inefficiencies have been identified, projects are implemented to reduce inefficiencies. Therefore, the decision-making process is immediately followed by implementation.

Abdelaziz, Saidur and Mekhilef [74] state that energy audits are a key part of decision-making in the context of energy management. These audits assist organisations to analyse energy use and

identify areas where usage can be reduced [74]. A typical energy audit process is shown in Figure 10.



**Figure 10: Typical energy audit process (adapted from [74])**

The energy audit process combines the prioritisation and implementation steps of energy-saving initiatives into a single step, outlined in red in Figure 10. This shows the close relationship between prioritisation and implementation. By drawing parallels between strategies developed in previous studies and the goal of this study, it is evident that implementation is an important next step following the prioritisation and filtering of energy-saving initiatives.

According to the prioritisation method developed in Section 2.3, the energy-saving initiatives that are identified using the prioritisation method are implemented chronologically from highest to lowest total score. Unfeasible energy-saving initiatives are not implemented. Detailed planning related to the implementation of energy-saving initiatives or the project management thereof is outside the scope of this study.

**2.5 Step 3: Reversing temporary energy-saving initiatives**

A production stoppage is similar to the blasting period during a typical production day, but it lasts for a longer period of time. This is because no production is taking place and compressed air demand is being limited during these periods. An example of the pressure demand profile of a typical production day is shown in Figure 5.

At the end of the blasting period, compressed air supply is increased to meet the demand of the cleaning shift. Similarly, compressed air supply must be increased after a production stoppage to

meet the demand of a typical production period. Occasionally, there may be periods during a production stoppage when demand increases temporarily due to non-production work requiring compressed air.

Therefore, energy-saving initiatives that reduce or limit the compressed air supply below the requirement must be reversed. Examples of such initiatives are throttled control valves, pressure set-point adjustments and compressor control, which limits the number of compressors. In the event of a temporary increase in demand during a production stoppage, energy-saving initiatives must be reimplemented when the demand lowers.

Each energy-saving initiative has a time requirement for implementation [5]; therefore, there will also be a time requirement for reversal should reversal be possible. This must be accounted for to ensure timely restoration of compressed air supply before production resumes.

## 2.6 Step 4: Quantifying energy savings

### 2.6.1 Data collection

Data is required to monitor the compressed air network and calculate the effect of energy-saving initiatives. A mine's supervisory control and data acquisition (SCADA) system can be used to monitor the real-time performance and condition of various systems, both above and underground [75]. The SCADA relies on sensors that are connected to programmable logic controllers (PLCs) to gather data [76]. Historical data from the SCADA is typically stored on a data server, referred to as a historian [75, 77]. If a mine does not have a SCADA, historian, or other method for collecting and storing the data remotely, then the data must be collected manually using portable equipment [75]. Figure 11 shows the flow of data from a sensor to the historian.

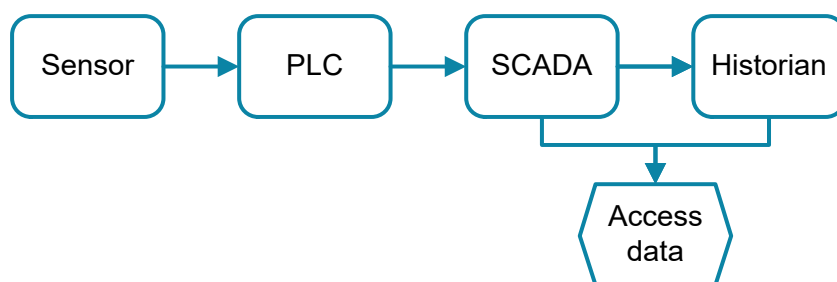


Figure 11: Data flow diagram (adapted from [76])

Eskom tracks the total electricity usage of a mine, which will be reflected on the monthly invoice. However, only the total usage of all systems during the month is provided [29]. Therefore, additional work must be done to determine the electricity usage of the compressed air network in

isolation or to calculate electricity usage over periods shorter than a month [29]. Some mines measure the electricity supplied at various points of delivery and directly measure the electricity usage of individual consumers, such as compressors and pumps, which enables the mines to monitor the system in more detail [29].

The electricity usage values provided on the Eskom invoices are regarded as 100% accurate according to the International Performance Measurement and Verification Protocol (IPMVP). The accuracy of the mine's own power meters must be compared to the invoiced values [29, 78]. Maneschijn [46] verified the accuracy of sub-metering at a case study mine and found that the absolute error of the mine group's total electricity consumption was 2.06%. Additionally, power meters with an absolute error of up to 1.9% were still classified as acceptable [46]. Therefore, for the purpose of this study, an absolute error of up to 1.9% will be accepted.

The following data will be used when evaluating the performance of a compressed air network:

- Compressor electricity usage
- Compressor set point
- Compressed air flow
- Compressed air pressure
- Valve set point (if an actuator is installed)

## 2.6.2 Data cleaning and error detection

After collecting the required data, it is important to check the data for errors and ensure that it is an accurate representation of the system [76, 79]. Data cleaning and error detection is used to obtain processed data [79]. An existing method for data cleaning and error detection on mine refrigeration systems [76] will be adapted for use on CASs in this study. The checks that apply include the following:

1. **Constant value check:** Measurements that remain at a constant value over a long period are considered erroneous and may be attributed to faulty instrumentation [75, 76].
2. **Measurement unit check:** The units of measurement for the data must be consistent in order to enable accurate comparison of the data [76]. Harmse proposes using Système Internationale (SI) units for consistency [76]. For example, compressed air flow for a CAS is converted from kg/h to kg/s.
3. **Redundancy check:** Measurements that have redundant instrumentation allow for comparisons between two data points [76]. A large discrepancy between these data points indicates erroneous data [76].

4. **Correlation check:** The measurements of a specific system need to correlate with one another [76]. For example, measuring the compressed air flow after a valve when the valve is fully closed in a CAS.
5. **Mass balance check:** The total sum of the mass flow rates before and after a point must be equal [76].

Data that fails any of the above-mentioned checks are considered erroneous and omitted from the data set. Additionally, compressor switching creates fluctuations in the CAS, which causes sensors to collect meaningless data during the switching period [79]. Data that is affected by the starting or stopping of compressors is also omitted from the data set.

### 2.6.3 Measurement boundary

Savings may be calculated for the entire facility or a section of the facility, depending on the energy-saving initiative [78]. A measurement boundary is drawn to isolate the equipment affected from those unaffected by energy-saving initiatives [78]. All energy used or generated must be measured at the measurement boundary [78]. The types of measurement boundary are summarised by the four IPMVP options in Table 10.

**Table 10: IPMVP options [78]**

Measurement boundary	Option	Description
Retrofit isolation	A	<p><b>Key parameter measurement:</b></p> <p>The purpose is to verify the energy savings for equipment affected by energy-saving initiatives. The measurement boundary is drawn around the affected equipment.</p> <p>This option allows the use of measured and estimated values to calculate baseline energy.</p>
	B	<p><b>All parameter measurement:</b></p> <p>The purpose is to verify the energy savings for equipment affected by energy-saving initiatives. The measurement boundary is drawn around the affected equipment.</p> <p>This option requires direct measurement of energy usage or consistent measurement of all parameters necessary to determine energy usage. The accuracy is typically higher than Option A.</p>

Measurement boundary	Option	Description
Whole facility	C	<p><b>Whole facility:</b></p> <p>The purpose is to verify and/or manage the total facility energy performance or verify the energy savings of multiple energy-saving initiatives that affect multiple systems. The measurement boundary is drawn around the entire facility.</p> <p>The electricity meters that measure the total supply to the facility can be used for calculations.</p>
	D	<p><b>Calibrated simulation:</b></p> <p>If the required data is unavailable or unreliable, a calibrated simulation model may be used. The model can be applied to the entire facility or a section thereof, and the measurement boundary is drawn accordingly.</p>

Option B will be used for the purpose of this study. The measurement boundary for energy usage will be drawn around the compressors supplying the compressed air network.

#### 2.6.4 Calculation of energy savings

Energy savings cannot be measured directly and must be determined by comparing the measured energy usage before and after an energy-saving initiative is implemented [78]. An example of energy usage before and after implementing an energy-saving initiative is shown in Figure 12.

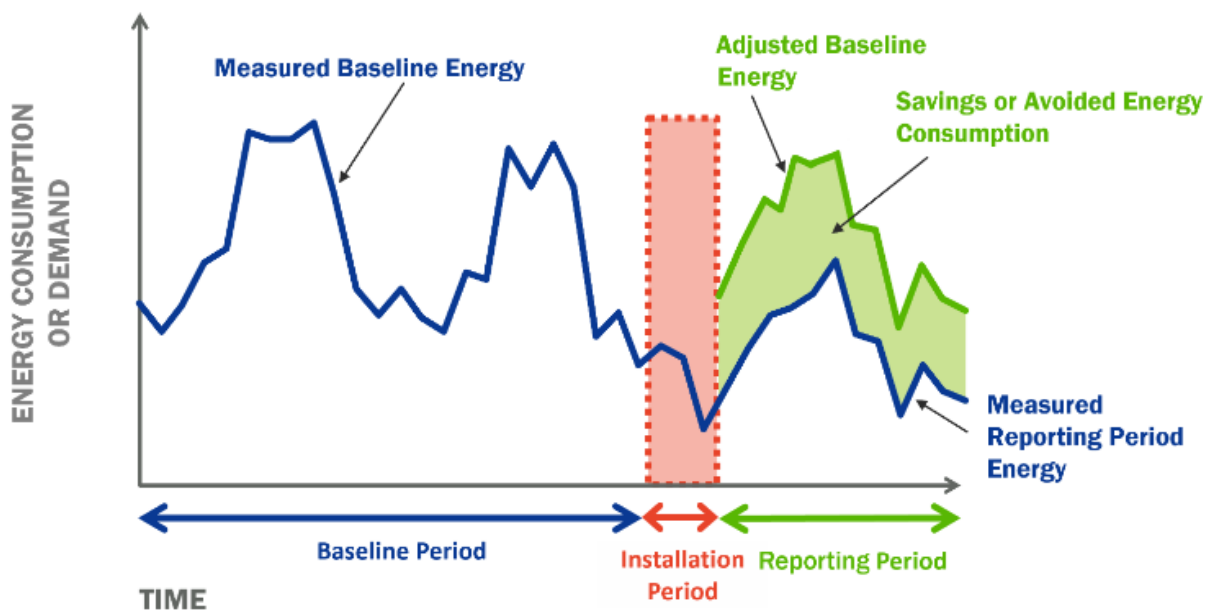


Figure 12: Example of savings after implementation of an energy-saving initiative [78]

The adjusted baseline energy represents the energy usage during the baseline period with adjustments made for the reporting period [78]. Savings are calculated from the difference between the energy usage during the reporting period and the adjusted baseline energy as shown by Equation 1 [78].

**Equation 1: General equation for calculating energy savings [78]**

$$\text{Savings} = \text{Baseline Period Energy} - \text{Reporting Period Energy} \pm \text{Adjustments} \quad (1)$$

The electrical energy over a period is calculated using Equation 2.<sup>10</sup>

**Equation 2: Formula to convert power to electrical energy**

$$E = P \times t \quad (2)$$

Here,  $E$  is the electrical energy transferred in kilowatt-hours (kWh),  $P$  is the power in kilowatts (kW), and  $t$  is the time in hours (h).

### **Energy split**

Some mines have measurement instrumentation to split the energy usage between different systems or shafts [29]. The split is done proportionally based on the compressed air flow supplied to each system [29].

### **2.6.5 Creation of a baseline**

A baseline is required to calculate the energy savings achieved through the implementation of energy-saving initiatives as discussed in Section 2.6.4. Previous studies have used a typical production day as a baseline [6]. Marais [29] considered seven methods for evaluating the savings for a production stoppage, six of which compared the energy usage to a baseline.

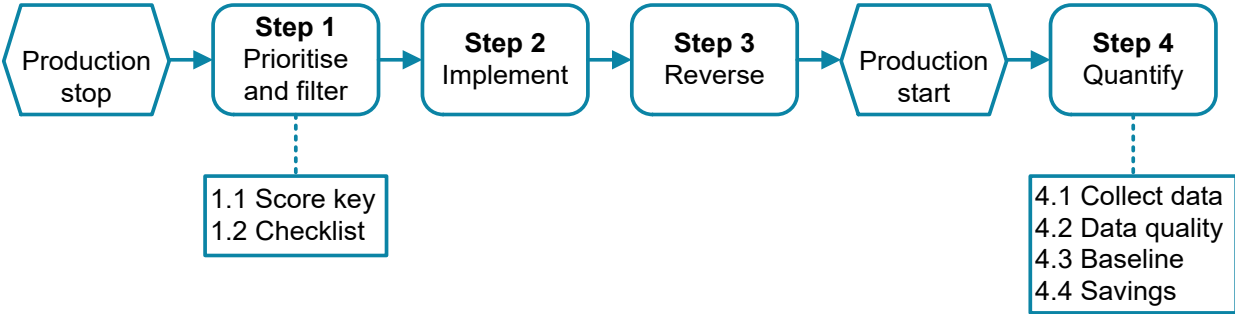
If data is not available for longer production stoppages, shorter production stoppages can be used to create a baseline for medium- to long-term production stoppages [29]. There is also a possibility of stopping more baseload equipment during a longer production stoppage as opposed to shorter stoppages [29].

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<sup>10</sup> Fire2Fusion, “*Understanding the Electric Energy Equation*”. Available: <https://www.fire2fusion.com/electric-energy/electric-energy-equation.html> [Accessed: 19 Nov. 2024].

## 2.7 Summary of developed strategy

The energy-saving strategy developed in Chapter 2 is summarised step by step in Figure 13.



**Figure 13: Strategy for prioritising energy-saving initiatives during production stoppages**

The first step (**Step 1**) following the beginning of a production stoppage is to determine the feasibility of the various energy-saving initiatives and prioritise them accordingly. This is done by using the score key in Table 8 (**Step 1.1**) and applying it to the energy-saving initiative checklist in Table 9 (**Step 1.2**) to generate a prioritised list of feasible energy-saving initiatives. These energy-saving initiatives should be ordered from the highest to the lowest score to determine their priorities, and unfeasible initiatives must be removed from the final list. If sufficient notice is given for a production stoppage, **Step 1** can be executed before the beginning of the stoppage.

The next step (**Step 2**) involves implementing the energy-saving initiatives identified in **Step 1**. The implementation order is the same as the priority of each initiative. Therefore, initiatives with higher scores are implemented before initiatives with lower scores.

It may become necessary to undo or reverse some of the energy-saving initiatives from **Step 2** when the production stoppage nears completion. Reversal of any initiatives forms part of **Step 3** and is done to prepare the system for standard production conditions. This is only necessary if an energy-saving initiative interferes with the CAS's ability to meet the demand of a typical production period. The timing of **Step 3** depends on the time it takes to reverse a temporary energy-saving initiative as well as the notice period given before resuming production.

Finally, after production resumes, the energy savings due to the implementation of energy-saving initiatives can be calculated in **Step 4**. This requires collecting the relevant data (**Step 4.1**), checking the data quality (**Step 4.2**), and creating a baseline based on an appropriate baseline period (**Step 4.3**). Thereafter, the energy savings can be calculated by comparing the actual energy consumption during the production stoppage with the baseline (**Step 4.4**).

## 2.8 Verification and validation

This section discusses the verification and validation of the strategy developed in Chapter 2. The strategy is summarised in Section 2.7 and is accompanied by the energy-saving initiative checklist presented in Table 9. The scoring key for the checklist is found in Table 8. Firstly, it must be determined whether the developed strategy addresses the need for a strategy to prioritise and filter energy-saving initiatives during a production stoppage. The criteria that were used to evaluate the literature as part of the state-of-the-art matrix will be used to evaluate the developed strategy. Table 11 summarises the findings of the evaluation.

**Table 11: Evaluation of developed strategy**

<b>Criteria from literature review</b>	<b>Achieved</b>	<b>Description</b>
<b>Compressed air</b>	✓	The strategy, including the checklist in Table 9, specifically focuses on energy-saving initiatives for compressed air. The checklist was built based on a summarised list of the most common compressed air energy-saving initiatives found in the literature. The list is shown in Table 4.
<b>Energy saving</b>	✓	The purpose of the energy-saving initiatives is to provide energy savings for a mine. Additionally, the goal of the strategy is to assist mines to save energy. The strategy includes a step for calculating energy savings, which is discussed in Section 2.6.
<b>Production stoppage</b>	✓	The prioritisation method used in the first step of the strategy is based on an existing method that was adapted for use during a production stoppage. The adaptation is discussed in Section 2.3.2. The scoring key in Table 8 is customised to implementing energy-saving initiatives during a production stoppage and accounts for limited labour, resources and time.
<b>Prioritising saving initiatives</b>	✓	The first step of the strategy is to prioritise and filter energy-saving initiatives. The scoring key in Table 8 and checklist in Table 9 were developed for this purpose.
<b>Mining</b>	✓	The energy-saving initiatives used as part of the checklist in Table 9 are primarily based on energy-saving initiatives found in literature that were applied to the CASs of mines. The initiatives are discussed in Section 2.2.

The developed strategy meets the criteria and addresses the need for a strategy to prioritise and filter energy-saving initiatives during a production stoppage.

Verification will be done in Chapter 3 by checking whether the developed strategy is implemented correctly. The prioritisation method will be validated by testing its accuracy and benefit during a case study. Additionally, the strategy will be validated by determining whether it delivers similar energy savings when compared to the literature.

## **2.9 Conclusion**

A strategy for prioritising energy-saving initiatives during a production stoppage was developed in this chapter. The developed strategy applies to the CASs of mines with the purpose of reducing electricity costs. The various energy-saving initiatives that are applicable to CASs were also discussed. Additionally, an existing prioritisation method was adapted for use during a production stoppage.

In the event of a production stoppage, the first step is to identify and prioritise feasible energy-saving initiatives using the aforementioned prioritisation method. Thereafter, the identified energy-saving initiatives must be implemented according to the order determined in the first step. When the production stoppage nears completion, it is necessary to prepare for normal operation by reversing any temporary energy-saving initiatives. These are energy-saving initiatives that may interfere with compressed air supply during a typical production period. Savings are quantified after production has resumed.

The developed strategy was evaluated based on the same criteria used to evaluate the literature as part of the state-of-the-art matrix. It was found that the developed strategy meets the criteria and addresses the need for a strategy to prioritise and filter energy-saving initiatives during a production stoppage.

## CHAPTER 3: RESULTS AND DISCUSSION



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<sup>11</sup> ETA Operations, "Actuated compressed air valves," [Photograph], South Africa, 2020.

### **3.1 Preamble**

This chapter discusses the case studies and results as part of the research methodology shown in Figure 8. Firstly, the strategy developed in Chapter 2 was tested by applying it to two case studies. The results of these case studies were compared with a baseline to determine energy savings. Finally, the developed strategy was reviewed. Figure 13 in Section 2.7 summarises the developed strategy.

The names of mines and underground levels have been changed, and details such as dates and locations have been omitted to protect the privacy of the case study mine. Two case studies were conducted at Mine A during separate production stoppages.

Case Study 1 was based on a strike at Mine A that caused production to be stopped for three and a half months. No focused strategy was used during the production stoppage and energy-saving initiatives were chosen based on industry knowledge and experience. The accuracy and benefit of the prioritisation method described in Section 2.3 were determined by comparing the results of the prioritisation method with the actual initiatives that were implemented.

Case Study 2 was also conducted at Mine A and was based on an annual December break. This case study was used to review the overall effectiveness of the developed strategy when implemented during a production stoppage.

### **3.2 Case Study 1**

#### **3.2.1 Case study background**

Mine A experienced a strike that lasted for three and a half months. The strike also affected Mine B and Plant A. All production was stopped at Mine A and Mine B for the duration of the strike period, and Plant A scaled down its demand due to no production from the mines.

The case study mine, Mine A, is a deep-level gold mine in South Africa with four compressors on surface to supply the mine's CAS. Mine A supplies compressed air to a gold plant, Plant A, on surface, which requires a constant pressure and flow. The CAS of Mine A is also integrated with Mine B on 5 Level (5L) and compressed air is supplied to Mine B's refuge bays.

Mine A and Mine B were integrated as part of an energy-saving initiative to reduce wastage. Mine A and Plant A's combined demand was too high for two compressors but too low for three compressors, which caused the compressors to blow off and release excess compressed air into

the atmosphere. The integration with Mine B diverted the excess compressed air to Mine B’s refuge bays, and the single compressor at Mine B was stopped. A summary of the compressors used at Mine A and Mine B is given in Table 12. Mine B is a hydropower mine that uses high-pressure water to power rock drills and therefore only uses compressed air for refuge bays. Figure 14 shows a simplified illustration of the integrated CAS for Mine A, Mine B and Plant A.

**Table 12: Mine A and Mine B’s compressor specifications**

Location	Compressor name	Type	Rated power (MW)
Mine A	C1	Sulzer	4.20
	C2	Sulzer	4.20
	C3	GHH	3.75
	C4	Demag VK-50	4.20
Mine B	C5	Sulzer	4.20

Compressor 3 (C3) is much smaller than the rest of the installed compressors and is typically used as a trimming compressor. The typical compressor combinations during normal production periods are C2 and C3, or C4 and C3.

**Data used to monitor the CAS**

The total compressed air supplied to underground is measured on surface at point F1 as indicated on Figure 14 and reflects the total supply to Mine A and Mine B. The totals for some levels are measured at the station, with Mine B’s total flow being measured on 4L at Mine A. Plant A’s compressed air flow is measured on surface at point F2. The energy usage of the compressors is split between the underground section and Plant A based on the actual compressed air usage measured by flowmeter F1 and F2, respectively, as mentioned in Section 2.6.4. The flowmeters occasionally measure erroneous values. The flows may fluctuate due to compressor changeovers and data may be lost due to power failures.

The compressor power meters, indicated at points P1 to P5 on Figure 14, are similarly affected by power failures. Large fluctuations in power occur when compressors are stopped and started. These values are excluded from the data set when calculating averages and are indicated as grey rectangles where applicable on each graph. Some grey rectangles are omitted from graphs to reduce clutter; however, the relevant data was still excluded from the data set.

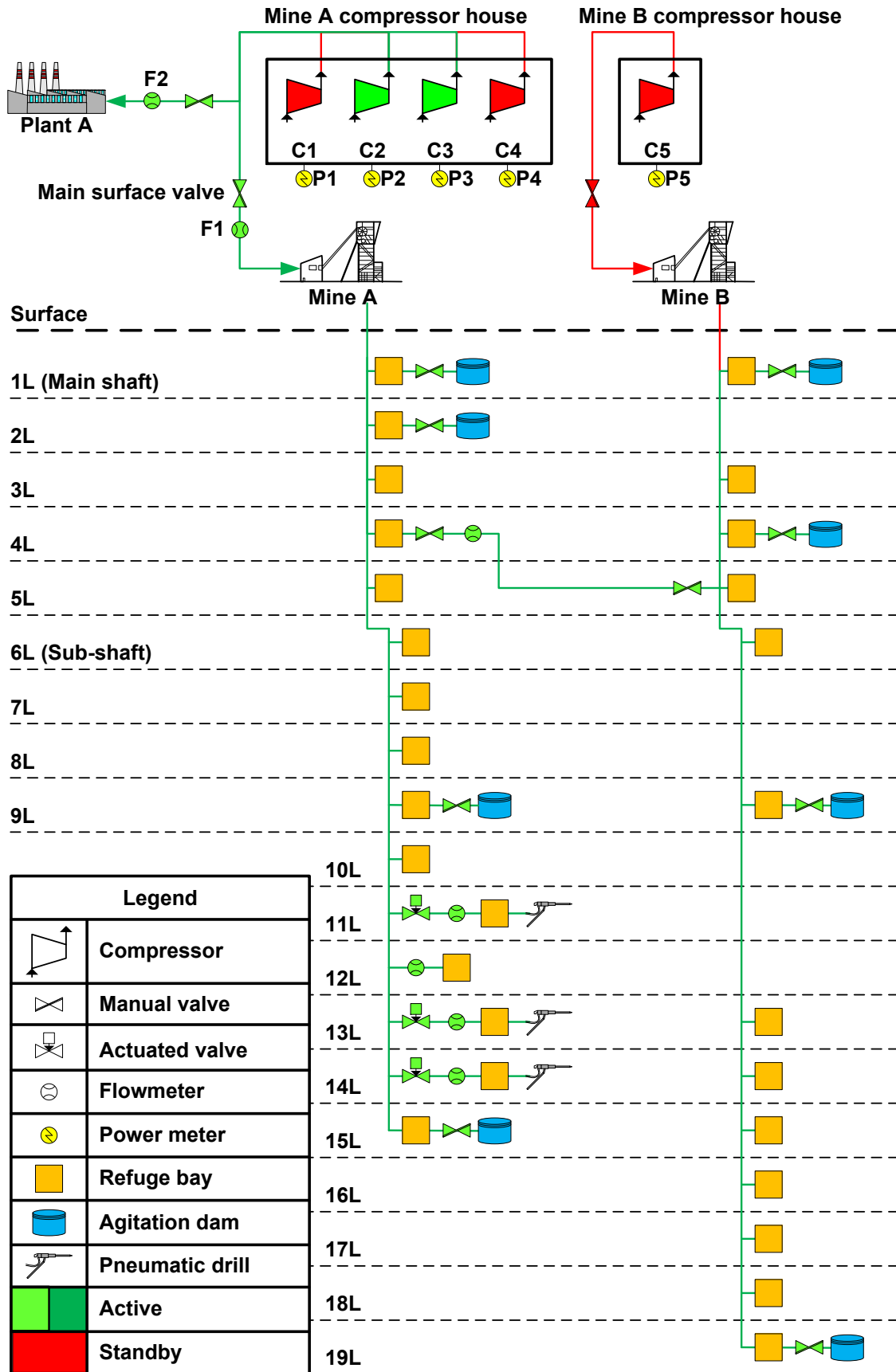


Figure 14: Case Study 1 – Compressed air system layout

The performance of each initiative was determined based on the power meter readings. It was therefore necessary to verify the accuracy of these power meters as mentioned in Section 2.6.1. After verification it was found that the power meters had an absolute error of 1.77%, which is within the acceptable range of 1.9%. More detail regarding power meter verification is shown in Annexure D.

### **3.2.2 Step 1: Prioritise and filter**

No strategy or prioritisation method was available to assist with decision-making at the start of the case study production stoppage. Initiatives were instead chosen based on industry knowledge and were implemented as a reaction to the events that occurred during the production stoppage. The lack of a focused strategy highlights the need for this study.

Therefore, Step 1 was implemented retrospectively and compared with the actual events that occurred. The initiative sequencing method (Table 8) and the energy-saving initiative checklist for production stoppages (Table 9) were used to generate a list of feasible initiatives based on what was known at the start of the production stoppage and compared to determine the accuracy of the prioritisation method.

The management of Mine A imposed the following limitations on the implementation of energy-saving initiatives:

1. Mine A was unwilling to spend any capital since no income was being generated for the duration of the strike.
2. The duration of the strike was unknown.
3. Only essential personnel were permitted near the mine. Labour was therefore very limited.
4. Mine B required compressed air for its refuge bays.
5. Plant A required a constant compressed air supply.

Table 13 shows the scores allocated to each energy-saving initiative for Mine A's CAS based on the prioritisation method from Section 2.3. The scores are discussed in more detail in Table 26 in Annexure B.

The list of 24 energy-saving initiatives from Table 9 were scored according to the scoring key in Table 8 based on five criteria. The list was also filtered by taking the given limitations of the production stoppage into account, which reduced the list to four feasible energy-saving initiatives. The remaining energy-saving initiatives were ordered from highest to lowest score to generate the sequenced list shown in Table 14.

**Table 13: Completed energy-saving initiative checklist for Case Study 1**

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Compressor control	Compressor selection	5	4	3	3	3	18
	Guide vane control	-	-	-	-	X	X
	Load sharing	-	-	-	-	X	X
	Load-unload	-	-	-	-	X	X
	Pressure set-point reduction	5	2	3	2	3	15
	Regular maintenance	-	-	X	-	-	X
	Stop-start	-	-	-	-	X	X
	VSD	X	-	-	-	-	X
Control valves	Peak-clipping	-	-	-	-	X	X
	Set-point control	5	5	4	4	3	21
	Stope isolation	-	-	X	-	-	X
	Surface valve control	5	4	3	4	3	19
	Underground valve control	-	-	X	-	-	X
Wastage reduction	Close inactive sections	-	-	X	-	-	X
	Eliminate/reduce unauthorised use	-	-	-	-	X	X
	Repair leaks	-	-	X	-	-	X
System changes	Adjust mining shifts	-	-	-	-	X	X
	Use dedicated compressors	X	X	-	-	-	X
	Eliminate/reduce pneumatic equipment	X	-	-	-	-	X
	Integrate smaller CASs	-	-	-	-	X	X
	Use optimally sized compressors	X	X	-	-	-	X
	Reconfigure pipes	X	X	-	-	-	X
	Reduce compressor inlet temperatures	X	-	-	-	-	X
	Reduce refuge bay flow	-	-	X	-	-	X

Table 14 shows the final list of feasible initiatives for Mine A in order of priority based on the scores allocated in Table 13.

**Table 14: Sequenced and filtered list of energy-saving initiatives for Case Study 1**

Sequence	Strategy	Initiatives	Total score
1	Control valves	Set-point control	21
2	Control valves	Surface valve control	19
3	Compressor control	Compressor selection	18
4	Compressor control	Pressure set-point reduction	15

All energy-saving initiatives that require capital expenditure or non-essential labour were excluded from the final list since labour was limited and Mine A’s management were unwilling to spend capital. Additionally, certain energy-saving initiatives were excluded since there was no expected benefit because they were pre-existing solutions, which would not operate any differently during the production stoppage.

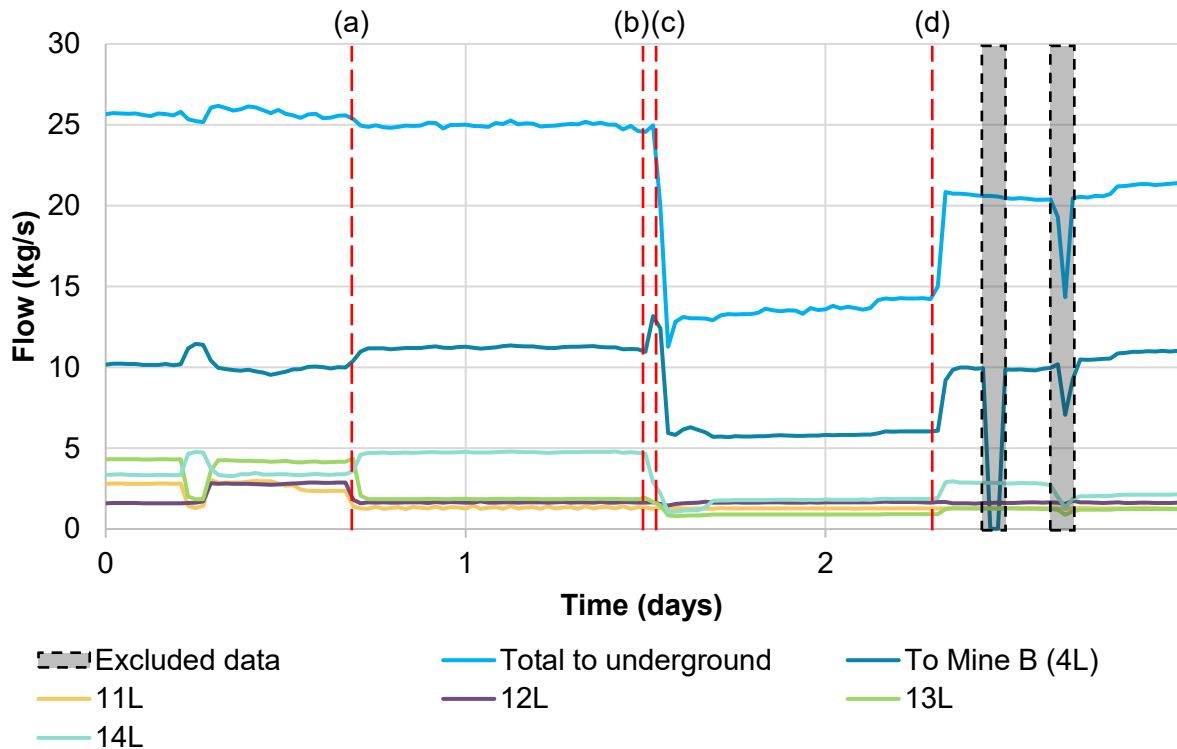
**3.2.3 Step 2: Implement**

This section discusses the implementation of energy-saving initiatives and actual events that occurred during the case study production stoppage. As mentioned in Section 3.1, there was no focused strategy when the production stoppage occurred, and initiatives were chosen and implemented based on industry knowledge.

The production stoppage officially started at 16:00 on the first day and the known energy-saving initiatives were implemented as soon as possible. Five energy-saving initiatives were implemented within the first 48 hours, referred to as the initial reduction period, with a sixth and final energy-saving initiative only being implemented more than a month later.

*3.2.3.1 Initial reduction (Initiatives 1 to 5)*

The compressed air flow during the initial reduction period is shown in Figure 15 and the corresponding compressed air power usage is shown in Figure 16.



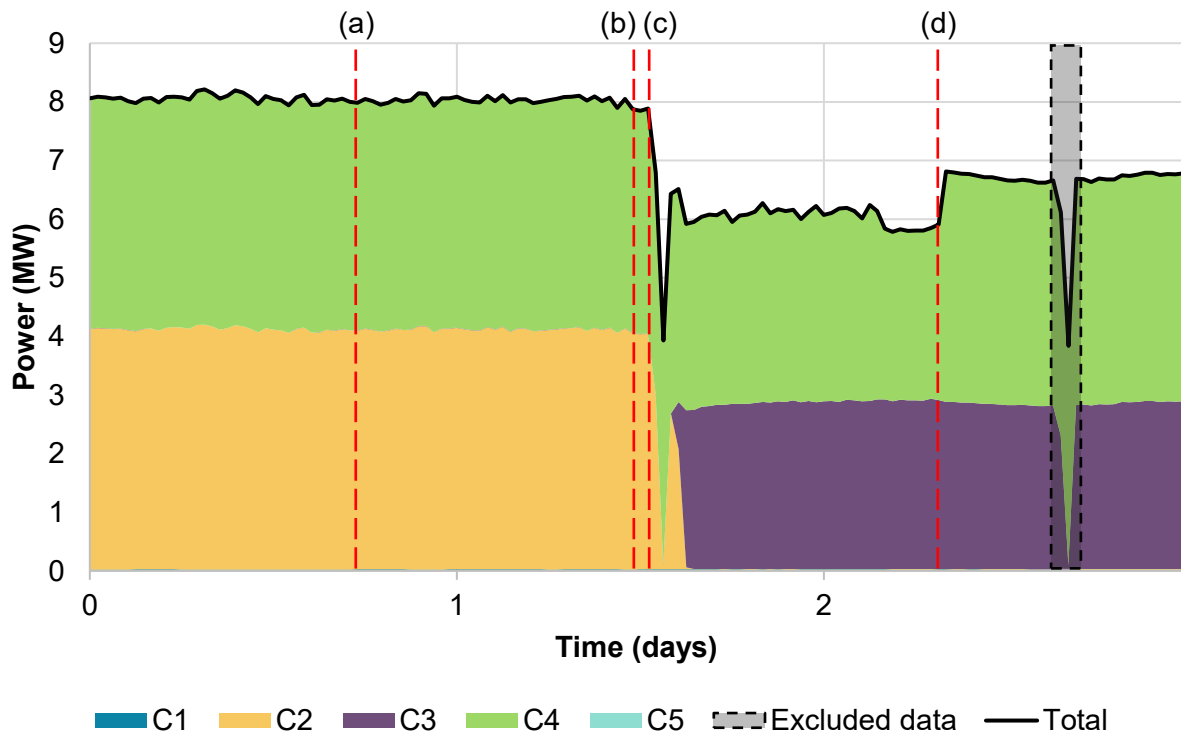
**Figure 15: Case Study 1 – Compressed air flow during initial reduction period**

Initiative 1, valve set-point control, was implemented at the start of the production stoppage shown at point (a) on Figure 15. This was done by reducing the pressure set points of the actuated valves located on 11L, 13L and 14L. The pressure set point was set to the minimum of 150 kPa for refuge bays as stated in Table 1. After the set-point adjustment, the 14L valve actuator malfunctioned and did not follow the set point, which led to the valve remaining fully open. The reduction of flow to other levels led to an increase in flow to 4L and 14L since these valves were not throttled.

An essential worker on standby was sent to 14L the next day to reduce the flow manually, shown at point (b). Since this level had no employees according to the mine's management, the essential worker also went to 13L to further reduce the flow manually, and the flow to the refuge bay was reduced. The reduction in flow to 13L and 14L further increased the flow to Mine B instead of reducing the total flow to underground. The manual control of underground valves and the reduction of refuge bay flow are regarded as Initiative 2 and Initiative 3, respectively.

The surface valve controlling the total compressed air flow to underground was throttled manually, indicated at point (c), and is regarded as Initiative 4. This led to a significant reduction in the total flow to underground. The CAS was given time to stabilise, and the valve was opened slightly the day after, indicated at point (d), to ensure that all refuge bays received sufficient compressed air.

The flow reductions at points (a) and (b) did not lead to a significant reduction in the total flow to underground, as shown in Figure 15. The lack of overall reduction meant that the compressor guide vanes could not cut back very far and little reduction in compressor power was observed, shown at points (a) and (b) in Figure 16.



**Figure 16: Case Study 1 – Compressor power during initial reduction period**

The throttling of the surface valve, point (c) in Figure 16, along with the underground valve control led to a large enough reduction in demand that allowed the compressor combination to be changed as part of Initiative 5. Compressor 2 (C2) was replaced by the smaller Compressor 3 (C3) and a reduction in compressor power usage of 1.8 MW was observed. The surface valve was opened more at point (d), which increased the compressor power usage, but an overall power reduction of 1.36 MW was achieved after the implementation of Initiatives 1 to 5. A summary of the effect of these energy-saving initiatives is shown in Table 15.

**Table 15: Case Study 1 – Compressor power reduction summary for Initiatives 1 to 5**

Phase	Initiative	Average power (MW)	Difference (MW)
Before production stoppage	–	8.06	0.00
Set-point control (a)	1	8.03	-0.03
Manual valve control (b)	2 & 3	7.86	-0.17
Surface valve control and compressor selection (c)	4 & 5	6.04	-1.82
Final surface valve adjustment (d)	4	6.70	+0.66
<b>Total difference (MW)</b>	1–5		<b>-1.36</b>

The manual control of valves that malfunctioned and the reduction of the refuge bay flow were reactions to unforeseen events that could not be planned for. Set-point control and surface valve control form part of the standard procedures that Mine A follows when a production stoppage starts, while compressor selection was another reaction to a sudden drop in demand. Therefore, only two of the five initiatives were planned.

### 3.2.3.2 Compressor set-point reduction (Initiative 6)

This initiative was not planned at the start of the production stoppage and was found as part of an investigation to further reduce the compressor power usage after the initial reduction. It took five weeks to complete the investigation, after which it was necessary to first convince the management of Mine A to approve the initiative. The management of Mine A agreed to adjusting the compressor set points after 48 days of continuous production stoppage.

The compressor combination was first changed to C2 and C4 before changing the pressure set points. This combination used more power and delivered more compressed air flow but was better suited to handle lower set points, according to the mine personnel. The guide vane for C2 was also manually overridden and adjusted to only use 3 MW instead of 4 MW of power. The constant angle of the guide vane allowed C2 to act as the baseload compressor with constant supply, which enabled C4 to act as the trimming compressor and automatically adjust as the demand changed. Figure 17 shows the compressed air flow before and after the compressor set-point adjustment, and Figure 18 shows the corresponding compressor power usage.

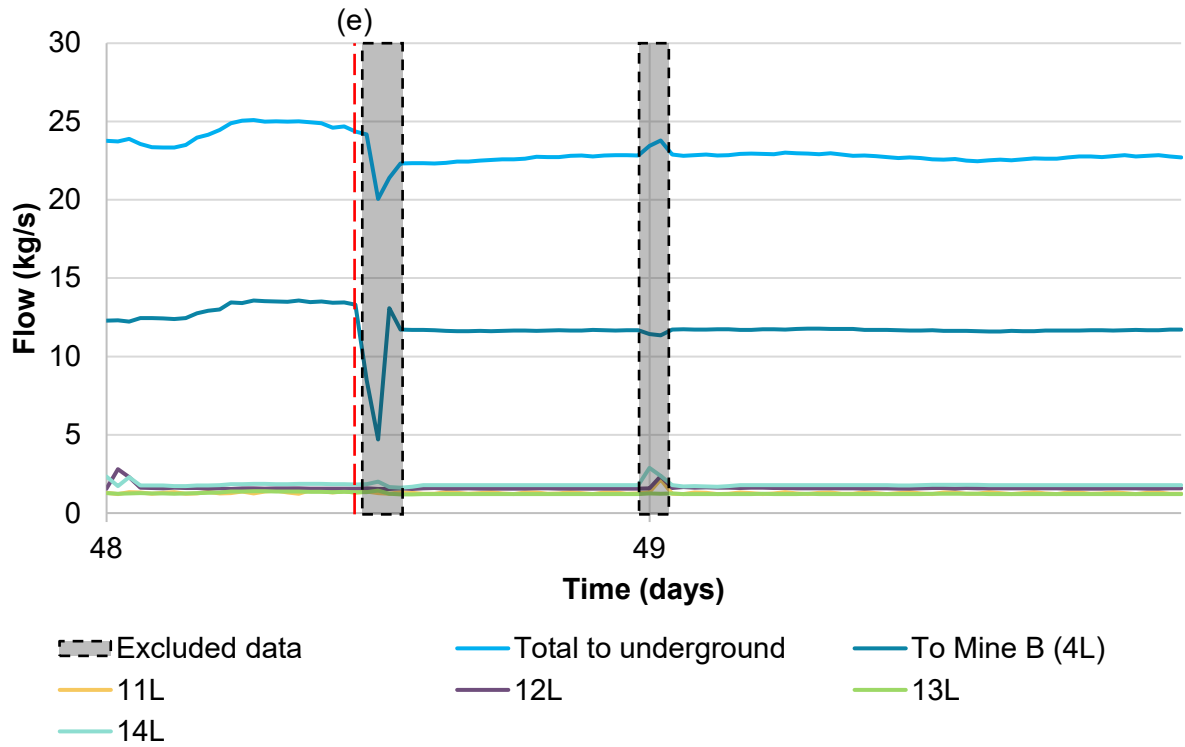


Figure 17: Case Study 1 – Compressed air flow before and after compressor set-point reduction

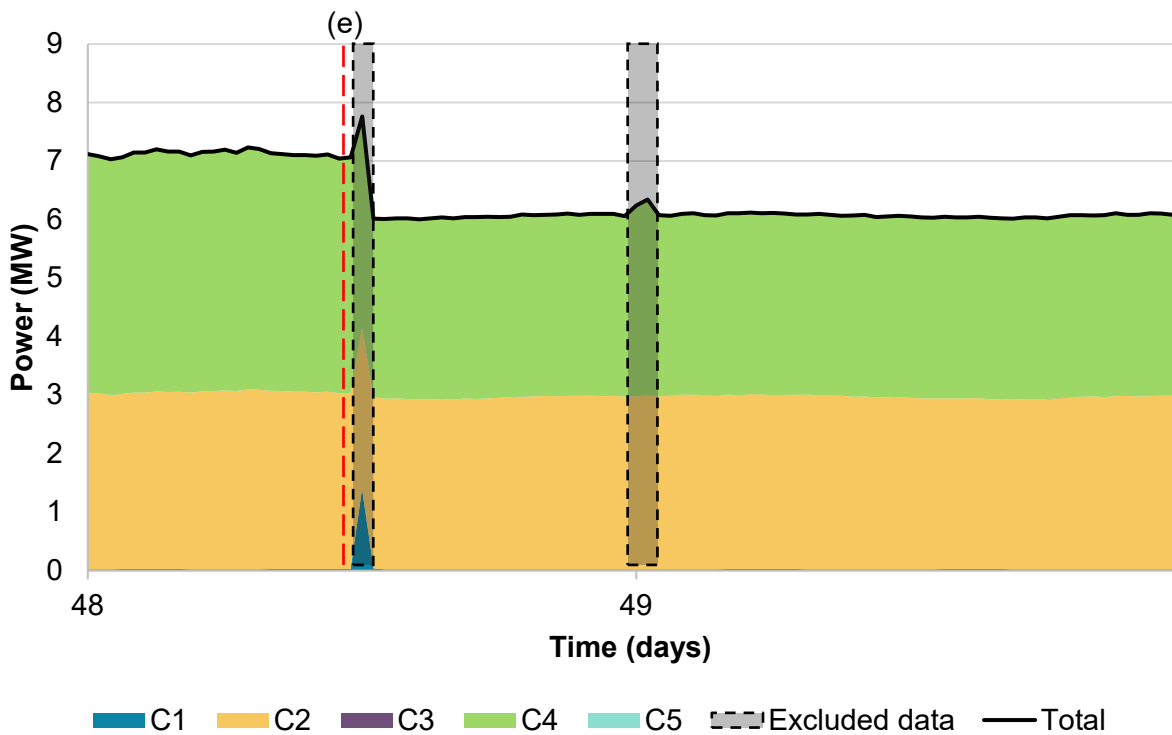


Figure 18: Case Study 1 – Compressor power before and after compressor set-point reduction

The pressure set point of C4 was reduced from 510 kPa to 430 kPa as part of Initiative 6, indicated at point (e) on Figure 17 and Figure 18. The adjusted set point resulted in a compressed air flow that was similar to the C3 and C4 combination, but with a lower power consumption. A summary of the effect of the compressor set-point reduction is shown in Table 16.

**Table 16: Case Study 1 – Compressor power reduction summary for Initiative 6**

Phase	Compressor combo	Initiative	Average power (MW)	Difference (MW)
After initial reduction period	C3 & C4	1–5	6.70	0.00
Before set-point adjustment	C2 & C4	–	7.13	+0.43
After set-point adjustment (e)	C2 & C4	6	6.06	-1.07
<b>Total difference (MW)</b>		6	<b>-0.64</b>	

Lowering the compressor pressure set point resulted in a power reduction of 0.64 MW despite switching to a less efficient compressor combination.

### 3.2.4 Step 3: Reverse

The reduced pressure set points for the compressors and throttled valves were sufficient to meet the demand during the production stoppage period. However, the supply was too low to accommodate the demand of a typical production period. Therefore, the initiatives implemented during the production stoppage were reversed near the end of the production stoppage to allow normal production to start. The compressor power during the reversal period is shown in Figure 19 with the corresponding compressed air flow shown in Figure 20.

Mine A released an announcement on day 96, indicated at point (a) on Figure 19 and Figure 20. The announcement stated that the strike was concluded and that normal operations would be restored gradually as part of a phased start-up. The compressor set points, Initiative 6, were reverted to 510 kPa on day 99 in response to the announcement. Additionally, the surface valve from Initiative 4 was reset to its standard position, and the compressor combination, Initiative 5, was adjusted. The reversion of Initiatives 4–6, shown at point (b), resulted in an increase in compressed air flow of 3.31 kg/s and a compressor power increase of 1.23 MW.

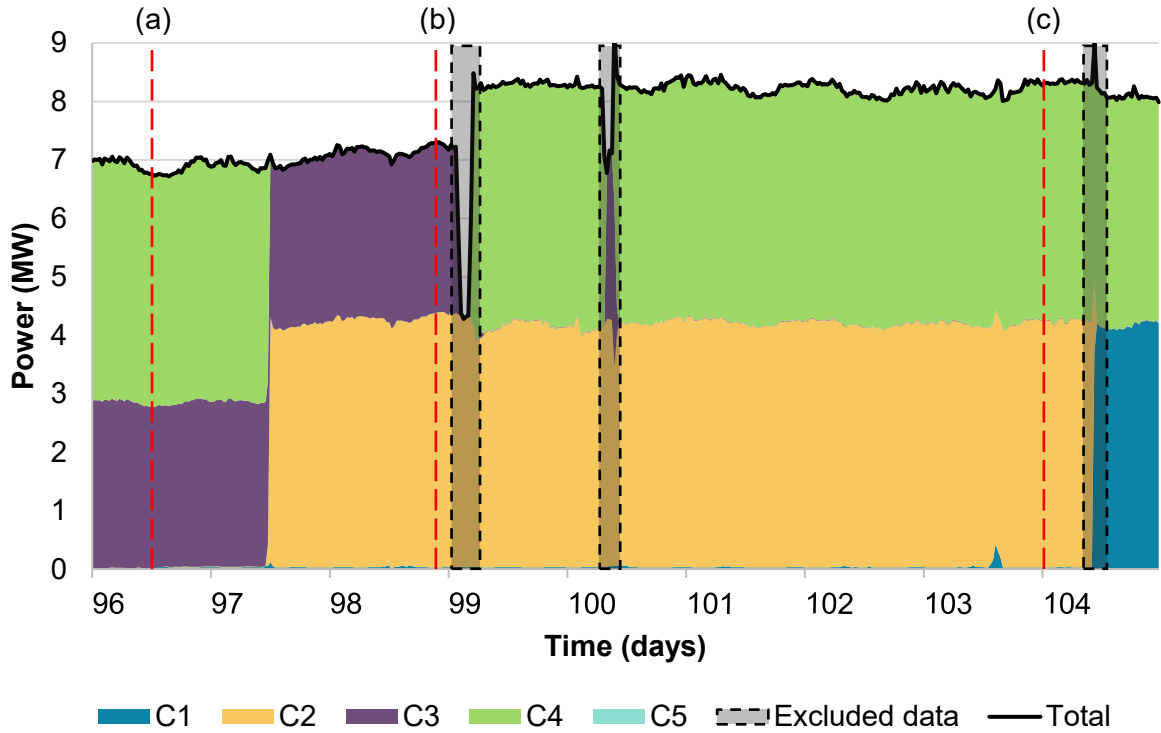


Figure 19: Case Study 1 – Compressor power during reversal period

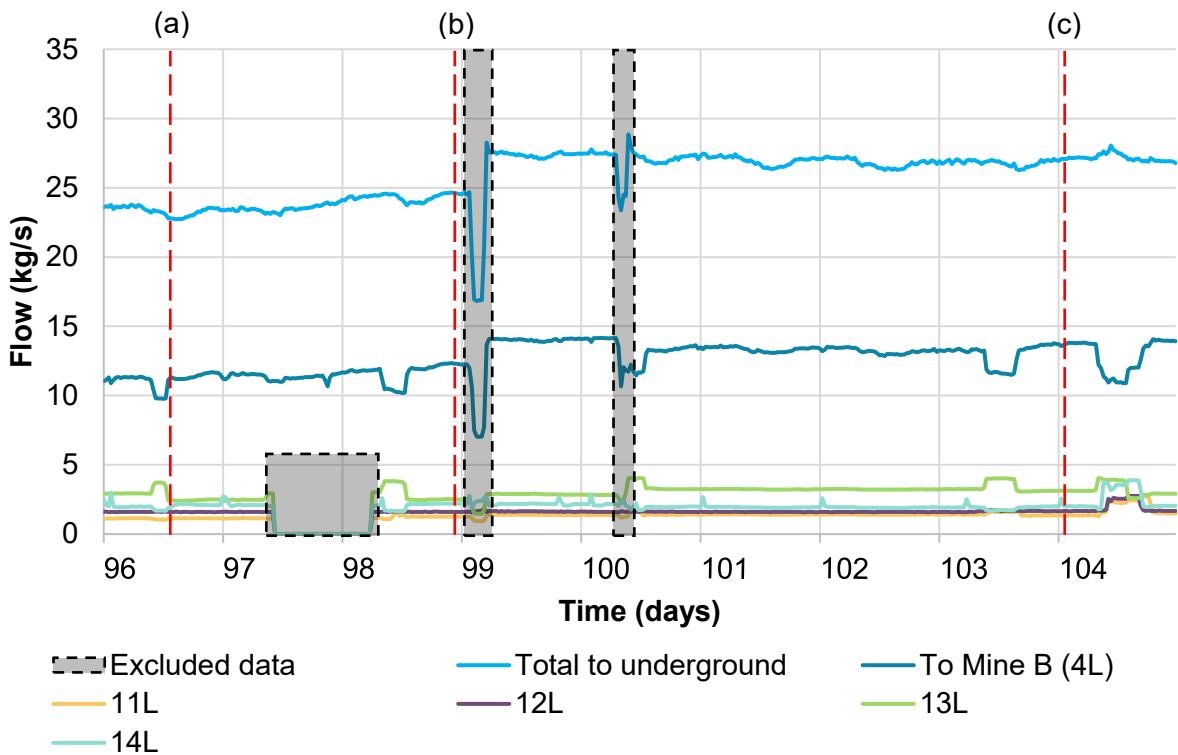


Figure 20: Case Study 1 – Compressed air flow during reversal period

The valve set points, Initiative 1, were only restored to the standard schedule on day 104 due to the phased start-up. This also required resetting the manually adjusted underground valves that formed part of Initiatives 2 and 3. The reversion of Initiatives 1–3, indicated at point (c), did not have a noticeable effect on the overall compressed air flow or compressor power. However, the flows of individual levels returned to the typical production period values as shown in Figure 20.

### **3.2.5 Step 4: Quantify**

This section discusses the overall performance of the energy-saving initiatives over the full duration of the production stoppage and some of the challenges faced after implementation.

#### *3.2.5.1 Baseline*

The performance of the implemented energy-saving initiatives is measured in terms of energy savings, which requires a baseline for comparison as discussed in Section 2.6.5. A previous production stoppage at Mine A was used to create the required baseline, and Mine A's power usage was ringfenced based on the compressed air flow, as mentioned in Section 2.6.4.

The baseline period chosen for Mine A was the Christmas break of the year prior to the production stoppage used for the case study. This period was chosen because it was the longest continuous production stoppage that occurred within a year of the case study. The proximity of these events ensured that the infrastructure and layout of the CAS were similar with comparable baseloads between the periods. Figure 21 shows the compressor power during the baseline period.

The baseline production stoppage started after the afternoon shift of day zero and continued for ten days. Three compressors accidentally ran at once, which was rectified after the night shift on day one. The period before the production stoppage, fluctuations in power during compressor changeovers, and the period during which three compressors were running were excluded from the baseline. The remaining data was averaged to obtain a baseline for the total compressor power usage as shown in Table 17. This was split between Mine A and Plant A based on the average compressed air flow during the baseline period to ringfence Mine A's power usage. The total flow to underground and the flow supplied to Plant A are shown in Figure 22.

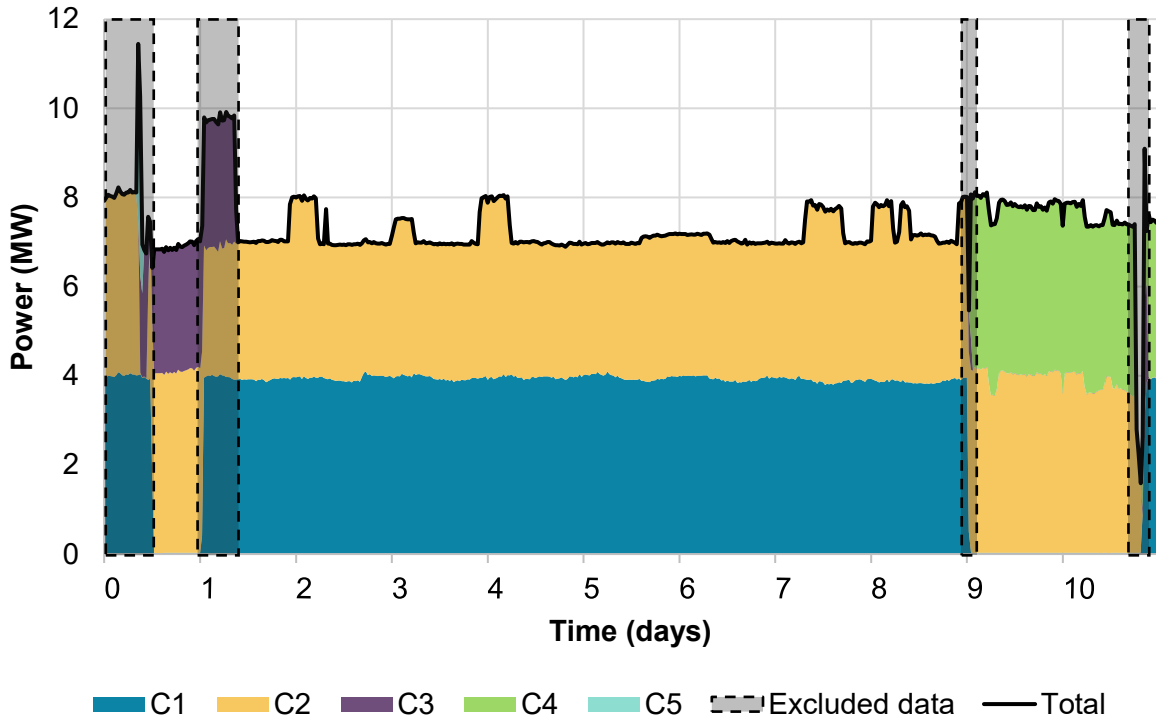


Figure 21: Case Study 1 – Compressor power during baseline period

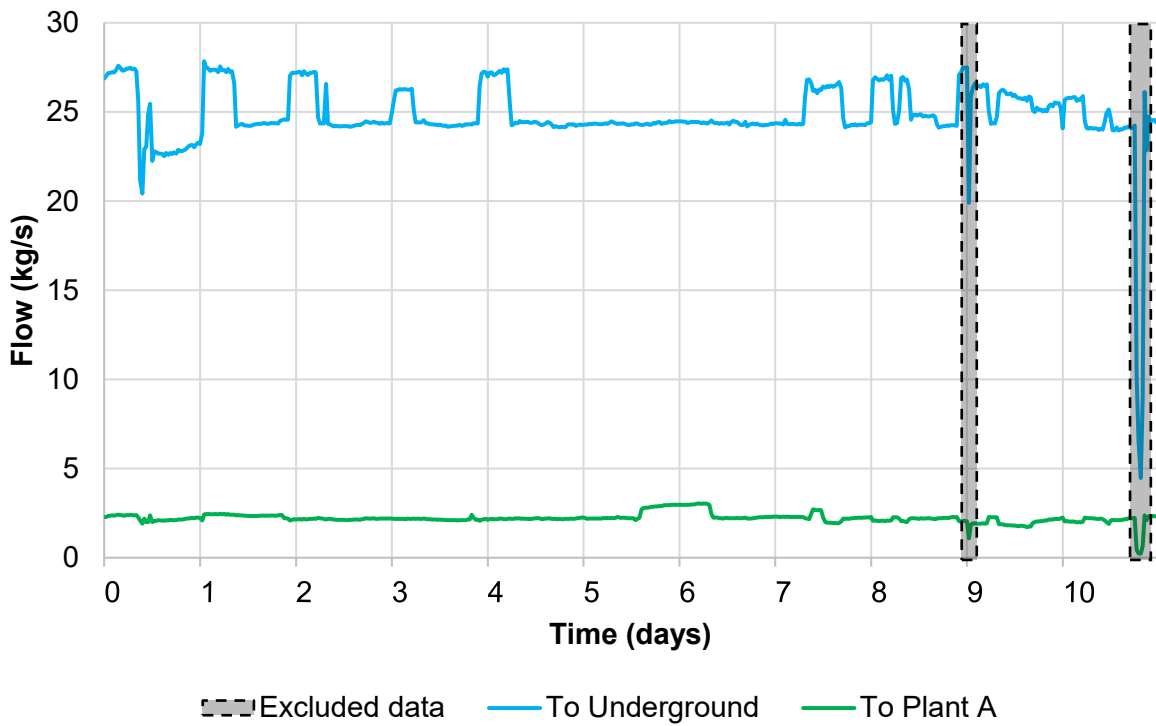


Figure 22: Case Study 1 – Compressed air flow during baseline period

**Table 17: Case Study 1 – Average compressed air flow and power split during baseline period**

<b>Section</b>	<b>Flow (kg/s)</b>	<b>Power split (MW)</b>
Underground (Mine A & Mine B)	24.84	6.67
Plant A	2.23	0.60
<b>Total baseline</b>	<b>27.07</b>	<b>7.27</b>

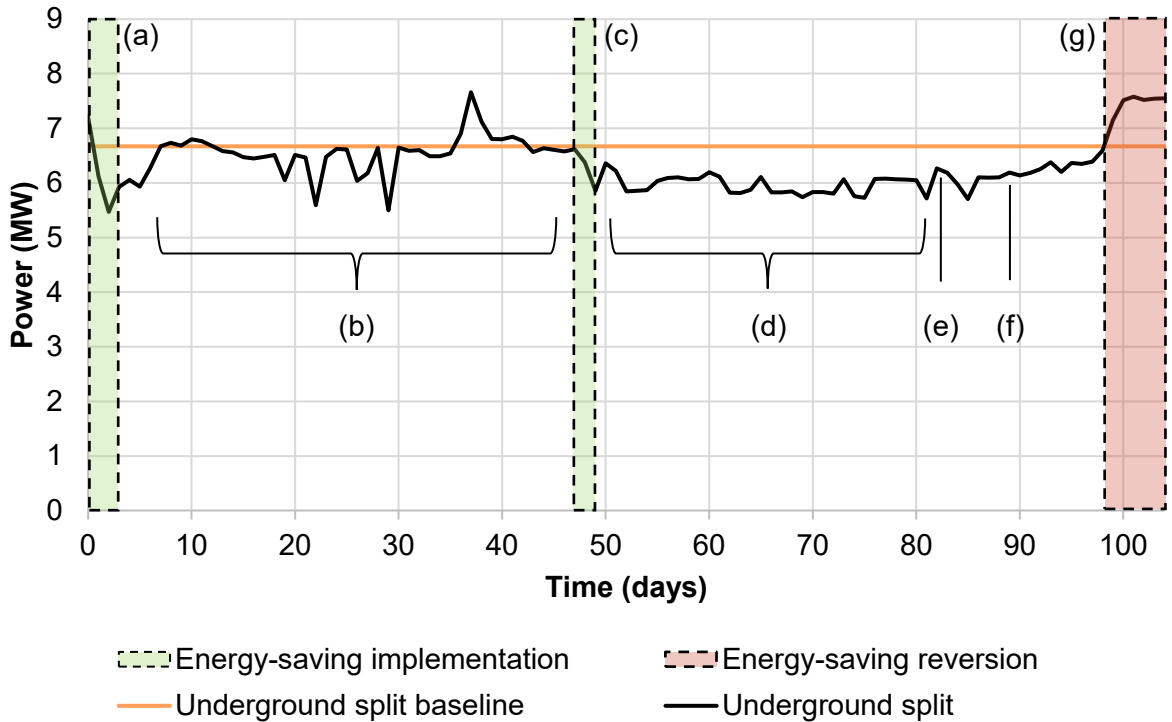
The compressed air usage for Plant A was 8% of the total compressed air supplied by the compressors, while 92% was sent underground at Mine A to supply Mine A and Mine B during the baseline period. A ringfenced baseline for the underground section was made by allocating 92% of the 7.27 MW average to the underground section. This resulted in a baseline for the underground section equal to 6.67 MW, which was used to evaluate the performance of the energy-saving initiatives applied during the case study.

### *3.2.5.2 Full production stoppage overview*

The energy-saving initiatives implemented in Section 3.2.3 only comprised a small portion of the roughly 100 days that the case study production stoppage lasted. This section discusses the production stoppage as a whole and the challenges that affected the overall performance of the energy-saving initiatives.

The total compressor power usage was split between the underground section and Plant A based on the average compressed air flow for each day according to the ringfencing method mentioned in Section 2.6.4. The compressor power usage of the underground section during the production stoppage is shown in Figure 23.

The initial implementation of energy-saving Initiatives 1 to 5, shown at point (a) on Figure 23, achieved a reduction of 1.36 MW. However, this reduction was only enough to match the baseline after the surface valve was readjusted to increase the flow to underground. The compressor combination was changed regularly during the period indicated at point (b) to ensure that each compressor functioned properly and did not stand idle for too long. Attempts were made to adjust and prevent inefficient combinations, such as the combination on day 37.



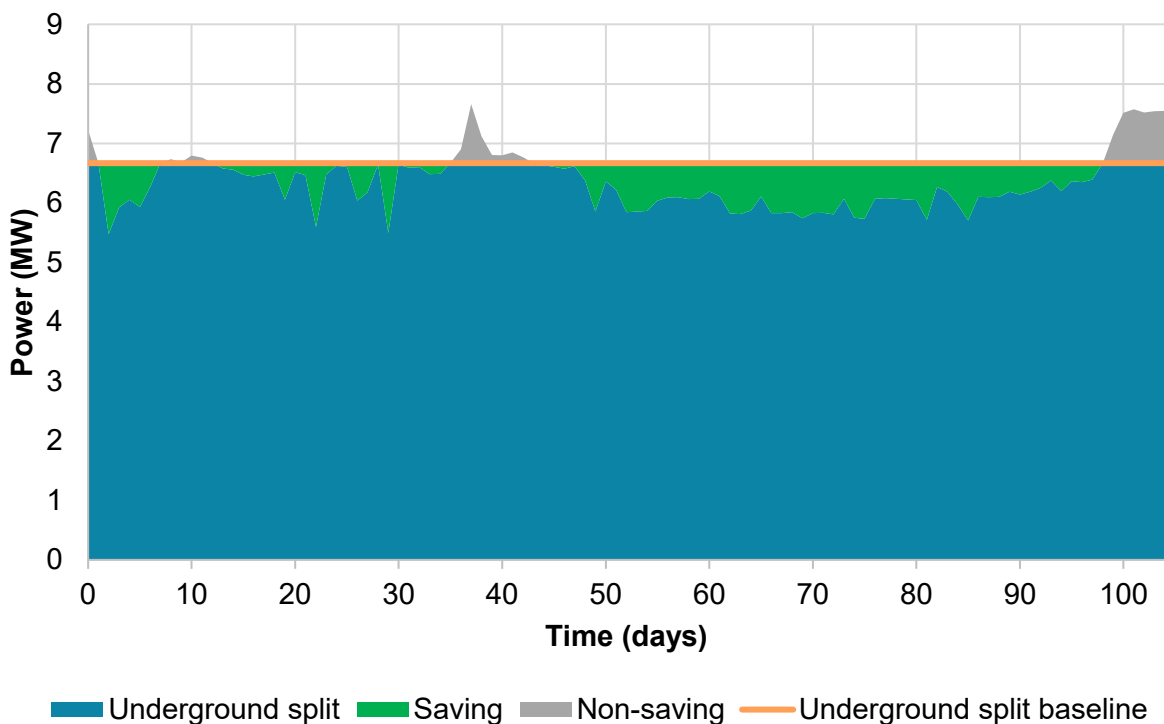
**Figure 23: Case Study 1 – Compressor power of underground split during production stoppage**

An investigation was done to find ways to further reduce compressor power. Initiative 6, at point (c), was discovered and the compressor set points were reduced on day 48 after weeks of little to no savings. A reduction of 640 kW was initially achieved after reducing the compressor set points. The compressor combination was optimised as part of Initiative 6, however, the combination was still switched regularly, which reduced the potential savings as shown at point (d). Despite the inconsistent compressor combination, the set-point reduction still achieved an average power reduction of 600 kW.

A power failure on day 82, shown as point (e), reset the compressor set points and was rectified the following day. The mine later started development on 11L with a limited crew, shown at point (f). This increased demand and compressor power usage, which further reduced savings. Finally, the compressor set points were reverted to 510 kPa, shown as point (g), following an announcement that the strike was ending. The mine reversed the implemented energy-saving initiatives during the days following the announcement, and steadily returned to normal operation by day 104.

### 3.2.5.3 Energy savings during production stoppage

The energy savings achieved by the implemented energy-saving initiatives were used to determine the performance when compared with the baseline. This was calculated by determining the difference between the baseline energy usage and the energy used by the underground section during the case study according to Equation 1. The energy was calculated by determining the area under the curve for the baseline and underground section using Equation 2. Monetary savings were calculated from the energy savings based on the applicable Eskom tariffs and TOU periods, which are discussed in more detail in Annexure E. The compressor energy savings during the case study production stoppage are shown in Figure 24.



**Figure 24: Case Study 1 – Compressor energy savings during production stoppage**

During the production stoppage, there were certain periods where the power usage was above the baseline, which would result in negative savings if those areas were included in the saving calculation. These periods are shown as grey areas in Figure 24. They were excluded from the saving calculation since the power increase was not due to the energy-saving initiatives that were implemented. The energy savings that were achieved are shown as green in Figure 24. The total equals 1.06 GWh, which is equivalent to a cost saving of R1.07 million based on the applicable Eskom tariffs during the production stoppage. This is equivalent to a cost saving of R1.6 million in FY2024/25.

### **3.3 Prioritisation method review**

#### **3.3.1 Preamble**

The prioritisation method was applied retrospectively in Case Study 1 as discussed in Section 3.2. This section reviews the method based on the case study results by considering the accuracy, benefit and shortcomings.

#### **3.3.2 Overview of the method**

The prioritisation method used for production stoppages was adapted from an existing method from Bredenkamp [37] as described in Section 2.3. The adapted prioritisation method uses a number-based scoring method. Energy-saving initiatives are scored based on multiple criteria, whereafter the scores are summed. The total scores are ordered from highest to lowest. Energy-saving initiatives are implemented according to this order similar to methods used by De Jager and Du Toit [5, 61]. Additionally, unfeasible energy-saving initiatives are excluded from the final prioritised list, which is consistent with the approaches taken by Maré *et al.* and Du Toit [48, 61]. Therefore, the prioritisation method used as part of Step 1 of the developed strategy, shown in Figure 13, operates in a similar manner to other prioritisation methods used in previous studies.

#### **3.3.3 Accuracy of the method**

The prioritisation method, consisting of the score key in Table 8 and the checklist in Table 9, was applied based on the information that was available at the start of the case study production stoppage. This resulted in a sequenced and filtered list of four energy-saving initiatives as shown in Table 14. Such a list was not available at the time of the case study production stoppage and energy-saving initiatives were instead implemented as a reaction to the events that occurred.

The performance of the prioritisation method was compared with the results obtained when relying on industry knowledge and expertise without a focused strategy. Table 18 compares the energy-saving initiatives generated by the prioritisation method with the energy-saving initiatives that were implemented during the production stoppage.

**Table 18: Implemented energy-saving initiatives compared with the sequenced list**

<b>Energy-saving initiative</b>	<b>Generated list sequence</b>	<b>Implemented sequence</b>
Valve set-point control	1	1. The set points on the actuated valves were reduced to 150 kPa.
Underground valve control	N/A	2. The 14L actuated valve malfunctioned and was adjusted manually.
Reduce refuge bay flow	N/A	3. The 13L valve was adjusted to reduce the refuge bay flow since there were no workers.
Surface valve control	2	4. The surface valve was adjusted to reduce the total flow to underground.
Compressor selection	3	5. The reduction in total compressed air flow allowed for a more efficient compressor combination.
Compressor pressure set-point reduction	4	6. The compressor set points were lowered on day 48.

The prioritisation method successfully identified four out of the six energy-saving initiatives that were implemented. The two unidentified initiatives were unforeseen events and the implementation of these two initiatives was only possible by using an essential worker in an emergency during the production stoppage. Additionally, the identified initiatives were in the same order as the implemented initiatives. This shows that the prioritisation method has a high level of accuracy.

### **3.3.4 Shortcoming of the method**

The method used to prioritise and filter the energy-saving initiatives did not take the failure of valves and the potential of reducing refuge bay flow into account because these events could not be foreseen. The list of initiatives generated by the prioritisation method included valve set-point control but did not account for the lack of power reduction that was witnessed when implementing the initiative during the case study. Similarly, the list included compressor selection but did not account for the need for regular compressor changes, which led to reduced savings during the production stoppage. Therefore, it is still necessary to monitor the CAS during a production stoppage and manage any unexpected events.

### **3.3.5 Benefit of the method**

There was a six-week period during the production stoppage with little to no savings since the initial energy-saving initiatives only managed to match the baseline. During this period, an investigation was conducted to determine whether the compressor power usage could be reduced. The investigation concluded after five weeks and found that the compressor set points could be reduced from 510 kPa to 430 kPa. The compressor set points were implemented a week later and reduced the compressor power usage by an average of 600 kW.

If the list of generated energy-saving initiatives was present at the start of the production stoppage, the five weeks of investigation could have been avoided and the compressor set points implemented sooner. A potential saving of 500 MWh could have been achieved if the 600 kW reduction was implemented five weeks earlier, which is equivalent to a cost saving of R410 000 (R600 000 in FY2024/25). Therefore, the utilisation of the prioritisation method provides a time saving by assisting with the decision-making process, which may lead to additional cost savings.

### **3.3.6 Validation of the method**

The prioritisation method was validated by comparing the generated list of energy-saving initiatives with those actually implemented in Case Study 1. As discussed in Section 3.3.3, the method successfully identified 67% of the initiatives that were implemented. The remaining energy-saving initiatives were unpredictable and beyond the scope of the method. Additionally, the order of identified energy-saving initiatives matched the sequence of implementation. This shows the method's reliability with regard to prioritisation.

The prioritisation method also shows potential for significant time and cost savings during the decision-making process. This is evident when considering the potential saving of R410 000 for Case Study 1. Therefore, the prioritisation method is accurate and valid for application in the context of mine CAS.

## **3.4 Case Study 2**

### **3.4.1 Case study background**

The second case study was also conducted at Mine A and occurred during the planned annual December break. System changes were made prior to the case study period, which significantly reduced the demand of Mine A. Figure 25 shows a simplified illustration of the modified CAS.

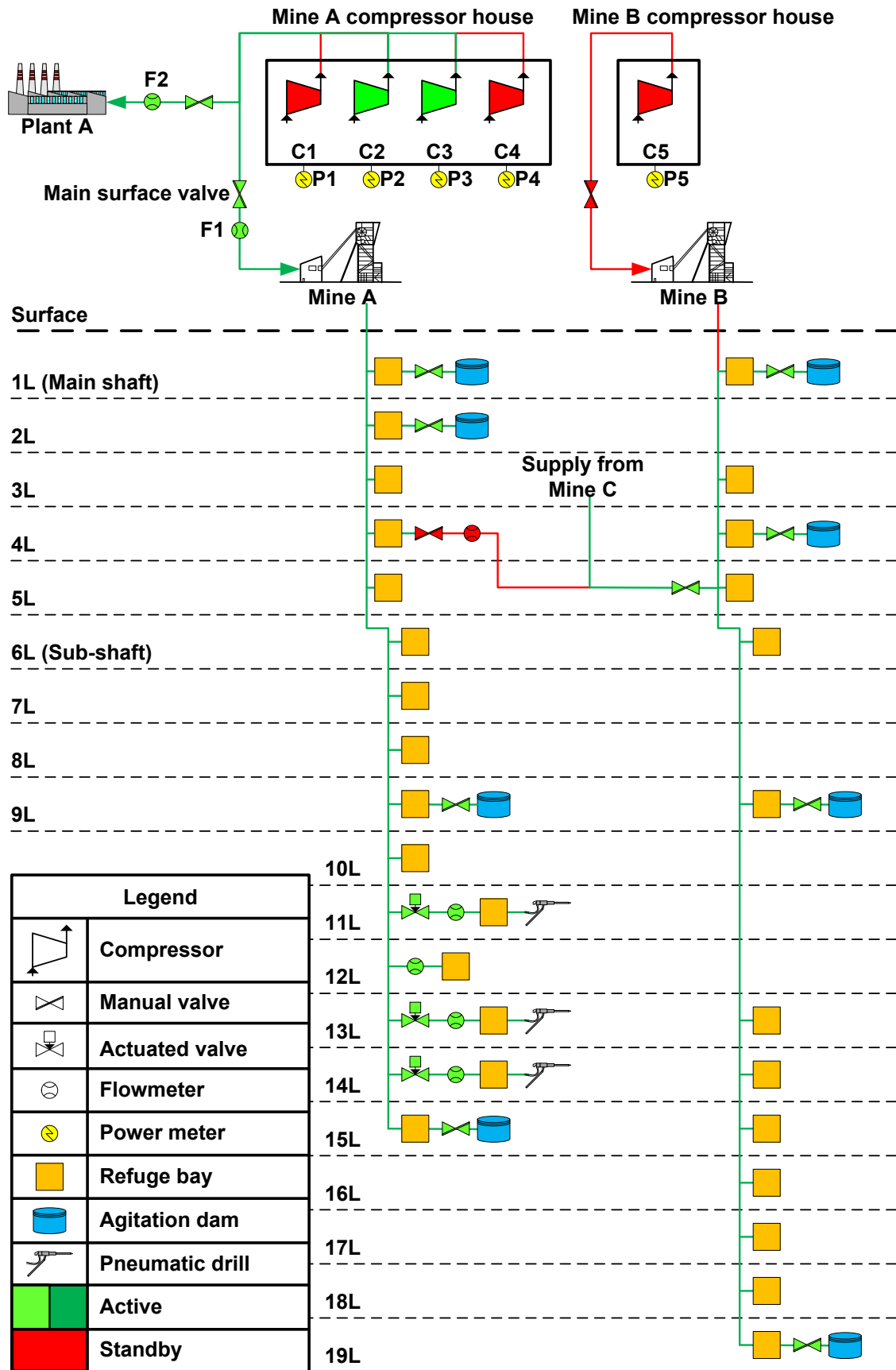


Figure 25: Case Study 2 – Compressed air system layout

Mine management decided to isolate the connection between Mine A and Mine B on 5L due to the poor condition of the distribution network. Mine C subsequently started supplying Mine B with compressed air via an underground connection. Mine A's compressor house continued to supply compressed air to Plant A and Mine A.

The compressors used by Mine A are identical to the first case study as listed in Table 12. Similarly, the power meters and flowmeters are the same as the first case study as discussed in Section 3.2.1. It is assumed that the accuracy of the power meters remains unchanged since both case studies occurred within the same year. The power meter verification is discussed in Annexure D.

Flowmeters F1 and F2, shown in Figure 25, are used to split compressor power consumption between Mine A and Plant A, respectively, based on compressed air flow. As mentioned in Section 3.2.1, power failures and compressor changeovers may cause data loss or fluctuations in measurements. Where applicable, erroneous values are indicated as grey rectangles on each graph and are not included in calculations. Although some grey rectangles are omitted to improve visibility, the relevant data is still excluded.

### **3.4.2 Step 1: Prioritise and filter**

The first step of the energy-saving strategy, shown in Figure 13, is to prioritise and filter energy-saving initiatives. This was done a week before the start of the production stoppage since it is a planned event that occurs on the same dates every year. However, there were still some limitations regarding the implementation of energy-saving initiatives as listed below.

1. Mine A was unwilling to spend any capital since no income was being generated.
2. Most employees were on leave during the annual break and only limited labour was available.
3. Plant A required a constant supply of compressed air.

The scoring key in Table 8 and the checklist in Table 9 were used to generate a prioritised and filtered list of energy-saving initiatives according to the prioritisation method discussed in Section 2.3. Each energy-saving initiative was scored based on five criteria with the given limitations considered. A detailed discussion of the scores can be found in Table 27 in Annexure C.

The scores allocated to each energy-saving initiative are summarised in Table 19. A total of four energy-saving initiatives were considered feasible and were ordered from the highest to the

lowest score to create a sequenced list. The energy-saving initiatives are listed in order of priority in Table 20.

**Table 19: Completed energy-saving initiative checklist for Case Study 2**

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Compressor control	Compressor selection	5	4	3	3	3	18
	Guide vane control	–	–	–	–	X	X
	Load sharing	–	–	–	–	X	X
	Load-unload	–	–	–	–	X	X
	Pressure set-point reduction	–	X	–	–	–	X
	Regular maintenance	–	–	–	–	X	X
	Stop-start	5	5	3	3	4	20
	VSD	X	–	–	–	–	X
Control valves	Peak-clipping	–	–	–	–	X	X
	Set-point control	5	5	5	5	2	22
	Stope isolation	–	–	X	–	–	X
	Surface valve control	5	5	4	5	2	21
	Underground valve control	–	–	X	–	–	X
Wastage reduction	Close inactive sections	–	–	X	–	–	X
	Eliminate/reduce unauthorised use	–	–	–	–	X	X
	Repair leaks	–	–	X	–	–	X
System changes	Adjust mining shifts	–	–	–	–	X	X
	Use dedicated compressors	X	X	–	–	–	X
	Eliminate/reduce pneumatic equipment	X	–	–	–	–	X
	Integrate smaller CASs	–	–	–	–	X	X
	Use optimally sized compressors	X	X	–	–	–	X
	Reconfigure pipes	X	X	–	–	–	X
	Reduce compressor inlet temperatures	X	–	–	–	–	X
	Reduce refuge bay flow	–	–	X	–	–	X

Table 20 shows the final list of feasible energy-saving initiatives.

**Table 20: Sequenced and filtered list of energy-saving initiatives for Case Study 2**

<b>Sequence</b>	<b>Strategy</b>	<b>Initiatives</b>	<b>Total score</b>
<b>1</b>	Control valves	Set-point control	22
<b>2</b>	Control valves	Surface valve control	21
<b>3</b>	Compressor control	Stop-start	20
<b>4</b>	Compressor control	Compressor selection	18

Energy-saving initiatives requiring capital investment or labour other than essential personnel were excluded according to the limitations of the production stoppage. Additionally, any energy-saving initiatives that were not expected to deliver a benefit were also excluded. These included pre-existing initiatives that were not expected to perform any differently during the production stoppage, such as guide vane control.

### **3.4.3 Step 2: Implement**

The selected energy-saving initiatives from Step 1 in Table 20 were used to draft an implementation plan for the production stoppage. This plan was communicated to the relevant mine personnel before the start of the production stoppage and included the expected dates and times at which the initiatives had to be implemented. The production stoppage started after the night shift at 05:00 on the first day. Figure 26 and Figure 27 show the compressed air flow and compressor power during the implementation of energy-saving initiatives, respectively.

The pressure set points of the underground control valves were set to the minimum refuge bay requirement of 150 kPa ahead of time. This was done by remotely adjusting the relevant valve schedules through the mine's SCADA. The set-point adjustment, Initiative 1, automatically reduced the compressed air flow of specific levels when the production stoppage started, as indicated at point (a) on Figure 26. The surface valve was throttled at the same time, Initiative 2, also at point (a). These valve adjustments significantly reduced the compressed air demand of Mine A and allowed a compressor to be stopped, Initiative 3, indicated at point (b) on Figure 27.

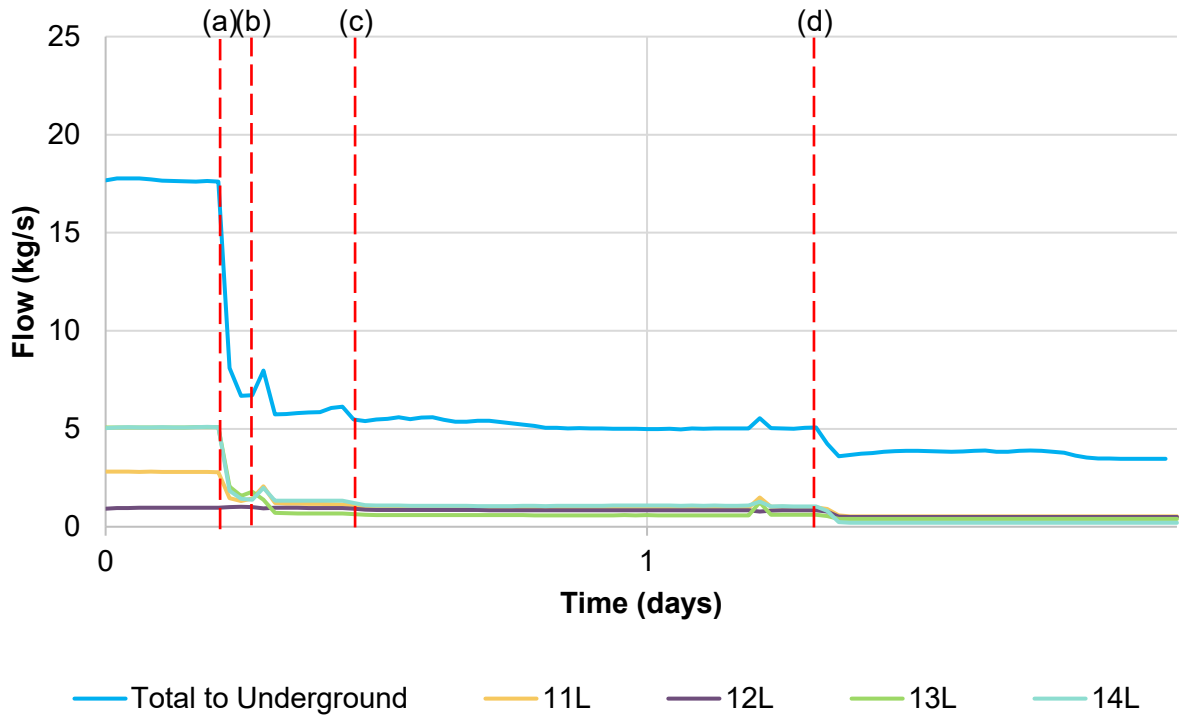


Figure 26: Case Study 2 – Compressed air flow during implementation

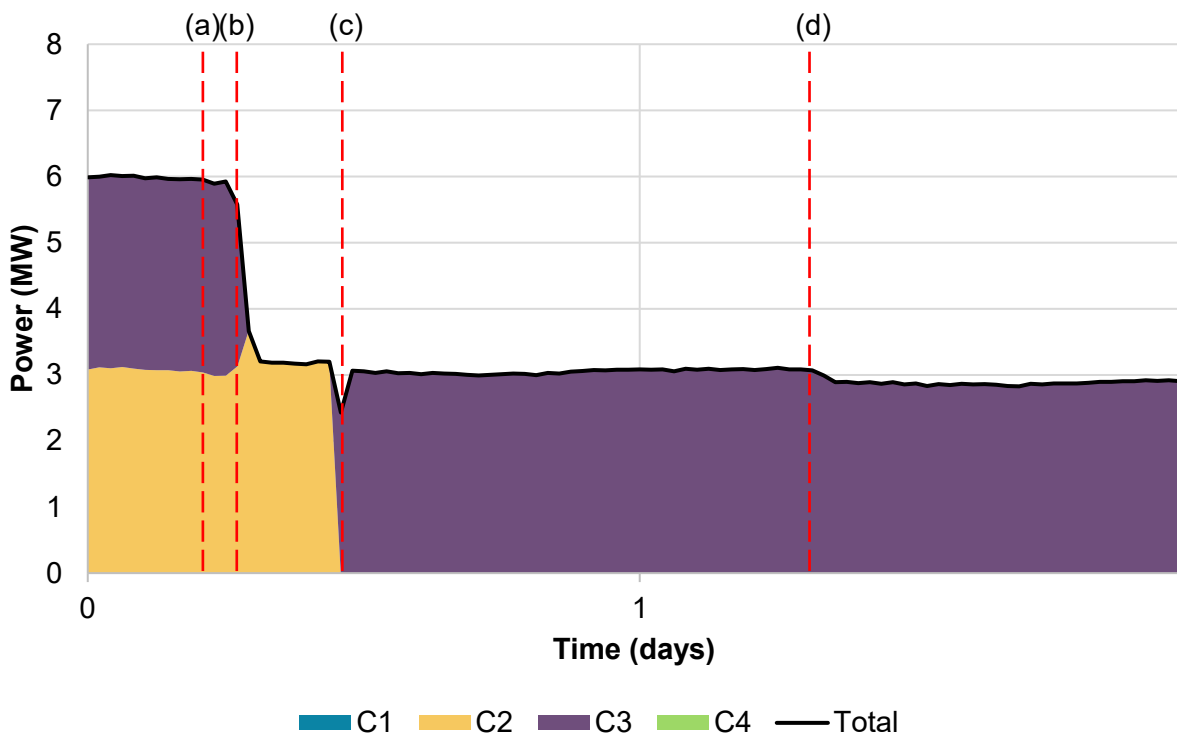


Figure 27: Case Study 2 – Compressor power during implementation

The stopping of a compressor reduced power consumption by 2.66 MW. Once the system stabilised, the active compressor (C2) was replaced by a more efficient compressor (C3). The changeover of compressors is indicated at point (c) on Figure 27 and is considered as compressor selection, Initiative 4. A final adjustment of the surface control valve was done the following day, which further reduced the compressor power consumption, as indicated at point (d).

Table 21 summarises the compressor power reduction achieved by implementing the energy-saving initiatives.

**Table 21: Case Study 2 – Compressor power reduction summary for Initiatives 1 to 4**

Phase	Initiative	Average power (MW)	Difference (MW)
Before production stoppage	–	5.98	0.00
Set-point control and surface valve control (a)	1 & 2	5.91	-0.07
Stop compressor (b)	3	3.25	-2.66
Compressor selection (c)	4	3.05	-0.20
Final surface valve adjustment (d)	2	2.88	-0.17
<b>Total difference (MW)</b>	1–4		<b>-3.10</b>

Mine A was operating at roughly 2 MW lower compressor power than the first case study due to the decreased compressed air demand after disconnecting Mine B from the CAS. The lower overall demand combined with the valve adjustments reduced the compressed air requirement enough to stop a compressor. Optimal compressor selection and further valve adjustments further reduced demand, and a total reduction of 3.1 MW was achieved after implementing Initiatives 1 to 4.

#### **3.4.4 Step 3: Reverse**

The third step of the strategy shown in Figure 13 was to reverse any energy-saving initiatives that would interfere with the supply of compressed air before the mine could return to normal operations. The full reversal was done on the last day of the production stoppage since the time taken to reverse each initiative was relatively short. Figure 28 shows the compressor power, and Figure 29 shows the compressed air flow during the reversal period.

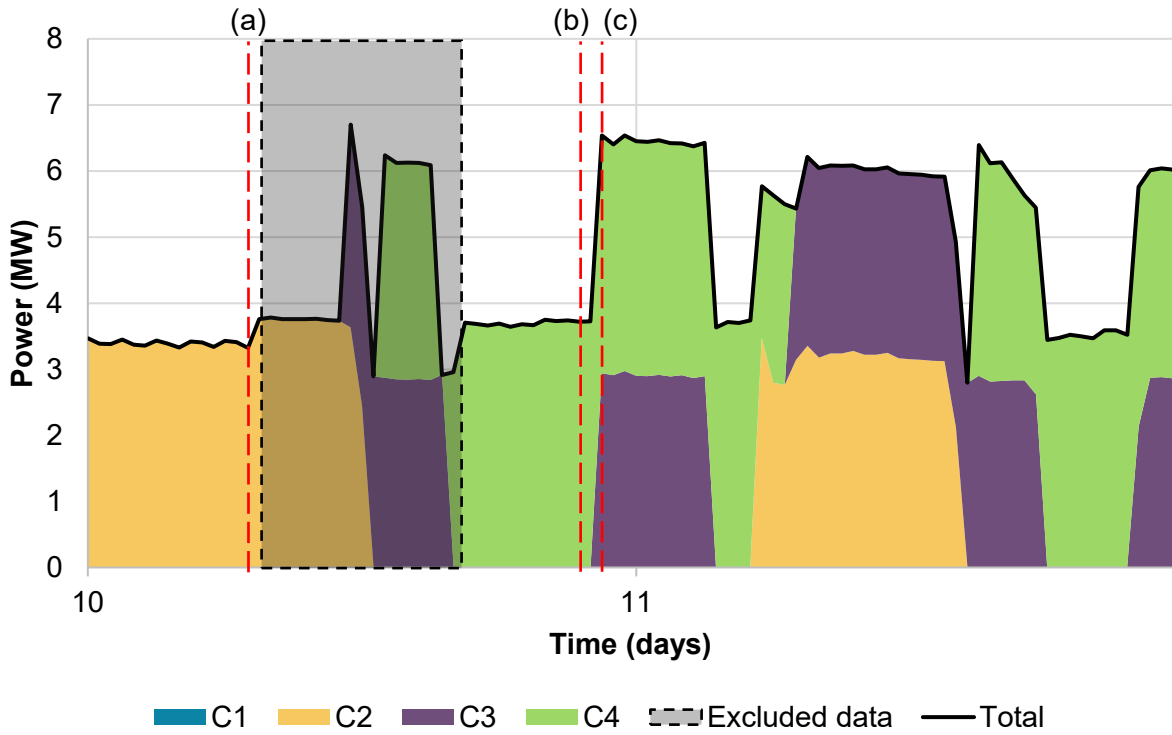


Figure 28: Case Study 2 – Compressor power during reversal period

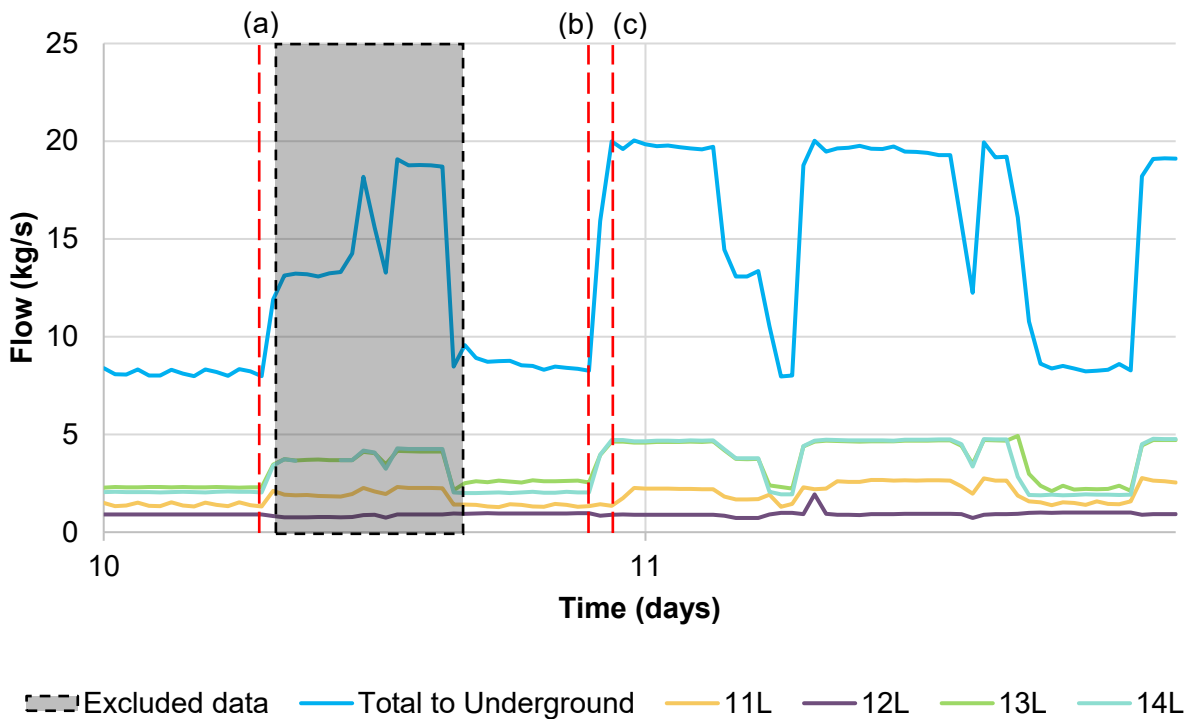


Figure 29: Case Study 2 – Compressed air flow during reversal period

Mine A uses planned production stoppages to perform necessary maintenance underground. The underground compressed air valves were opened occasionally, and a second compressor was started to accommodate work that required compressed air during the production stoppage. These events are considered temporary reversals since all energy-saving initiatives were reimplemented when compressed air was no longer required. An example of a temporary reversal is indicated at point (a) on Figure 28 and Figure 29.

The production stoppage concluded after 10 days and initiatives were fully reversed before the night shift of the last day. The pressure set points for the underground control valves were set to follow the schedule for a typical production period and the surface control valve was reset. Adjusting the valves led to an increase in compressed air flow as indicated at point (b) on Figure 29. A second compressor was started following the increase in compressed air demand, which also led to an increase in power consumption, indicated at point (c) on Figure 28. Mine A returned to normal operations the following day.

The total compressor power consumption increased by 2.86 MW after Initiatives 1 to 3 were reversed. Initiative 4, compressor selection, was not implemented for the full duration of the production stoppage. The compressors were cycled regularly to ensure that each compressor remained operational. Initiative 4 was therefore reversed halfway through the production stoppage by changing the active compressor to a less efficient one.

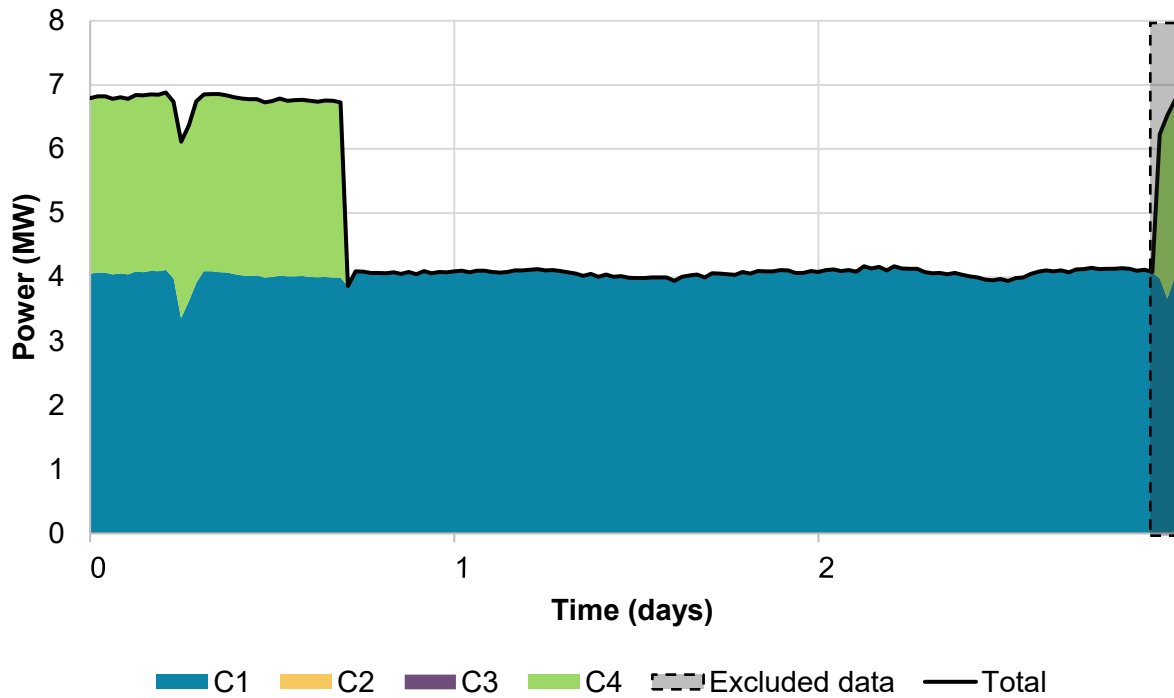
### **3.4.5 Step 4: Quantify**

The final step of the energy-saving strategy developed in Chapter 2 is to calculate the savings achieved by the implemented energy-saving initiatives. This is done after production has restarted.

#### **3.4.5.1 Baseline**

It is necessary to create a baseline for comparison before savings can be calculated, according to Section 2.6.4. The same baseline used for Case Study 1 could not be used for Case Study 2 since the layout and baseload of the CAS were different. Therefore, the nearest non-production or off weekend with the same system configuration was used as a baseline.

Mine A's power consumption was separated from Plant A based on the compressed air flow according to the ringfencing method discussed in Section 2.6.4. The total compressor power during the baseline period is shown in Figure 30.

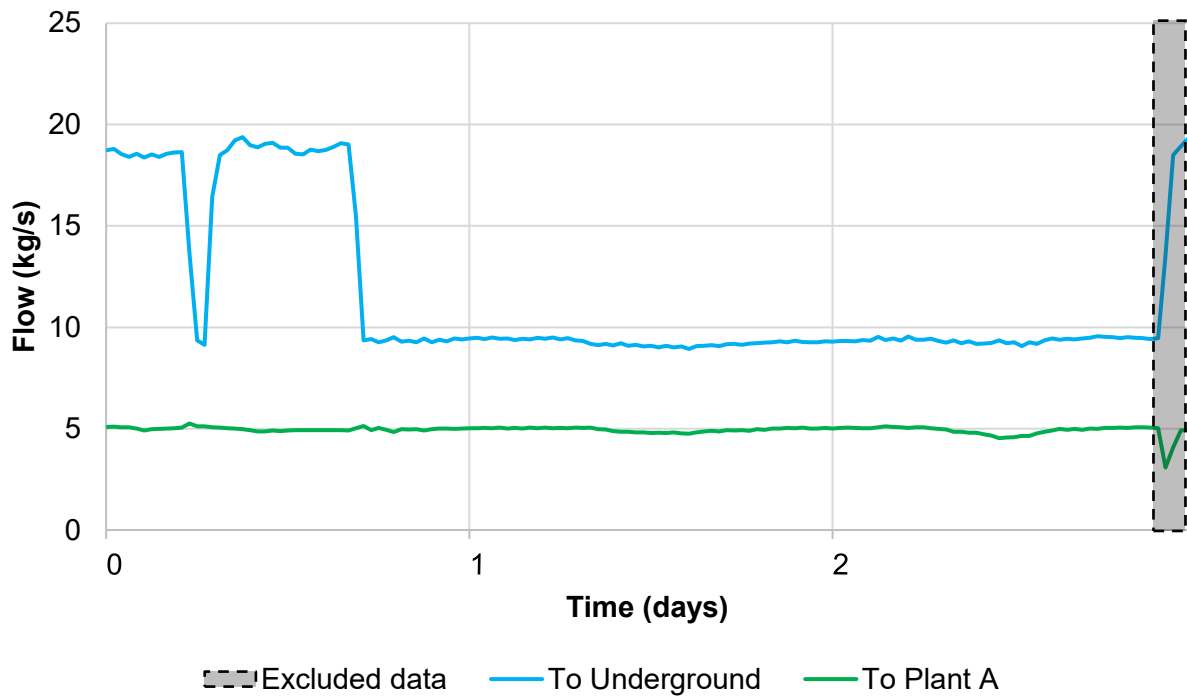


**Figure 30: Case Study 2 – Compressor power during baseline period**

The baseline production stoppage started on Friday after the afternoon shift and continued until the night shift of Sunday. A compressor was stopped at the start of the production stoppage, and only one compressor was required to supply the demand of Mine A and Plant A. The average of the compressor power during the baseline period was used as the baseline for the total compressor power as shown in Table 22. This was split further between Mine A and Plant A based on the average compressed air flow to ringfence Mine A’s power usage. The compressed air flow during the baseline period is shown in Figure 31.

**Table 22: Case Study 2 – Average compressed air flow and power split during baseline period**

Section	Flow (kg/s)	Power split (MW)
Underground (Mine A)	9.31	2.66
Plant A	4.95	1.41
<b>Total baseline</b>	<b>14.26</b>	<b>4.07</b>



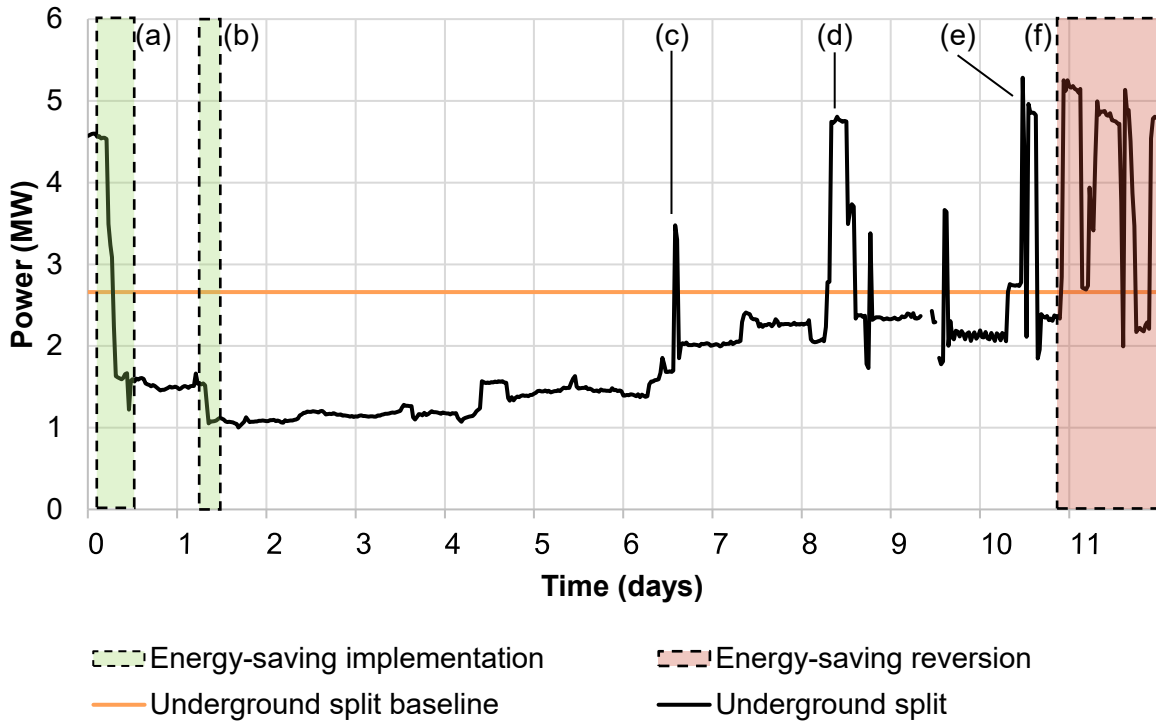
**Figure 31: Case Study 2 – Compressed air flow during baseline period**

The compressed air usage of Mine A comprised 65% of the total compressed air supplied by Mine A's compressor house. The remaining 35% of the compressed air was used by Plant A. Allocating 65% of the 4.07 MW total power consumption to Mine A resulted in a ringfenced baseline of 2.66 MW. This was used to calculate the savings achieved during the case study.

#### 3.4.5.2 Full production stoppage overview

The implementation and reversal periods discussed in Sections 3.4.3 and 3.4.4, respectively, only cover a portion of the case study production stoppage. An overview of the full production stoppage and challenges faced during this period will be provided in this section.

The ringfencing method from Section 2.6.4 was used to split the total compressor power between Mine A and Plant A based on the average compressed air flow of each day. The compressor power usage allocated to Mine A during the production stoppage is shown in Figure 32.



**Figure 32: Case Study 2 – Compressor power of underground split during production stoppage**

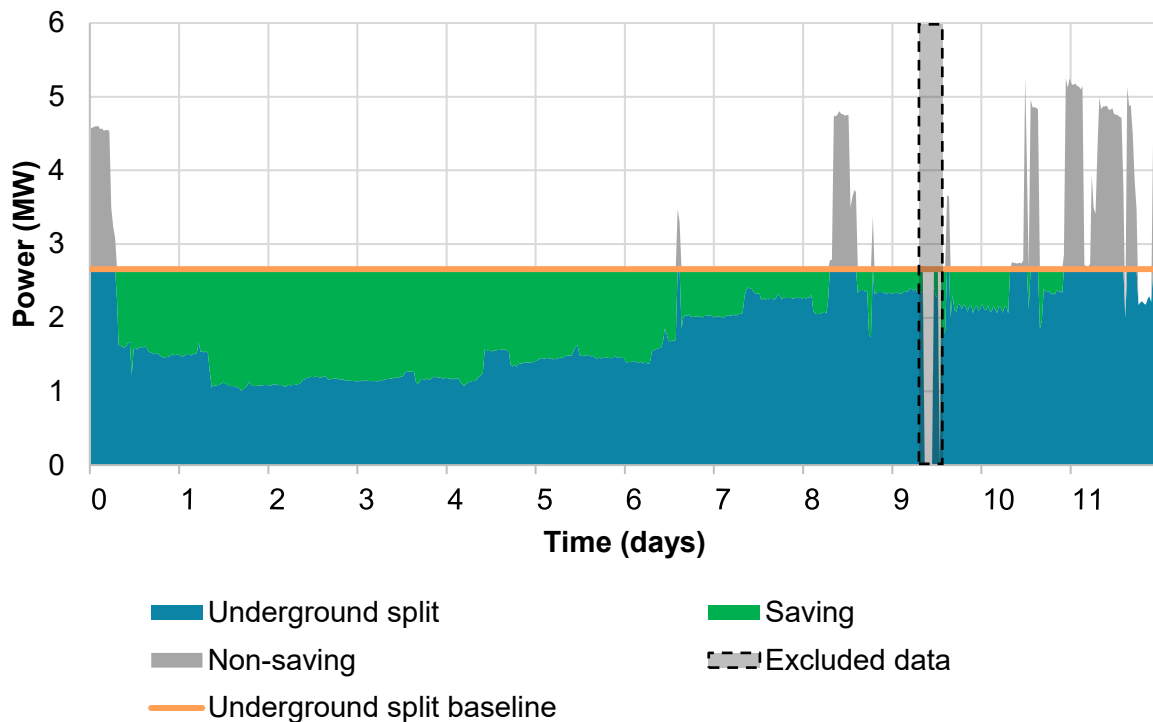
Energy-saving initiatives were implemented immediately after the production stoppage began due to the automated control valves possessing an adjustable schedule. Initiatives 1 to 4 were implemented within a short period and resulted in a reduction of 2.93 MW, as indicated at point (a) on Figure 32. The surface valve was readjusted a day later and achieved a further 0.17 MW reduction, shown at point (b). A total reduction of 3.1 MW was achieved after the implementation of all energy-saving initiatives.

The most efficient compressor was used initially; however, less efficient compressors were used later to ensure that each compressor remained operational, indicated at point (c). This reduced the overall saving achieved but power usage remained below the baseline. Changing to a less efficient compressor is considered a reversal of Initiative 4.

During two events, indicated at points (d) and (e), the underground valves were opened and a second compressor was started. This was done to accommodate work that required compressed air. These events further reduced savings and are regarded as temporary reversals of the implemented initiatives. All initiatives were reversed fully before the night shift of the last day, indicated at point (f). The mine returned to normal operations the following day.

### 3.4.5.3 Energy savings during production stoppage

The baseline created in Section 3.4.5.1 was compared with the power usage of Mine A during the production stoppage to determine the savings achieved during the production stoppage. Equation 1 was used to determine the power reduction, and Equation 2 was used to determine the total energy savings. The cost saving was calculated from the energy saving based on the relevant Eskom tariffs and TOU periods. More detail regarding tariffs and TOU periods is given in Annexure E. Figure 33 shows the compressor energy savings during Case Study 2's production stoppage.



**Figure 33: Case Study 2 – Compressor energy savings during production stoppage**

The grey areas on Figure 33 indicate periods during which the power usage was higher than the baseline, which are classified as non-saving periods. These values would result in a negative saving if included in the saving calculation and are not attributed to any energy-saving initiatives. Therefore, these periods were excluded from the final saving calculation. The energy savings, shown as green on Figure 33, add up to a total of 250 MWh and a cost saving of R200 000 based on the applicable Eskom tariffs during the production stoppage. This is equivalent to a cost saving of R270 000 in FY2024/25.

The developed strategy was applied to a case study and achieved a reduction in electricity cost, which accomplishes **Objective 3** listed in Section 1.4.3.

## **3.5 Developed strategy review**

### **3.5.1 Preamble**

The strategy developed in Chapter 2 was successfully applied to a case study production stoppage, and the effectiveness will be reviewed in this section.

### **3.5.2 Verification of strategy**

#### *3.5.2.1 Step 1: Prioritise and filter*

The first step is to decide which energy-saving initiatives to implement. As shown in Case Study 2 in Section 3.4.3, energy-saving initiatives could be implemented as soon as the production stoppage started since initiatives have already been prioritised. This is in strong contrast to the delayed implementation of compressor set-point adjustments in Case Study 1 due to the lack of a focused strategy. This delay led to missed savings as shown in Section 3.3. Therefore, Step 1 and the prioritisation method are necessary components of an effective strategy.

#### *3.5.2.2 Step 2: Implement*

Step 2 is the critical component of achieving energy savings and is included in multiple energy-saving strategies [40, 74]. Without this step, no savings are possible. It involves implementing the energy-saving initiatives identified in Step 1. The step can also be executed without a plan similar to the approach taken during Case Study 1, as discussed in Section 3.2.3. However, the lack of planning may reduce the effectiveness of energy-saving initiatives.

As mentioned previously, the prioritised energy-saving initiatives were implemented as soon as possible during Case Study 2. This allowed for the maximum reduction of compressor power at the start of the production stoppage, which ensured energy-saving initiatives were active for a longer duration. The longer a power reduction is in effect, the more energy is saved, resulting in greater cost savings.

#### *3.5.2.3 Step 3: Reverse*

Step 3 is dependent on the nature of the energy-saving initiatives and the demand during a typical production period. If the energy-saving initiatives implemented during a production stoppage reduce the supply below a point that is sustainable for the typical production demand, then the initiatives need to be reversed before returning to normal operation. This was the case for both Case Study 1 and Case Study 2 as discussed in Sections 3.2.4 and 3.4.4, respectively.

Additionally, temporary reversals were done during Case Study 2 to accommodate non-production work that required compressed air.

#### *3.5.2.4 Step 4: Quantify*

Lastly, Step 4 is executed after production resumes. It consists of calculating the savings that were achieved by implementing the previous steps of the strategy. This step assists the end user with evaluating the performance of energy-saving initiatives and may provide valuable insight for future production stoppages.

This step was successfully implemented after Case Study 2's production stoppage concluded. The compressor energy was split dynamically between Mine A and Plant A based on their respective compressed air consumption. A total saving of R200 000 at Mine A was calculated by comparing the compressor energy consumption with a baseline.

#### *3.5.2.5 Summary*

Each step of the developed strategy was correctly and successfully implemented during Case Study 2. Additionally, the four simple steps of the developed strategy followed the logical order of operations when faced with a need for energy savings during a production stoppage.

### **3.5.3 Validation of strategy**

De Jager [5] developed a strategy that included prioritising compressed air energy-saving initiatives. This strategy was implemented on two case studies, which are referred to as X and Y, respectively. The CASs in De Jager's case studies were significantly larger than the CAS used in Case Study 2 in Section 3.4 of this study. Case Study X has seven compressor houses in its CAS, while Case Study Y has five compressor houses. In contrast, Case Study 2 only has one compressor house in its CAS.

The implementation of the developed strategy during Case Study 2 resulted in a cost saving of R200 000 over an eleven-day period. Previous studies typically reported savings calculated annually based on the applicable tariffs for the year in which savings were achieved. The savings of previous studies and the savings achieved during this study were normalised to an annual value based on the FY2024/25 tariffs to accurately compare results. Table 23 compares each case study's normalised savings.

**Table 23: Normalised annual savings comparison**

<b>Case study</b>	<b>Source</b>	<b>Normalised annual savings for FY2024/25 (R million p.a.)</b>	<b>Compressor houses</b>	<b>Average savings per compressor house (R million p.a.)</b>
<b>X</b>	De Jager [5]	39.1	7	5.6
<b>Y</b>	De Jager [5]	20.1	5	4.0
<b>2</b>	Section 3.4	8.9	1	8.9

When averaging the normalised savings of each case study across all compressor houses, it can be seen that the strategy developed in this study, summarised in Figure 13, delivered substantial savings. The developed strategy performed comparably to De Jager’s strategy, making it a valid option for obtaining compressed air energy savings during a production stoppage.

### **3.6 Summary**

The prioritisation method successfully identified and prioritised four out of the six energy-saving initiatives that were implemented in Case Study 1. However, the method did not account for equipment failures, hidden opportunities, CASs that performed differently than expected, and operational changes. Nonetheless, the prioritisation method still demonstrated a high level of accuracy.

Case Study 1 also showed that a potential time saving could be achieved if the prioritisation method is applied at the start of a production stoppage, rather than relying solely on industry knowledge and experience. Despite some limitations of the method, it can lead to significant energy and cost savings, thus proving to be a considerable benefit to mines during production stoppages.

It was verified that the developed strategy was correctly and successfully implemented during Case Study 2. A prioritised list of feasible energy-saving initiatives was generated, which allowed proper planning of the implementation phase. Energy-saving initiatives were implemented as soon as the production stoppage started and were reversed without delay at the end of the production stoppage. An overall cost saving of R200 000 was achieved during the production stoppage with the aid of the strategy. A comparison of the developed strategy with the strategy from a previous study revealed that both produced similar results. It confirms the validity of the developed strategy for achieving compressed air savings during a production stoppage.

The prioritisation method assists the end user in deciding which energy-saving initiatives are feasible and determines the priority of each initiative. Additionally, successful implementation of the developed strategy leads to energy and cost savings. Therefore, the strategy, when used alongside the prioritisation method, accomplishes the aim of the study.

### 3.7 Overview of study objectives

Table 24 summarises the objectives of the study, listed in Section 1.4.3, and the sections that address the respective objectives.

**Table 24: Summary of objectives achieved**

<b>Objective</b>	<b>Achieved</b>	<b>Section</b>	<b>Description</b>
<b>1</b>	✓	2.2.5	A generalised list of compressed air energy-saving initiatives was compiled based on the literature. This list is summarised in Table 4. A total of 24 energy-saving initiatives were identified from the literature which exceeds the 15 initiatives required for this objective.
<b>2</b>	✓	2.3.3, 2.3.4 and 3.3.6	<p>An existing prioritisation method for energy-saving initiatives was adapted for use during a production stoppage, and the ability to filter unfeasible initiatives was added. The prioritisation method was combined with Table 4 to create a checklist to assist with decision-making.</p> <p>The score key is summarised in Table 8 and the checklist is contained in Table 9. A printable version of Table 9 is available in Annexure A.</p> <p>Validation of the prioritisation method was done after the first case study by comparing the generated list of energy-saving initiatives with the initiatives that were actually implemented. It was found that the method can accurately identify and prioritise energy-saving initiatives.</p>

Objective	Achieved	Section	Description
3	✓	2.7, 3.2, 3.4 and 3.5	<p>The prioritisation method was incorporated into an energy-saving strategy that provides guidance for achieving energy savings during a production stoppage. This strategy is summarised in Section 2.7.</p> <p>The developed strategy was implemented on a mine during two case studies. The first case study, discussed in Section 3.2, showed that using the first step of the strategy to properly plan energy-saving initiatives saves time and increases potential cost savings.</p> <p>The second case study, discussed in Section 3.4, fully implemented the developed strategy and achieved a cost saving of R200 000 over 11 days. Thereafter, in section 3.5, it was verified that the developed strategy was applied correctly. Additionally, the developed strategy delivered savings comparable to literature, thus proving to be a valid solution.</p>

The objectives of the study have been completed successfully as shown in Table 24.

## CHAPTER 4: CONCLUSION



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<sup>12</sup> G. P. Read, "Compressed air flowmeters," [Photograph], South Africa, 2022.

## 4.1 Summary

Deep-level mines in South Africa face challenges affecting profitability, such as increasing electricity costs. Electricity comprises 20% of a mine's total costs with compressed air being the single largest consumer of electricity, contributing 21% to the overall electricity demand. Compressed air is also considered inefficient to generate, with 40% to 80% of generated compressed air being wasted. It is therefore necessary to improve the efficiency of CASs to reduce costs. This can be done by implementing energy-saving initiatives, which are a proven method of reducing electricity consumption and reducing costs.

Previous studies primarily focused on implementing energy-saving initiatives during typical production periods. However, mines experiencing events, such as production stoppages, face additional limitations that may affect the implementation of energy-saving initiatives. Mines also produce little to no income during a production stoppage, which necessitates that costs are reduced where possible. Some studies have provided methods for filtering and prioritising energy-saving initiatives for the purpose of saving time and resources, but these methods were only applicable during production periods. Therefore, there is a need for a strategy that can identify and prioritise feasible energy-saving initiatives to lower compressed air demand and reduce electricity costs during a production stoppage.

The following objectives were identified to address the need:

- 1. Compile a generalised list of at least 15 compressed air energy-saving initiatives from the literature.**

A list of energy-saving initiatives was compiled from literature focusing on compressed air savings. The list was divided into categories based on the area of focus, namely compressor control, valve control, wastage reduction and system changes. The list of 24 energy-saving initiatives was generalised so that it could be applied to most mines using compressed air. The list is summarised in Table 4 and exceeds the planned number of 15 initiatives.

- 2. Adapt an existing method for identifying feasible energy-saving initiatives that can prioritise each based on specific criteria. Validate the method based on the accuracy when compared to a case study.**

An existing energy-saving prioritisation method was adapted to the unique conditions of a production stoppage. Shortcomings in the existing method were addressed, and the method was updated to include the ability to filter out unfeasible energy-saving initiatives. This updated method

was subsequently combined with the generalised list of energy-saving initiatives to form an easy-to-use checklist. This checklist, presented in Table 9, is used in conjunction with a score key, Table 8, to assign a score to each initiative. Unfeasible initiatives are removed from the list and the remaining initiatives are ordered from highest to lowest score to generate a prioritised list. The implementation order of the initiatives is the same as the prioritised list.

Validation of the prioritisation method was done after the first case study by comparing the generated list of energy-saving initiatives with the initiatives that were actually implemented. It was found that the method can accurately identify and prioritise energy-saving initiatives.

**3. Develop an energy-saving strategy to reduce compressed air energy usage during a production stoppage at a mine. Validate the developed strategy by applying the strategy to a case study and comparing the savings with previous studies. Verify whether the strategy was correctly applied during the case study.**

An energy-saving strategy was developed that incorporates the prioritisation method to assist mines to prepare for a production stoppage. The strategy is summarised in Figure 13. The strategy was implemented at a mine during two case study production stoppages. A potential saving of R410 000 was identified in the first case study, and a saving of R200 000 was achieved during the second case study.

It was determined that each step of the strategy was correctly implemented during the second case study. Additionally, implementation of the strategy delivered similar results than a previous study. Therefore, the strategy is verified and validated.

#### **4.2 Reflection on the developed strategy**

The developed strategy was evaluated in Section 2.8 according to the same criteria used for the literature as part of the state-of-the-art matrix. It was determined that the strategy meets the criteria and addresses the need for a strategy that prioritises and filters energy-saving initiatives during a production stoppage.

Thereafter, the strategy was applied during two case studies according to the case study methodology. The first case study applied the prioritisation method retrospectively to assess the accuracy and benefit compared with industry knowledge and expertise without a focused strategy. The second case study assessed the effectiveness of the strategy when implemented fully.

During the first case study, the prioritisation method correctly identified four out of the six energy-saving initiatives that were implemented during the production stoppage. The identified initiatives

also matched the implementation order of the initiatives that were actually implemented. However, the prioritisation method is limited to energy-saving initiatives that can be planned for, and the results may be affected by unforeseen events. The method cannot compensate for events such as equipment failure, hidden opportunities, CASs performing differently than expected, and operational changes.

Additionally, the prioritisation method would have saved five weeks if it was used at the start of the case study production stoppage compared to only relying on industry knowledge and expertise. This would have allowed compressor set points to be lowered earlier, which equates to a potential energy saving of 500 MWh with an equivalent cost saving of R410 000. Despite the shortcomings of the prioritisation method, it proved to assist with the decision-making process by saving time, which may lead to additional cost savings.

The developed strategy was successfully implemented during the second case study production stoppage. A prioritised list of energy-saving initiatives was generated, which allowed for the creation of an implementation plan. The plan ensured that energy-saving initiatives were implemented speedily after the production stoppage started. The reversal step of the strategy also proved useful since the energy-saving initiatives were reversed without delay at the end of the production stoppage. Application of the strategy achieved a cost saving of R200 000 during the production stoppage, which is a result comparable to that obtained by a previous study using a different strategy.

Overall, the developed energy-saving strategy provides a method for accurately identifying and prioritising feasible energy-saving initiatives during a production stoppage. Additionally, the strategy follows the logical order of operations of a production stoppage while consisting of four simple steps to help lower compressed air demand and reduce electricity costs.

Finally, the case study methodology proved useful for testing the developed strategy in a real-world context to determine how a dynamic system reacts to each step. However, it is challenging to prepare for a case study due to the short notice period associated with unplanned production stoppages. Additionally, planned production stoppages are typically short with a limited number occurring during a year. A simulated approach may assist with testing if no production stoppages are scheduled within a reasonable time frame.

### **4.3 Recommendations for further study**

The strategy developed in this study proved to be useful for achieving energy savings during a production stoppage in the context of a mine's compressed air system. However, there are

potential applications of this strategy that were not within the scope of this study. The following are suggestions for future studies:

- This study did not focus on factories, open-cast mines, or other industrial sectors. Future studies could investigate the use of a prioritisation and filtering strategy in the context of production stoppages at the aforementioned industries.
- This study only focused on compressed air and did not consider ventilation, dewatering, refrigeration, hoisting or auxiliary systems. Future studies could investigate the adaptation of the developed strategy to prioritise and filter energy-saving initiatives for other systems during a production stoppage.
- Production stoppages due to equipment failure or limited to no electrical supply were not considered. These stoppages may require a modified approach to accommodate the additional limitations and could be considered for future studies.
- Future studies could include the benefit of pre-emptively implementing energy-saving initiatives with high capital and time costs to prepare a mine for planned production stoppages.

## REFERENCE LIST

- [1] Sibanye-Stillwater, "Integrated report 2019," Annual report SSW-IR19, 2019. Accessed: 1 Oct. 2022. [Online]. Available: <https://reports.sibanyestillwater.com/2019/download/SSW-IR19.pdf>
- [2] Eskom, "Generation plant mix," Fact sheet GX-0001 Rev. 30, 2024. Accessed: 4 Apr. 2023. [Online]. Available: <https://www.eskom.co.za/wp-content/uploads/2024/08/GX-0001-Generation-Plant-Mix-Rev-30.pdf>
- [3] Eskom, "Tariffs & charges booklet 2024/2025," Tariff book ESK114, 2024. Accessed: 10 Jul. 2024. [Online]. Available: [https://www.eskom.co.za/distribution/wp-content/uploads/2024/05/ESK114-Eskom-Digital-Tariff-Booklet-2024\\_Final.pdf](https://www.eskom.co.za/distribution/wp-content/uploads/2024/05/ESK114-Eskom-Digital-Tariff-Booklet-2024_Final.pdf)
- [4] L. N. Zietsman, "Novel solutions for compressed air demand management on deep-level mines," Ph.D. Thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2020.
- [5] M. M. de Jager, "Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2021.
- [6] J. Taljaard, "Practical low-cost method to sustain mine compressed air savings," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2019.
- [7] A. Y. Botha, "Improving demand-side pressure of compressed air distribution networks in mines," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2023.
- [8] J. H. Marais, M. Kleingeld, and J. F. van Rensburg, "Simplification of mine compressed air systems," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 20–21 Aug. 2013, pp. 1–8.
- [9] S. W. van Heerden, "A dynamic optimal control system for complex compressed air networks," Ph.D. Thesis, Computer and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2016.

- [10] P. Lin and V. Avelar, "The different types of cooling compressors," Schneider Electric, White paper 254, 2017. Accessed: 20 Sep. 2024. [Online]. Available: [https://download.schneider-electric.com/doc/SPD\\_VAVR-AE7T7G\\_EN/VAVR-AE7T7G\\_R0\\_EN.pdf](https://download.schneider-electric.com/doc/SPD_VAVR-AE7T7G_EN/VAVR-AE7T7G_R0_EN.pdf)
- [11] H. Potgieter, "Target profiles for critical parameters in compressed air systems to reduce missed energy savings opportunities," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2023.
- [12] S. Chaudhari, A. Abbas, A. Botts, S. Sundaramoorthy, and T. Wenning, "Load sharing energy savings methodology for systems with multiple centrifugal compressors," *Journal of Cleaner Production*, vol. 433, pp. 1–12, 2023, Art no. 139630.
- [13] P. de Villiers, "Reducing deep-level mine refuge bay compressed air consumption," M.Eng. Dissertation, Development and Management Engineering, North-West University, Potchefstroom, South Africa, 2019.
- [14] R. F. Marais, "A zero-wastage approach to benchmark energy efficiency on platinum mines," Ph.D. Thesis, Development and Management Engineering, North-West University, Potchefstroom, South Africa, 2024.
- [15] I. Breedt, "Utilising automated control principles to reduce compressor operating costs on mines with limited infrastructure," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2023.
- [16] W. T. Gerber, "Developing a demand-driven compressed air management system for energy efficiency in deep-level gold mining," M.Eng. Dissertation, Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa, 2024.
- [17] A. van der Merwe, A. G. S. Gous, and C. S. L. Schutte, "Using zero-waste baselines to identify compressed air system inefficiencies in deep-level mines," *South African Journal of Industrial Engineering*, vol. 33, no. 3, pp. 55–68, 2022.
- [18] J. I. G. Bredenkamp, "Reconfiguring mining compressed air networks for cost savings," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [19] South African Government, *Mine Health and Safety Act No. 29 of 1996 (no. 17242)*. Government Gazette, 1996.

- [20] B. M. Friedenstien, "Simulating operational improvements on mine compressed air systems," M.Eng. Dissertation, Electrical and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2018.
- [21] M. Biffi and D. Stanton, "Cooling power for a new age," in *3rd International Platinum Conference 'Platinum in Transformation'*, Johannesburg, South Africa, 6–9 Oct. 2008, pp. 239–247.
- [22] A. de Coning, "Sustained energy performance on compressed air systems for expanding gold mines," M.Eng. Dissertation, Computer and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2013.
- [23] A. J. M. van Tonder, G. Bolt, and J. F. van Rensburg, "Compressed air alternative solutions: Challenges encountered in deep level mining," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 15–16 Aug. 2012, pp. 1–8.
- [24] M. D. Adams, Ed. *Advances in Gold Ore Processing* (Developments in mineral processing Series 15). Amsterdam, The Netherlands: Elsevier, 2005.
- [25] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2017.
- [26] M. Tenza, "The effects of violent strikes on the economy of a developing country: a case of South Africa," *Obiter*, vol. 41, no. 3, pp. 519–537, 2020.
- [27] G. du Venage, "South African mines contend with 21-day shutdown," *Engineering and Mining Journal*, vol. 221, no. 4, p. 47, 2020.
- [28] A. Gałaś, A. Kot-Niewiadomska, H. Czerw, V. Simić, M. Tost, L. Wårell, and S. Gałaś, "Impact of Covid-19 on the mining sector and raw materials security in selected European countries," *Resources*, vol. 10, no. 5, pp. 1–23, 2021, Art no. 39.
- [29] J. H. Marais, "Evaluating the impact of energy management on deep-level mines during medium-term production stoppages," MBA Mini-dissertation, Business Administration, North-West University, Potchefstroom, South Africa, 2021.

- [30] J. I. G. Bredenkamp, A. J. Schutte, and J. F. van Rensburg, "Challenges faced during implementation of a compressed air energy savings project on a gold mine," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 18–19 Aug. 2015, pp. 23–29.
- [31] S. Ayvaz and K. Alpay, "Predictive maintenance system for production lines in manufacturing: A machine learning approach using IoT data in real-time," *Expert Systems with Applications*, vol. 173, pp. 1–10, 2021, Art no. 114598.
- [32] South African Government, *Labour Relations Act No. 66 of 1995 (no. 16861)*. Government Gazette, 1995.
- [33] Y. Xiao and M. Watson, "Guidance on conducting a systematic literature review," *Journal of Planning Education and Research*, vol. 39, no. 1, pp. 93–112, 2019.
- [34] B. Jacobs. "Inaugural mining indaba strikes gold." <https://news.nwu.ac.za/inaugural-mining-indaba-strikes-gold> (accessed 10 Feb. 2025).
- [35] North-West University. "Centre of Research And Continued Engineering Development (CRCED)." <https://engineering.nwu.ac.za/research/centre-research-and-continued-engineering-development-crced> (accessed 10 Feb. 2025).
- [36] C. J. Oosthuizen, "A compressed air cost savings identification model for deep-level mines," M.Eng. Dissertation, Electric and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2019.
- [37] J. I. G. Bredenkamp, "An integrated energy management strategy for the deep-level gold mining industry," Ph.D. Thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [38] W. G. Shaw, "Analysing mine energy management considering utility demand," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2019.
- [39] J. A. du Preez, "Analysing the influence of compressed air pressure on gold production," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2020.

- [40] J. Kunneke, "Applying a benchmark method to identify utility cost-saving opportunities on a platinum mine," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2022.
- [41] J. Jonker, "Automated mine compressed air control for sustainable savings," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [42] A. J. M. van Tonder, "Automation of compressor networks through a dynamic control system," Ph.D. Thesis, Electrical Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [43] C. Cilliers, "Benchmarking electricity use of deep-level mines," Ph.D. Thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [44] J. Vermeulen, C. Cilliers, and J. H. Marais, "Cost-effective compressor control to reduce oversupply of compressed air," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 15–16 Aug. 2017, pp. 1–7.
- [45] S. W. van Heerden, R. Pelzer, and J. H. Marais, "Developing a dynamic control system for mine compressed air networks," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 19–20 Aug. 2014, pp. 1–8.
- [46] R. Maneschijn, "Developing a dynamic operational energy management strategy for energy intensive industries," Ph.D. Thesis, Development and Management Engineering, North-West University, Potchefstroom, South Africa, 2017.
- [47] D. L. du Plooy, "Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2019.
- [48] P. Maré, J. I. G. Bredenkamp, and J. H. Marais, "Evaluating compressed air operational improvements on a deep-level mine through simulations," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 15–16 Aug. 2017, pp. 1–8.
- [49] F. J. L. Matthee, "Evaluating the feasibility of integrating mine compressed air systems for energy savings," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2021.

- [50] L. Zhong, Y. Liu, J. Zhao, and W. Wang, "Hierarchical reinforcement learning based operational optimization for compressed air system," *Control Engineering Practice*, vol. 136, pp. 1–11, 2023, Art no. 105524.
- [51] A. Trianni, D. Accordini, and E. Cagno, "Identification and categorization of factors affecting the adoption of energy efficiency measures within compressed air systems," *Energies*, vol. 13, no. 19, pp. 1–38, 2020, Art no. 5116.
- [52] S. J. Fouché, "Improving efficiency of a mine compressed air system," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2017.
- [53] D. L. du Plooy, P. Maré, J. H. 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.
- [54] A. J. A. Visagie, "Modelling the effect of changes in mining compressed air networks on refuge chambers," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2021.
- [55] C. J. R. Kriel, J. H. Marais, and M. Kleingeld, "Modernising underground compressed air DSM projects to reduce operating costs," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 19–20 Aug. 2014, pp. 1–6.
- [56] F. Bonfá, M. Benedetti, S. Ubertini, V. Introna, and A. Santolamazza, "New efficiency opportunities arising from intelligent real time control tools applications: The case of compressed air systems' energy efficiency in production and use," *Energy Procedia*, vol. 158, pp. 4198–4203, 2019.
- [57] J. Vermeulen, "Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems," Ph.D. Thesis, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2018.
- [58] J. Galvão, L. Moreira, S. Leitão, É. Silva, and M. Neto, "Sustainable energy for plastic industry plant," in *4th International Youth Conference on Energy*, Siófok, Hungary, 6–8 Jun. 2013, pp. 1–8.

- [59] M. H. P. van Niekerk, S. W. van Heerden, and J. F. van Rensburg, "The implementation of a dynamic air compressor selector system in mines," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 18–19 Aug. 2015, pp. 129–132.
- [60] W. G. Shaw, M. J. Mathews, and J. H. Marais, "Using specific energy as a metric to characterise compressor system performance," *Sustainable Energy Technologies and Assessments*, vol. 31, pp. 329–338, 2019.
- [61] E. du Toit, "A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2022.
- [62] H. Coombs, "Case study research defined," Southern Utah University, White paper 2022. Accessed: 20 Sep. 2024. [Online]. Available: <https://doi.org/10.5281/zenodo.7604301>
- [63] S. Teegavarapu, J. D. Summers, and G. M. Mocko, "Case study method for design research: A justification," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, New York city, NY, USA, 3–6 Aug. 2008, vol. 43284, pp. 495–503.
- [64] H. J. Groenewald, "Developing a framework for managing compressed air in the Platinum Group Metal Mining Industry in South Africa," MBA Mini-dissertation, Business Administration, North-West University, Potchefstroom, South Africa, 2020.
- [65] United Nations Environment Programme, "Electrical energy equipment: Compressors and compressed air systems," Technical report 2006. Accessed: 20 Sep. 2024. [Online]. Available: <https://zagroscompressor.com/wp-content/uploads/2019/11/Compressors-and-Compressed-Air-Systems.pdf>
- [66] G. J. Stols, "Expanding compressed air management through cross cut isolation," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2022.
- [67] J.-A. Snyman, "Integrating various energy saving initiatives on compressed air systems of typical South African gold mines," M.Eng. Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2011.

- [68] K. Abela, E. Francalanza, and P. Refalo, "Utilisation of a compressed air test bed to assess the effects of pneumatic parameters on energy consumption," *Procedia CIRP*, vol. 90, pp. 498–503, 2020.
- [69] J. J. C. Eras, A. S. Gutiérrez, V. S. Santos, and M. J. C. Ulloa, "Energy management of compressed air systems. Assessing the production and use of compressed air in industry," *Energy*, vol. 213, pp. 1–13, 2020, Art no. 118662.
- [70] G. F. Martin Nascimento, F. Wurtz, P. Kuo-Peng, B. Delinchant, and N. Jhoe Batistela, "Quantifying compressed air leakage through non-intrusive load monitoring techniques in the context of energy audits," *Energies*, vol. 15, no. 9, pp. 1–24, 2022, Art no. 3213.
- [71] R. Patil and K. Rickert, "Compressed air as energy savings, leak survey and recognizing right fittings to show cost benefits," *International Journal of Chemical Engineering and Applications*, vol. 11, no. 2, pp. 53–56, 2020.
- [72] H. P. R. Joubert, G. Bolt, and J. F. van Rensburg, "Energy savings on mining compressed air networks through dedicated process plant compressors," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 15–16 Aug. 2012, pp. 1–4.
- [73] A. C. Burns, R. F. Bush, and J. Nash, *Basic Marketing Research: Using Microsoft Excel Data Analysis*. Upper Saddle River, NJ, USA: Pearson Prentice Hall 2008.
- [74] E. A. Abdelaziz, R. Saidur, and S. Mekhilef, "A review on energy saving strategies in industrial sector," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 150–168, 2011.
- [75] J. Lodewyk, "Holistic evaluation of surface cooling plant configurations for different seasons at deep mines," M.Eng Dissertation, Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2023.
- [76] M. D. Harmse, "Optimising mining refrigeration systems through artificial intelligence," M.Eng. Dissertation, Electrical and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2021.
- [77] J. Suaboot, "A holistic approach for efficient host-based data exfiltration detection," Ph.D. Thesis, Computer Science, RMIT University, Melbourne, Australia, 2021.

- [78] *International performance measurement and verification protocol: core concepts*, EVO 10000 – 1:2022, Efficiency Valuation Organization, Washington, DC, USA, 2022.
- [79] K.-H. Chang, Y.-J. Sun, C.-A. Lai, L.-D. Chen, C.-H. Wang, C.-J. Chen, and C.-M. Lin, "Big data analytics energy-saving strategies for air compressors in the semiconductor industry: An empirical study," *International Journal of Production Research*, vol. 60, no. 6, pp. 1782–1794, 2022.

# ANNEXURE A: PRINTABLE ENERGY-SAVING INITIATIVE CHECKLIST

**Table 25: Printable energy-saving initiative checklist for production stoppages**

Instructions							
<p>The purpose of this checklist is to assist the end user in filtering and prioritising various compressed air energy-saving initiatives during a production stoppage at a mine.</p> <ul style="list-style-type: none"> <li>• Refer to Section 2.3.3 for the scoring key and a description of each criterion.</li> <li>• Scores are added together in the Total column and initiatives are to be implemented chronologically from highest to lowest total score.</li> <li>• Energy-saving initiatives that receive one or more Xs are considered unfeasible and are removed from the sequence.</li> </ul>							
Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Compressor control	Compressor selection						
	Guide vane control						
	Load sharing						
	Load-unload						
	Pressure set-point reduction						
	Regular maintenance						
	Stop-start						
	VSD						
Control valves	Peak-clipping						
	Set-point control						
	Stope isolation						
	Surface valve control						
	Underground valve control						
Wastage reduction	Close inactive sections						
	Eliminate/reduce unauthorised use						
	Repair leaks						
System changes	Adjust mining shifts						
	Use dedicated compressors						
	Eliminate/reduce pneumatic equipment						
	Integrate smaller CASs						
	Use optimally sized compressors						
	Reconfigure pipes						
	Reduce compressor inlet temperatures						
	Reduce refuge bay flow						

## ANNEXURE B: DETAILED ENERGY-SAVING INITIATIVE CHECKLIST FOR CASE STUDY 1

Table 26: Detailed energy-saving initiative checklist for Case Study 1

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
<b>Compressor control</b>	Compressor selection	5	4	3	3	3	<b>18</b>
		The labour required for compressor selection forms part of the essential workers who oversee the operation of the compressor house, which allows the initiative to be implemented given enough time.					
	Guide vane control	–	–	–	–	X	<b>X</b>
		The compressed air demand reduction from other energy-saving initiatives allows for a reduction in supply and energy usage by adjusting the guide vanes of the compressors. The compressors of Mine A already use automatic guide vane control to regulate the compressed air supply and reduce energy usage. Therefore, no additional benefit can be gained from this initiative since it is always active.					
	Load sharing	–	–	–	–	X	<b>X</b>
		The compressors at Mine A are already set up to share the load automatically, and no additional benefit can be gained from this initiative since it is always active.					
	Load-unload	–	–	–	–	X	<b>X</b>
		Since there are already two compressors running, unloading a compressor would result in a compressed air supply that falls below the minimum requirement. The unloaded compressor would still be using energy while not meeting the demand of the compressed air network. No benefit is expected from implementing this initiative during this production stoppage.					

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Compressor control	Pressure set-point reduction	5	2	3	2	3	15
		Adjusting the pressure set points of the compressors is only considered during a long production stoppage due to the higher difficulty. Workers must ensure that compressors do not go into a surge state with the new settings. Implementing and reversing the process is not instant and could cause a delay if the compressors are not ready when production restarts. The specialised labour required forms part of the essential workers; however, the initiative can only be implemented if the strike continues for an extended period.					
	Regular maintenance	-	-	X	-	-	X
		The compressors undergo regular maintenance during normal production periods, but the required labour is unavailable during the strike.					
	Stop-start	-	-	-	-	X	X
The production stoppage is set to start before the night shift of the first day. The minimum number of two compressors is already running at the start of the strike due to the low-demand blasting shift before the night shift. The lack of production during the strike period will also prevent a third compressor from being stopped-started during peak drilling times. Therefore, this initiative is not expected to provide any benefit during the time period that falls within the boundaries of the production stoppage.							
VSD	X	-	-	-	-	X	
	The compressors at Mine A do not have VSDs installed and rely on guide vane control to regulate energy usage. The installation of VSDs would require a large amount of capital and is therefore unfeasible.						
Control valves	Peak-clipping	-	-	-	-	X	X
		The compressed air demand during the production stoppage is expected to remain fairly constant near the minimum of 150 kPa per level; therefore, it is not possible to further reduce demand during the Eskom peak periods. This initiative is not expected to provide any benefit.					

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Control valves	Set-point control	5	5	4	4	3	<b>21</b>
		Mine A has automatic control valves on some of the underground levels that operate on a schedule and pressure set point. These set points can be adjusted remotely within a brief period and the valves will automatically regulate the flow.					
	Stope isolation	–	–	X	–	–	<b>X</b>
		Stope isolation would require checking each cross-cut to ensure that the manual isolation valves are closed. This process is labour-intensive and unfeasible during a strike.					
	Surface valve control	5	4	3	4	3	<b>19</b>
		The main control valve on surface can be adjusted to reduce the total supply to the underground compressed air network of Mine A and Mine B. Adjustments may cause large fluctuations in pressure. The system further requires time to normalise before making more adjustments. This process takes longer to implement than the adjustments to the underground valves.					
Underground valve control	–	–	X	–	–	<b>X</b>	
	Some of Mine A's underground valves have actuators that allow for automatic control of the compressed air based on a pressure set point. The remaining valves are all manual and would require additional labour to adjust.						
Wastage reduction	Close inactive sections	–	–	X	–	–	<b>X</b>
		The process of finding and closing inactive sections is time-consuming and labour-intensive. The lack of required labour during the strike makes this initiative unfeasible.					
	Eliminate/reduce unauthorised use	–	–	–	–	X	<b>X</b>
		The mine issued a full lockout, which prevents most employees from going underground. The lack of employees minimises the opportunity for unauthorised use. This initiative is not expected to provide any benefit.					
Repair leaks	–	–	X	–	–	<b>X</b>	
	A production stoppage is a good opportunity for repairing leaks; however, the required labour is unavailable during the strike. The lack of labour prevents this initiative from being implemented.						

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
System changes	Adjust mining shifts	-	-	-	-	X	X
		There are no shifts that specifically use compressed air during this production stoppage and adjusting the shifts would have no benefit.					
	Use dedicated compressors	X	X	-	-	-	X
		Dedicated compressors would require a significant capital investment and can take months to be approved, which is not feasible during the strike period.					
	Eliminate/reduce pneumatic equipment	X	-	-	-	-	X
		Replacing pneumatic equipment requires capital investment, which is not feasible during the strike period.					
	Integrate smaller CASs	-	-	-	-	X	X
		Mine A is already integrated with Mine B and Plant A. No further integration is possible and therefore no additional benefit is expected from this initiative.					
	Use optimally sized compressors	X	X	-	-	-	X
		Similar to installing dedicated compressors, this project would require a significant capital investment and long approval times. This initiative is not feasible during the strike period.					
Reconfigure pipes	X	X	-	-	-	X	
	Changing the pipe configuration requires a redesign of the system which, in turn, requires more capital and time than is available.						
Reduce compressor inlet temperatures	X	-	-	-	-	X	
	Adjusting the inlet temperatures of the compressors would require a redesign of the current infrastructure and capital investment. This is not feasible during the strike period.						
Reduce refuge bay flow	-	-	X	-	-	X	
	The actuated valves are set to reduce the pressure to the minimum of 150 kPa to keep the refuge bays life sustainable. The remaining refuge bays have manual valves, and it would require more labour than is available.						

## ANNEXURE C: DETAILED ENERGY-SAVING INITIATIVE CHECKLIST FOR CASE STUDY 2

Table 27: Detailed energy-saving initiative checklist for Case Study 2

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
<b>Compressor control</b>	Compressor selection	5	4	3	3	3	<b>18</b>
		The optimal compressor will depend on the demand after other energy-saving initiatives are implemented. Essential personnel are available to implement the initiative.					
	Guide vane control	-	-	-	-	X	<b>X</b>
		Guide vane control is already in effect on all compressors. No further benefit is expected from reimplementing the initiative.					
	Load sharing	-	-	-	-	X	<b>X</b>
		The demand of Plant A and Mine A is expected to decrease enough to only use one compressor. Therefore, no load sharing will take place.					
	Load-unload	-	-	-	-	X	<b>X</b>
		Stopping unnecessary compressors would provide more benefit than unloading. Therefore, unloading will not be used.					
Pressure set-point reduction	-	X	-	-	-	<b>X</b>	
	The production stoppage is considered too short to justify making changes to the compressor controllers.						
Regular maintenance	-	-	-	-	X	<b>X</b>	
	The compressors do not require maintenance yet.						
Stop-start	5	5	3	3	4	<b>20</b>	
	It is expected that one compressor will be sufficient to supply the demand of Plant A and Mine A when the production stoppage starts. All but one compressor must be stopped. Essential personnel are available to manage the compressors.						

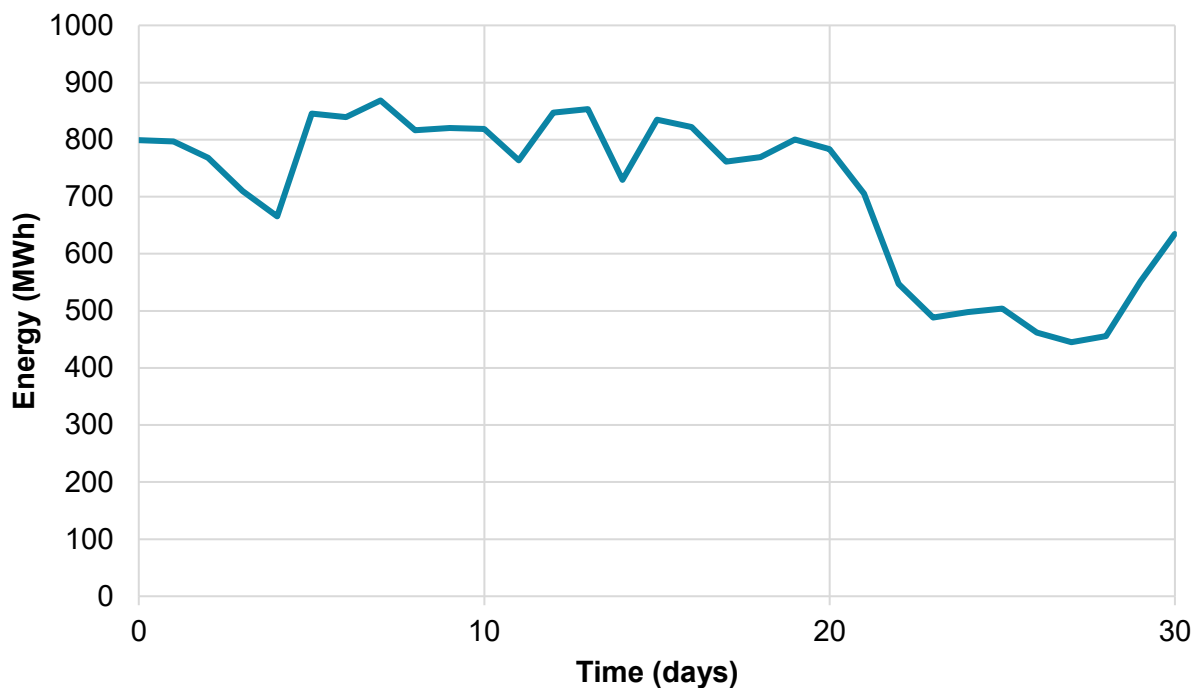
Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
Comp. control	VSD	X	–	–	–	–	<b>X</b>
		Mine A's compressors do not have VSDs. Installing such equipment would require a significant capital and time investment.					
Control valves	Peak-clipping	–	–	–	–	X	<b>X</b>
		The compressed air demand during the production stoppage is expected to remain constant. There would be no peaks to adjust and therefore no benefit to this initiative.					
	Set-point control	5	5	5	5	2	<b>22</b>
		Mine A's has automatic compressed air valves that follow a set schedule. These schedules can be adjusted remotely ahead of time.					
	Stope isolation	–	–	X	–	–	<b>X</b>
		Labour is too limited to check each cross-cut valve. Employees are expected to close these valves after work is completed.					
Surface valve control	5	5	4	5	2	<b>21</b>	
	Adjusting the main control valve on surface is a manual process that requires labour but will assist with reducing the compressed air flow to Mine A. One of the essential personnel is available for the specified task.						
Underground valve control	–	–	X	–	–	<b>X</b>	
	Manually adjusting valves underground would require additional labour, which may not be available during the December break.						
Wastage reduction	Close inactive sections	–	–	X	–	–	<b>X</b>
		Finding and closing inactive sections is time and labour-intensive.					
	Eliminate/reduce unauthorised use	–	–	–	–	X	<b>X</b>
There will be a limited number of individuals underground. These workers are required to perform essential services or maintenance work. Unauthorised use of compressed air is unlikely.							
Repair leaks	–	–	X	–	–	<b>X</b>	
	Maintenance work is scheduled for critical infrastructure; however, large-scale leak repairs are not planned for the case study period.						

Strategy	Initiatives	Criteria score					
		Cost	Time	Complexity	Difficulty	Benefits	Total
System changes	Adjust mining shifts	-	-	-	-	X	X
		No benefit is expected from adjusting mining shifts since no shift-related work requiring compressed air will be done.					
	Use dedicated compressors	X	X	-	-	-	X
		Buying additional compressors for specific applications requires significantly more time and capital than available during the production stoppage.					
	Eliminate/reduce pneumatic equipment	X	-	-	-	-	X
		Capital investment is required to replace equipment, which is not available during the production stoppage.					
	Integrate smaller CASs	-	-	-	-	X	X
		Mine A was recently disconnected from Mine B due to concerns over the condition of the distribution network between the mines. Mine A is also integrated with Plant A and no further integration is available.					
	Use optimally sized compressors	X	X	-	-	-	X
		The project would require a capital and time investment, which is not feasible during the production stoppage.					
	Reconfigure pipes	X	X	-	-	-	X
		Reconfiguring the CAS is time-consuming and expensive. Such a project is not feasible during the production stoppage.					
Reduce compressor inlet temperatures	X	-	-	-	-	X	
	Temperatures are already regulated as far as possible. Further reductions would require a change of infrastructure and a capital investment.						
Reduce refuge bay flow	-	-	X	-	-	X	
	The only way to reduce refuge bay flow at Mine A is to manually adjust valves underground. This requires labour, which may not be available.						

## ANNEXURE D: POWER METER ACCURACY VERIFICATION

The Eskom bill only shows the total energy usage for a month and does not provide a breakdown of the energy usage for individual consumers or specific days. The case study mine has power meters that measure the total power consumption. There are also power meters that measure the individual power consumption of certain consumers such as compressors. This power consumption can be converted to an energy consumption value by using Equation 2 discussed in Section 2.6.4.

The accuracy of these meters needs to be verified as mentioned in Section 2.6.1. This was done by comparing the sum of all the power meters' energy to the total energy shown on the Eskom bill for the observation month. The daily total energy consumption of Mine A during the observation month is shown in Figure 34.



**Figure 34: Total energy usage measured for Mine A during observation month**

The total energy shown on the Eskom bill for Mine A was 22.4 GWh and the total energy measured by the power meters was 22 GWh. This is a total difference of 0.40 GWh less than what was measured by Eskom, which is equivalent to an error of  $-1.77\%$ . This falls within the accepted 1.9% error mentioned in Section 2.6.1. Since it is not possible to verify individual power meters, it is assumed that the average error of the compressor power meter is also within 1.77%.

## ANNEXURE E: ESKOM TARIFFS

Eskom has various costs that may form part of the monthly bill of a customer. This includes but is not limited to active energy, administration, transmission, network demand and network capacity charge [3]. Only the active energy charge will be considered for the purpose of this study. The monetary cost of active energy used is calculated based on the tariffs set out in Eskom's tariff booklet and are billed in cents per kilowatt-hour (c/kWh) [3]. The applicable active energy tariff for a customer is based on various factors, namely [3]:

- Tariff structure
- Local or non-local authority
- Transmission zone
- Voltage
- Demand season
- TOU period
- Day of the week and public holidays

Tariffs are reviewed yearly and regulated by the National Energy Regulator of South Africa [3]. The yearly tariff changes are effective from 1 April to 31 March of the next year for non-local authorities and from 1 July to 30 June of the next year for local authorities [3]. Local authority tariffs are applicable to municipal bulk points of supply while non-local authority tariffs are applicable to Eskom's direct customers [3]. The case study mine uses the Megaflex, non-local authority tariff structure.

Transmission zones are based on the distance from Johannesburg and are used to factor in costs associated with the delivery and transmission of energy [3]. There are a total of four transmission zones as illustrated in Figure 35. The transmission zone and exact tariffs of the case study mine are not disclosed as part of the confidentiality agreement; however, the 2024/25 active energy tariff for the Megaflex, non-local authority tariff structure is included in Table 28 as an example.

The tariffs are further divided according to the voltage requirements of the consumer, which differ between tariff structures. However, the Megaflex, non-local authority is divided into four groups as shown in Table 28. The case study mine forms part of the  $\geq 500$  V &  $< 66$  kV group.

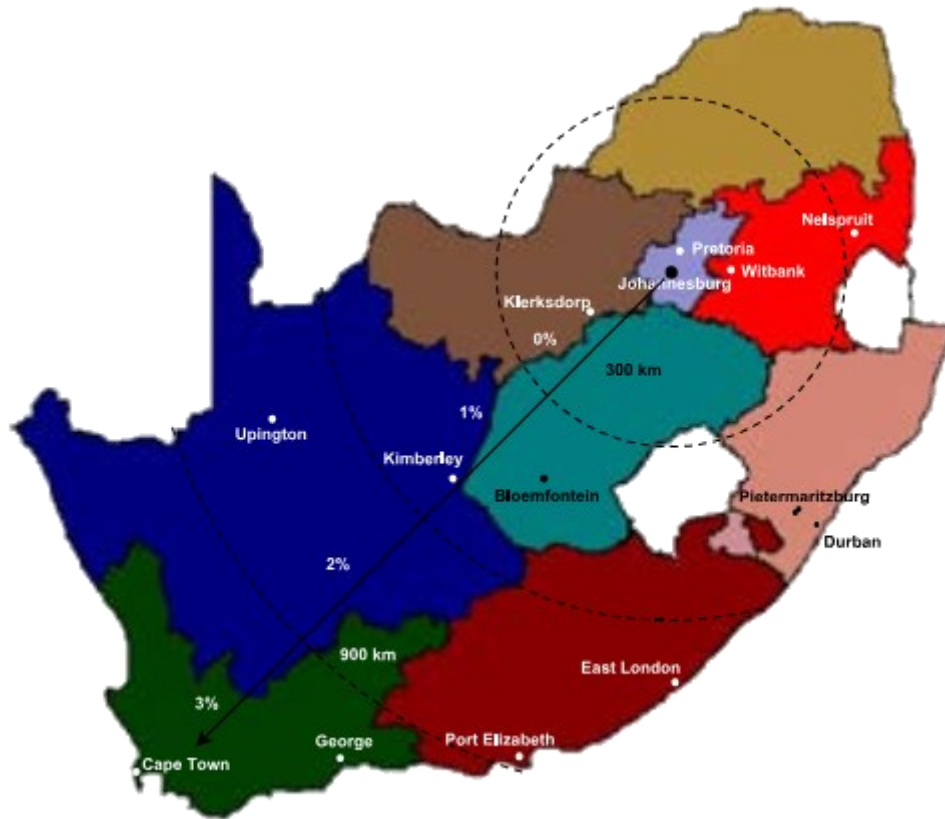


Figure 35: Eskom transmission zones [3]

The tariffs are finally split based on the TOU periods. These periods are peak, standard, and off-peak periods and are applicable at specific times of the day depending on the day of the week and the demand season [3]. The TOU periods for the Megaflex tariff structure are shown in Figure 36.

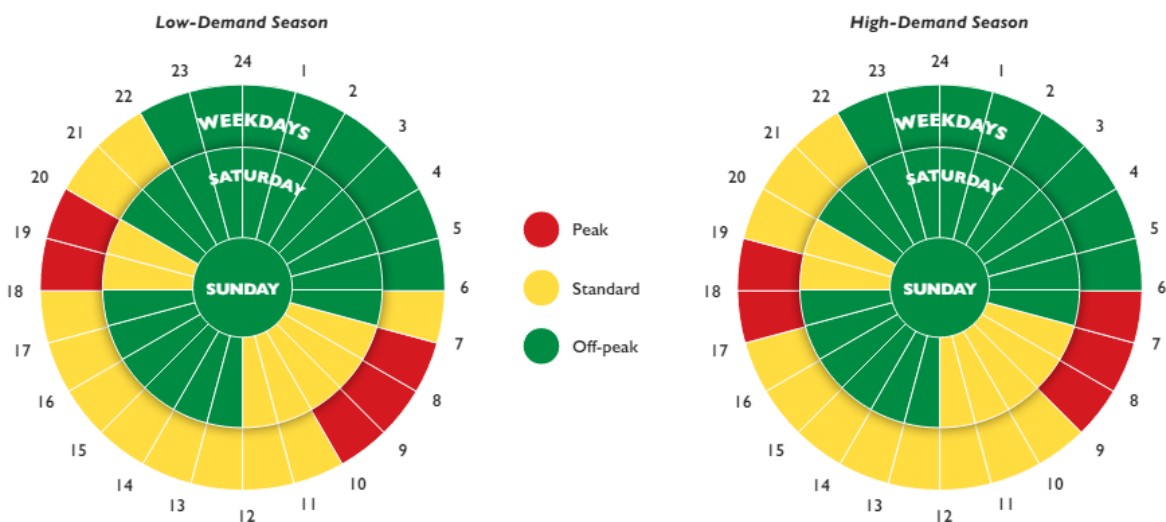


Figure 36: Eskom TOU periods [3]

Eskom may apply different rates on certain days, such as public holidays. For example, 1 April 2024 is Family Day in South Africa. Although it is a Monday, it is billed based on Sunday TOU periods [3]. A list of public holidays and the applicable TOU periods are included in the tariff booklet [3].

The tariff for TOU periods also differs during high- and low-demand seasons [3]. The high-demand season spans from 1 June to 31 August, and the low-demand season spans from 1 September to 31 May of each year [3]. The tariffs in Table 28 exclude VAT.

**Table 28: Eskom active energy tariff for Megaflex, non-local authority, FY2024/25 [3]**

Transmission zone	Voltage	Active energy tariff (c/kWh)					
		High demand season			Low demand season		
		Peak	Std.	Off-peak	Peak	Std.	Off-peak
≤ 300 km	< 500 V	611.94	186.18	101.66	200.38	138.26	88.15
	≥ 500 V & < 66 kV	602.34	182.47	99.11	196.46	135.24	85.80
	≥ 66 kV & ≤ 132 kV	583.26	176.67	95.96	190.28	130.92	83.11
	> 132 kV	549.70	166.49	90.44	179.37	123.42	78.31
> 300 km and ≤ 600 km	< 500 V	616.92	186.92	101.49	201.26	138.57	87.91
	≥ 500 V & < 66 kV	608.35	184.27	100.07	198.48	136.57	86.64
	≥ 66 kV & ≤ 132 kV	588.99	178.40	96.85	192.12	132.23	83.90
	> 132 kV	555.21	168.22	91.29	181.09	124.61	79.04
> 600 km and ≤ 900 km	< 500 V	623.07	188.75	102.47	203.25	139.91	88.73
	≥ 500 V & < 66 kV	614.46	186.17	101.08	200.44	137.97	87.52
	≥ 66 kV & ≤ 132 kV	595.01	180.25	97.86	194.08	133.61	84.77
	> 132 kV	560.80	169.85	92.30	182.92	125.89	79.89
> 900 km	< 500 V	629.34	190.72	103.51	205.32	141.29	89.66
	≥ 500 V & < 66 kV	620.57	187.97	102.04	202.40	139.28	88.38
	≥ 66 kV & ≤ 132 kV	600.97	182.03	98.84	196.02	134.92	85.59
	> 132 kV	566.26	171.61	93.24	184.83	127.26	80.77