

Expanding compressed air management through cross cut isolation

GJ Stols

 orcid.org/0000-0003-4675-3916

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

Supervisor: Dr HJ Groenewald

Co-supervisor: Dr JH Marais

Graduation: July 2022

Student number: 25929615

ACKNOWLEDGEMENTS

Alle eer aan God

Dankie aan my ouers

Baie dankie aan my studie leier en mentor Dr Handré Groenewald

Dankie aan my vriend en kollega Joshua van den Berg

Dankie aan my sussie Marike Stols

Dankie aan ETA Operations (Pty) Ltd en Mine Clever (Pty) Ltd vir die geleentheid

ABSTRACT

Title: Expanding compressed air management through cross cut isolation

Author: GJ Stols

Supervisor: Dr HJ Groenewald

Keywords: *compressed air, demand side management, cross cut isolation, energy efficiency, sustainability, misappropriation*

Compressed air on deep-level mines is regarded as an important source of energy for underground mining operations, as the compressed air network forms the backbone of several mining processes over a 24-hour mining cycle. Historically, compressed air networks on deep-level mines were found to have low energy efficiencies due to mismanagement of infrastructure and misappropriation of compressed air. Therefore, compressed air becomes an inefficient and costly way of supplying energy to underground mining operations, if not correctly managed.

To address the low energy efficiency, several supply and demand side energy management initiatives have been implemented. However, the majority of these initiatives predominantly focus on matching compressed air supply with an artificially lowered demand, achieved through surface or level valve control. These initiatives therefore only address the symptoms of mismanagement and misappropriation, as they do not directly address the root cause of the high demand for compressed air.

There is therefore still significant scope to improve the overall efficiency of compressed air networks on deep-level mines by implementing measures to directly address compressed air misappropriation and mismanagement. One such measure is the implementation of cross cut isolation valves. The primary objective of this study is to investigate the scope and requirements for implementing cross cut isolation on deep-level platinum mines.

A solution strategy was developed which quantified the energy benefit of implementing both manual and automatic cross cut isolation. Thereafter, the sustainability requirements for ensuring the success of both manual and automatic cross cut isolation control strategies were identified.

The solution strategy was applied to a deep-level platinum mining shaft in South Africa. It was identified that the cross cuts accounted for approximately 85% of the total wastage consumption. Thus, the energy benefit quantification of implementing cross cut isolation determined that a

potential daily energy saving of 43,3 MWh can be achieved over the 24-hour weekday mining profile as a result of a 50% demand reduction.

The sustainability requirements were successfully identified for both manual and automatic cross cut isolation control strategies. The sustainability and impact of manual cross cut isolation was found to be highly dependent on the cooperation of the mining personnel and was unable to provide a sustainable solution. It was therefore concluded that this strategy comes with high project maintenance and resource management requirements when attempting to achieve sustainable energy savings.

However, automatic cross cut isolation effectively eliminated the reliance on the human factor and the case study was able to obtain a sustainable energy saving as a result of this. Therefore, the implementation of an automated control philosophy is preferred to eliminate the human error in order to maximise the energy savings and the sustainability of the initiative.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
ABSTRACT	II
TABLE OF CONTENTS.....	IV
LIST OF FIGURES.....	VII
LIST OF TABLES	X
NOMENCLATURE.....	XII
LIST OF ABBREVIATIONS	XIII
CHAPTER 1: THE USE OF COMPRESSED AIR IN DEEP-LEVEL PLATINUM MINING	1
1.1 Introduction to compressed air on deep-level mines in South Africa	1
1.2 Expanding on compressed air usage in platinum mining	3
1.3 Expanding on compressed air wastage	13
1.4 The impact of inefficient compressed air utilisation due to wastage.....	17
1.5 Existing compressed air demand side management initiatives.....	20
1.6 Need and objective for the study	34
1.7 Overview of dissertation	35
CHAPTER 2: DEVELOPMENT OF A SOLUTION TO EXPAND COMPRESSED AIR MANAGEMENT THROUGH CROSS CUT ISOLATION	36
2.1 Introduction.....	36
2.2 Compressed air network analysis	37
2.3 Technical feasibility	44

2.4	Energy benefit quantification	47
2.5	Financial feasibility calculations	56
2.6	Implementation of cross cut isolation	56
2.7	Sustainability requirements.....	62
2.8	Conclusion.....	63
CHAPTER 3: RESULTS		64
3.1	Introduction.....	64
3.2	Compressed air network analysis	66
3.3	Technical feasibility	77
3.4	Energy benefit quantification	81
3.5	Financial feasibility	90
3.6	Implementation and verification of cross cut isolation on the CA network.....	91
3.7	Conclusion.....	101
CHAPTER 4: CONCLUSION AND RECOMMENDATIONS		102
4.1	Introduction.....	102
4.2	Summary of the study.....	102
4.3	Meeting the required study objectives.....	106
4.4	Recommendations for future work.....	107
BIBLIOGRAPHY		109
APPENDIX A: COMPRESSED AIR FLOW NORMALISATION CALCULATION		115
APPENDIX B: BASELINE FLOW PROFILES AND DRILL SHIFT ENERGY NEUTRAL ADJUSTMENT METHOD		116

APPENDIX C: ESKOM MEGAFLEX TOU TARIFF STRUCTURE	119
APPENDIX D: EQUIPMENT USED BY THE VARIOUS CREWS AND THEIR RESPECTIVE UTILISATION FACTORS.....	121
APPENDIX E: HALF-LEVEL BASELOAD TEST RESULTS	124
APPENDIX F: EXPLANATION OF THE ENERGY AND FINANCIAL SAVING CALCULATION	129
APPENDIX G: EXPLANATION OF THE PAYBACK PERIOD CALCULATION	133

LIST OF FIGURES

Figure 1: Breakdown of the electricity expenditure on a representative deep-level platinum mine (Adapted from [10])	2
Figure 2: An example layout of the CA network on a deep-level platinum mine shaft	4
Figure 3: Simplified diagram of the underground CA layout on a mining level.....	6
Figure 4: Top view layout of the CA distribution in the working areas	7
Figure 5: Typical daily shift cycle for a deep-level mine	8
Figure 6: Pneumatic hand-held rock drill [35].....	9
Figure 7: Pneumatic loader loading waste rock [43].....	11
Figure 8: Underground refuge bay [28]	11
Figure 9: Pressure requirement profile for the 24-hour mining shift cycle.....	13
Figure 10: Breakdown of CA misappropriation.....	14
Figure 11: CA leak on a pipe flange and a corroded CA pipe [8].....	14
Figure 12: Leakage rates (Nm^3/h) for various supply pressures and approximate hole sizes	16
Figure 13: Typical CA consumption profile over the 24-hour shift cycle [8]	18
Figure 14: Effect of CA wastage across a half-level (Adapted from [50])	19
Figure 15: Integrated approach to improve the energy efficiency of CA on deep-level mines (Adapted from [53]).....	21
Figure 16: Flow and pressure profile for a deep-level platinum mine	23
Figure 17: CA demand ratio profile	24
Figure 18: CA pressure and flow profile measured during an audit [8].....	27
Figure 19: Process flow diagram used to develop the proposed solution.....	36

Figure 20: Schematic illustration of a mining shaft's CA network layout.....	40
Figure 21: CA flow and pressure profile for a baseload test (Adapted from [8])	41
Figure 22: Typical haulage CA network and systematic audit procedure	42
Figure 23: Top view of a detailed half-level surveying drawing	45
Figure 24: Authorised CA consumers identification process flowchart	46
Figure 25: Proposed control philosophy for a cross cut isolation valve over a 24-hour period.....	47
Figure 26: An example flow profile on how the validation and verification of the CA theoretical model will be done	54
Figure 27: Implementation methodology to verify cross cut isolation	56
Figure 28: Electric and pneumatic actuator.....	60
Figure 29: Underground layout of the mining shaft used for the case study.....	65
Figure 30: Surface flow and pressure profile obtained during a shaft baseload test.....	67
Figure 31: Normalised baseload over a 12-month averaged 24-hour supply pressure profile	68
Figure 32: Flow and pressure profile obtained during the CA audit on half-level number 1.....	71
Figure 33: Visual audit results for cross cut number 1	73
Figure 34: Visual audit results for cross cut number 2	74
Figure 35: Flowrate comparison between a 32 mm and 5 mm hole at different pressures.....	75
Figure 36: Wastage breakdown analysis	76
Figure 37: Cross cut isolation control philosophy for Levels 2 and 3 over a 24-hour period	81
Figure 38: Theoretical flow profile of 2 Level vs the baseline and baseload result flow profile	83

Figure 39: Theoretical flow profile of 3 Level vs the baseline and baseload result flow profile	84
Figure 40: Weekday profile when the cross cuts are isolated during the non-drilling shifts	87
Figure 41: Saturday profile when the cross cuts are isolated during the non-drilling shifts.....	88
Figure 42: Sunday profile when the cross cuts are isolated	88
Figure 43: Implementation methodology to verify cross cut isolation	91
Figure 44: (a) Weekday flow profile highlighting the impact achieved from manual cross cut isolation, (b) The remaining flow that can be reduced if the initiative's sustainability is improved	92
Figure 45: (a) Cross cut isolation valves were closed when no mining activities were conducted in the cleaning shift but then left open after the drilling shift, (b) Cross cut isolation valves were closed during the cleaning shift but then left open after the drilling shift.....	93
Figure 46: Cross cut isolation valve assembly	97
Figure 47: (a) SCADA user interface for the operator to open and close the valve, (b) Valve visible on the SCADA with the remote and valve fault feedback	98
Figure 48: Flow reduction achieved from the automatic cross cut isolation control strategy....	99
Figure 49: Example of CA flow baselines for weekdays, Saturday, and Sunday.....	116
Figure 50: An example of scaling a baseline profile	118
Figure 51: Flow and pressure profile obtained during the CA audit on half-level number 2...	124
Figure 52: Flow and pressure profile obtained during the CA audit on half-level number 3...	125
Figure 53: Flow and pressure profile obtained during the CA audit on half-level number 4...	126
Figure 54: Flow and pressure profile obtained during the CA audit on half-level number 5...	127
Figure 55: Flow and pressure profile obtained during the CA audit on half-level number 6...	128

LIST OF TABLES

Table 1: Overview of the different categories that form part of the CA network	3
Table 2: CA end users [1]	12
Table 3: Summary of CA energy saving initiatives on deep-level mines.....	29
Table 4: General information on portable CA measuring instrumentation	38
Table 5: General authorised CA consumers active during the non-drilling periods on a half-level	45
Table 6: Stopping crew and their equipment active during the drilling shift.....	49
Table 7: Flat-end cleaning crew and their equipment active during the cleaning shift	49
Table 8: Example of the theoretical flow calculation	50
Table 9: IPMVP's framework for developing a baseline [72].....	52
Table 10: CA isolation valves most commonly used on deep-level mines	58
Table 11: Differences between a butterfly and v-notch ball valve [75]	59
Table 12: Differences between a electric and pneumatic actuator [39].....	60
Table 13: Summary of the shaft's CA baseload consumption	69
Table 14: Consumers active during the period in which cross cut isolation will be implemented	77
Table 15: Mining shift schedule for both Levels 2 and 3.....	80
Table 16: Planned MRM crews for Level 2 and 3.....	82
Table 17: Model validation calculations	86
Table 18: Compressors on South Ring	89
Table 19: Potential power and energy savings on weekdays, Saturdays, and Sundays.....	90

Table 20: Seasonal costs and days	90
Table 21: Eskom Megaflex TOU tariff table 2021/2022 (c/kWh) [11]	119
Table 22: B Shaft's compressed air half-hourly power saving calculations for the weekdays.....	129
Table 23: B Shaft's compressed air power saving for weekdays, Saturdays, and Sundays ..	130
Table 24: Cost savings for both summer and winter tariffs	131
Table 25: Summary of the total weekday, Saturday, and Sunday cost savings	132
Table 26: Weekday power saving for the cross cut isolation valve	133
Table 27: Summary of the total weekday cost saving for the cross cut isolation valve	134

NOMENCLATURE

Symbol	Description	Units
$\dot{m}$	CA mass flowrate	[kg/s]
$C_{discharge}$	Discharge coefficient	[-]
k	Specific heat ratio of air	[-]
P	Pressure in the compressed air pipe	[kPag]
R	Gas constant	[KJ/kg.K]
T	Temperature in the compressed air pipe	[K]
A	Area	[m ²]
P_{spec}	Specific power	[kWh/Nm ³]
P	Power	[kW]
F	Compressed air flow	[Nm ³ /h]
P_{saving}	Power saving	[kW]
ΔF	Reduction in flow	[Nm ³ /h]
E_A	The total measurement period energy consumption in the drill shift	[kWh]
E_B	The total baseline period energy consumption in the drill shift	[kWh]

LIST OF ABBREVIATIONS

CA	Compressed air
CFM	Cubic feet per minute
CMH	Cubic meters per hour
FAD	Free air delivery
Flat-Dev	Flat-end development
IPMVP	International Performance Measurement and Verification Protocol
KPI	Key performance indicator
MRM	Mineral resources management
OEM	Original equipment manufacturer
On reef	On reef development
PLC	Programmable Logic Controller
Re-Dev	Re-development
RDO	Rock drill operator
Ref-Bay	Refuge bay
SCADA	Supervisory Control and Data Acquisition
SIMRAC	The Safety in Mines Research Advisory Committee
SLA	Service Level Adjustment
TOU	Time-of-use
X/Cut	Cross cut

CHAPTER 1: THE USE OF COMPRESSED AIR IN DEEP-LEVEL PLATINUM MINING

1.1 Introduction to compressed air on deep-level mines in South Africa

Compressed air (CA) is regarded as an important source of energy for underground mining operations on deep-level mines in South Africa [1, 2]. Historically, CA was introduced in the mining industry as an easy-to-use, cost effective and relatively safe medium to transfer energy underground [3-5]. The easy-to-use nature of CA equipment in the working areas implies that mines do not require skilled labour to conduct mining operations [6].

However, converting electrical power into mechanical power by means of compressing air is in fact the least efficient utility in the mining industry [1]. Fraser [2] highlighted the overall energy inefficiency of CA when compared with other mediums that deliver energy from a generating source to the tip of a drill. The overall energy efficiency of CA is calculated at 2%, which is very low in comparison with other mediums such as electrohydraulic drills at 24%, hydropower drills at 23% and electric drills at 31% [2].

A major contributing factor towards CA inefficiency is that CA is highly susceptible to wastage and misappropriation, as it has no smell or colour, resulting in large volumes of CA being wasted without being easily noticed [1]. Misappropriation is a collective noun that refers to the mismanagement and malpractice of CA, i.e. the use of CA for ventilation purposes and wastage as a result of negligence [7].

Highlighting the extent of this issue, recent studies have identified that up to 75% of a mining shaft's CA consumption can be attributed to leaks and misappropriation [1, 8]. Therefore, CA becomes a very costly form of supplying energy to the underground mining operations if not correctly managed, especially when considering the varying impact that the misappropriation factor has on this already inefficient commodity [9].

Figure 1 gives a breakdown of the electricity costs for the different mining utilities on a platinum mining shaft with an average CA consumption to production ratio. This particular shaft was selected from a sample of 19 deep-level platinum mining shafts [10]. It is evident that the CA utility on the example shaft accounts for approximately 38% of the total electricity expenditure, making it the highest energy expense.

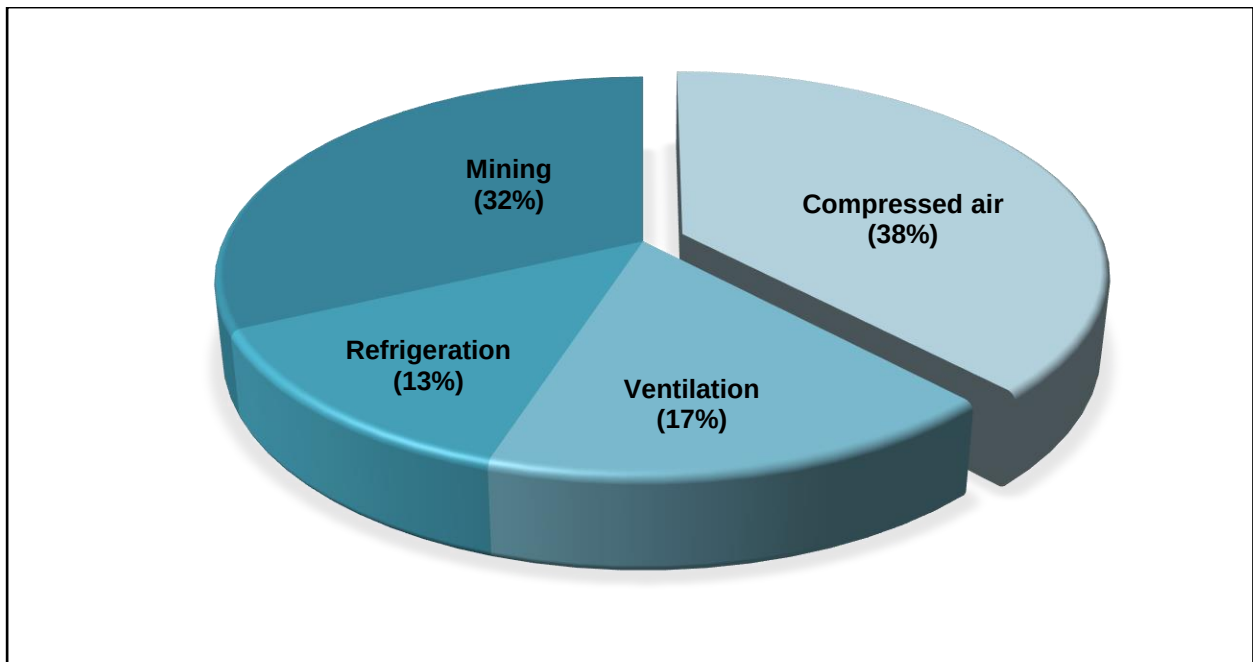


Figure 1: Breakdown of the electricity expenditure on a representative deep-level platinum mine
(Adapted from [10])

This representative deep-level platinum mine, spends at least R5-million per month during Eskom's low demand season (September to May) on CA [10, 11]. During Eskom's high demand season (June to August), electricity tariffs are on average 72% higher when compared to the low demand season. Therefore, the monthly CA expenditure during the high demand season increases by the same percentage [11].

Expanding on the topic of rising costs in the industry, Ernst & Young Global Limited [12] highlighted that energy issues, directly related to supply and cost, have featured among the top ten business risks facing the mining industry. Sustainable energy management therefore becomes a cornerstone to risk and business management in this sector [13]. In the mining industry, electricity tariff increases have been a major driver of increased operational costs over the past 14 years [14, 15]. In addition to increased operational costs, the inefficient energy usage in CA operations ultimately places the industry under financial pressure as profit margins are negatively affected.

Since 2007, Eskom's active energy charge electricity tariffs (Megaflex non-local authority charges) during the peak time of use in the high demand season increased by 562% from 63,04 c/kWh to 417,14 c/kWh in 2021 [11]. Therefore, a need for energy mitigation strategies exist and are rapidly becoming a vital strategic consideration in the mining industry to alleviate the overall impact of rising electricity costs [13].

1.2 Expanding on compressed air usage in platinum mining

The purpose of this section is to discuss the use of CA for general mining operations. More detail will be provided on each component that is relevant to this study. In order to identify the scope of expanding and improving energy management initiatives, it is necessary to understand a mine's CA system in terms of network infrastructure and the CA requirements for mining operations. The latter half of this section will evaluate the individual requirements of the CA users and how it forms part of the 24-hour mining cycle. This information will assist in effectively identifying and addressing the problem statement of this study.

1.2.1 Compressed air network infrastructure and mining operations

The CA network forms the backbone of several mining processes. Table 1 gives an overview of the three major categories that make up a CA network. Each category consists of various components that differ in size, application, and function. The different categories will be discussed in more detail throughout the succeeding sections.

Table 1: Overview of the different categories that form part of the CA network

Category	Description
Supply side	Supply side refers to the compressors that generate the CA supplied to the mining operations.
Reticulation network	The generated CA is supplied to various mining shafts and is channelled underground to the different working areas via a piping network.
Demand side	The demand side can be collectively referred to as the CA end-users.

A visual illustration of the three above-mentioned categories integrated to form the CA network on a deep-level platinum mine is presented in Figure 2. The figure illustrates the compressors found in the compressor houses which generate the CA, collectively referred to as the “supply side”. The generated CA is distributed to different mining shafts where it is transported to the underground mining levels via the reticulation network. The end-users of the CA, i.e. the “demand side”, are located on the underground mining levels.

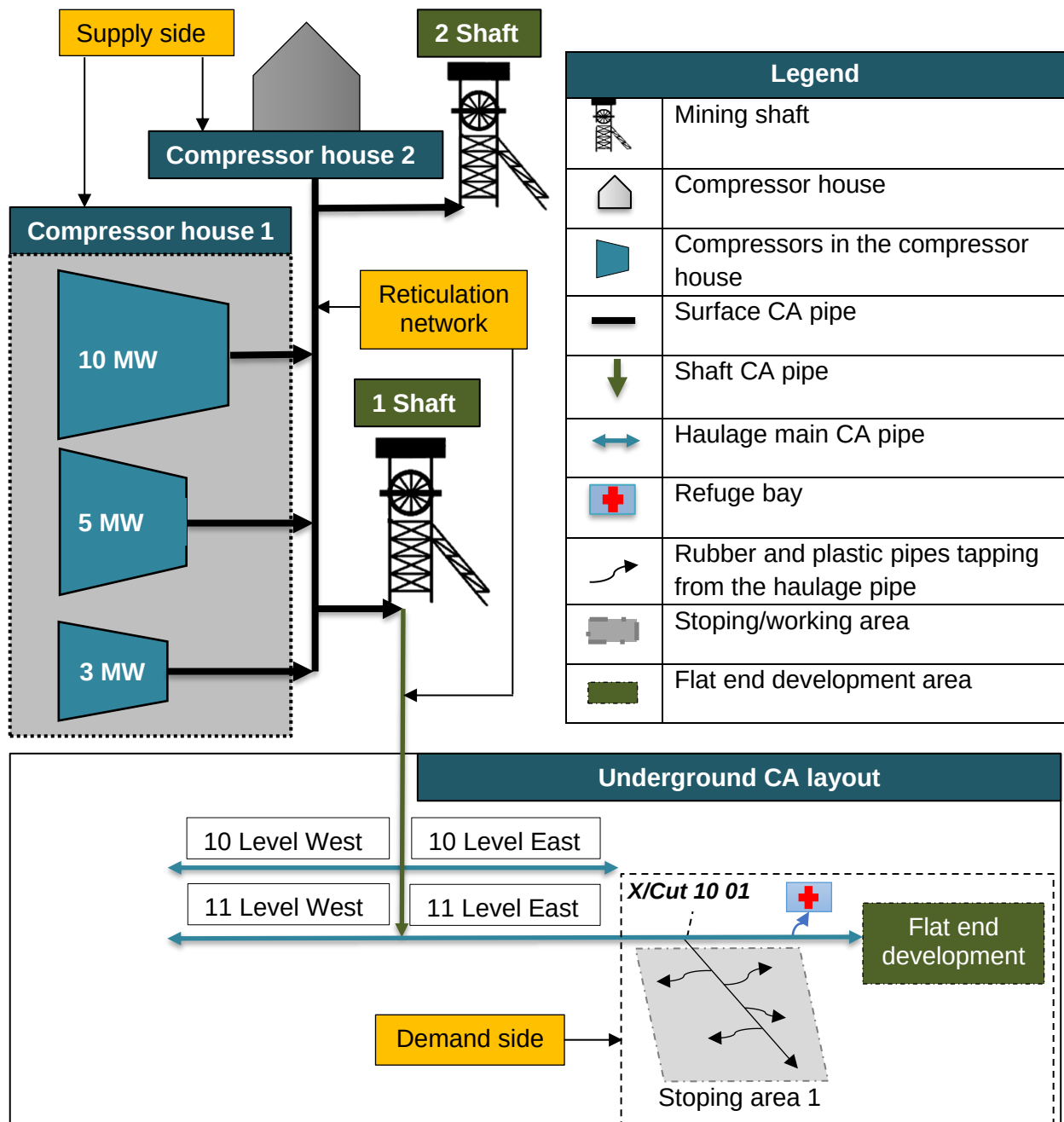


Figure 2: An example layout of the CA network on a deep-level platinum mine shaft

Supply side

The supply side category consists of multiple compressors that generate compressed air. The compressors are grouped in different compressor houses, as illustrated in Figure 2 [4, 16, 17]. This supply side category is regarded as the heart of the CA network.

Note that pressure and flow are two very common terms used when discussing a CA system. Pressure refers to the amount of force required to perform a specific amount of work at any given point in time [18]. Generally, in the mining industry, pressure is measured in KiloPascal (kPa) or bar (1 kPa = 0,01 bar) [19]. Note that these pressure measurements are generally measured as gauge pressure, meaning that it is referenced to the atmospheric pressure [19].

Flow, also known as free air delivery (FAD), is generally measured in nominal cubic meters per hour (Nm³/h). It can also be measured in cubic feet per minute (CFM) or kilogram per second (kg/s) [18]. However, flow is regarded as the ability of the compressor to continuously perform a task within an acceptable time frame [18]. In order to supply a sufficient amount of CA for a given application, it is important to consider the amount of CA flow required at a specific pressure for the process to operate efficiently [18, 20].

Generally, multi-stage centrifugal compressors are used on deep-level mines to generate the CA supplied to the underground mining operations [21-24]. These mining operations require high-volume CA supplied at pressures ranging between 200 and 600 kPa gauge [1]. The use of multi-stage centrifugal compressors is particularly attractive in the mining industry due to their mechanical simplicity which makes them easy to maintain and operate [6, 25].

The motors on centrifugal compressors have a power rating of up to 15 MW [26-28]. This enables the operation of various combinations of compressors in parallel to meet the required flow and pressure demands of the different end-users [23]. In addition to this, it is important to note that most deep-level mines operate a combination of baseload and trimming compressors [29]. Baseload compressors are generally operated at full capacity for extended periods, as they are responsible for maintaining the minimum pressure setpoints on the different mining shafts. Trimming compressors are responsible for supplying additional CA capacity during the high demand periods [23, 26].

Reticulation network

The generated CA is distributed via a steel pipe network that connects the different compressor houses with the various mining shafts, as shown in Figure 2. Generally, the size of these pipes used for this application ranges anywhere between 150 to 700 mm as it depends on the demand requirements of the various shafts [8, 27, 30]. The pipe network that connects the shafts is referred to as the CA ring [4, 23]. Multiple benefits exist when operating shafts on a CA ring, one of which is the advantage of better matching the supply with the demand as different compressor running combinations can be used [22-24, 27]. Note that on smaller scale mining operations, stand-alone compressors are often used instead of a compressed air ring [31].

Figure 2 also provides a simplified diagram of how the CA is channelled down the shaft, via the shaft CA pipe, into the underground mining levels. Some mining shafts extend up to 2 km vertically underground, depending on the depth at which mining operations are required [32]. The depth of the shaft determines the number of levels required to conduct mining operations [24]. The underground levels are all connected to the main shaft pipe. Figure 3 presents a more detailed overview of the CA distribution network into a mining level.

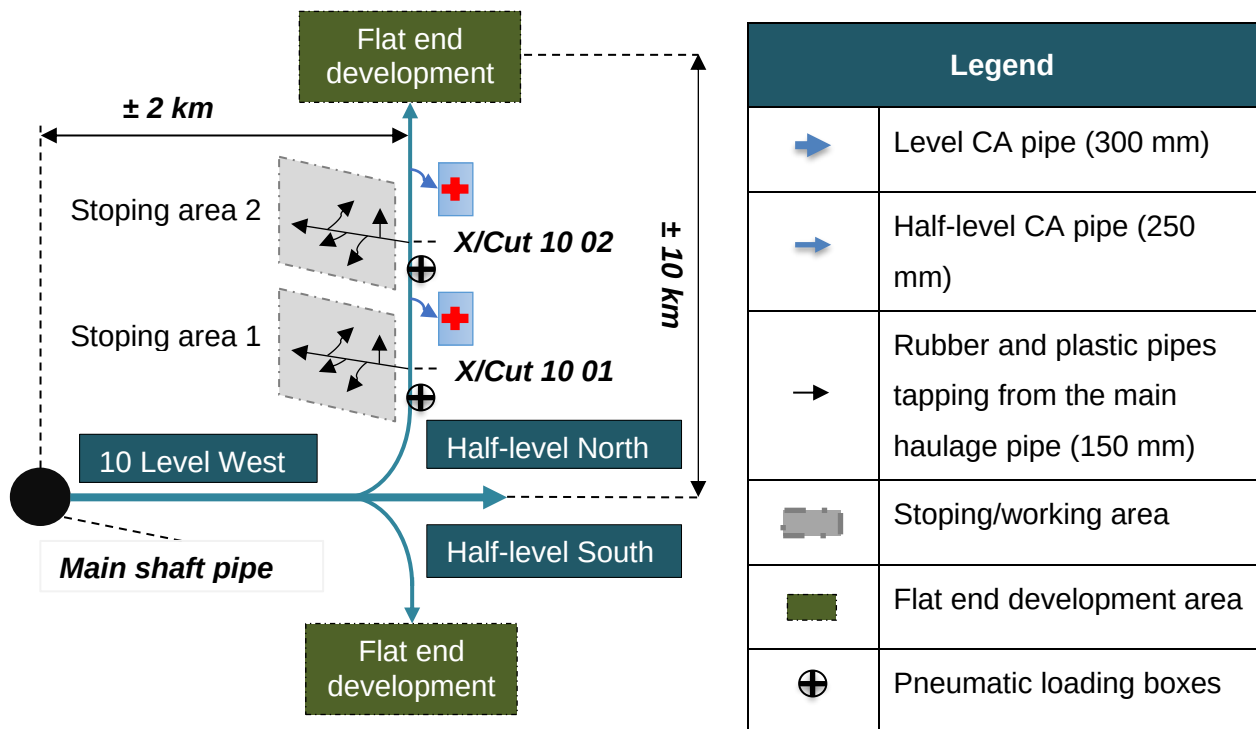


Figure 3: Simplified diagram of the underground CA layout on a mining level

As shown in Figure 3, the CA is further distributed among the level haulage (indicated as 10 Level West) and extends into the half-level haulages (indicated as the North and South half-levels). The level and half-level haulages are used for the transportation of ore, mining personnel and all the relevant services such as CA, service water, drinking water, electricity, and instrumentation communication cable [8].

The CA network branches off from half-levels into sections known as the cross cuts (X/Cuts). The cross cuts are smaller passages that lead into the stoping areas where the majority of mining operations are conducted. Stopping is referred to as the removal of the orebody from the surrounding rock, which is also known as the stope face [33]. Furthermore, the CA is generally channelled into the cross cuts to the stoping areas via a combination of 150 mm diameter plastic pipes and rubber pipes [34]. The pipe sizes tend to decrease as they extend from the cross cuts into the stoping areas, as shown in Figure 4 [35].

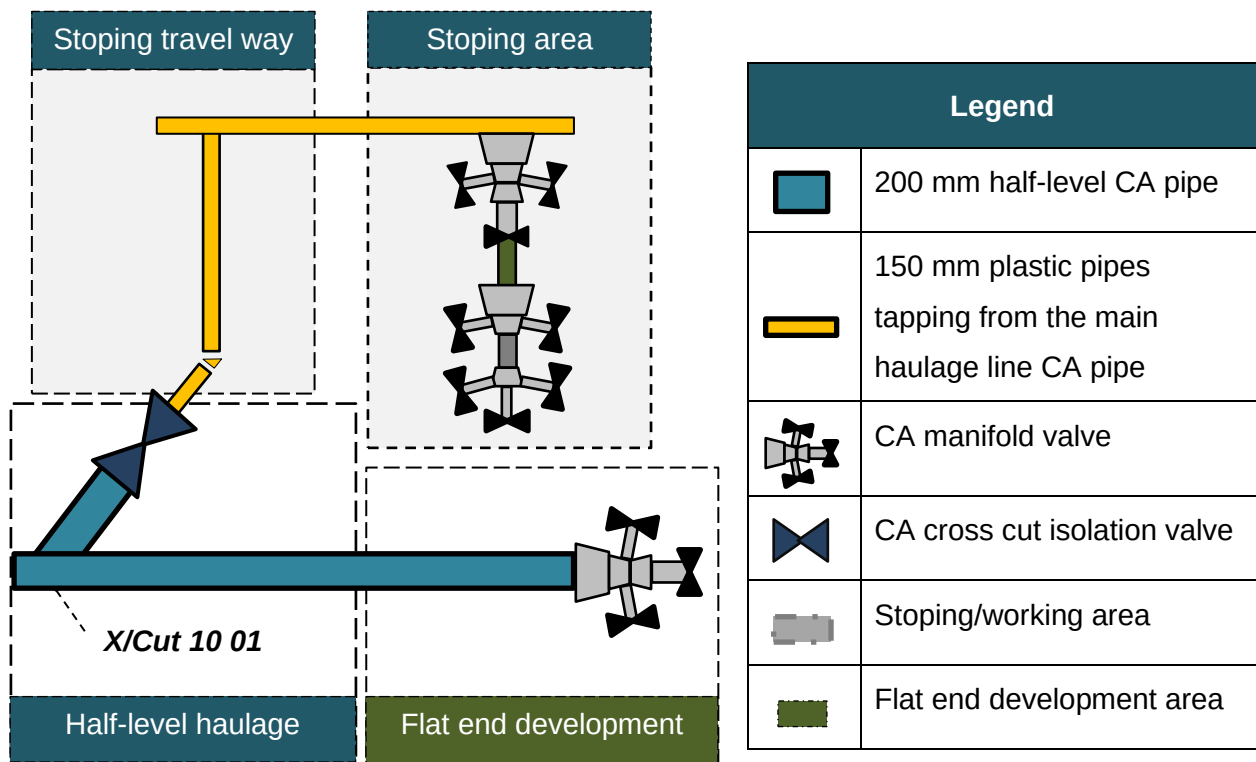


Figure 4: Top view layout of the CA distribution in the working areas

The yellow line, as represented in Figure 4, gives a visual illustration of how the CA is channelled from the half-level haulage through the cross cut and into the stoping area. In the stoping area, a CA manifold with multiple connections is fitted to the main line. These manifolds make use of quick coupling pipes to accommodate the dynamic nature of the stoping areas [36]. A second

manifold with multiple connections is located closer to the stope face and is responsible for supplying CA to a variety of mining equipment [35].

These flat end development areas, as shown in Figure 4, are generally located at the end of the half-level haulages. “Flat end development” refers to the development and excavation for new mining working areas [37]. This working area is in fact the furthest point from the surface compressors and could extend as far as 3.5 km from the main shaft supply pipe on a level [8].

Underground deep-level platinum mining usually practises narrow-reef mining methods, which can also be referred to as conventional mining [38]. The methods used to conduct conventional mining operations will further be discussed under the demand side section. However, it is important to note that this mining method is highly dynamic in terms of network size and configuration. Therefore, it is not uncommon for the network to develop outside of the original design specifications [35].

Demand side

As mentioned under the supply side and reticulation network, CA is used on deep-level mines to operate a variety of equipment to carry out the different mining operations [8]. The equipment used underground is specific to the different mining shifts where important mining tasks need to be completed to ensure that continuous mining operations can be conducted [21, 39].

Platinum mining is a continuous process over a 24-hour mining cycle. Figure 5 shows a typical daily mining cycle for a deep-level platinum mine.

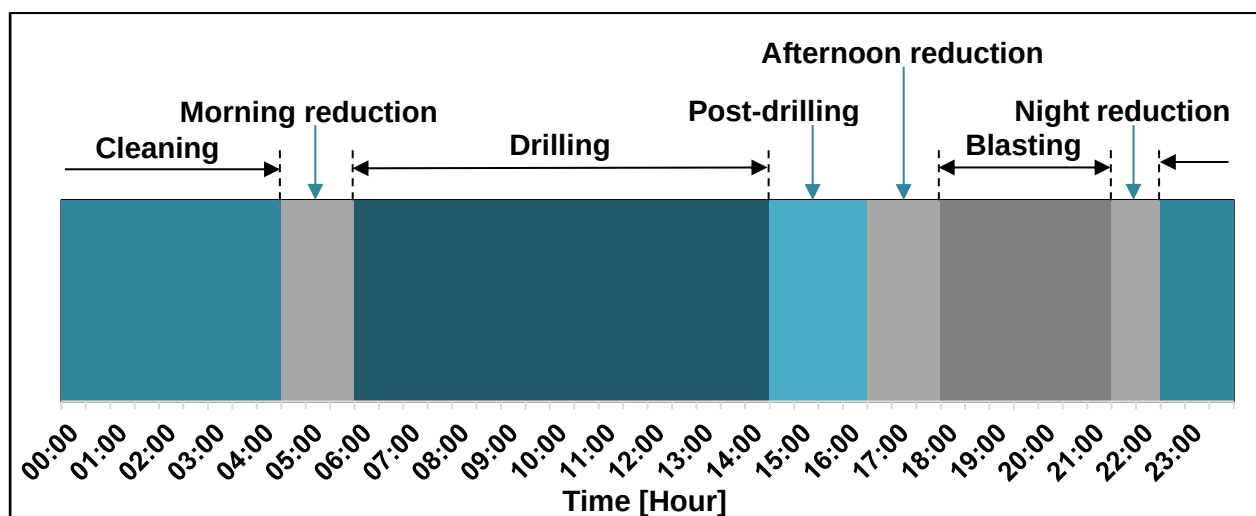


Figure 5: Typical daily shift cycle for a deep-level mine

Three distinct shifts are present in this cycle, namely the drilling, cleaning, and blasting shifts. Note that the focus of this study is mainly on the shifts outside of the drilling shift. During the drilling shift, the mining shaft's CA flow and pressure requirements are at their highest, as a result of the large work force and drills in operation [28]. It is therefore not recommended to introduce energy saving initiatives during the drilling shift. This is due to the risk of negatively affecting the drilling operations and ultimately the mining shaft's production performance.

The nature of work conducted during each shift will be explained in more detail to gain a better understanding as to how they integrate and influence each other:

- ***Drilling shift (06h00 – 14h00)***

Drilling in conventional mining refers to the process of literally drilling holes in the rock face with rock drills. These holes are drilled by the rock drill operators (RDOs) with the use of pneumatically driven drills, which are supplied from the CA network [35]. Figure 6 illustrates a pneumatic hand-held rock drill.



Figure 6: Pneumatic hand-held rock drill [35]

- ***Post-drilling shift (14h00 – 16h00)***

Generally by 14h00, the majority of the work force have stopped drilling, which ultimately results in a reduction of the CA demand. During this period, explosive charges are placed in the holes drilled in the rock face. This shift is also referred to as the explosive charge-up shift. The explosives are remotely detonated from surface to ensure safe operations [5].

- ***Blasting shift (18h00 – 21h00)***

The blasting shift represents the detonation period of the explosive charges placed in the drilled holes underground. The initiation of the explosives is an instantaneous event that occurs at the

start of the shift. Mining activities during this shift are prohibited with no mining personnel allowed near the underground working areas [5]. This is due to the dangerous nature of using explosive charges underground, and most importantly, allowing enough time for the blasting fumes and noxious gasses to clear from the working areas as a result of detonating the explosive charges. [38, 40].

The blasting shift is also the period with the lowest CA demand, as there is no active equipment during this period that consumes CA. The CA demand during this period is referred to as the baseload consumption. The baseload consumption is attributed to the underground CA wastage [21]. Generally, the biggest baseload consumers are underground leaks, on the CA infrastructure, and open-ended blowing pipes that are left open to ventilate the working areas [2, 34, 36]. Section 1.3 will further elaborate and discuss this baseload consumption and the effects thereof.

- ***Cleaning shift (22h00 – 04h00)***

After blasting has been completed, the cleaning shift can commence. The cleaning process entails collecting the blasted ore from the stope face by means of large scrapers powered by electrical winches. The collected ore is transported to ore passes supplying the pneumatically operated loading boxes [35, 41]. These loading boxes are located at specific locations in the haulages, near the cross cuts, as illustrated in Figure 3. Note that there is generally no CA consuming equipment in the stoping areas during the cleaning shift.

Small pieces of rocks or dust, which are also referred to as fines, left over after the blasting shift, are collected through a process known as sweeping. The sweeping process is normally conducted with the use of brooms or water hoses on the stope face. This is to ensure that all fines are washed from the blasted area [42]. However, an expensive and dangerous method of sweeping is also used by the mining personnel which is regarded as a negligent culture. This method entails using CA to blow all the fines from the stope face. The use of this method is prohibited due to the high risk of workers getting injured when blowing the fines at high pressures [35]. Workers using high pressure CA for sweeping are also exposed to high noise levels, which can cause significant hearing damage [1].

Another important task performed during the cleaning shift entails the cleaning of the flat-end development areas. The rock blasted in the flat-end development areas are collected by means of pneumatic loaders which directly connect to the half-level haulage CA pipe.

Generally, one loader is located per half-level haulage. These loaders are track-bound machinery which are used to load the development ore into hopper cars that transport the material. CA is

used to pivot the arm of the loader in order to catapult the scooped ore into the hopper car [37]. Figure 7 shows a pneumatic loader in the process of loading ore into the hopper car.

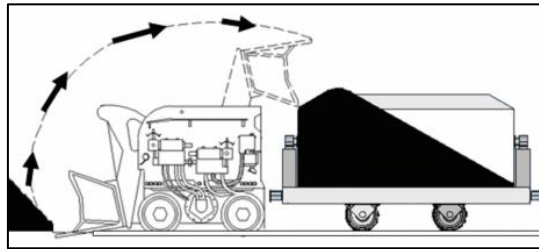


Figure 7: Pneumatic loader loading waste rock [43]

- ***Morning, afternoon, and night reduction:***

The three light grey areas as shown in the 24-hour shift cycle in Figure 5 represent the shift changeover periods. There are three distinct changeover periods present in the 24-hour cycle, namely the morning, afternoon, and night reduction shifts. During these periods the mining personnel working in the next shift are transported to the underground working areas, whilst the personnel from the previous shift are transported to surface [5, 8, 28].

The most important CA consumer during the 24-hour mining shift cycle are the refuge bays. The refuge bays are generally the main CA consumers during the reduction shifts. Mines have a legal responsibility to provide safe refuge areas in the case of emergency events, such as fires [25, 35]. This entails supplying a constant flow of CA to an enclosed area to maintain positive pressure conditions inside of the area, as this prohibits any harmful gas from entering this safe area [31]. As shown in Figure 3, the refuge bays are generally located in the haulages of the mining levels. Figure 8 shows a refuge bay on a half-level of a deep-level platinum mine.



Figure 8: Underground refuge bay [28]

1.2.2 Compressed air pressure demand of end-users

In this section, the requirements for the different CA end-users will be discussed to identify the minimum operating pressures for each mining shift. As previously mentioned, pressure is an important driving factor for the use of pneumatic equipment and is dependent on the amount of CA flow required by the end-user [18, 28]. It is therefore crucial that sufficient pressure and flow are supplied to the end-users with the highest requirements to ensure that efficient operations can be conducted [1, 17, 28]. Low operating pressure will compromise the overall efficiency of the equipment and could possibly result in a loss of time and production [34, 35].

Table 2 gives the typical pressure and flow requirements for a selection of compressed air equipment used to conduct mining operations. The equipment discussed in the table below is regarded as the highest consumers in terms of pressure and flow requirements.

Table 2: CA end users [1]

Equipment	Pressure Requirement	Flow Requirement	Operating shift
Rock drills [31, 44]	450 – 600 kPa	0,12 kg/s @ 600 kPa	Drilling shift
Explosive charge [31]	400 – 450 kPa	0,3 kg/s @ 450 kPa	Post-drilling shift
Rock loaders [1, 28]	350 – 450 kPa	0,8 kg/s @ 450 kPa	Cleaning shift
Shotcrete machine [1]	450 kPa	0,9 kg/s @ 450 kPa	Cleaning shift
Loading boxes [1, 4, 21]	400 – 500 kPa	0,1 kg/s @ 450 kPa	Cleaning shift
Actuators on valves [21]	350 – 400 kPa	<0,02 kg/s @ 400 kPa	All shifts
Refuge bays [1, 5, 8]	150 – 200 kPa	<0,06 kg/s @ 200 kPa	All shifts

All the above-mentioned end-users are supplied from the CA network, which implies that the minimum pressure requirements for each mining shift are determined by the user with the highest operating pressure. The end-users listed in Table 2 are generally the users with the highest pressure and flow requirements. Note that there is a variety of CA equipment not mentioned in the table due to their small demand requirements, as the demand in terms of pressure and flow are determined by the users with the most significant pressure requirements [35].

Figure 9 gives the pressure demand profile for the 24-hour mining shift cycle as presented in Figure 5. This figure provides a visual example of the minimum pressure requirements determined by the end-user with the highest operating pressure, as presented in Table 2, for each of the individual mining shifts.

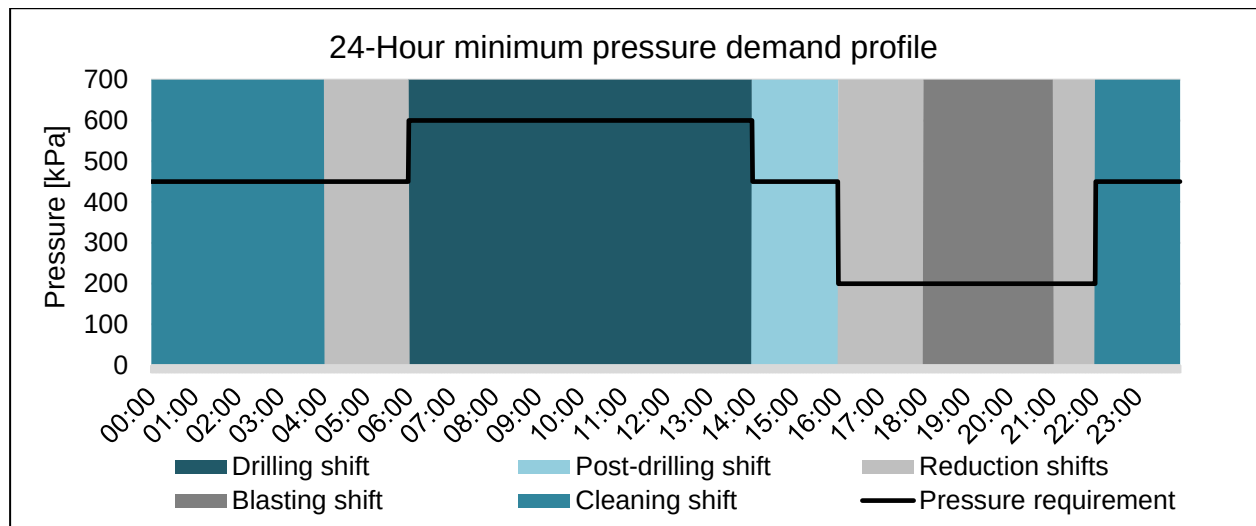


Figure 9: Pressure requirement profile for the 24-hour mining shift cycle

1.3 Expanding on compressed air wastage

The majority of deep-level mines have an intricate underground distribution network through which CA is supplied to the different mining sections [45]. As previously mentioned, these deep-level mines generally practise narrow reef mining methods and will share a similar CA layout as illustrated in Figure 3.

The risk of CA wastage and misappropriation become even more apparent, especially when introduced to this highly dynamic underground working environment [4, 35, 46]. CA networks can develop outside of its original design specifications in order to accommodate the expansion and development for new mining ground [35]. This dynamic nature adds to the difficulty of effectively managing the CA network [28, 34]. Figure 10 gives a detailed breakdown of the different contributing factors responsible for CA wastage on a deep-level mine.

CA wastage can be divided into two categories, namely leaks and misappropriation, as shown in Figure 10. Since leaks are commonly found on CA networks, studies suggest that an acceptable leakage rate is anywhere between 10 to 15% of the total shaft consumption [4, 6]. CA misappropriation is a result of mismanagement and malpractice due to negligent culture among the mining personnel who work underground.

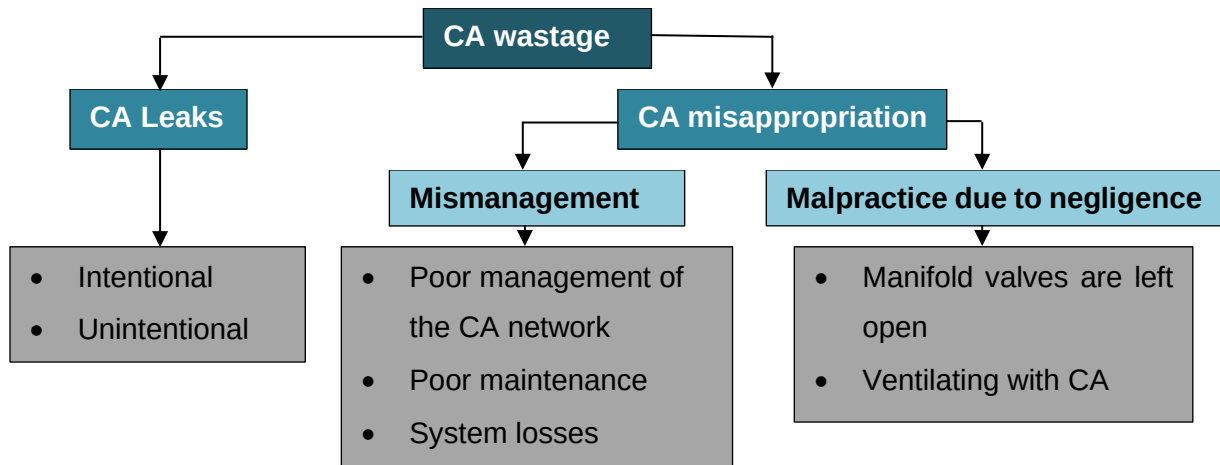


Figure 10: Breakdown of CA misappropriation

The CA network is exposed to an extremely harsh underground environment often resulting in the deterioration of the CA infrastructure [4, 39]. High moisture and temperatures in the underground environment cause corrosion of the infrastructure, while heavy machinery and rock falls result in punctured pipes [8]. Note that unintentional leaks often occur at pipe flanges and quick couplings [4, 8, 35]. Figure 11 gives an example of an unintentional CA leak found on a pipe flange. This figure also illustrates corrosion in the form of rust found on the haulage pipes as a result of the harsh environment.



Figure 11: CA leak on a pipe flange and a corroded CA pipe [8]

Although leaks can occur in any part of the CA network, the most common problem areas are couplings, hoses, tubes, fittings, pipe joints, quick couplings, valves, flanges and point of use devices [47]. As previously mentioned, it is required for the CA network to further extend in order to accommodate the expansion of a mining shaft. In larger networks, this results in more connections and piping, which adds to the risk of creating new leaks. It is evident that the dynamic nature and expansion of the underground mining network are directly linked to CA inefficiencies [28, 34].

To highlight the extent of CA leaks, consider the case study of a 20-year-old mine which involved measuring the CA flow during a period when no mining activities were taking place [1]. Visual audits were conducted to identify the unauthorised CA consumers. It was identified that 39% of the installed compressor capacity was consumed by leakages specifically. In total, 867 leaks were discovered, of which 46% involved mechanical quick couplings, 10% threaded pipe couplings, 23% faulty valves and 12% damaged hoses. The remaining 9% were attributed to miscellaneous faults [1].

Note that the mass flowrate through a leak is a function of the supply pressure in an uncontrolled system, and will increase with higher system pressures [47]. The mass flowrate can be determined by substituting the size of the leak and the supply pressure into an empirical equation, such as Equation 1 [19].

$$\dot{m} = C_{discharge} \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \left(\frac{P}{RT} \right) A \sqrt{KR \left(\frac{2}{k+1} \right) T} \quad (1)$$

Where:

$\dot{m}$ = CA mass flowrate in [kg/s]

$C_{discharge}$ = Discharge coefficient [for a hole with sharp edges = 0.6]

k = Specific heat ratio of air [Assumed value = 1.4]

P = Supply pressure in the CA column [kPa_g]

$R =$ Gas constant [0.287 KJ/kg.K]

$T =$ Temperature in the CA column [K]

$A =$ Area of the leak [m^2]

By using Equation 1, the magnitude of CA wastage through various hole sizes, representing the size of the leaks at different operating pressures, can be quantified. Figure 12 illustrates the exponential relationship between the mass flowrate and the size of the leak at various operating pressures.

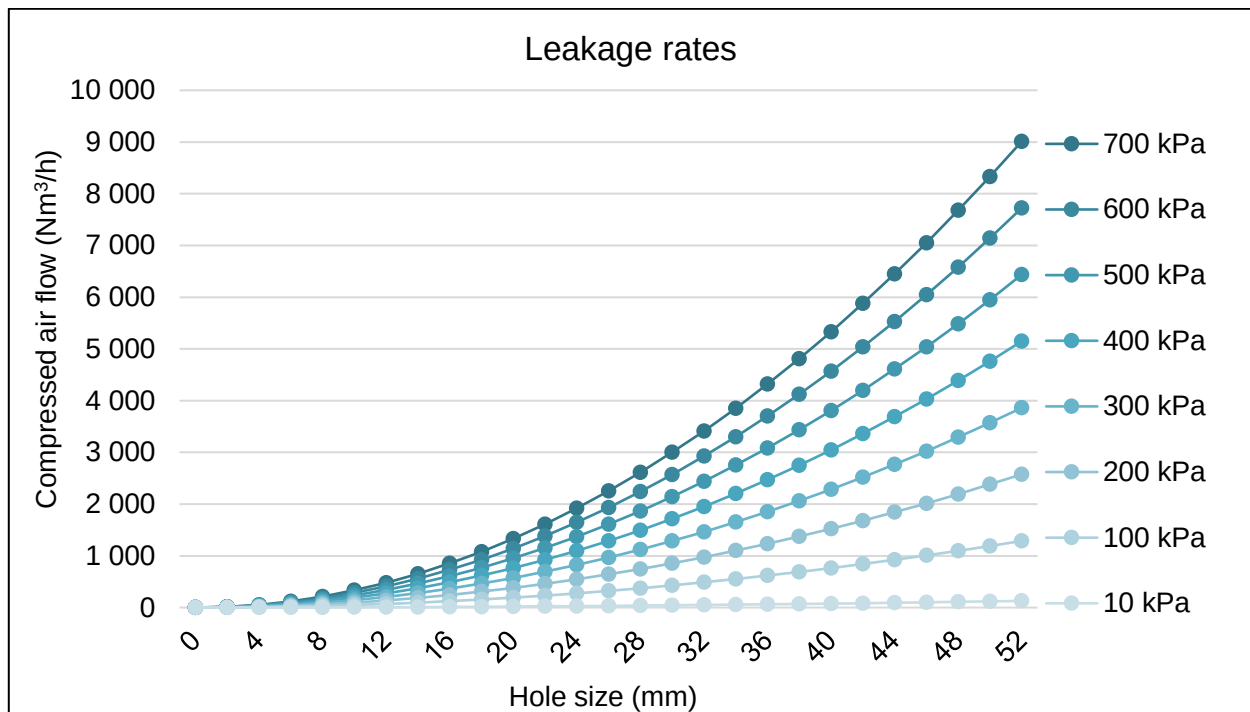


Figure 12: Leakage rates (Nm^3/h) for various supply pressures and approximate hole sizes

It is evident from Figure 12 that the flowrate is proportional to the square of the hole diameter. However, the mass flowrate increases significantly as the supply pressure increases [47]. It is therefore important that the supply from the compressors adhere to the demand requirements of the CA network, without adding to the risk of oversupplying the network. Oversupplying the network increases the wastage consumption, which ultimately leads to unnecessary increases in operating costs.

Due to high virgin rock temperatures and the high geothermal gradient, refrigeration and ventilation must be provided to the underground working areas from the early stages of development and must be sustained throughout the life of a deep-level platinum mine [13]. The risk of CA misappropriation is much higher when inadequate ventilation is experienced in warm working areas. Numerous studies have identified that the employees working in these hot underground environments readily make use of the easily accessible CA to cool themselves [4, 6, 8, 27, 36]. The reason for this is that CA, initially at high pressure, cools down when pressure is released to the atmosphere [19]. This is also known as the Joule-Thomson effect, which is defined as the phenomenon of temperature change produced when CA is allowed to expand adiabatically from a region of high pressure to a region of extremely low pressure [48].

It was found that the Rock Drill Operators (RDOs) leave the thrust legs or manifold valves of rock drills open for ventilation purposes in the stoping areas [36]. Considering the information presented in Figure 12, the valve sizes on these manifolds range anywhere between 25,4 and 50,8 mm. In conjunction with the excessive amount of CA wasted, a negligent habit is also present among the employees in leaving manifold pipes open after their working shifts [4, 6, 27, 35]. The studies also highlighted that open-ended blowing pipes are often left open when there are no mining personnel underground.

Numerous leak detection surveys conducted at various gold and platinum mines have shown that the most of the CA wastage occurs in the stoping areas [36]. Thus, the use of CA for ventilation purposes could explain why the stoping areas are highlighted as a major area where CA wastage and leaks occur [34, 49].

There is often no understanding as to how the CA network is constructed. In addition to this, mining personnel often do not fully comprehend the extent and state of the underground distribution network [27, 35]. Considering the size and age of the network, along with the dynamic nature of mining activities, it becomes very difficult to analyse and maintain the network [4]. Therefore, repairing all CA leaks is regarded as not realistic [8].

1.4 The impact of inefficient compressed air utilisation due to wastage

Figure 13 gives an example of a CA flow profile over the 24-hour mining shift cycle [8]. This figure highlights the extent of the CA wastage on a deep-level mining shaft which makes use of CA to operate pneumatic equipment. This is done by comparing the actual shaft consumption (shown as the dotted profile) with the expected theoretical consumption of the authorised end-users (shown as the green areas). These authorised end-users are referred to as production-related

consumers, as discussed in Section 2.2. Note that the authorised end-user consumption profile was obtained through simulation software developed for the example mining shaft as presented in Figure 13. In this example only the major CA consumers were considered in the simulation.

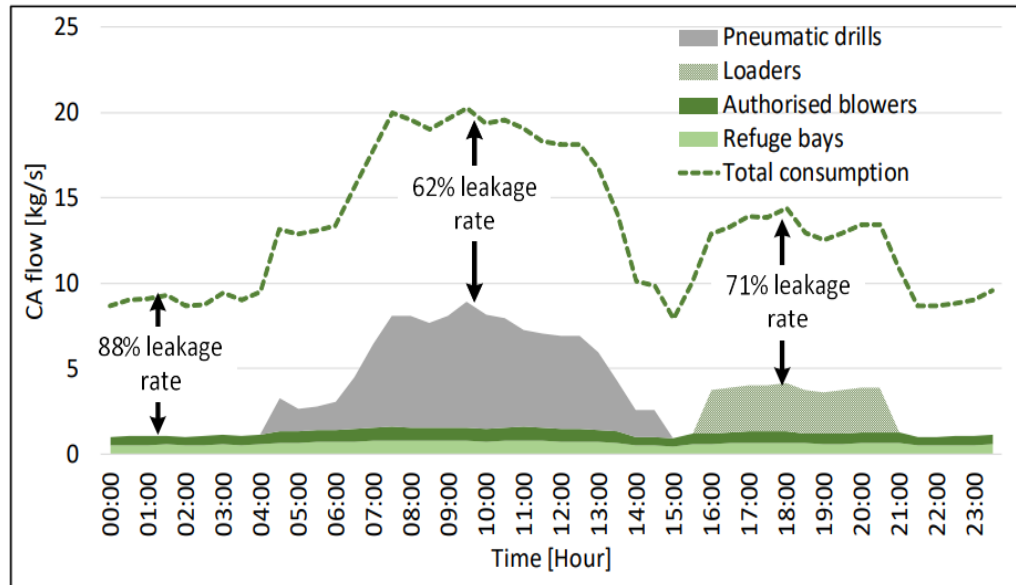


Figure 13: Typical CA consumption profile over the 24-hour shift cycle [8]

As shown in Figure 13, during the drilling shift the mining shaft's CA flow and pressure requirements are at their highest, as a result of the large work force and drills in operation [5, 28]. More importantly, it also indicates that there is an average difference of 75% between the total CA consumption of the shaft and the theoretical consumption of the authorised end-users [8]. This discrepancy is referred to as the baseload consumption or the CA wastage [2, 5, 36].

It is evident that leaks and misappropriation are responsible for a significant amount of CA consumed by a mining shaft. The inefficient use of CA can be regarded as a significant source of wasted energy [45]. Energy is used to compress air and any losses in the network directly translates to a loss in energy [8, 25, 36]. High system losses ultimately reduce the overall energy efficiency of a CA system, as more energy is consumed than what is used for production purposes [39]. The energy wasted due to leaks and misappropriation can be expressed in monetary terms by quantifying the electrical power wasted through these leaks and open ends [35]. Thus, the lower the energy efficiency of the CA system, the higher the operational cost [31].

Furthermore, inefficient CA utilisation causes a pressure drop over the network, which results in reduced operating pressures in the working areas [34, 36]. To highlight the extent of the pressure drop created across the network, Figure 14 illustrates a calculation model over the CA network of a typical half-level for a deep-level mine.

Note that this model is adapted from a study highlighting the pressure drop created when various leaks are present on a pipe [50]. Figure 14 shows a CA supply of 8.3 kg/s at a pressure of 500 kPa for a typical half-level at a length of ± 2 km. The different cross cut consumptions are also shown in the figure as a result of the CA leaks and misappropriation in the stopping areas.

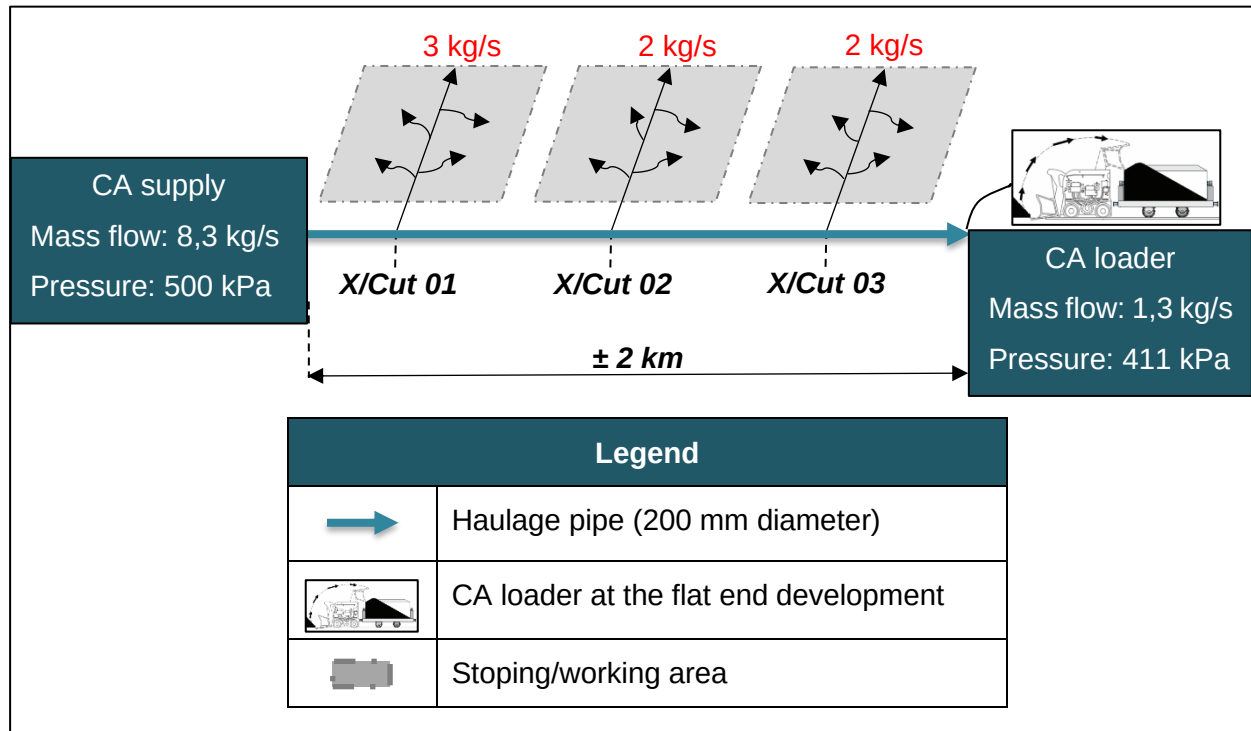


Figure 14: Effect of CA wastage across a half-level (Adapted from [50])

Friction losses over the haulage pipe and the wastage in the cross cuts only allow for 1.3 kg/s of the supplied CA to reach the flat end development area at a pressure of 411 kPa. A pressure drop of 89 kPa is experienced over the half-level as a result of these friction losses and CA wastage. If low or insufficient supply pressure is experienced in any working area, the operating efficiency of the mining equipment will be compromised and it may result in extended operating times, which lead to an increase of CA consumption. Thus, more energy is supplied to the network to overcome these system losses which ultimately contributes to the overall operational costs [31, 34].

The impact of poor CA utilisation highlights the immediate need and opportunity to reduce CA wastage on deep-level mines. By reducing the high underground demand, the network will become more energy efficient as the service delivery will increase for the same or lower energy input [31]. Addressing the high demand, by minimising any unnecessary losses and pressure drops over the network, will add to the reduction in energy consumption as the working pressure

does not have to compensate for higher demand [51]. This allows for a constant service delivery for less energy input.

1.5 Existing compressed air demand side management initiatives

The purpose of this section is to evaluate existing demand side management strategies to improve the overall energy efficiency of a CA system by addressing the high underground wastage demand. The latter half of this section will highlight the opportunities of further expanding demand side management initiatives, and the importance of addressing the human factor when implementing new mitigation strategies. The literature review will critically analyse initiatives implemented on the CA demand and whether or not they directly address CA misappropriation. The sustainability and impact of these initiatives will also be investigated. The information obtained from this analysis will assist with identifying the need for the study.

1.5.1 Existing compressed air optimisation strategies

It is evident from the previous section that there is significant scope to improve the overall energy efficiency of CA systems on deep-level mines. Therefore, the opportunity to save on electricity cost through the implementation of energy efficiency measures make it financially viable for a mining shaft to implement a wide variety of projects on their CA system [52].

Figure 15 gives the sequence of an integrated approach to which energy efficiency initiatives can be implemented on a deep-level mine's CA system (Adapted from [53]). The sequence can be divided into three categories starting with supply side management, artificial demand side management and demand side management. The sequence starts with supply side management and progresses to underground waste management.

Each category highlights the energy savings potential and the resources required to achieve sustainable energy savings. As mentioned in Section 1.2.1, supply side is regarded as the heart of the CA network, therefore, any energy efficiency initiative is implemented with the aim of reducing compressor power consumption - this is illustrated in Figure 15.

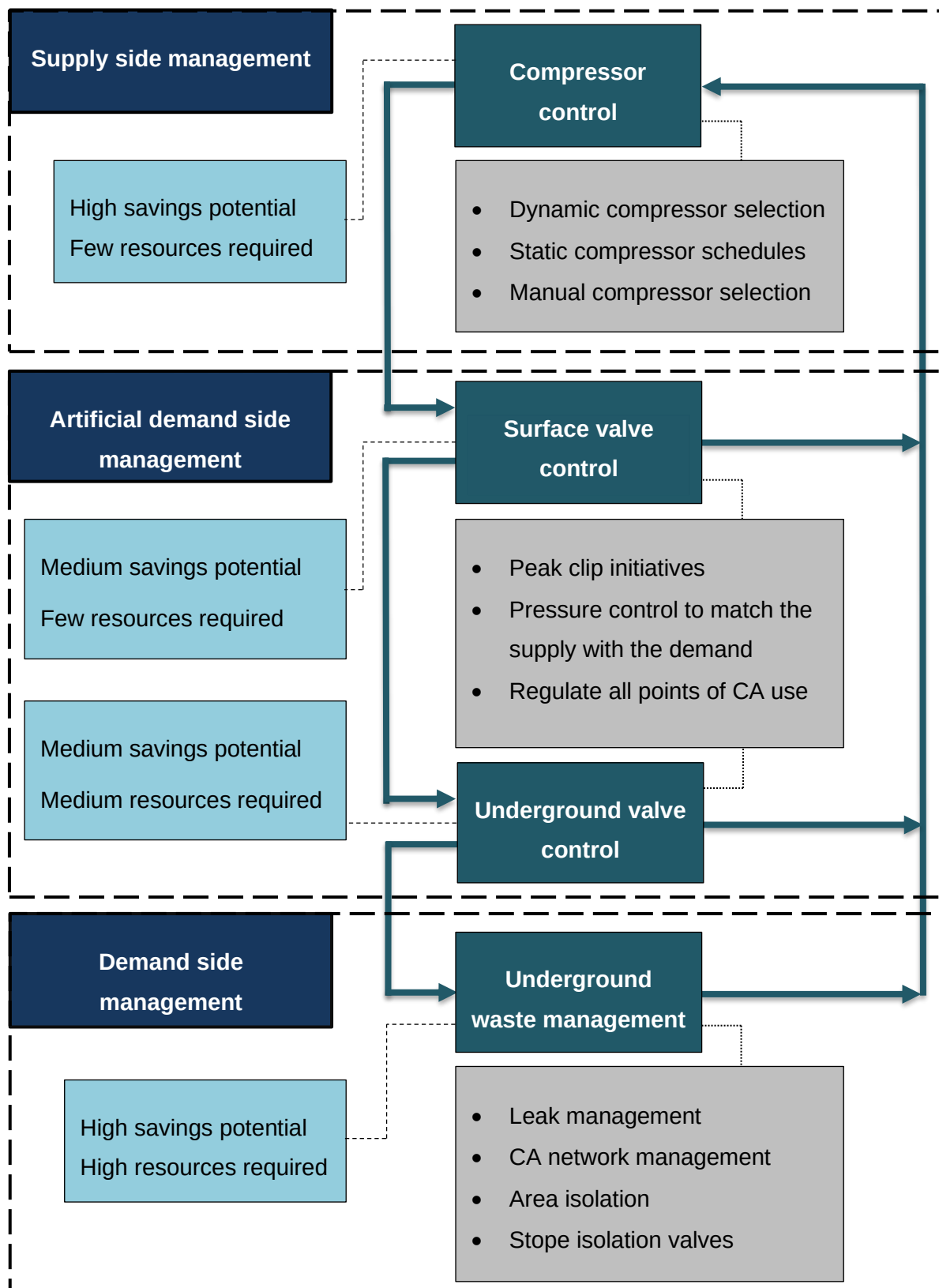


Figure 15: Integrated approach to improve the energy efficiency of CA on deep-level mines
(Adapted from [53])

Importance of supply side management

The cost of CA is determined by the amount of power a compressor consumes in order to satisfy the pressure and flow requirements of the relative end-users throughout a typical production day [30]. Supply side management aims to match the supply with the demand through a variety of compressor control strategies [21, 28, 45], thus reducing CA wastage by mitigating the risk of oversupplying the network with CA during the low demand periods [39, 52].

An existing and effective supply side energy saving initiative is to control the supply pressure of a compressor to a predetermined pressure set point during low demand periods [21]. Reducing the system pressure during these periods results in less CA wasted through existing leaks and open ends [53].

The ideal scenario is that compressors should be switched off during the low demand periods to achieve the highest energy savings potential, when compared with operating at partial load. This can be achieved by implementing measures such as dynamic compressor selection, which refers to a sophisticated control system that selects the most suitable compressor and combination of compressors to operate, based on compressor efficiency, location, and demand requirements [30].

Switching off compressors or controlling compressor pressure set points to match the supply and demand does not address the number and size of leaks/open-ends responsible for the high underground demand. It does, however, treat the symptoms as a result of CA leaks and misappropriation [6, 17, 28, 52]. These supply side management initiatives are regarded as low-cost and low-maintenance measures to reduce compressor energy consumption. However, the energy savings potential is limited to the minimum demand requirements of the CA end-users.

It is important to note that supply side management plays a vital role when demand side management energy initiatives are implemented. The goal of demand side initiatives is to reduce the high demand caused by leaks and misappropriation. In order to achieve any energy saving, brought about by a reduction in the CA demand, it is essential that the compressor control adjusts to match the lowered demand. Without effective compressor pressure supply control, CA energy savings obtained from demand side management initiatives will be limited [21].

Artificial demand side management

The function of CA control valves is to control and sustain a specific downstream pressure supplied to either the mining shaft or underground levels. The energy saving strategy is to reduce

the downstream pressure which ultimately reduces the CA flow supplied to the mining shaft or levels. These valves aim to match the supply with the specific sites demand requirements in order to minimise CA wastage during the low demand periods. The implementation of these valves allows for a more accurate and refined control, as the individual demand requirements for the different mining sections can be satisfied, thereby, increasing the energy savings potential of the CA system.

Figure 16 shows the expected flow reduction, shown as the green area, achieved as a result of implementing control valves on a typical deep-level platinum mine's CA network. The dark blue line and dotted black line, as shown in the figure, represents the initial shaft flow and pressure profile before any control was implemented. The light blue line represents the adjusted shaft flow profile resulting from controlling the valves on the different pressure setpoints, as depicted in red.

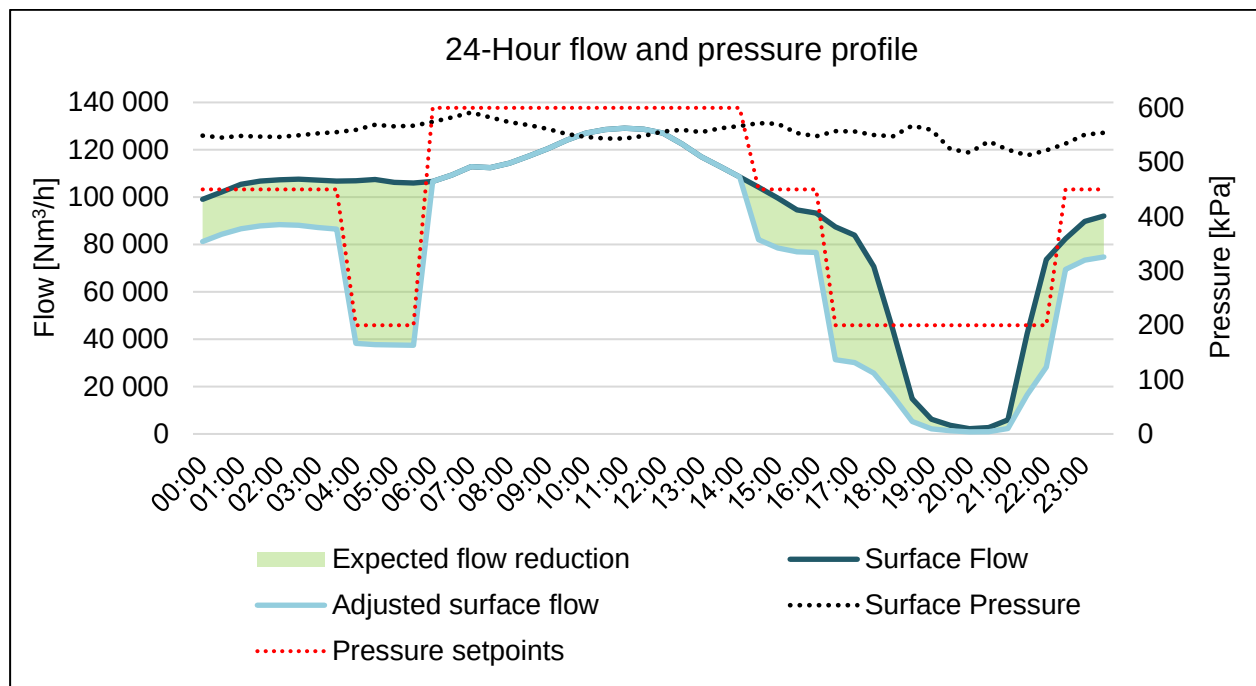


Figure 16: Flow and pressure profile for a deep-level platinum mine

The CA demand can be shown as the ratio between the amount of flow consumed per kPa, which includes both authorised and unauthorised consumers. The lower the flow to kPa ratio, the better the CA demand performance, as less flow is consumed per kPa of supply pressure. Figure 17 compares the initial demand ratio profile (shown as the grey line) with the demand ratio profile after valve control was implemented (shown as the dotted black line). The dotted red line represents the demand profile as seen from the compressor supply side.

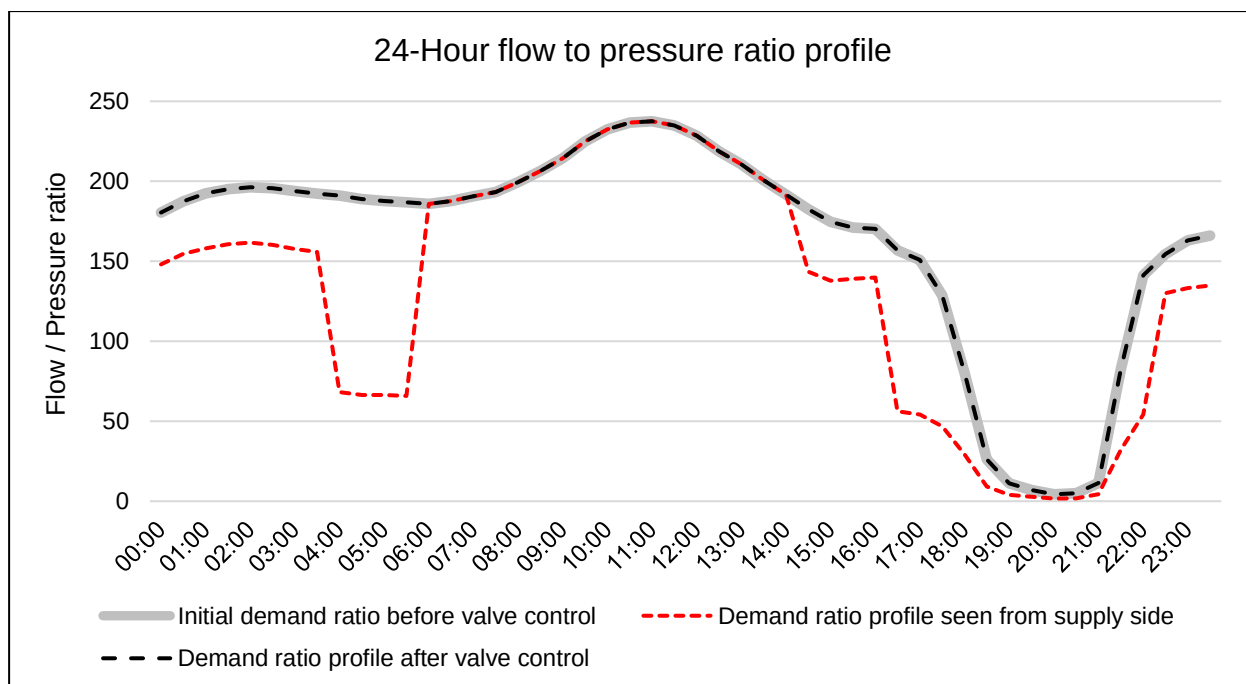


Figure 17: CA demand ratio profile¹

By controlling on lower pressure setpoints, the CA flow is artificially reduced, as shown in Figure 16, and a lower demand can be observed from the compressor supply as shown in Figure 17. This is where the energy saving is achieved, as less CA generation is required due to the lower demand at the specific site.

However, it is evident from Figure 17 that the underground demand remains the same as the number and size of the leaks/open ends are not directly addressed. Therefore, valve control only enables the shaft to address the symptoms of CA leaks and misappropriation by artificially reducing the CA flow, through lowering the supply pressure to the working areas.

It is important to note that when reducing the CA consumption through supply-side management or valve control, the consumption of both the authorised and unauthorised consumers is affected. However, the consumption ratio for both these consumers remains unchanged. Thus, the obvious solution to improving the energy efficiency of the CA system is to reduce the demand by directly addressing CA leaks and misappropriation [49, 52, 54].

¹ The data used for this analysis is obtained from a deep-level platinum mine in SA.

Demand side management

The demand side is easily one of the most overlooked areas of the CA network, and effective management and control of it can be beneficial for energy efficiency, longevity, and capital expenditure. Effective management of the demand can lead to higher standards for the use of CA, energy savings and ultimately a reduction in the demand which improves service delivery, which results in higher CA pressures.

- ***Conventional leak auditing and repair on deep-level mines***

Leak management is a typical initiative used for CA demand-side management. This involves collecting data, through CA network audits, storing the data and finally reporting on the findings identified during the audits [55]. This initiative is considered as a small change to the system which requires little investment to obtain substantial benefits [3, 54, 56].

The sustainability of leak management is highly dependent on continuous monitoring and effective reporting on the performance of the CA network. Energy managers therefore frequently resort to comprehensive audits, which involve visual or audible inspections of the entire CA network to locate leaks [3, 4, 26, 30, 39]. These conventional leak detection methods are resource intensive and time consuming, especially on the large CA networks found on deep-level mines [5, 22, 55, 57]. However, innovative auditing procedures have been identified to cost-effectively identify and prioritise the repair of CA leaks in a shorter amount of time [8, 53].

In addition to CA audits, newly developed local benchmarking methodologies bring about a more efficient way to identify and report CA inefficiencies. Novel KPIs (Key Performance Indicators) are used to compare different mining sections with one another. This comparison highlights and assists by prioritising mining levels or working areas with significant scope to reduce inefficient CA use [5].

It is well known by now that the CA networks on deep-level mines are intrinsically large and complex. In addition to this, the dynamic underground nature add to the difficulty of managing and maintaining the network. Some leaks are not easy to find, when compared with a fluid such as water, and are not always easy to repair [4].

Therefore, efficient leak management can be utilised when effective reporting systems are in place. These reports then become a valuable tool to track efficiency measures, prioritise leak repairing and assist mining personnel to better manage the allocation of resources for maintenance-related work [5, 55].

- ***Area isolation***

Demand side management can further be improved by investigating the possibility of isolating certain working areas from the CA network. This can be done during the low CA demand periods or by isolating inactive working areas that do not require any CA. This either involves blanking off inactive sections, which are generally identified during audits, or the implementation of isolation valves that are closed during non-drilling periods. This contributes to minimising CA wastage as a result of leaks and misappropriation.

Highlighting the scope of isolating certain working areas during the low demand periods, a study conducted on a mining shaft in South Africa focused on optimising supply and artificial demand side management [17]. This was done through compressor control in conjunction with level valve control which resulted in a daily demand reduction of 5,4 MW over the 24-hour mining cycle [17]. The energy initiative expanded by automatically closing the underground CA level valves during the Eskom afternoon peak demand period, from 18:00 to 20:00 [11]. This period is also known as the blasting shift, with no mining personnel allowed in the working areas during this period. By closing the underground level valves, the unauthorised consumers were isolated at the extremities of each underground level. This allowed for an additional demand reduction of 1,89 MW [17].

- ***Stope isolation***

It was mentioned in Section 1.3 that most of the CA wastage occurs in the stoping areas [36]. Therefore, a number of studies have recommended further investigation into expanding demand side management through isolating the CA supplied to the stoping areas during the non-drilling periods. This initiative involves the installation of isolation valves on the pipes supplying the stoping areas with CA. The aim is to close the isolation valves during the non-drilling periods to terminate CA wastage in the stoping areas [21].

A study that focused on developing novel solutions for CA demand management identified an ideal audit procedure which was conducted on a half-level of a deep-level platinum mine in South Africa [8]. The audit procedure involved measuring the CA flow and pressure supplied into the half-level during the cleaning shift by means of portable measuring equipment. Manual isolation valves found at the cross cuts of the half-level, as shown in Figure 4, were then closed one at a time and the flow reductions were recorded as a result of isolating the CA. Figure 18 illustrates the effect on the flow and pressure profile when the CA supplying the stoping areas was isolated.

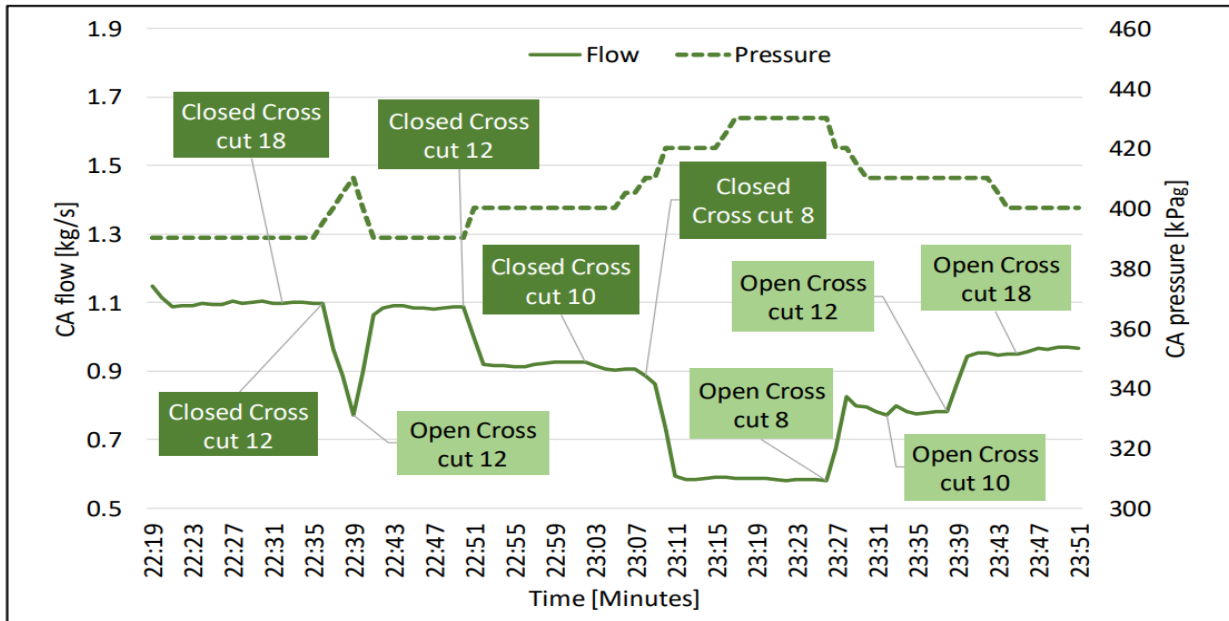


Figure 18: CA pressure and flow profile measured during an audit [8].

According to the results illustrated in Figure 18, the half-level had a total flow of approximately 1.1 kg/s, which is considered high for a typical half-level during the low-demand period. This high flow resulted in a lower pressure measured at the flat end development area where the loader operated. However, after closing all the manual cross cut valves, the total haulage consumption was reduced to 0.66 kg/s. This means that a 40% reduction in the consumption was achieved when isolating the CA supplied to the stoping areas. In addition to the flow reduction, a pressure increase of 30 kPa was measured at the flat end development area [8, 53].

Following these results, a comprehensive conventional audit was conducted in one of the stoping areas and it was identified that two 1-inch rubber pipes were used to ventilate the stoping face. This serves as a verification that a large portion of CA wastage can be attributed to misappropriation [8, 53]. This culture of ventilating with CA can be regarded as a variable factor, as it differs in location from day to day, which ultimately add to the difficulty of managing the CA demand.

According to mining best practices and standards, manual isolation valves are generally located on the pipe network that supply the stoping areas [8]. Two studies recommended that the isolation valves should be closed by appointed personnel after each drilling shift. The mining personnel are required to manually reopen the isolation valves at the start of the next drilling shift [22, 58].

However, having faulty isolation valves on the pipes leading to the stoping areas is a common occurrence on deep-level mines. A case study was conducted on a deep-level mine's CA network,

and it was identified that faulty valves were the second most common source of CA wastage [1]. It was identified that these valves leaked through as they were not able to be isolated effectively [1, 35]. This can be attributed to the harsh underground environment and the exposure thereof.

Apart from the risk of having faulty valves, the success of this initiative is highly dependent on the cooperation of the mining personnel. Highlighting the negligent culture, it was mentioned that manifold valves used for ventilation purposes are often left open as there is no cooperation from mining personnel to close these valves [8, 36]. Therefore, this large human factor and negligent culture only add to the difficulty of managing and sustaining this initiative [59].

To overcome this issue, several studies have suggested the implementation of local timer-based isolation valves, which close automatically during the non-drilling periods [58, 60, 61]. These valves can either be pneumatically or electrically driven [62]. The studies stated that a typical deep-level platinum mine generally consists of nine working levels with 20 half-levels, each having more than one active cross cut. This means that the project can become a high capital investment when considering the additional instrumentation and large number of valves required.

However, all the above-mentioned studies that recommended stope isolation, whether manual or automatic, did not quantify the expected energy savings to be achieved when implemented. Therefore, there is no clear understanding whether or not stope isolation can bring about improved CA energy consumption and if it is financially feasible to pursue in the deep-level platinum mining industry.

1.5.2 Critical analysis of deep-level mine compressed air efficiency studies

Numerous CA artificial demand and demand side management initiatives have been discussed. These initiatives are individually listed and critically analysed in Table 3 to assist with the identification of the need for this study. The analysis will focus on studies that implemented initiatives such as valve control, leak management and cross cut isolation. It was mentioned in Section 1.3 that misappropriation is a major contributor to CA wastage on deep-level mines. It is therefore important to analyse each initiative in terms of its effectiveness in addressing CA misappropriation or whether the study only addressed the symptoms of CA misappropriation. This will assist with quantifying the overall impact that the initiative had on the CA network's energy efficiency. Lastly, it is important to investigate if the study addressed and identified the requirements to obtain sustainable energy savings. This information will assist with identifying the sustainability requirements to implement the proposed solution.

Table 3: Summary of CA energy saving initiatives on deep-level mines

Study	Control valves	Leak management	Cross cut or stope isolation	Addressing CA misappropriation	Project impact on the CA energy efficiency	Sustainability requirements identified
[28]	✓	-	-	Addresses symptoms	Moderate - Opportunity to improve	✓
[21]	✓	-	Recommended by the study	Addresses symptoms	Moderate - Opportunity to improve	✓
[31]	✓	Recommended by the study	-	Addresses symptoms	Moderate - Opportunity to improve	✓
[8]	-	✓	CA was isolated as part of the study	Study identifies misappropriation but does not address it	Highly dependent on the cooperation of mining personnel	✓
[55]	-	✓	-	Identifies misappropriation	Highly dependent on the cooperation of mining personnel	✓
[36]	-	-	✓	✓	Not quantified	The proposed solution has not been implemented
[5]	-	✓	-	Identifies misappropriation	Highly dependent on the cooperation of mining personnel	✓

Study	Control valves	Leak management	Cross cut or stope isolation	Addressing CA misappropriation	Project impact on the CA energy efficiency	Sustainability requirements identified
[59]	 Implemented on service water	 Implemented on service water	 Implemented on service water	 Implemented on service water	High - Major energy efficiency improvement achieved	 Cross cut isolation was in the implementation phase
[25]		-	-	Addresses symptoms	Moderate - Opportunity to improve	
[63]		-	-		Moderate - Opportunity to improve	
[60]		-	Recommended by the study	Addresses symptoms	Moderate - Opportunity to improve	
[29]		-	-	Addresses symptoms	Moderate - Opportunity to improve	
[17]		-	-	Addresses symptoms	Moderate - Opportunity to improve	

Study	Control valves	Leak management	Cross cut or stope isolation	Addressing CA misappropriation	Project impact on the CA energy efficiency	Sustainability requirements identified
Study ²	-	-			High - Major energy efficiency improvement achieved	The project was not formally documented
[39]			-	Identifies misappropriation	Highly dependent on the cooperation of mining personnel	
[62]			Recommended by the study	Addresses symptoms	Not quantified	
[26]			Recommended by the study	Addresses symptoms	Quantification model developed	
[45]		-	-	Addresses symptoms	Moderate - Opportunity to improve	
[22]		-	Recommended by the study	Addresses symptoms	Moderate - Opportunity to improve	

² Information based on personal communication on 19 August 2020 with an energy management engineer working in the gold mining industry.

It is evident from Table 3 that there is a research gap with regards to the implementation of cross cut isolation valves to address CA misappropriation. Therefore, the energy benefit brought about by cross cut isolation has not been quantified. However, four studies in particular identified scope for further research. Three of these studies were CA related and one study focused on implementing cross cut isolation on a mining shaft's service water.

Study 1

A conversation was held with energy managers in the gold mining industry that implemented timer-based cross cut isolation valves. This was done on a mining site in South Africa. The implementation of the initiative brought about a significant reduction in energy consumption, as a result of isolating the unauthorised consumers during the non-drilling periods. However, the energy savings were not sustained due to the valves and instrumentation being vandalised and tampered with. The initiative was never formally documented to quantify the energy savings obtained during the project's implementation. This lack of formal documentation also means that the sustainability requirements for the initiative could not be identified and addressed. This does, however, highlight the need to investigate the sustainability requirements especially when the initiative brought about a positive impact on the mining shaft's CA energy consumption.

Study 2 [59]

This study was done on the implementation of stope isolation on a deep-level mine's water reticulation network. This was done in an attempt to improve the mining shaft's overall energy efficiency. Note that this mining shaft suffered from water wastages, which corresponds to a large extent with the typical CA misappropriation found in stoping areas. The study identified that good practice would be to automatically isolate the water supplied to the stoping areas when no water-consuming mining activities were conducted.

As part of this study, a total of 30 stope isolation valves were planned to be installed at the most active stoping areas on the main production levels. The mine had a previously installed centralised blasting system clearance box at the entrance of each cross cut. In simpler terms, this refers to communication cable (i.e. optic fibre) through which information is transmitted. An auxiliary contact on the centralised blasting system was then used to implement automatic control over the stope isolation valves. The basic operating principle was that once the "shift boss" cleared the section in that specific cross cut, the valves would automatically close and the water supply to that stoping area would be terminated. The valves would then reopen automatically when the drilling shift commenced. The mine at which the study was done was unable to complete the commissioning of the stope isolation valves during the study period.

The study did, however, report on the implementation of a successful leak management plan that resulted in a daily water consumption reduction of 7 ML. This accounted to an energy cost saving of approximately R5,6-million per annum. However, the impact of implementing stope isolation was estimated at an additional reduction of 1,6 ML.

The study mentioned that the implementation of stope isolation may appear to be complex and expensive when compared with the cost and simplicity of identifying and repairing leaks. However, it was highlighted that the sustainability of an automated stope isolation valve control system could be far more beneficial in comparison with leak management when the aim is to pursue sustainable energy savings in the long run. This is due to the unpredictable nature of underground mining, resulting in new leaks being continuously added, and the fact that leak management is highly dependent on the cooperation of mining personnel. Note that the statement made with regards to the sustainability of stope isolation assumed that the automated system can be sufficiently maintained.

Study 3 [8]

The focus of this study has already been mentioned under stope isolation in Section 1.5.1. The study focused on developing novel solutions for CA demand management. Part of the focus was the development of an ideal CA audit procedure to assist with a leak management plan. The CA consumption was measured during the non-drilling periods whereafter the manual isolation valves found at the cross cuts were closed systematically. This new audit methodology resulted in a 65% increase in wastage identification rate when compared to conventional audit methods. Further investigation into the areas with high wastage consumption identified that CA misappropriation was responsible for a large portion of the shaft's CA wastage consumption.

More importantly, this study highlighted the importance of addressing CA misappropriation and has partially identified the scope of isolating the stoping areas during the non-drilling periods. The study estimated that an annual electricity cost saving of R620-million could be achieved when the CA consumption is reduced by 40% during non-drilling shifts. Note that this estimation was based on the cumulative consumption of 25 deep-level mining shafts in South Africa.

Study 4 [36]

This study identified that CA misappropriation is a major contributor to a mining shaft's CA wastage. The study developed a smart valve that is installed on the CA manifolds in the stoping areas. This valve automatically isolates CA during the non-drilling periods. However, the valve is still in the developing and manufacturing phase and the expected benefit was not quantified.

1.6 Need and objective for the study

1.6.1 Need for the study

CA efficiency initiatives on deep-level mines predominately focus on matching the supply with the underground demand. It is evident from Table 3 that the majority of the underground efficiency initiatives involve reducing the CA demand by artificially matching the supply with the demand, through valve control. However, these initiatives only address the symptoms caused by CA leaks and misappropriation. They do not directly reduce the high underground demand, as seen in Figure 17. There is still significant scope to improve the CA efficiency as the energy savings achieved from artificial demand side management are limited to the end-user pressure requirements.

Leak management does, however, focus on reducing the CA demand. This initiative is very resource intensive and highly dependent on the cooperation of the mining personnel. Innovative approaches have been developed to cost effectively identify, prioritise, and repair leaks to reduce the CA wastage consumption of deep-level mines. However, fixing all leaks is regarded as non-realistic due to the dynamic underground nature. Research has shown that a large contributor to CA wastage is misappropriation. Therefore, leak management does not directly address CA misappropriation, as it can only highlight the areas with large wastage consumptions.

Thus, numerous studies have suggested further investigation into expanding demand side management through isolating the stoping areas from the CA network during the non-drilling periods. It is evident from Table 3 that there is a gap with regards to research on the scope for implementing cross cut or stope isolation aimed at improving energy efficiency.

There exists a need to investigate the scope and requirements for expanding CA demand side management through cross cut isolation on a deep-level platinum mine to directly address CA misappropriation.

1.6.2 Objective of the study

The primary objective of this study is to identify the scope for improving the energy efficiency of a deep-level platinum mine's CA network when cross cut isolation is implemented. This scope identification involves determining the technical feasibility to implement cross cut isolation and quantifying the potential energy benefit as a result of implementing the initiative. The study will investigate different implementation control strategies, namely manual and automatic control, to determine what the requirements are for sustainable energy savings. In order to achieve this, this

study aims to implement and verify the impact of cross cut isolation through the study objectives listed below:

1. Quantifying the CA wastage in the cross cuts and stoping areas.
2. Determining the technical feasibility of implementing cross cut isolation.
3. Quantifying the energy savings benefit of implementing cross cut isolation.
4. Investigating manual vs automatic cross cut isolation.
5. Identifying the sustainability requirements for implementing cross cut isolation.

1.7 Overview of dissertation

Chapter 1

Chapter 1 gives an overview of the CA system on deep-level platinum mines and the use of CA for mining operations. The CA wastage in the network is highlighted and discussed to obtain a better understanding of the direct impact that it has on energy efficiency. This is followed by a literature review on existing energy savings initiatives, which identify the scope for further improvement of energy efficiency. The overview and literature review provided in this chapter are used to identify the need for the study and the study objectives.

Chapter 2

Chapter 2 presents the solution strategy developed to address the need and study objectives identified in Chapter 1. The sequential steps in the solution strategy are identified and discussed to determine what the scope and requirements are needed to expand CA demand side management through cross cut isolation with the aim of achieving sustainable energy savings.

Chapter 3

In Chapter 3, the proposed solution strategy for the initiative is implemented and applied to an actual case study. The implemented solution strategy is validated to ensure that all the study objectives were clearly met. The results of the implemented solution strategy are also presented and explained in this chapter.

Chapter 4

Chapter 4 concludes the results of the study and compares the outcome observed with the study objectives stated in Chapter 1. The problem statement is then addressed, and the study conclusions are presented. Finally, recommendations for future studies are highlighted and discussed.

CHAPTER 2: DEVELOPMENT OF A SOLUTION TO EXPAND COMPRESSED AIR MANAGEMENT THROUGH CROSS CUT ISOLATION

2.1 Introduction

This chapter presents the process developed to determine the solution for expanding compressed air (CA) management on deep-level mines through cross cut isolation, specifically in the non-drilling shifts. Figure 19 gives a process flow diagram that presents the sequential steps in the methodology to address the need and objectives of this study.

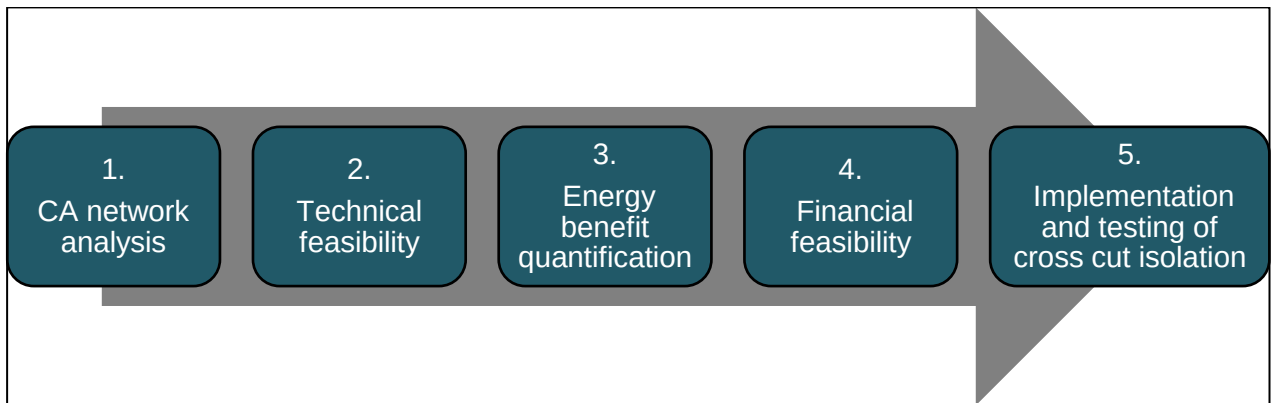


Figure 19: Process flow diagram used to develop the proposed solution

The first step in the procedure requires an in-depth analysis of the CA network. The main objective in this step is to accurately quantify the wastage consumption in the cross cuts by using a distribution analysis. This will also enable the study to verify the unauthorised consumers that are responsible for the high wastage consumptions in the stoping areas, as mentioned in Chapter 1.

The next step is to determine the technical feasibility to implement cross cut isolation. This is a crucial step as no CA related mining operations should be affected when the initiative is implemented. Therefore, it is important to identify the authorised consumers and to develop a control philosophy that will complement the relevant mining operations.

Following this, the potential energy reduction can be quantified when cross cut isolation is implemented. This energy benefit quantification will be determined through the use of a theoretical CA consumption model and actual CA data obtained during the network analysis. The goal of the model developed is to apply it to various mining shafts in order to determine the potential energy benefit of introducing cross cut isolation.

Any reduction in CA energy consumption directly relates to a reduction in utility costs. Therefore, the next step is to determine the financial feasibility in implementing the initiative. This step will elaborate on the financial calculations to quantify the monetary saving that can be achieved when reducing the CA wastage through cross cut isolation. These financial calculations will be used to determine the time required to pay back any capital investments used to implement cross cut isolation in Chapter 3.

The final step in the methodology is to investigate the various control strategies for cross cut isolation, as recommended by the research studies in Chapter 1. The aim of this section is to determine the implementation methodology and the operational requirements to effectively implement manual and automatic cross cut isolation control strategies in Chapter 3. The purpose of implementing both strategies is to determine what the sustainability requirements are for maximum and sustainable energy savings.

2.2 Compressed air network analysis

This section discusses the first step of the solution strategy as presented in Figure 19. The measuring instrumentation that will be used for the CA network analysis is discussed along with the different test methodologies used to conduct the distribution analysis.

2.2.1 Compressed air measuring instrumentation

The first step in analysing the CA network is to determine where existing permanent measuring instrumentation is installed. Existing CA instrumentation is generally connected to a Supervisory Control and Data Acquisition (SCADA) system [35]. Therefore, to identify permanently installed CA instrumentation the user can inspect the SCADA user interface that is located in the control room of a mining shaft³ [26].

³ A major advantage of having permanently installed instrumentation is that the SCADA system enables the mining shaft to monitor the CA consumption in real time. The measured CA data is then saved to an historian which can be retrieved from a server to conduct future CA analyses.

However, it is important to note that the majority of deep-level mines lack the capability of adequately monitoring their CA network, as most of these mines only have permanent CA measuring instrumentation installed on surface or at the station of each level. This means that the underground CA network deeper into the levels is operated without a clear measure of performance [8, 53].

In this case where measuring instrumentation is absent for a specific mining section, CA data can be obtained manually using portable measuring instrumentation. Table 4 presents examples of both a portable pressure logger and a flow meter that can be used to obtain CA data manually. Additional specifications for the presented instruments are also provided in the table.

Table 4: General information on portable CA measuring instrumentation

Instrument	Specifications	Visual illustration
Portable pressure logger [64]	• Power source: Battery • Battery life: 100+ hours • Data accuracy: 0,1% of span • Max: 250 bar • Min: 0 kPa	
Portable CA flow meter [65]	• Power source: Battery • Battery life: 6 – 8 Hours • Data accuracy: 0.00001 • Max: 600 m/s • Min: 0 m/s	

2.2.2 Compressed air network distribution analysis

This section will provide the reader with the necessary steps as to how a distribution analysis of the CA network should be done. Two distribution analysis methodologies will be presented and discussed which will be used to accurately quantify the CA wastage in the cross cuts.

Baseload test methodology

Baseload tests on deep-level mines are performed to accurately quantify the CA wastage of various mining sections [66]. These tests are generally conducted in the event of absent or inaccurate measuring instrumentation across the CA network.

The test entails measuring the total flow consumption and pressure (through either existing or portable instrumentation) supplied to a specific mining section/s, whereafter pre-identified valves are sequentially closed to isolate specific mining sections from the CA network. The isolation of each valve will result in a reduction of flow as observed from the point of measurement. This reduction in flow will give an indication as to what that specific mining section is consuming. Therefore, a baseload test present the opportunity to identify large wastage consumption areas, without conducting comprehensive audits of the entire CA network [67].

It is important to note that baseload tests are performed during the off periods when no CA related mining operations are active. There are two reasons for this: firstly, to ensure that no CA related mining operations are compromised in the event of isolating a specific mining section, and secondly, that the consumption measured during the test period is as a result of wastage [5, 8].

For the purpose of this study two baseload test methodologies are presented and discussed, namely a shaft baseload test and a half-level baseload test.

Shaft baseload test methodology

Figure 20 presents a visual layout of a mining shaft and the different mining levels. The methodology to conduct a shaft baseload test is as follows:

1. If the mining shaft has an already installed surface CA control valve, ensure that the automated control of the valve is aborted and fully open.
2. Ensure that all level valves, as shown in Figure 20, whether control or manual isolation valves, are aborted from automatic control and fully open.
3. Measure the CA flow and pressure supplied to the mining shaft via either permanently installed or portable CA measuring instrumentation, as shown in Figure 20.

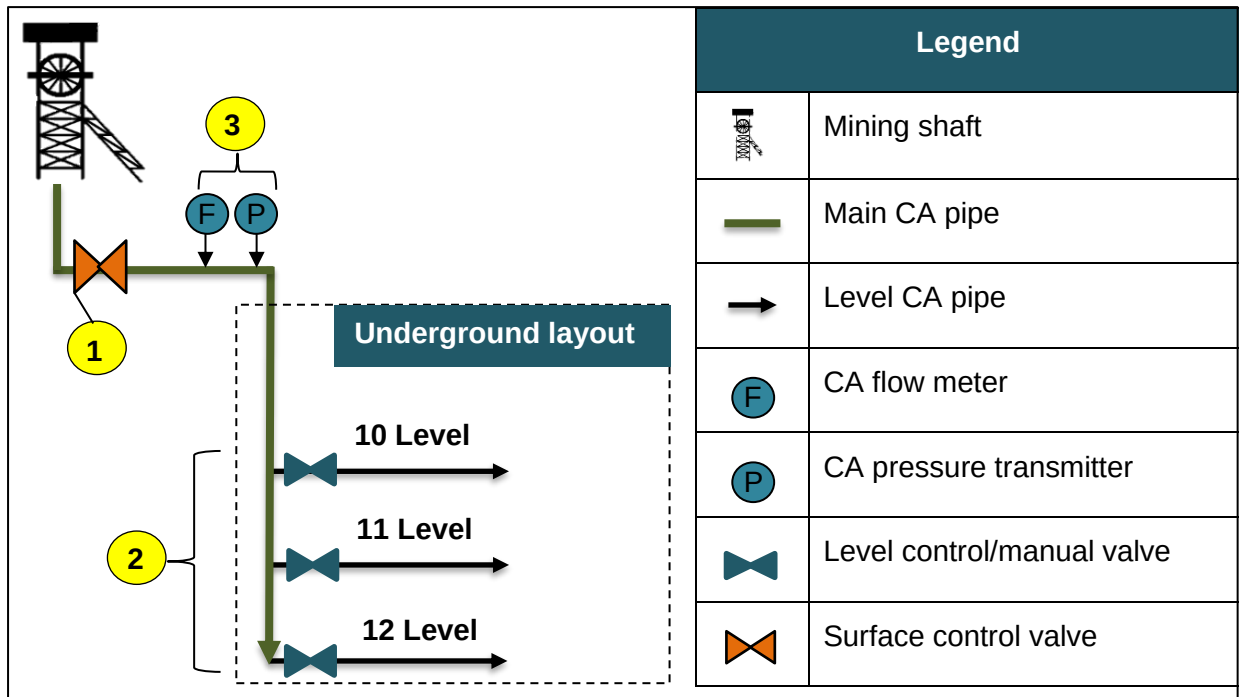


Figure 20: Schematic illustration of a mining shaft's CA network layout

- Next each level valve must be sequentially isolated, starting from either the top or bottom level, whilst allowing enough time in between each isolation (10-15 minutes) for the flow and pressure to stabilise. Note the time at which each valve was closed.
- Extract the data from the historian or portable measuring instrumentation.
- The final step is to analyse the extracted CA data.

Figure 21 illustrates the expected results obtained from a shaft baseload test conducted on the mining shaft presented in Figure 20. The figure presents the measured flow and pressure profile over the time period when the baseload test was conducted. The valves were sequentially isolated from 10 Level down to 12 Level with enough time allowed in between each isolation for the system to stabilise.

Each mining level's fraction of the maximum flowrate is then calculated as a result of the reduction in flow when the level was isolated. These flow fractions give a good indication as to which level has the highest wastage consumption. As per the example in Figure 21, it is observed that 12 Level is responsible for approximately 50% of the maximum flowrate measured during the baseload test, therefore making it the highest wastage consuming level on the shaft.

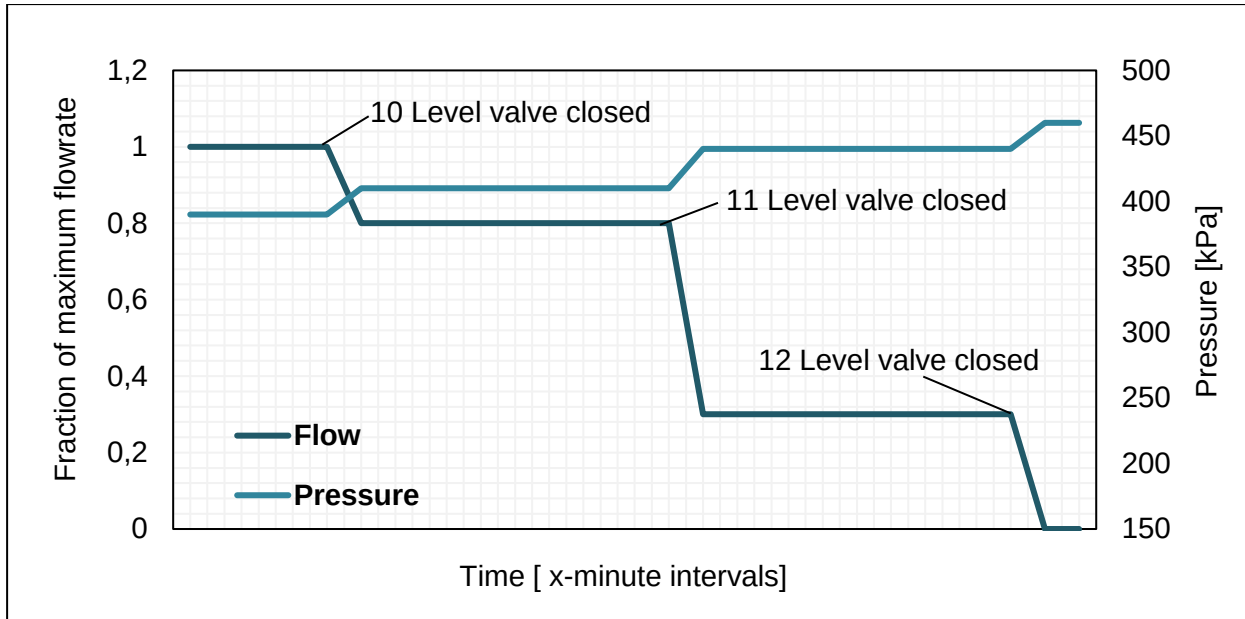


Figure 21: CA flow and pressure profile for a baseload test (Adapted from [8])

It was discussed in Chapter 1 and shown in Figure 18 that the CA flow is directly related to the supply pressure. This phenomenon can also be observed in Figure 21, where the supply pressure increases as the CA flow is reduced on the mining shaft. This means that, as the first valve is isolated, the wastage consumption on the remaining levels will increase due to the increasing supply pressure.

Therefore, in order to benchmark each level's CA wastage consumption, it is important to make a lateral comparison through normalising each of the level's wastage consumption to a specific reference pressure. This will allow for a fair comparison to identify the highest wastage consuming levels. A more detailed explanation with regards to normalising the different flows to a specific reference pressure can be found in Appendix A.

Half-level baseload test methodology

Following the shaft baseload test, the next step in the procedure is to determine which mining sections are responsible for high wastage consumption on the identified levels. This is done by expanding the shaft baseload test methodology onto the CA network of a half-level to determine the flow distributions into each cross cut.

Figure 22 presents a visual illustration of the CA network on a half-level for a deep-level mine. The CA pipe layout with the various isolation valves, cross cuts, stopping areas, refuge bays and the CA loaders at the flat-end development area are presented. This figure will be used as a visual guide to discuss the half-level baseload test methodology.

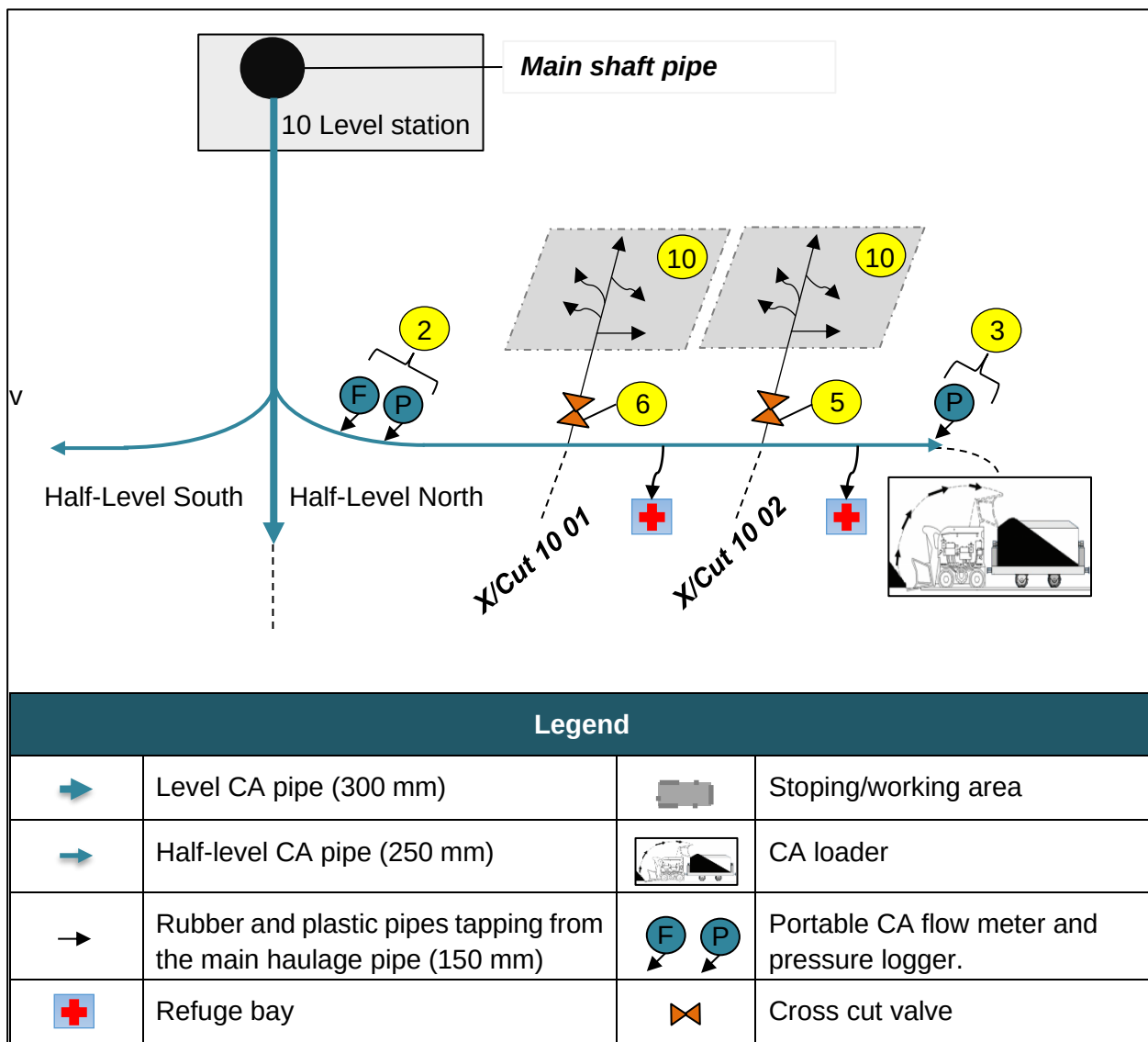


Figure 22: Typical haulage CA network and systematic audit procedure

The half-level baseload test methodology is as follows:

1. The first step is to obtain the underground layout drawings from the surveying department. Section 2.3 will give a more detailed overview of these surveying drawings. However, these underground layouts should be investigated to identify active and inactive mining sections on the half-level haulage.
2. Next, the portable CA flow meter and pressure logger should be installed on the CA pipe at the start of the half-level haulage.
3. Proceed to the flat-end development area and install a portable CA pressure logger on the manifold used to supply CA to the loader, as shown Figure 22.

4. Once the instrumentation is installed, the personnel conducting the test can proceed to the first cross cut closest to the development end. Using the surveying drawings, the inactive mining sections should be investigated to determine whether or not the CA flow is blanked off. It is regarded as good mining practice to blank off the CA pipelines supplying any inactive sections to ensure that no flow is supplied to these working areas.
5. However, if an active mining section is identified, the personnel conducting the test can proceed to close the manual isolation valve found at the entrance of the cross cut, as shown in Figure 22. It is important to note at what time the valve was closed to correlate the CA data measured with that specific cross cut.
6. Once the first valve is isolated, the personnel conducting the test can proceed to the next cross cut. Steps 4 and 5 can now be repeated for this specific cross cut. However, it is important to allocate at least 5 minutes in between each cross cut valve isolation. This will allow the CA flow and pressure to stabilise to ensure that accurate data is measured.
7. The personnel conducting the test can then proceed by repeating steps 4, 5 and 6 until all the cross cut valves on the half-level haulage are closed. Once this step is completed the test is deemed finished. The personnel conducting the test can then proceed to re-open all manual cross cut isolation valves on their way back to the flat-end development area.
8. Collect the portable measuring instrumentation at the flat-end development area and at the start of the half-level haulage.
9. Extract the data from the portable measuring instrumentation.
10. The final step is to analyse the extracted CA data, as discussed in the shaft baseload test methodology. A similar flow and pressure data profile can be expected as shown in Figure 21. Once the high wastage consuming cross cuts are identified, the personnel responsible for the distribution analysis can proceed to conduct visual audits in the stoping areas to identify the unauthorised consumers.

The shaft and half-level baseload test methodologies follow the same principle of isolating specific mining sections to determine a wastage distribution analysis. However, the information obtained from the half-level baseload test will provide the opportunity to understand the CA distribution across the half-level haulages. This information will ultimately assist with addressing study objective number 1. This will be done by effectively quantifying the CA wastage through the distribution analysis and to verify the unauthorised consumers responsible for the high wastage consumptions.

2.3 Technical feasibility

The distribution analysis will provide good insight into the scope for expanding CA management through cross cut isolation. The next step in the solution strategy, as presented in Figure 19, is to determine the technical feasibility to isolate the cross cuts from the CA network during the non-drilling periods.

2.3.1 Compressed air consumers

It is crucial that no production or mining related activities are affected in the event of introducing any new underground CA demand side management initiative. Significant income losses could occur if the production or mining activities are indeed affected [36].

It is therefore important to identify the authorised CA consumers that are active during the non-drilling periods. This will ensure that these consumers are not affected when cross cut isolation is tested or implemented. This will also enable the opportunity to determine the ideal cross cut isolation control philosophy to accommodate these authorised consumers.

The South African Mine Health and Safety Act requires deep-level mines to have accurate and up-to-date underground layout drawings [68]. These underground mining layouts of the deep-level mine should give a good indication as to where the relevant CA consumers are located. As briefly mentioned in the half-level baseload test methodology, these layouts will give a good indication as to which mining sections are active or inactive.

MRM (Mineral Resources Management) bookings are used to track a mining shaft's production performance and the working teams responsible for the different mining operations. Therefore, using these bookings in conjunction with the detailed drawings, the authorised CA consumers can be identified during the non-drilling shifts.

Figure 23 gives a detailed surveying layout of a typical half-level. The green area in the figure represents the active working areas that are being mined. If the mining area is represented in red, it can be referred to as inactive. Figure 23 also presents the authorised CA consumers that are generally active on the half-levels during the non-drilling periods. Table 5 provides a more detailed description of the general authorised consumers active during the non-drilling periods.

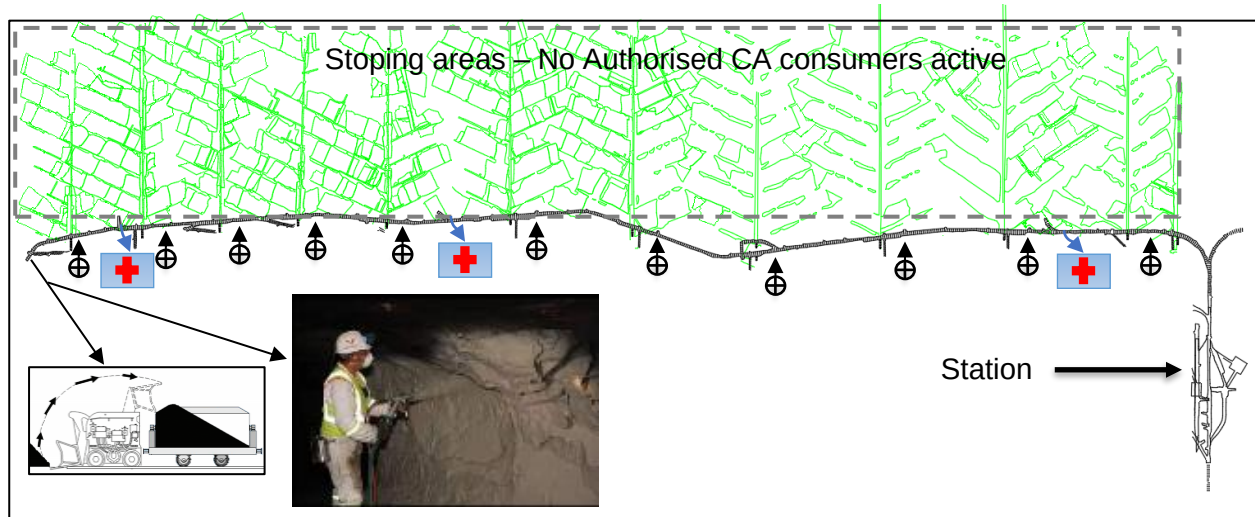


Figure 23: Top view of a detailed half-level surveying drawing

Table 5: General authorised CA consumers active during the non-drilling periods on a half-level

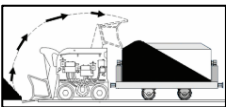
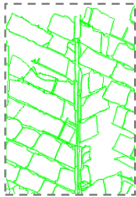
Authorised consumers	Description	Operating location	Time of use
	Refuge bay	Half-level haulage	All shifts
	Pneumatic CA chute	Half-level haulage	Cleaning shift
	CA loader	Flat end development area in the half-level haulage	Cleaning shift
	CA shotcrete machine	Half-level haulage development areas	Cleaning shift
	Stoping area	During the non-drilling periods there are generally no authorised CA consumers active in the stoping areas. As discussed in Section 1.2.1, the blasted ore is cleaned by means of electrical scrapers and winches.	

Figure 24 presents a process flow chart that will be used as a guide to determine the technical feasibility of implementing cross cut isolation. As shown in the figure, if a non-specified authorised consumer is identified, the person conducting the analysis should determine the essential nature of this consumer. If the consumer is identified as essential, then two scenarios become relevant. Either the control philosophy needs to be adapted to accommodate this consumer, or a business case should be developed to determine the scope of converting the consumer to an alternative solution other than using CA.

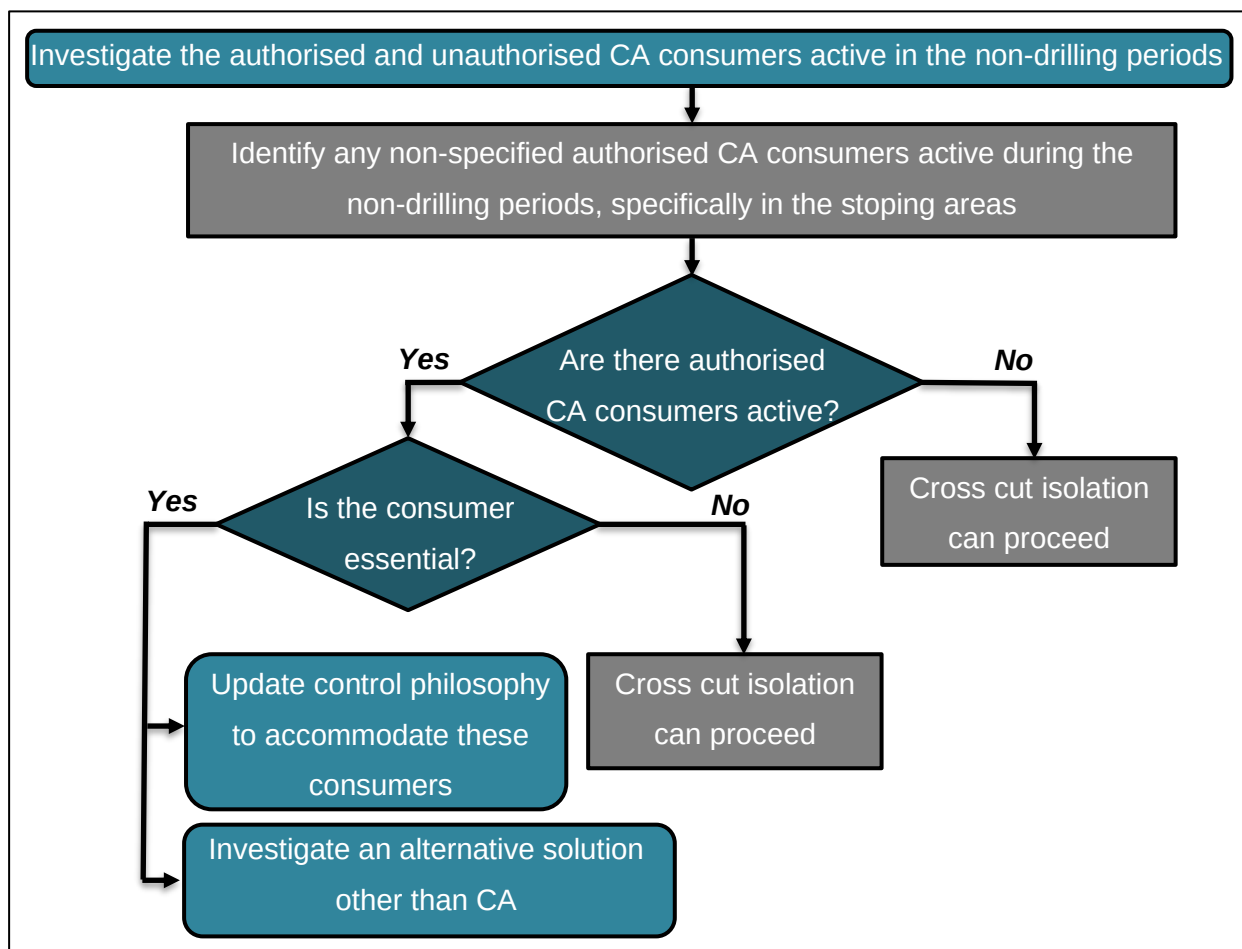


Figure 24: Authorised CA consumers identification process flowchart

2.3.2 Proposed control philosophy for cross cut isolation

The technical feasibility analysis represent the first step in developing the proposed control philosophy to isolate the cross cuts during the non-drilling periods. However, another important factor that needs to be taken into consideration is the mining schedule of the specific cross cut [69]. This entails that the mining shaft's operating schedule with regards to the different mining shifts needs to be identified.

This information can be obtained from the shaft's winder schedule. The winder schedule generally follows a time-based schedule to which the specific mining personnel are transported underground [35]. This should give a good indication of the time schedule followed for the different mining shifts.

The control philosophy can only be implemented once it is confirmed that there are no authorised consumers in the stoping or cross cut areas, and that the specific cross cut's mining shift cycle is incorporated in the control philosophy. Figure 25 provides an example of the proposed control philosophy profile for each of the cross cut isolation valves over the 24-hour mining shift cycle. The philosophy presented in the figure shows that the cross cut valves should be fully closed for the majority of the mining shifts, excluding the drilling and post-drilling shift.

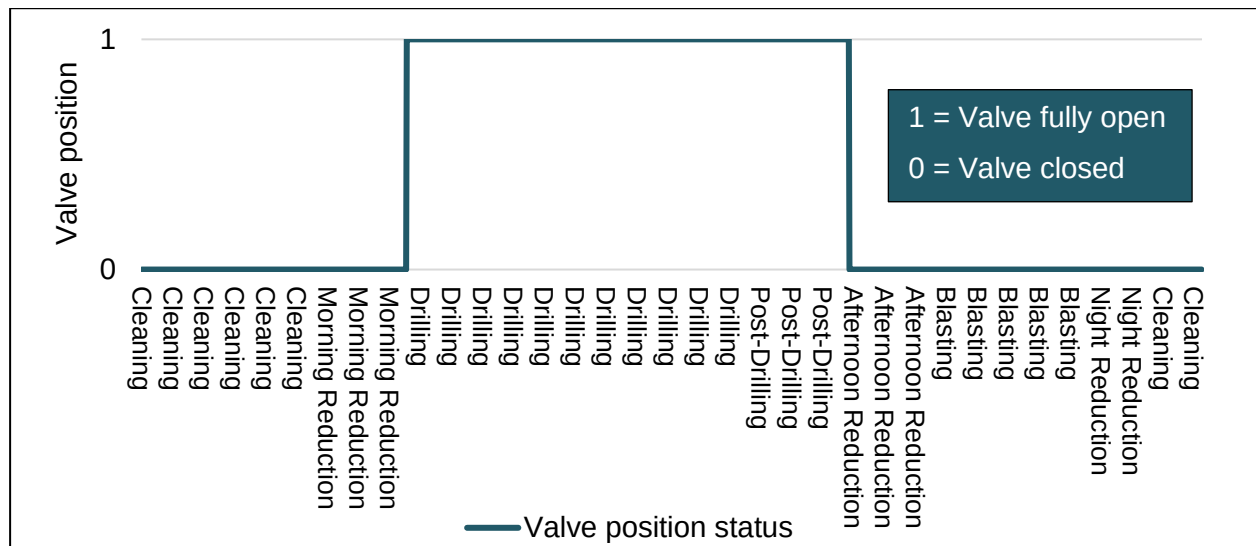


Figure 25: Proposed control philosophy for a cross cut isolation valve over a 24-hour period

2.4 Energy benefit quantification

A theoretical model will be used to predict the energy efficiency impact of implementing cross cut isolation on a deep-level mine's CA network. In essence, the developed theoretical model will be able to predict what the potential flow reduction is when the cross cuts on a mining shaft are isolated. This potential flow reduction can then be translated to an energy saving, which will then be used to determine the financial feasibility of implementing cross cut isolation.

This section will provide the necessary information and tools as to how such a model is developed. The process presented can be used to develop a theoretical model for a specific mining shaft in order to quantify what energy benefit exists when cross cut isolation is introduced.

2.4.1 Development of the theoretical consumption model

Step 1: Obtain actual compressed air data

The first step in developing a theoretical consumption model is to obtain the CA consumption data and mining schedule information for the mining section to which the model is going to be applied. Section 2.2.1 gave the necessary information as to how the relevant flow and pressure data can be retrieved. In addition to this, Section 2.3.2 provided the relevant information as to how the mining shift schedule can be identified using the shaft winder schedule.

Step 2: Identify all the mining crews

The next step is to identify the different underground mining crews. A crew refers to a team of mining personnel that is responsible for a specific mining task [8]. These crews will give an indication as to what equipment is used and during which mining shift the equipment is used.

This mining crew information is generally tracked by the MRM bookings, as mentioned in Section 2.3.1. However, this information can also be obtained from the mine planning department on the specific shaft for which the model is intended.

Step 3: Identify the equipment used per mining crew

The third step in the development of the theoretical model is to identify the various types of equipment used by the mining crews. Note that the type and number of equipment used per crew is shaft dependent. Therefore, it is recommended that the person developing the model consult with the mining shaft to verify what equipment is utilised per crew and how much equipment is allocated per crew.

Once this is identified, the CA consumption data for the various equipment needs to be obtained. This information can be gathered from the Original Equipment Manufacturer (OEM) specification sheets. This will provide the user developing the model with the equipment's flowrate at various operating pressures.

Note that the equipment used by the crews is not all continuously utilised throughout the relevant shifts. For this reason, an equipment utilisation percentage factor is incorporated in the theoretical model. However, this utilisation percentage factor for the different types of equipment used can vary from site to site. For example, a particular shaft might require more pumping of water compared with another shaft. Therefore, the user developing the model should consult with the relevant mining personnel to determine the approximate utilisation percentage factors for the equipment used per crew.

Table 6 and Table 7 present an example of two different mining crews that operate in different shifts. Presented is a stoping crew for the drilling shift, a flat-end development cleaning crew for the cleaning shift as well as the relevant equipment used by these two crews. As per the example, the flowrate for each piece of equipment is presented at a specified pressure with a utilisation percentage.

Table 6: Stoping crew and their equipment active during the drilling shift

Crew	Equipment	Number of equipment used	Consumption [m ³ /h] at 7 bar [1]	Drilling shift utilisation
Stoping [1]	Rock-drill (S215)	4	305,82	80%
	Roof-bolter	1	305,82	80%
	Water pump	1	37,38	90%
	Cheetah saw	1	30,58	70%
	Anfex loader	1	8,49	60%
	Air whistle	3	3,4	5%

Table 7: Flat-end cleaning crew and their equipment active during the cleaning shift

Crew	Equipment	Number of equipment used	Consumption [CMH] at 7 bar [1]	Cleaning shift utilisation
Flat-end development cleaning	Water pump	1	37,37822	80%
	Cement pump	1	1274,2575	60%
	Loader (B56)	1	1019,406	80%

Step 4: Calculating the theoretical flow profiles

Using the information presented in Table 6 as an example, the procedure will be discussed as to how the theoretical flow profile is calculated for a specific crew, and then extrapolated over a mining section with multiple crews to determine the total theoretical consumption.

1. The first step is to obtain a 24-hour pressure profile of the mining section for which the model is developed, as discussed in Step 1. Table 8 presents an example of the operating pressure data, obtained in half hourly increments, from 07:30 to 09:30 in the drilling shift for the specific mining section that the crew operates in. For illustration purposes as to how the calculations are performed, this specified time in the drilling shift will be used to show how the calculations are done.
2. Next, the time schedule for when the different equipment is used by the crew needs to be specified, as shown in Table 8. The table shows the example where the rock drills and roof bolter are active from 07:30 and the water pump switches on one hour later.
3. Then, using the equipment flow and pressure consumption information listed in Table 6, the theoretical flow for the different equipment can be calculated. This is done by using the normalisation calculation, found in Appendix A, to normalise the equipment's specified flow and pressures to the actual operating pressures over the 24-hour mining shift cycle, as shown in Table 8.

Table 8: Example of the theoretical flow calculation

Time	Shift	Operating pressure	4 Rock-Drills and 1 Roof Bolter flow at operating pressure [Nm ³ /h]		Water pump flow at operating pressure [Nm ³ /h]	
07:30	Drilling	503	Active	769	Inactive	0
08:00	Drilling	463	Active	707	Inactive	0
08:30	Drilling	450	Active	688	Active	22
09:00	Drilling	457	Active	699	Active	22

4. Steps 2 and 3 should be repeated for all the equipment used by the crew. Once this is done the theoretical consumption for that specific crew will be calculated.
5. Once step 4 is completed, the total theoretical consumption for the specific crew will be determined. The MRM bookings provide the number of that specific crew active on the mining section for which the model is developed. This number should then be multiplied by the individual crew's theoretical consumption to determine the total theoretical consumption for that specific crew.
6. Step 5 should be repeated for all the relevant crews active on the specific mining section.
7. Once step 5 is completed, the total theoretical consumption for the planned crews of that specific mining section will be calculated.
8. The most important step is to include a wastage factor in the total theoretical consumption profile to account for the wastage in the haulages. This factor will be determined through the half-level baseload tests, as discussed in Section 2.2.2.
9. Note that not all crews are active at the same time during the relevant mining shifts. To accommodate for this, a crew utilisation factor will be introduced in the theoretical model. This crew utilisation factor refers to the number of crews that are active at the same point in time during the relevant shift. However, this crew utilisation factor is mainly applicable to the drilling shift as this shift has the largest amount of workforce active. The drilling shift crew utilisation factor will be assumed as 60%; this factor was determined through drilling trial investigations, and a 100% crew utilisation factor will be assumed for the non-drilling shifts .
10. The total theoretical consumption can then be plotted as a flow diagram over a 24-hour period.

2.4.2 Quantifying the potential flow reduction for cross cut isolation

Baseline flow profile

A baseline flow profile is a record of what the CA flow is prior to the implementation of cross cut isolation. This flow baseline will be used to quantify the energy saving brought about by the implementation of cross cut isolation, and in this case what the theoretical model predicts. The baseline flow profile can also be used to track the energy performance of the initiative once it is implemented [6]. This is done by comparing the baseline flow profile with the newly adjusted flow profile as a result of reducing the CA wastage, through isolating the cross cuts during the non-drilling periods [70, 71].

The International Performance Measurement and Verification Protocol framework (IPMVP) [72], as presented in Table 9, will be used to develop the flow baseline.

Table 9: IPMVP's framework for developing a baseline [72]

Criteria	Description
Measurement boundary	The mining section in which cross cut isolation is going to be implemented forms the measurement boundary of the baseline.
Selection of the measurement period	Operational changes, i.e. an increase in production, could affect the measurement of the project's performance against the baseline. The effect of system changes that occurred not as a result of the cost saving initiative, should be excluded from the performance measurements [8]. It is recommended that the maximum amount of available data, backdated to the most recent system change, is used to develop the baseline. A weekday, Saturday, and Sunday baseline should be developed. The reason for this is that the flow profiles differ for the different days of the week on a mining shaft.
Adjustment methods	The peak scaling or drill shift energy neutral method will be used to adjust the baseline according to system changes experienced [26]. For more information regarding this baseline scaling methodology, please refer to Appendix B.

Figure 26 gives an example of the theoretical model compared with a flow baseline developed for a mining level. The potential flow reduction when cross cut isolation is implemented will be quantified through the developed theoretical model. The quantification will be based on the following:

Non-drilling shifts – The theoretical model's predicted flow profile during the non-drilling shifts represents the CA flow supplied to the mining section with zero wastage supplied to the cross cuts. This is as a result of implementing cross cut isolation and with the wastage in the haulages already accounted for. However, in the event of the proposed example, as illustrated in Figure 26, the potential flow reduction is showcased as the difference between the baseline flow profile and what the model predicts.

Drilling shift – The cross cut isolation valves are fully open during the drilling shift as depicted in the proposed control philosophy shown in Figure 25. Thus, the wastage consumption is not addressed during this shift and any energy saving obtained during this period will be excluded from the cross cut isolation energy savings quantification calculations. The model does, however, provide a target theoretical flow based on the number of active crews, equipment, and the mining level's production targets. Therefore, this model can be used to determine the potential energy improvements for the drilling shift.

2.4.3 Model verification and validation

Model verification and validation is an enabling methodology for the development of computational models that can be used to make engineering predictions with quantified confidence [73]. This is regarded as an important activity that forms part of the model development process [74]. The verification and validation of the theoretical model is important to ensure that the energy quantification for isolating the cross cuts in the non-drilling shifts can be done accurately [35].

The theoretical model will be verified through determining whether or not the model accurately represents its predicted results [8]. The information obtained during the half-level baseload tests, referring to Sections 2.2.2, will be used to verify the accuracy of the theoretical model when predicting the effect of cross cut isolation on the flow profile of the CA network. An example of this process is shown in Figure 26. The figure shows the baseline flow profile (as the light blue line), before any changes were brought about to the levels CA network. The figure also shows the theoretical model's predicted flow profile (shown as the dark blue line) and the new flow profile obtained from the half-level baseload tests when the cross cuts are isolated (shown as the black dotted line).

The theoretical model will then be validated by quantifying the error percentage between the half-level baseload test results, as a result of isolating the cross cuts, and the predicted results obtained from the theoretical model, as shown in Figure 26.

Note that before any half-level baseload tests can be conducted, the CA network will be audited to ensure that all cross cut valves, that are planned to be closed, are in working condition. This is to ensure that all of the CA wastage in the cross cuts is accounted for. By doing this, an accurate comparison between the actual and predicted flow profiles can be made. The audits will also investigate CA wastage in the level and half-level haulages to ensure that the assumption made in the model with regards to the haulage wastage factor is accurate.

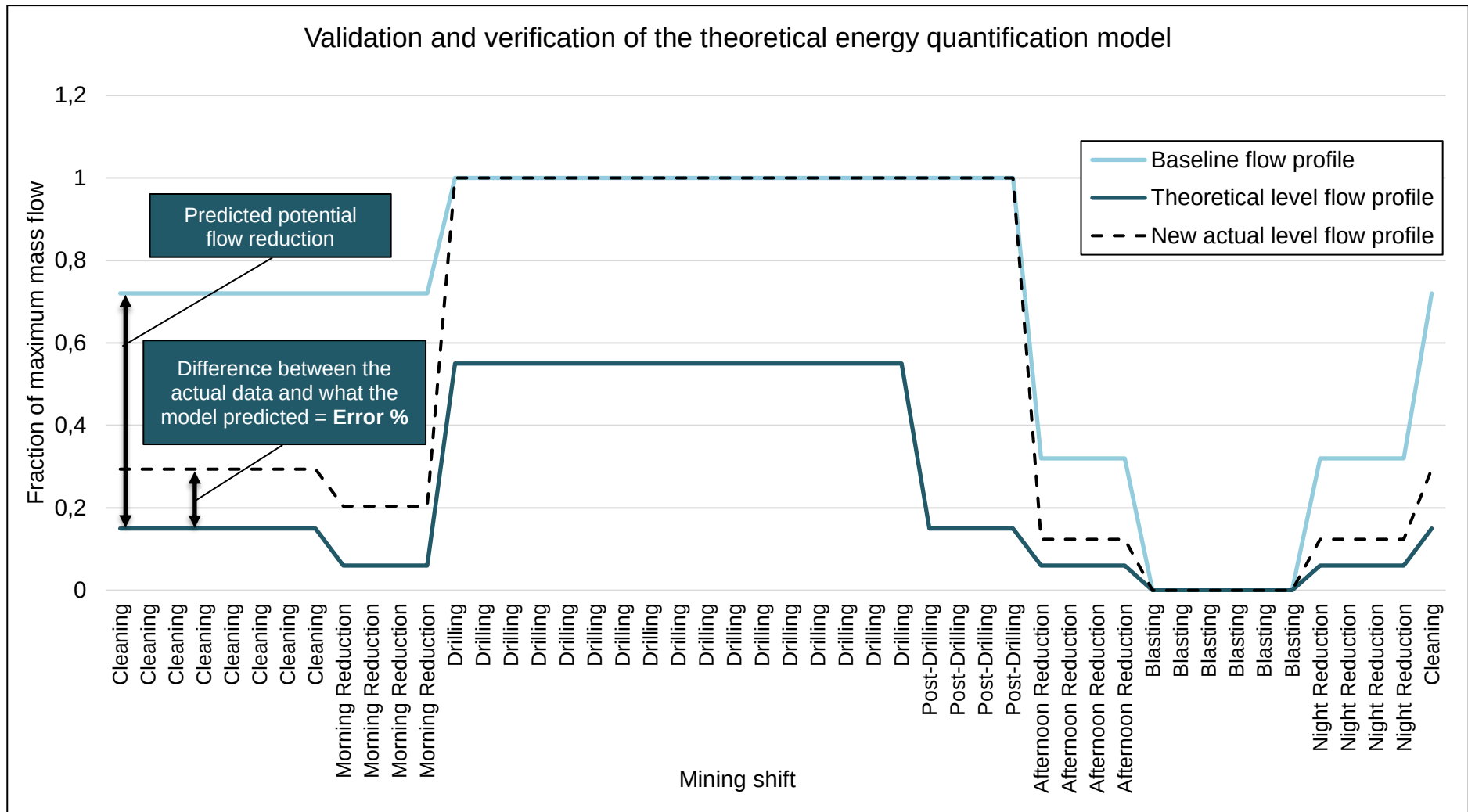


Figure 26: An example flow profile on how the validation and verification of the CA theoretical model will be done

2.4.4 Energy saving benefit quantification

Compressed air power savings calculations

In order to determine the power savings, as a result of reducing the CA flow, the specific power [kWh/Nm³] of the CA network must be calculated. The specific power approximates the compressor power [kW] required to provide a unit of CA flow [Nm³/h]. By taking the compressors' specific powers into account, as well as the number of the various compressors on the network, the following formula can be used to calculate the specific power, as given by Equation 2.

$$P_{spec} = \frac{P}{F} \quad (2)$$

Equation 2: Specific power calculation

Where,

P_{spec}	=	Specific power [kWh/Nm ³]
P	=	Compressor power [kW]
F	=	Compressor discharge flow [Nm ³ /h]

In order to approximate the power saving which results from a CA savings initiative, the specific power can be multiplied by the reduction in flow resulting from the initiative. This is shown in Equation 3 below.

$$P_{saving} = P_{spec} \times \Delta F \quad (3)$$

Equation 3: Power saving calculation

Where,

P_{saving}	=	Power saving [kW]
P_{spec}	=	Specific power [kWh/Nm ³]
ΔF	=	Reduction in flow [Nm ³ /h]

The total amount of electrical energy reduced, in kWh, is then calculated by multiplying the total power reduction by the total time of the power reduction.

2.5 Financial feasibility calculations

The mining industry generally operates on the Eskom Megaflex tariff structure, which is a time-of-use (TOU) tariff structure [11]. This TOU tariff structure operates on the principle that the consumer is billed for electrical power consumption at different tariff rates, depending on the time of day when the power is consumed. This time period for the Megaflex TOU tariff structure can be divided into three categories, namely off-peak, standard, and peak period. This tariff structure for 2021/2022 can be found in Appendix C.

The tariff rates, as presented in Appendix C, differ according to the time of day, day of the week, and the season of the year, and are based on the cost of generating electricity during these periods. The goal for the different tariff periods is to encourage consumers to reduce their power consumption during the peak demand period. This is to alleviate the overall strain placed on the generating system during the peak demand periods [59].

For the purpose of this study, the Megaflex TOU tariff structure will be used to calculate the financial benefit that can be achieved in the event that cross cut isolation is implemented. This will be done by using the Eskom TOU tariffs in conjunction with the power saving to quantify the saving as a monetary value.

2.6 Implementation of cross cut isolation

The implementation methodology for implementing and verifying cross cut isolation is presented in Figure 27. This section in Chapter 2 will mainly focus on addressing steps number 1 and 2 in the methodology, as shown in the figure. Chapter 3 will address steps 3, 4 and 5.

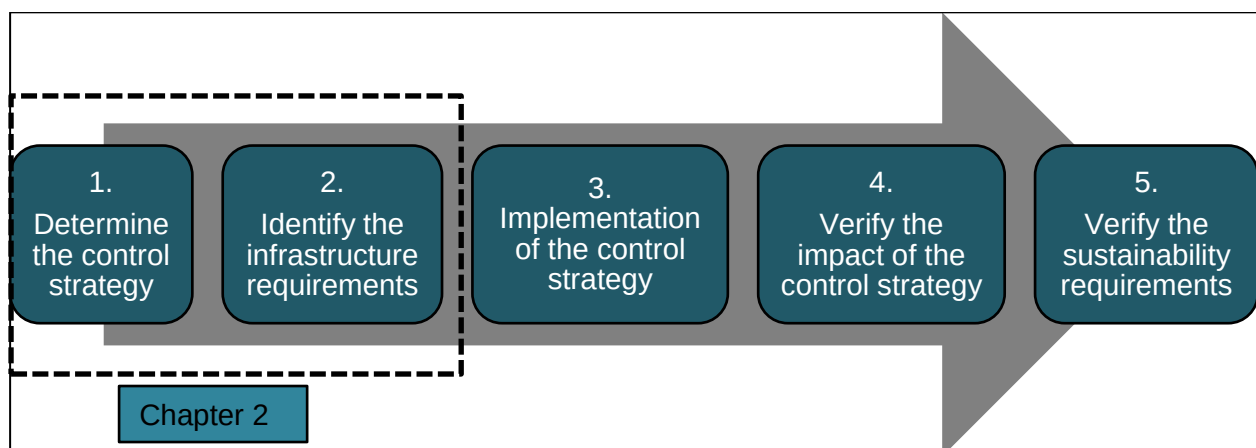


Figure 27: Implementation methodology to verify cross cut isolation

Two control strategies will be investigated, namely manual and automatic cross cut isolation. The methodology presented in Figure 27 will be applied to both strategies in order to implement and verify the impact thereof. This section will therefore focus on determining the operational and infrastructural requirements to implement both manual and automatic cross cut isolation.

2.6.1 Manual cross cut isolation implementation strategy

As discussed in Section 2.2.1, manual cross cut isolation valves are generally located on each cross cut. The proposed control philosophy will operate on the principle that appointed mining personnel will close their cross cut valve after each drilling shift. The appointed mining personnel will then reopen the valve at the start of the next drilling shift.

Unfortunately, this control philosophy becomes highly dependent on the cooperation of the mining personnel. Considering the already identified negligent culture that exists, i.e. manifold valves being left open, the risk of mining personnel not closing their cross cut valves is high. Therefore, a large human factor is present when implementing this control strategy and this should be taken into consideration when identifying the sustainability requirements.

In order to monitor and track the performance of this implementation strategy, the use of CA measuring instrumentation and effective reporting will be used to determine if the relevant cross cut isolation is occurring or not. The actual CA consumption of the level or half-level will be compared with the theoretical CA consumption model, as discussed in Section 2.4, to determine if the cross cut valves are being isolated.

However, as mentioned in Section 2.1.1, existing instrumentation is generally only installed at the station of the mining level. An issue faced with using level flow meters to verify cross cut isolation is that there can be multiple areas of responsibility downstream of the flow meter. This makes it difficult to identify which responsible personnel is not cooperating. An alternative solution is to install half-level flow meters which should narrow the area of responsibility.

In addition to the flow meters, Section 1.5.1 highlighted that having faulty valves on the CA network is not uncommon for deep-level mines. Replacing these valves will require low capital expenditure as the mining shaft generally keep these manual isolation valves as spares on the shaft.

2.6.2 Automatic cross cut isolation implementation strategy

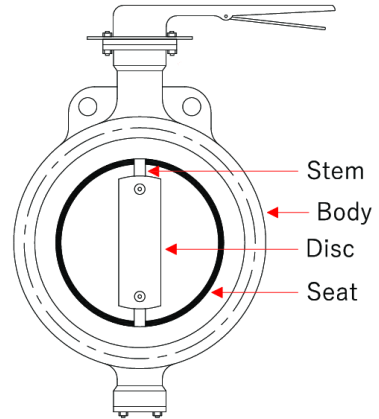
Before the control strategies can be investigated, the various isolation valves, actuators and controllers required to implement automatic cross cut isolation need to be discussed. Controllers

refers to Programmable Logic Controllers (PLCs) that are generally used in conjunction with actuated valves.

A. Isolation valves

Table 10 presents two types of isolation valves that are considered compatible for cross cut isolation. The table provides a brief description of each valve and a visual presentation.

Table 10: CA isolation valves most commonly used on deep-level mines

Valve type	Description	Visual presentation
Butterfly valve [21]	Butterfly valves are most commonly used in the mining industry for open and close applications, and in some cases for control purposes. When it comes to CA, it is preferred to use a metal seat valve as they are most compatible with the harsh underground environment. The metal seat on the valve is specifically designed for severe applications with high pressure or temperatures.	 A cross-sectional diagram of a butterfly valve. The diagram shows a circular body with a central disc. A stem connects the disc to a handle at the top. The disc is seated within the body. Labels with red arrows point to the Stem, Body, Disc, and Seat.
V-notch ball valve [21]	V-notch ball valves are also used in the mining industry for open/close applications, but not as often as butterfly valves. An additional advantage that this valve provides is that it can be effectively used in pressure control applications [45].	 A photograph of a V-notch ball valve. The valve has a cylindrical body with a V-shaped notch in the ball. It has a handle on top and a flange at the bottom.

Although some similarities are shared between butterfly and v-notch ball valves, there are still distinct differences between the two valves which can be advantageous in specific applications. Table 11 provides a comparison that highlights the characteristics of each valve and their

advantage against one another. This information will become relevant when deciding which valve assembly (valve and actuator) will be used to implement and test automatic cross cut isolation.

Table 11: Differences between a butterfly and v-notch ball valve [75]

Criteria	Metal seated butterfly valve	V-notch ball valve
Weight	The valve is light-weight, especially at larger pipe diameters.	The valve becomes very heavy at larger pipe diameters. In some cases, the valve might require additional support.
Installation space	Small installation space is required.	Larger installation space is required compared with the butterfly valve.
Leakage	The valve can become prone to leakages at high pressure applications.	Provides a tight seal especially at high pressure applications.
Cost	Valve is cheaper. It is particularly cheaper for larger sizes.	The valve is more expensive when compared with butterfly valves.
Control capability	More compatible for open/close applications. However, it can be used for proportional control.	Operates efficiently for open/close and modulating control applications.
Flow restriction	The valve disc can restrict flow to a small extent, which can cause a pressure drop.	The full port of the valve will create no pressure drop.

B. Valve actuators

An actuator is used to apply a force onto the valve in order to change the valve position. The valve position refers to the open or close status of the valve. There are various types of actuators available on the market, namely hydraulic, pneumatic, manual, and electrical. However, the two most commonly used actuators in the mining industry are electrical and CA pneumatically driven actuators. Figure 28 provides a visual presentation for both an electric and a pneumatic actuator.

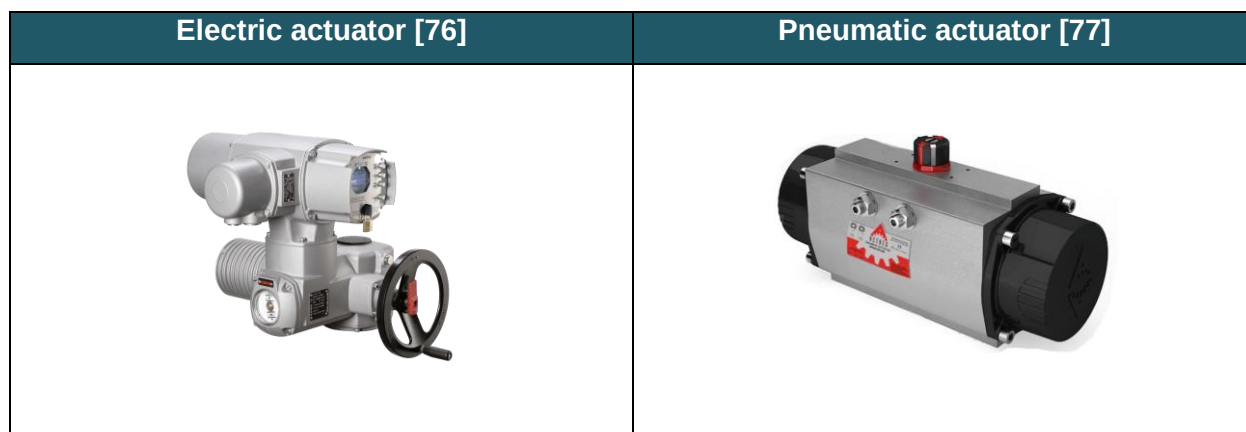


Figure 28: Electric and pneumatic actuator

As mentioned with the isolation valves, similarities are shared between electric and pneumatic actuators. However, there are distinct differences between the two actuators. Table 12 provides a comparison that highlights the characteristics of each actuator and their advantages against one another. This information in conjunction with the information listed in Table 11 will become relevant when deciding what valve assembly will be used to implement and test cross cut isolation.

Table 12: Differences between a electric and pneumatic actuator [39]

Criteria	Electrical actuator	Pneumatic actuator
Durability	Must be modified with an enclosure for the hazardous environment. Can overheat, must be sealed from moisture.	Explosion proof, shock proof and spark proof. Not sensitive to a wet environment.
Power source	Voltage of 110 ,220 or 525.	Minimum CA supply at 380 kPa.
Cost	Actuator is more expensive compared with pneumatic actuators.	Actuator is cheaper. It is particularly cheaper for larger sizes.
Torque	Low torque to weight ratio.	High torque to weight ratio.
Fail safe application	Spring return (fail-safe) option is not available.	Spring return (fail-safe) option is available.

There are two important factors that need to be taken into consideration when installing the proposed valve and actuator assembly for automatic cross cut isolation. Firstly, what is the fail-safe application and alternatives for the valve and actuator assembly? Secondly, is the valve and actuator assembly compatible with level or surface control valves where the supply pressure varies to different pressure setpoints?

C. Programmable Logic Controller (PLC)

Mines generally standardise on one PLC manufacturer throughout the property as this is good practice in the industry. This simplifies the general maintenance and connections to the SCADA systems. The PLC is used to monitor and command a control philosophy by supplying the valve with information on whether it should be open or closed during the 24-hour mining cycle.

The feedback instrumentation on the actuators plays a vital part for the automatic cross cut isolation strategy. In order for the PLC to control the valve output, the system status information is required from the actuator. The valve position is obtained from a positioner that is situated on the actuator body or the valve itself. The feedback can be a 4-20 mA analogue signal, or a digital signal obtained from a limit switch.

Automatic cross cut isolation control strategy

Two control strategies are considered when implementing automatic cross cut isolation. The first strategy makes use of a timer-based isolation valve which should be programmed according to the specific cross cut's mining schedule. The infrastructure required for this system to operate is an electric or pneumatic isolation valve, a timer-based unit, i.e. a locally installed PLC unit, and electricity supply from the haulage.

The only drawback with regards to using a timer-based isolation valve is that each individual timer has to be set according to each specific cross cut's mining schedule [59]. The electrical actuator has a manual override in the case that CA is required in that cross cut. However, having this feature, the risk of mining personnel leaving the valve open in manual override is high. This in essence will increase the project maintenance requirements to ensure that sustainable energy savings are achieved.

The second strategy is to connect each valve to the mining shaft's SCADA system to enable remote control and monitoring of each valve. This is the current control strategy implemented for a large majority of surface and level control valves in the mining industry [17, 21, 25, 28, 29, 31, 63].

In order to connect the cross cut isolation valves to the mining shaft's SCADA system, an instrumentation cable between the actuator and PLCs is required. This will, however, come with a high capital cost.

Furthermore, an additional advantage when these valves are connected to the SCADA system is that constant feedback with regards to the valve status can be obtained. This will allow management to effectively monitor the control of each valve and identify valves that are faulty or left in manual override.

2.7 Sustainability requirements

It is important to identify and monitor the various risks that could occur during the implementation and testing of cross cut isolation. It was found in Section 1.5.2 that numerous initiatives exist to improve the energy management of the CA systems on deep-level mines. However, the majority of these initiatives lacked long-term sustainability.

Therefore, it is important that the following factors are taken into consideration when introducing cross cut isolation to the CA network of a deep-level mine [36]:

- Cross cut isolation must under no circumstances negatively affect the production performance of a mining shaft. It is therefore important that the installed equipment should not have a negative effect on production performance in the event of equipment or power failure.
- Therefore, it is crucial to ensure that the implemented control philosophy absolutely complements the mining schedule of the specific cross cut. This will ensure that no mining personnel are required to tamper with or bypass the valve in the event that the valve is closed during normal mining operations or when ad hoc work is conducted.
- Adding to the above-mentioned points, this initiative should not have any negative impact on the working experience underground. Once a negative perception is created around the initiative, it is almost certain that the valves will get damaged or tampered with.
- The valves, actuators and instrumentation must be robust, as they are exposed to humid, dusty, and hot underground conditions.
- And most importantly, the valves must be tamperproof. This is to prevent mining personnel bypassing the valve. This is important when considering the sustainability of the initiative.

Communication between management and the mining personnel will be important when cross cut isolation is introduced. This will play a key role in the success and sustainability of the initiative.

The energy management team responsible for the initiative needs to create awareness among all relevant levels of mining personnel through effective reporting on the initiative's performance. Regular feedback will contribute towards the cooperation and acceptance of the initiative among the mining personnel, especially when positive results are achieved.

2.8 Conclusion

Chapter 2 presented and discussed the solution strategy developed to determine the scope of expanding CA management on deep-level mines through cross cut isolation during the non-drilling shifts. This strategy, as presented in Figure 19, provides the sequential steps in the methodology to address the need and objectives of this study.

Section 2.2 presented and discussed the process that is used to conduct a shaft and half-level baseload test. These two baseload test methodologies will enable the study to conduct a CA distribution analysis to determine which mining sections are responsible for high wastage consumptions.

In Section 2.3, the process to determine the technical feasibility of implementing cross cut isolation is presented and discussed. This technical feasibility analysis will be applied to a case study to determine if cross cut isolation can be implemented without affecting the mining operations. The results obtained from this analysis will enable the study to determine what the proposed control philosophy is to implement both manual and automatic cross cut isolation control strategies.

Section 2.4 provided a detailed discussion as to how the theoretical model will be developed to quantify the energy benefit for when cross cut isolation is implemented. In addition to this, the process that will be used to verify and validate the model's prediction to ensure that an accurate quantification can be made is discussed in Section 2.4.3.

In Section 2.6, the implementation methodology for implementing and verifying cross cut isolation is presented. This implementation methodology will be followed to determine what the sustainability requirements are for both manual and automatic control strategies. Furthermore, background information with regards to the sustainability requirements when introducing new initiatives on deep-level mines is discussed in Section 2.7. This information must be taken into consideration during the implementation phase of the two control strategies, which will be discussed in Chapter 3.

CHAPTER 3: RESULTS

3.1 Introduction

The purpose of this chapter is to report on the implementation of the solution strategy developed in Chapter 2 on a real world deep-level platinum mining shaft. The results obtained from this case study will be used to verify and validate the solution to expand CA demand side management through the implementation of cross cut isolation valves during the non-drilling periods.

The first step in the methodology required an in-depth analysis of the case study's CA network. This was done by conducting a CA distribution analysis across the network by means of multiple shaft and half-level baseload tests. Following these results, visual audits were conducted in the cross cuts to identify unauthorised consumers responsible for the high wastage consumption. This offered the opportunity to accurately quantify the wastage consumption in the cross cuts.

The results obtained from the CA network analysis highlighted the need to address the high wastage issues in the cross cuts. Therefore, a technical feasibility analysis was done on the shaft to determine whether the cross cuts can be isolated during the non-drilling shifts. Alternative solutions were investigated to accommodate the authorised consumers that are active during the period of isolation, and to ensure that mining operations were not negatively affected. The technical feasibility analysis ultimately provided the solution to develop and implement the proposed ideal control philosophy.

Once it was confirmed that cross cut isolation is technically feasible, the theoretical model, discussed in Chapter 2 Section 2.4, was developed and applied to the case study to determine the potential flow reduction when isolating the cross cuts. The model was verified and validated by determining the error percentage between the predicted results and actual results obtained during the CA network analysis. An acceptable error percentage was obtained and the potential energy benefit that can be achieved was quantified. Following this, the financial impact of reducing the energy consumption was calculated and presented.

Finally, the two control strategies, namely manual and automatic cross cut isolation, were implemented on the case study shaft's CA network. Both strategies followed the proposed control philosophy developed in the technical feasibility analysis. The implementation of both strategies identified the sustainability requirements to effectively implement cross cut isolation with the aim of achieving sustainable energy savings.

3.1.1 Case study background

A deep-level platinum mining shaft in South Africa was used as the case study to identify the energy benefit of implementing cross cut isolation. Due to a confidentiality agreement the mining shaft will hereafter be referred to as B Shaft. This mining shaft exercises narrow reef mining operations on both the Merensky and UG2 ore reefs of the Bushveld Complex [10]. Figure 29 gives a visual illustration of the mining shaft's level layout and relevant existing CA infrastructure.

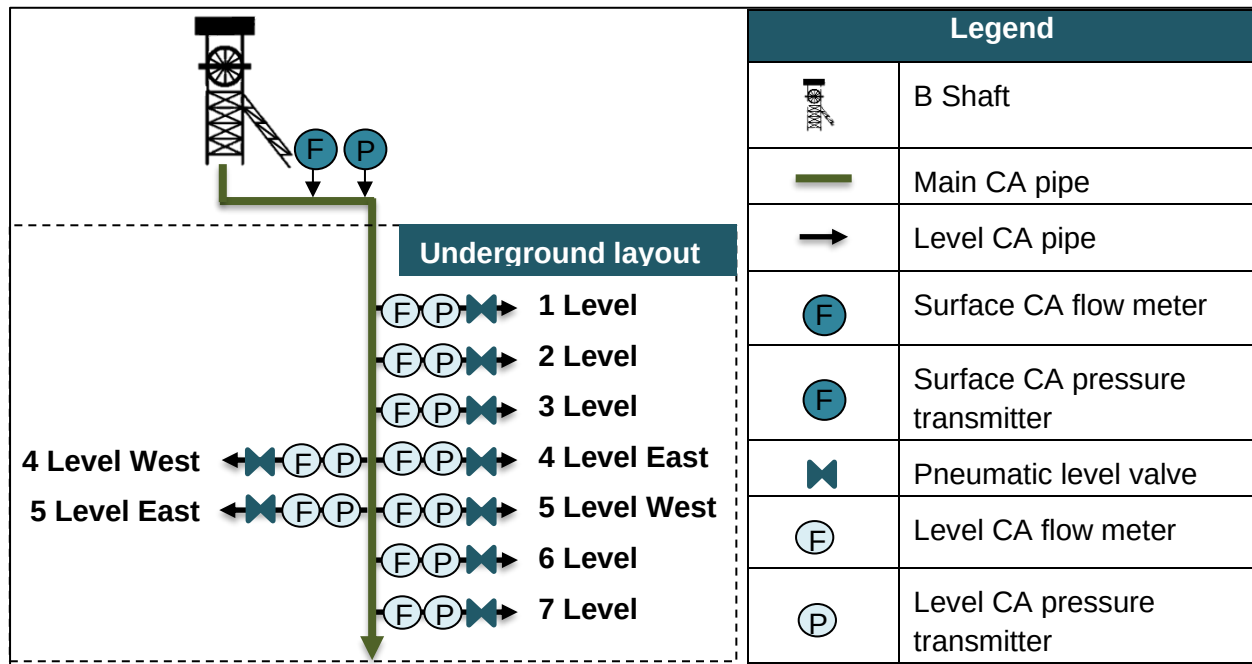


Figure 29: Underground layout of the mining shaft used for the case study

As shown in Figure 29, the shaft had an already permanently installed surface mass flow meter and pressure transmitter on the main CA pipe going down the shaft. This instrumentation is connected to a SCADA system which allows for remote monitoring of the CA consumption and storing of data to the historian.

Note that the shaft had already installed volumetric flow meters and pneumatic isolation butterfly valves on each level, before any CA energy management initiatives were implemented. However, the measuring instrumentation was outdated and damaged, which meant that the measurements obtained from the flow meters were not reliable. Due to the lack of operational level flow meters, the already installed permanent surface mass flow meter, surface pressure transmitter and working pneumatic level isolation valves, were used to conduct regular shaft baseload tests to monitor the wastage consumption on the different levels. In addition to this, manual measurements with portable instrumentation, as discussed in Section 2.2.1, were used to obtain CA flow and pressure information on the underground level haulages.

3.2 Compressed air network analysis

The surface mass flow meter only allowed the opportunity to quantify the CA wastage across the whole shaft. However, in order to address this wastage issue, the levels with the highest CA wastage consumption had to be identified and investigated. Therefore, regular baseload tests, as discussed in Section 2.2.2, were conducted over a 12-month period to track the wastage consumption across the shaft.

- **Shaft baseload test results**

The shaft baseload tests were conducted during the blasting shift, when no mining personnel were allowed underground. This was strategically done to accurately quantify the wastage consumption as there were no authorised consumers active during this period.

The tests were conducted by using the pneumatic level isolation valves in conjunction with the permanently installed surface mass flow meter and pressure transmitter. The valves were remotely isolated from the shaft's control room via the SCADA user interface, through relaying command outputs to the PLCs connected to the valves.

Figure 30 shows an example of the results obtained from a single shaft baseload test, conducted in accordance with the procedure discussed in Section 2.2.2. The figure shows the surface flow measurement, presented as the dark blue line, reducing as each individual level is sequentially isolated.

As a result of systematically reducing the flow, the shaft supply pressure, presented as the dotted black line, increases as each level is isolated. This observation can clearly be seen when the 2 Level valve was closed, at 18:17, when the flow and pressure before the isolation was measured as 81 000 Nm³/h at a pressure of 613 kPa. After the isolation, the flow eventually stabilised, at 18:24, with a flow measurement of 68 000 Nm³/h at an increased supply pressure of 645 kPa. This means that a 30 kPa pressure increase was experienced as a result of reducing the CA flow by approximately 13 000 Nm³/h. Note that at 18:31, the pressure started to reduce as a result of a compressor switching off on the CA ring.

However, as discussed in Section 2.2.2, to account for the increase in pressure, the surface flow measurement was normalised to a reference pressure of 500 kPa. This ensures that a fair comparison for the different level wastage consumptions are made, as all the measured flow reductions are compared with one another at the same supply pressure. The normalised flow is shown as the light blue line in Figure 30.

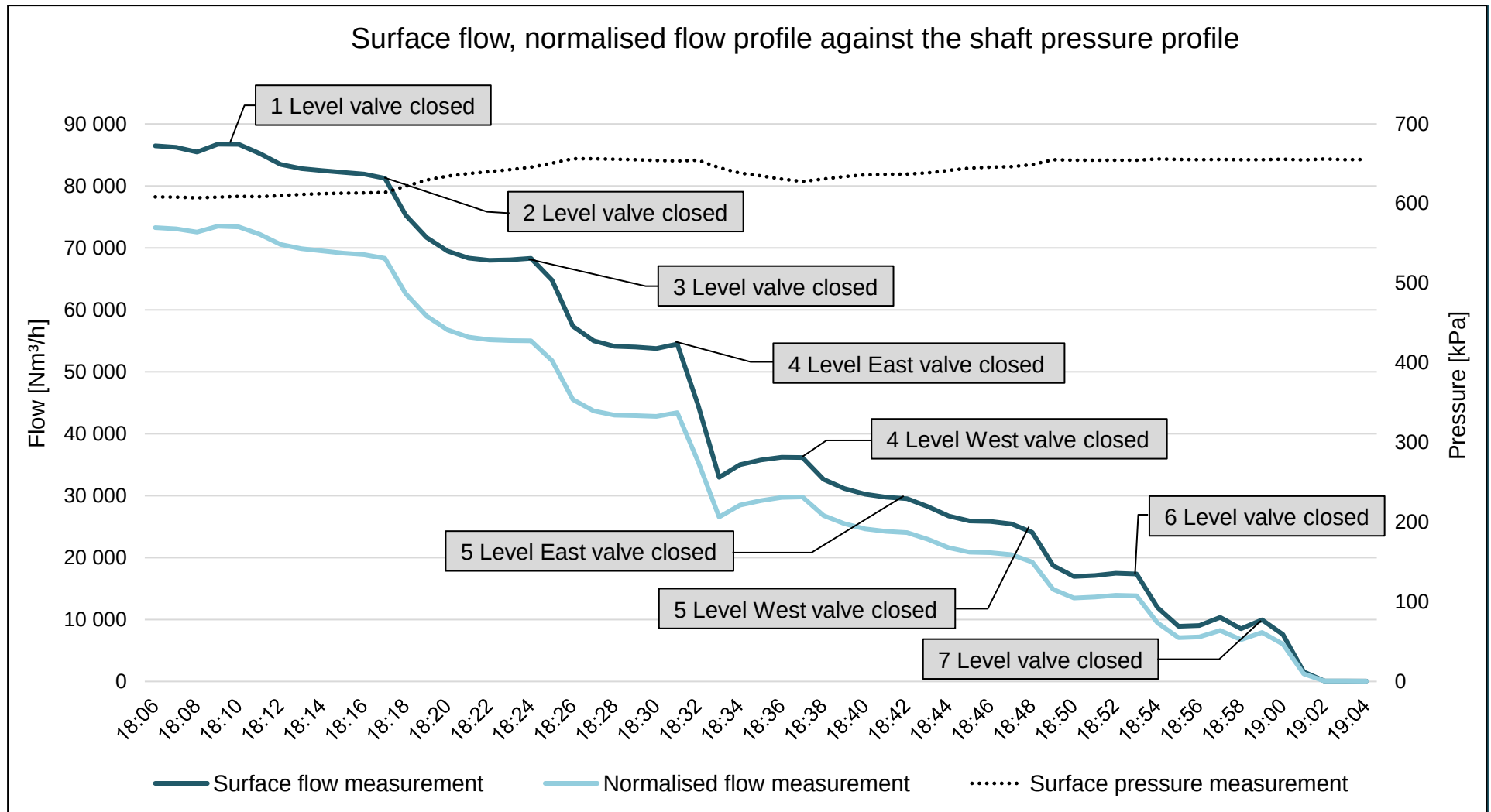


Figure 30: Surface flow and pressure profile obtained during a shaft baseload test

To emphasise the extent of B shaft's wastage consumption, each level's baseload flow is normalised over an average 24-hour pressure profile for the 12-month monitoring period. When comparing this normalised flow profile with actual CA flow data, the extent of the shaft's wastage consumption can be quantified over the 24-hour mining shift cycle.

Figure 31 shows the total normalised baseload consumption of the shaft, as the stacked area of each level's baseload, and the actual average 24-hour flow profile, shown as the dark blue line. When comparing the total normalised baseload and actual flow data over the 24-hour period, the data indicated that up to 74% of the mining shaft's total CA consumption is attributed to wastage. This means that only 26% of the total CA consumption is used for production-related mining operations, shown as the area between the actual flow and stacked baseload consumption profiles.

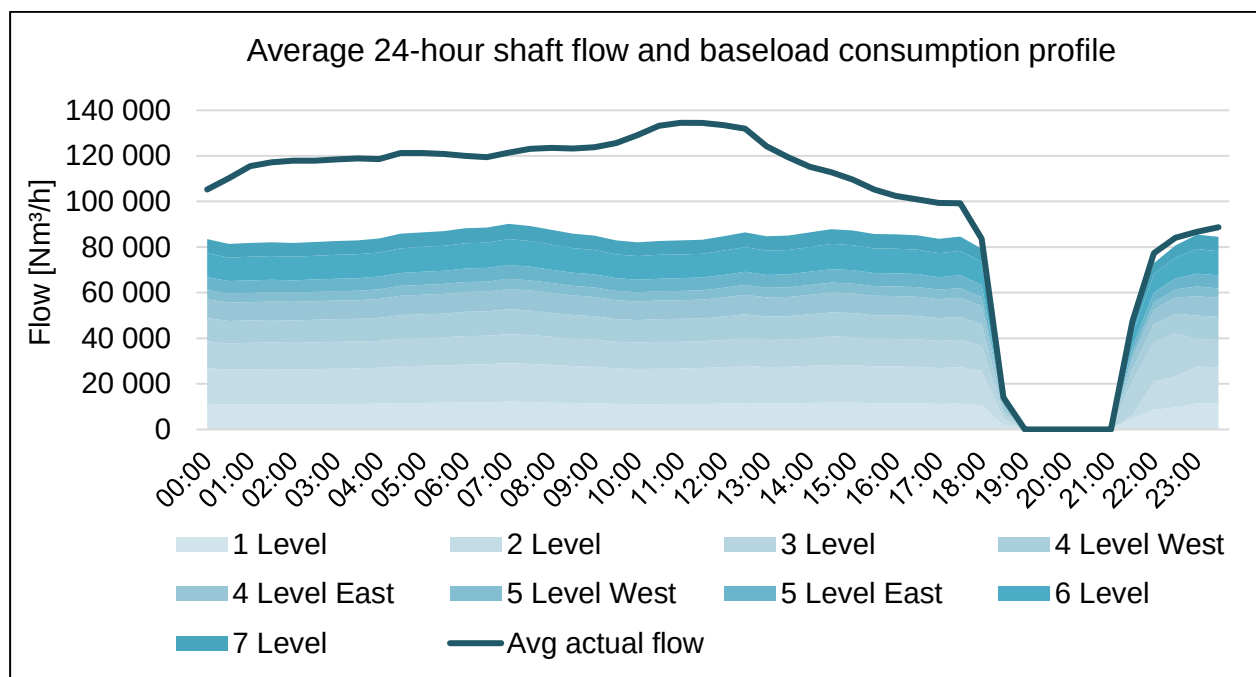


Figure 31: Normalised baseload over a 12-month averaged 24-hour supply pressure profile

Table 13 presents the normalised baseload flows and percentage distribution of each level's baseload across the shaft, averaged over the 12-month monitoring period. An annual monetary value is calculated for each level's baseload consumption using the Eskom Megaflex TOU tariff structure, as presented in Appendix C. The total annual baseload cost is compared with what the mining shaft actually spends on CA generation. The high wastage consumption, as shown in Figure 31, ultimately comes down to an annual capital expenditure of approximately R71,4-million on wastage consumption, which is 74% of the total capital spent annually (R96,6-million) on CA generation for this mining shaft.

Table 13: Summary of the shaft's CA baseload consumption

Level	Normalised average baseload flow [Nm3/h]	Consumption % of the total baseload	Annual baseload cost [Rand]
1 Level	10 094,5	13%	R9,5-million
2 Level	14 133,3	19%	R13,2-million
3 Level	10 633	14%	R10,5-million
4 Level East	9 040,1	12%	R8,6-million
4 Level West	7 439,3	10%	R7-million
5 Level East	3 730,2	5%	R3,6-million
5 Level West	5 020,2	7%	R4,8-million
6 Level	9 465,2	13%	R8,9-million
7 Level	5 558,3	7%	R5,3-million
Total	75 113,96		R71 ,4-million
Total actual CA cost			R96,6-million
Baseload cost percentage			74%

From the shaft baseload test results, it was identified that levels 2 and 3 were the highest wastage consuming levels, as these levels are collectively responsible for 33% of the total baseload consumption. These two identified levels were used as the next case study on which the half-level baseload tests were performed.

- **Half-level baseload test results**

The mining layout of each half-level was obtained from the surveying department to assist with pre-infrastructure investigations. These drawings were used in conjunction with visual audits to get familiarised with the half-level haulage layout, and to determine if the already installed manual isolation valves were in working condition. The faulty valves identified during the visual audits were replaced by the mining personnel. This ensured that the results obtained from the half-level baseload tests were accurate and that all the wastage in the cross cuts was accounted for. The half-level baseload tests were performed in accordance with the process discussed in Section 2.2.2.

Note that numerous half-level baseload tests were conducted across the shaft during the course of this study. However, for the purpose of this study, the results obtained from the half-level baseload tests conducted on the two identified case study levels are presented. In total six half-levels were analysed, and their relevant test results are presented. For illustration purposes Figure 32 is presented in this section, the remaining test results can be found in Appendix E.

Figure 32 shows the measured CA flow profile (as the grey area), level supply pressure profile (as the black dotted line) and the half-level pressure profile (as the blue line) for the half-level baseload test. The flow consumptions across the six half-levels, without any cross cut valves closed, ranged anywhere between 2500 to 7500 Nm³/h.

The pressure profile in Figures 32 indicates a clear pressure drop experienced across the half-level CA network. Referring back to Section 1.4, this is as a result of a dynamic pressure drop caused by the high CA flowrate. However, once the cross cuts were isolated from the half-level CA network, a clear reduction in the CA flowrate is observed. This in turn resulted in a reduction of the dynamic pressure drop, resulting in an increase of the operating pressure at the flat-end development area.

It is also important to take note that the sudden peaks in the CA flowrate represent the pneumatic equipment being used on the half-level haulage. This equipment includes pneumatic loaders operated at the flat-end development area, a shotcrete machine used in the development areas and the haulage chutes used to load ore into the tram cars. All of the above-mentioned equipment was connected to the main CA haulage pipe and was therefore not affected during the half-level baseload tests.

Furthermore, once all the cross cut valves were isolated, the ideal CA flowrate was measured for the half-level. This remaining flowrate could be attributed to the constant CA flow supplied to the refuge bays and the wastage in the haulage. The half-level baseload tests did, however, identify that the wastage consumption in the haulages is small, as only minor flange and pipe leaks were found.

Note that the results presented for the half-level baseload test conducted in Figure 52, as presented in Appendix E, showed that a 50 kPa dynamic pressure drop was eliminated as a result of isolating the cross cuts which brought about an 85% reduction in the CA flowrate. As a result of this major flow reduction an additional pressure benefit was experienced due to auto compression [28].

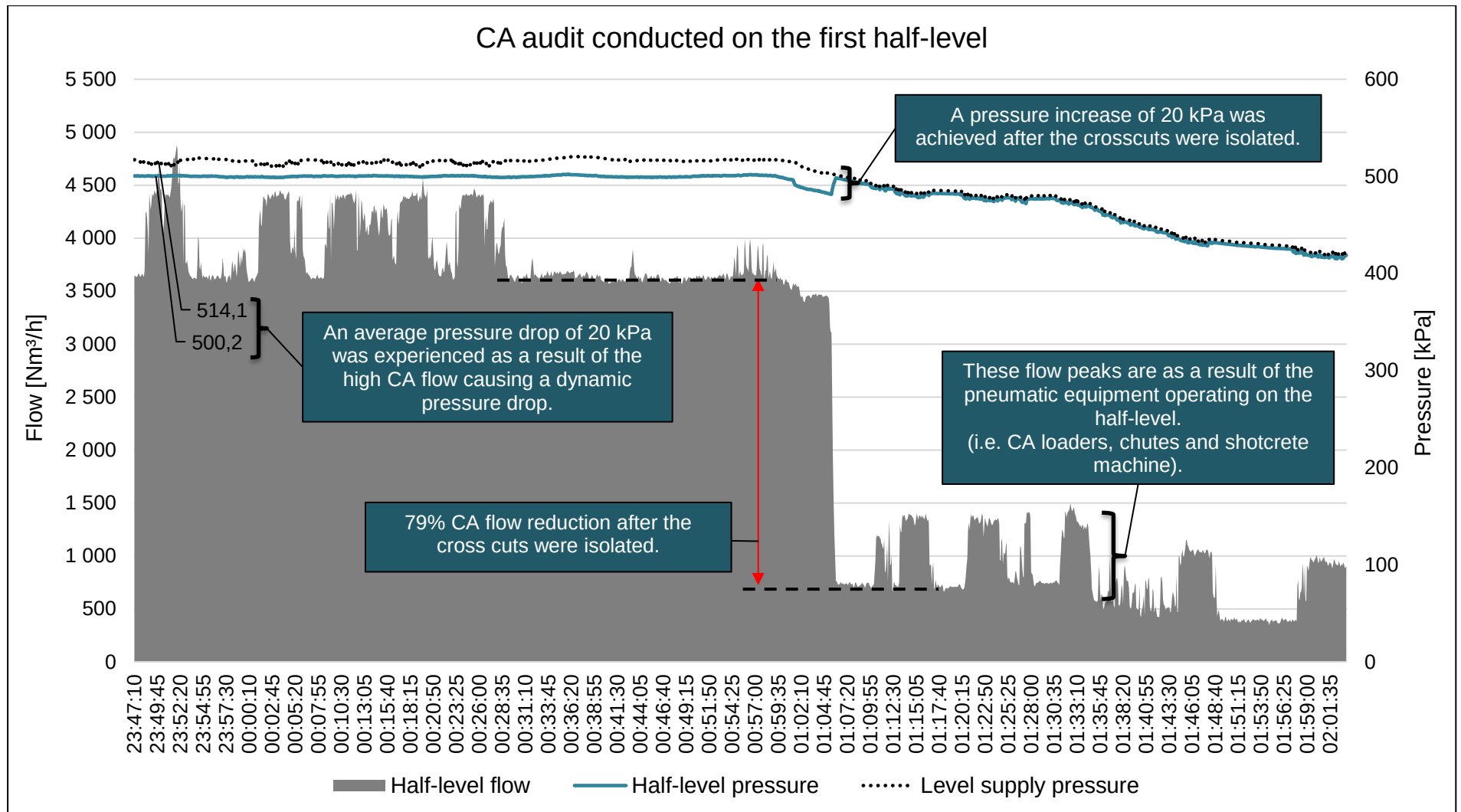


Figure 32: Flow and pressure profile obtained during the CA audit on half-level number 1

Following the half-level baseload tests, visual CA network audits were conducted in the stoping areas of the cross cuts. These audits identified the unauthorised consumers responsible for the high wastage consumption in the cross cuts, as identified by the half-level baseload tests.

Figure 33 and Figure 34 provide simplified layouts of the CA network of the stoping areas investigated for two different cross cuts. To simplify the findings, the results for two stoping areas are presented, and a summary of the findings identified for all the stoping area investigations are presented in Section 3.2.1. The red dots, as depicted in the legend of Figure 33 and Figure 34, indicate unregulated open-ended pipes, used to ventilate the area with CA. The orange dots represent big CA leaks (>10mm), and the yellow dots represent small CA leaks (<10mm) found during the investigation.

The stoping area, as presented in Figure 33, showed that good leak management and maintenance were conducted by the mining personnel, as few leaks were found. The only leaks that were found were unintentional leaks on a flange and a quick coupling. However, several unregulated 32 mm pipes (supply pipe for the rock drills) and 25 mm pipes (supply pipe for the pumps) that were used for CA ventilation purposes were identified during the investigation. The open-ended pipes, as identified in the figure, were mainly used by the winch operators for CA ventilation. During the investigation it was found that the working environment temperature was higher than normal, but still below the legal limit as stated by the Mine Health and Safety Act [78].

In addition to this observation, it was found that the stoping area's ventilation infrastructure was substandard, which is a major contributor to the higher working environment temperature. This is an important factor that needs to be taken into consideration, as the ventilation of the cross cuts needs to be up to standard when implementing cross cut isolation, to avoid the risk of mining personnel bypassing any cross cut isolation valves in order to ventilate with CA. Note that on B Shaft the ventilation of CA is strictly prohibited unless a permission letter is issued by the ventilation department to allow specific mining sections to ventilate with CA.

Poor CA leak management was encountered in the stoping area presented in Figure 34, as multiple leaks were found. Three unregulated open-ended pipes were found during the investigation. Note that these open ends were left open by the previous shift's mining personnel, as there were no mining activities conducted during the time of the investigation in this stoping area. These findings therefore highlight the negligent culture that exists among the mining personnel, and the major contribution that misappropriation has on the total CA wastage consumption.

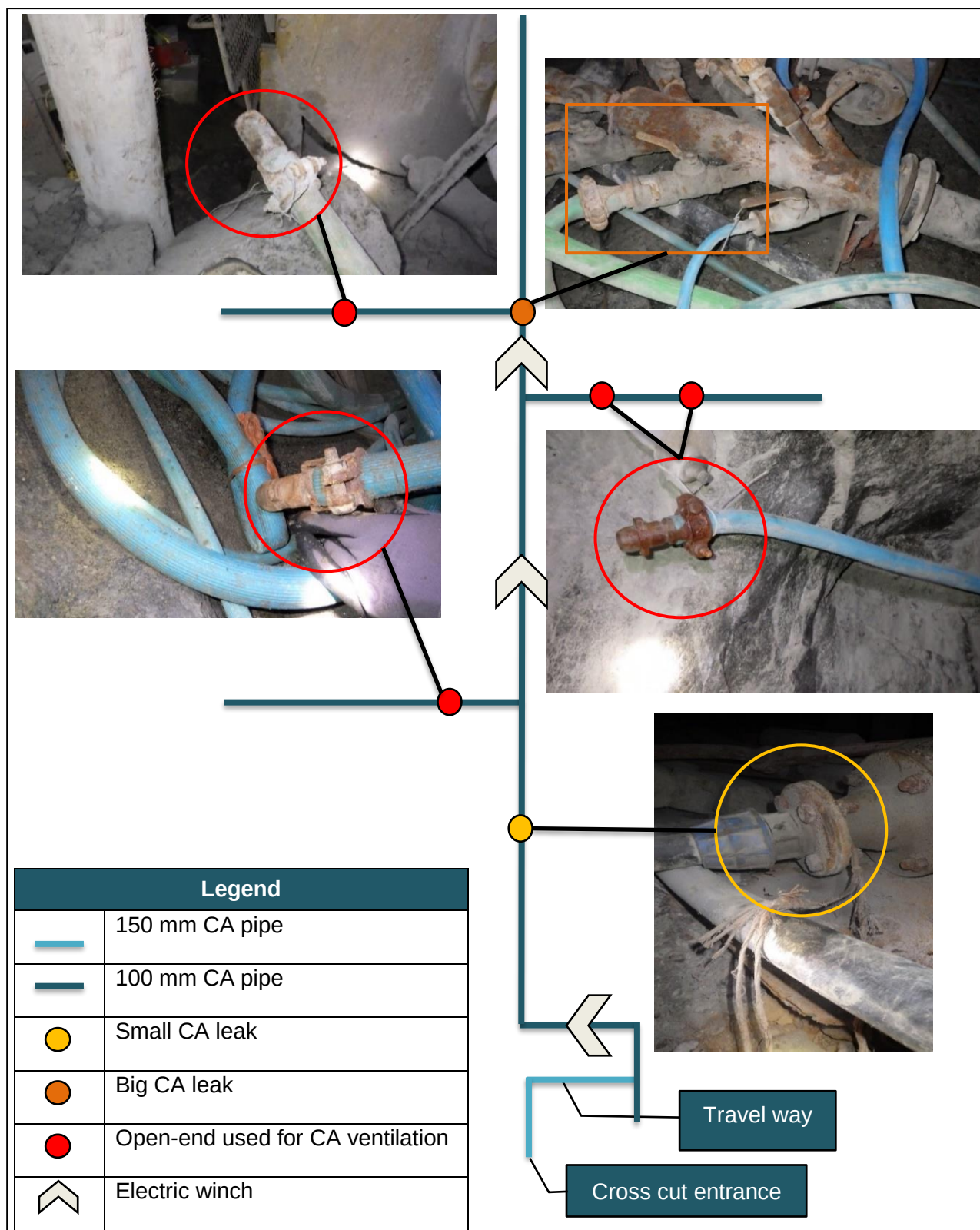


Figure 33: Visual audit results for cross cut number 1

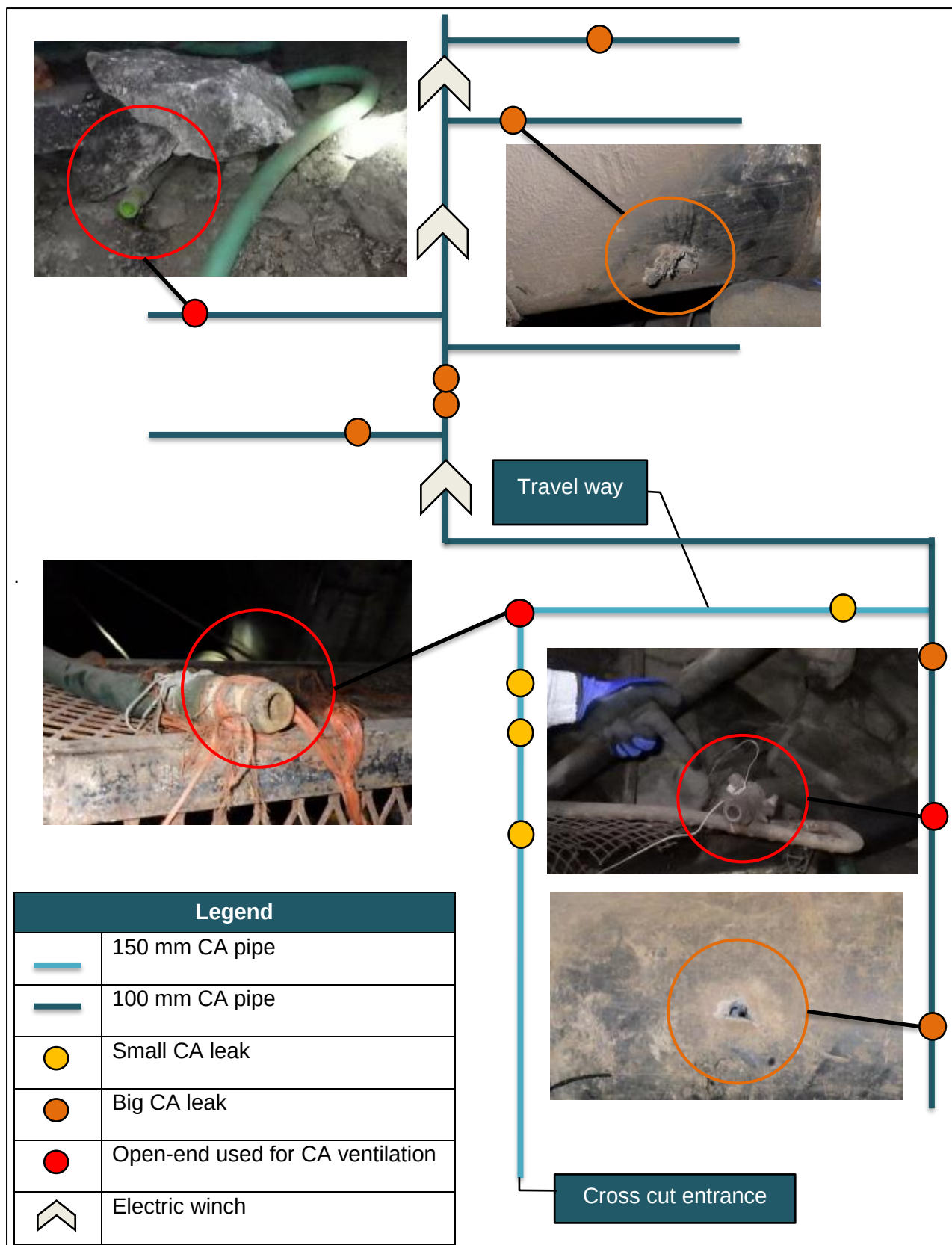


Figure 34: Visual audit results for cross cut number 2

In Section 1.4 it was stated that the leakage rate through a hole in a CA pipe is proportional to the square of the hole diameter. Therefore, Figure 12, as presented in Chapter 1, will be used to highlight the extent of the CA wastage caused by an unregulated open-ended 32 mm hose used for ventilation purposes, as shown in Figure 35.

For an operating pressure of 500 kPa, a leakage rate increase of 4024% can be observed when the leakage rate of a 32 mm hole is compared with that of a 5 mm hole. The information presented in the figure therefore justifies the need to isolate the cross cuts from the CA network, especially with regards to the unregulated open ends in the stoping areas.

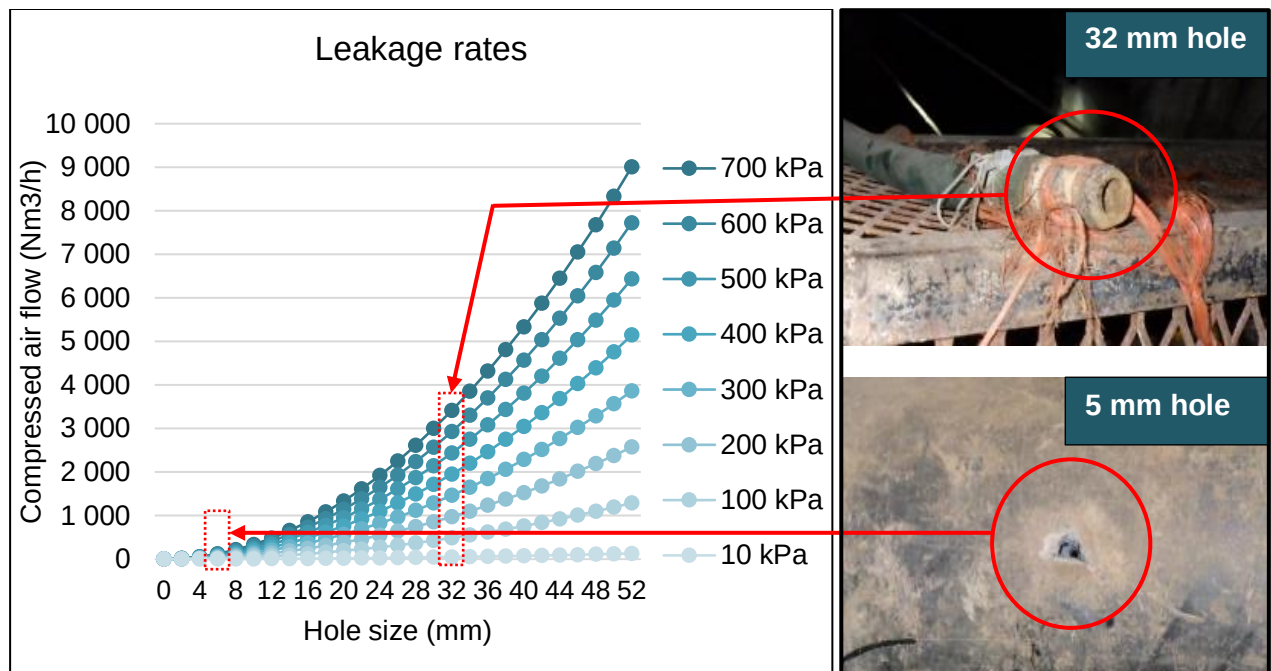


Figure 35: Flowrate comparison between a 32 mm and 5 mm hole at different pressures

3.2.1 Conclusion

The CA network analysis provided valuable insight with regards to the CA wastage distribution across the shaft. The wastage distribution can be divided into two main categories, namely wastage in the haulage and wastage in the cross cuts, as shown in Figure 36. The half-level baseload test results determined that the cross cuts are responsible for approximately 85% of a mining level's CA wastage consumption. The remaining 15% is allocated to wastage in the level and half-level haulages.

The wastage consumption for both the cross cuts and haulages can further be categorised as either leaks or misappropriation, as shown in Figure 36.

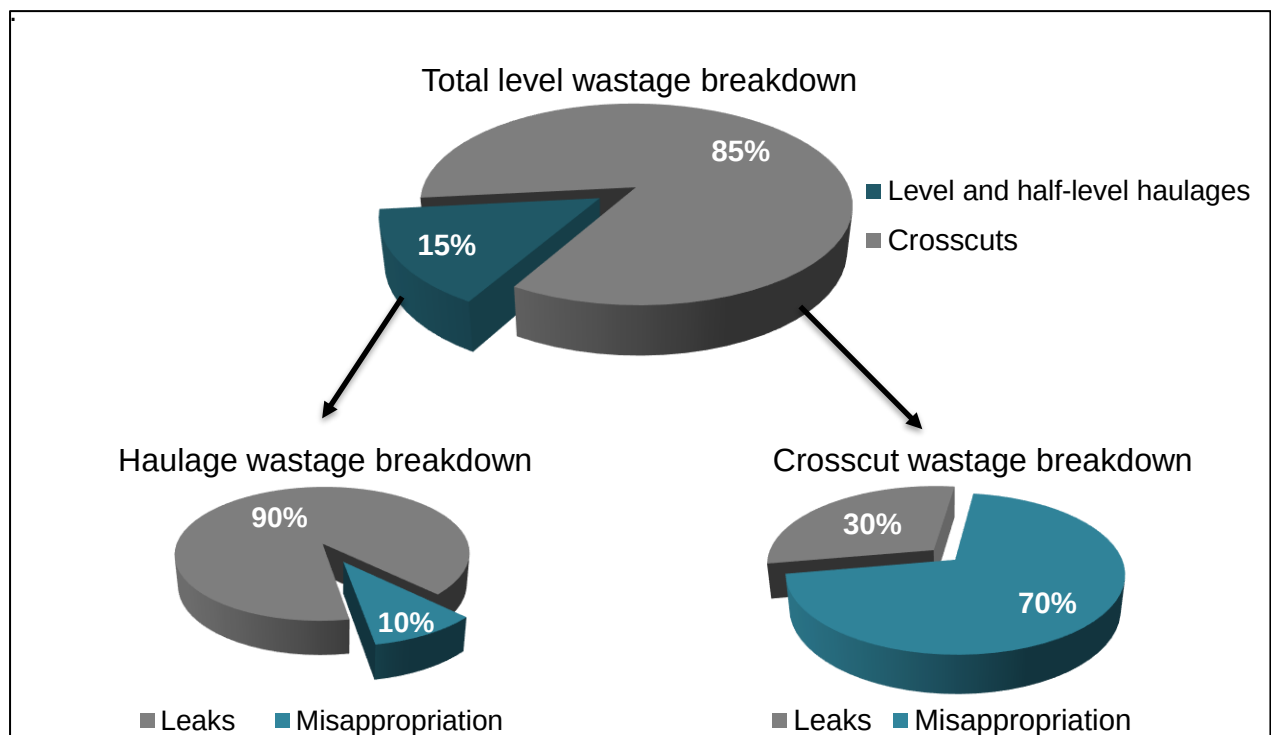


Figure 36: Wastage breakdown analysis

Haulage wastage breakdown: The CA network analysis determined that approximately 90% of the CA wastage in the haulage can be attributed to unintentional leaks, i.e. flange leaks or a leak formed on corroded pipes. Misappropriation only accounts for 10% of the haulage wastage consumption. The haulage wastage originates from mining personnel ventilating with CA, which was mainly observed at the flat-end development areas.

Cross cut wastage breakdown: The distribution analysis determined that CA misappropriation is largely responsible for the wastage consumption in the cross cuts. Approximately 70% of the cross cut wastage consumption is attributed to unregulated open-ended hoses used by mining personnel for ventilation purposes. The remaining 30% is attributed to leaks on the CA pipeline supplying the stoping areas.

The first study objective is therefore successfully addressed, as an accurate quantification of the wastage consumption in the cross cuts was made. In essence the information presented in this section supports the need for this study to isolate the cross cuts from the CA network to address the wastage issue brought about by CA misappropriation. This solution is particularly relevant to the case study as the cross cuts are responsible for 85% of the total wastage consumption. There is a general habit among mining personnel to ventilate with CA, irrespective of the temperatures in the stoping areas; therefore, isolating the cross cuts will assist with addressing this issue.

3.3 Technical feasibility

3.3.1 Compressed air consumers

As discussed in Section 2.3.1, it is crucial that no production- or mining-related activities are affected in the event of introducing cross cut isolation. Table 14 provides a summary of the identified authorised CA consumers that are active on the half-levels during the non-drilling shifts. There were in fact two authorised consumers identified that would be affected in the event of isolating the cross cuts, namely air whistles and water pumps. These consumers were investigated, and alternative solutions were introduced to enable the isolation of the cross cuts in Section 3.3.2.

Table 14: Consumers active during the period in which cross cut isolation will be implemented

Equipment	Location	Shift	Description
Shotcrete machine	Development areas	Cleaning	The main CA pipe in the haulage is used to supply the machine with CA. Therefore, the shotcrete machine will not be affected during the implementation of cross cut isolation [79].
Loader	Flat-end development area	Cleaning	The main CA pipe in the haulage is used to supply the machine with CA. Therefore, the loader will not be affected during the implementation of cross cut isolation.
Chutes	Haulages	Cleaning and drilling	The chutes are all connected to the main CA pipe in the haulage and will not be affected during the implementation of cross cut isolation.
Refuge bays	Haulages	All shifts	Most of the pipes supplying the refuge bays with CA are connected to the main CA pipe in the haulage. There are refuge bays that tie-off from the pipeline in the cross cut; however, the isolation valves are located after the tie-off. Therefore, the

			refuge bays will not be affected during the implementation of cross cut isolation.
Water pumps	Stoping areas	Cleaning	In some instances, water pumps in the stoping areas will require CA to pump out excess service water. Refer to Section 3.3.2.
Air whistles	Stoping areas	All shifts	It was identified during the visual audits that some stoping areas still make use of air whistles to operate the winches. Refer to Section 3.3.2.
Drop raise drill	Cross cut development areas	Cleaning	The main CA pipe in the haulage is used to supply the machine with CA. Therefore, the drop raise drill will not be affected during the implementation of cross cut isolation.

3.3.2 Alternative solutions

By using the authorised CA consumers' identification process flowchart presented in Figure 24, the water pumps and air whistles were further investigated to identify an alternative solution.

- **Water pumps**

During the investigations there were some instances where water positive stopes was found; this implies that more water was coming in than could be pumped out. Further investigation revealed that a large contributor to this issue was mining personnel not isolating the water supply in periods when water was not used, resulting in large amounts of water wastage. Note that this was not a regular occurrence; however, in the event of this happening, the water pumps are regarded as an essential service and should be accommodated in the implementation of a cross cut CA control philosophy.

Due to the rare occurrence of this issue, it was decided that the diaphragm pumps in the stoping areas will remain on CA. Therefore, the proposed control philosophy will be updated to supply CA during periods when pumping is required. An alternative solution to avoid the oversupply of water in the stoping areas is to implement water cross cut isolation on the service water reticulation network [59], as discussed in Section 1.5.2.

- **Air whistles**

During the cleaning shift, mining personnel in the cross cuts make use of scraper winches to clean the blasted rock from the stopes and gullies, as discussed in Section 1.2.1. However, there are major hazards and risks associated with the design, installation, and cleaning operations of the scraper winch systems [80].

The Safety in Mines Research Advisory Committee (SIMRAC) did an investigation into the causes of accidents on these scraper systems in platinum and gold mining sectors [80]. The investigation highlighted that winch operators, stope workers, drillers, and general miners are prone to scraper winch accidents.

In addition to this, it was determined that most of the injuries occurred at the beginning of the drilling shift, when most workers are in groups of occupation, and that fatal accidents occurred mostly during the cleaning shifts (night shifts). This was attributed to absence of supervision and loss of concentration and awareness amongst workers.

The main finding of the underground observations was that “rigging”, “signalling devices” and “winches being started without warning” were identified as the main/significant hazards. It was recommended that effective warning devices should be put in place, as the current communication systems were deemed inadequate [80].

As a result of this, the majority of the mining properties in South Africa upgraded/converted their existing signaling devices, i.e. air whistles, to electronic winch signaling devices. This was done to improve the communication between the workers and winch operators.

B Shaft converted the majority of their air whistles in the stoping areas to electrical winch signalling devices. However, it was identified during the feasibility analysis that there were still certain areas making use of air whistles. As mentioned above, the communication between the operator and personnel is highly important to avoid serious injuries and fatalities.

Therefore, the air whistles are regarded as an essential consumer and it was decided from the mining shaft to convert the existing air whistles to electrical winch signalling devices [81]. This meant that the proposed control philosophy did not need to be amended to accommodate the air whistles.

- **Chutes and refuge bays**

The chutes and refuge bays were not an issue with regards to implementing cross cut isolation at B Shaft. However, each mining site is unique with regards to their CA network layout.

Therefore, the chutes and refuge bays may have to be addressed at other mining sites. For instance, some sites may have refuge bays and chutes tying off from the CA pipeline in the cross cut. In this instance it is recommended that the isolation valve is installed or moved to after the tie-off or that the tie-off is moved to before the isolation valve, if it is not logistically possible to install a valve after the tie-off.

3.3.3 Proposed control philosophy

Levels 2 and 3, as identified in Section 3.2, will be used as the case study levels at which cross cut isolation will be implemented. The control philosophy that will be used to implement cross cut isolation on Levels 2 and 3 is developed and presented in this section.

The mining shift schedules for both Levels 2 and 3 were determined from the winder schedule and are presented in Table 15. These mining schedules depict the time schedule for when the cross cut isolation valves will be open and closed.

Table 15: Mining shift schedule for both Levels 2 and 3

	2 Level		3 Level	
Shift	Start time	End time	Start time	End time
Drilling	06:00	12:00	06:30	12:30
Post-Drilling	12:00	15:00	12:30	15:30
Afternoon Reduction	15:00	18:00	15:30	18:00
Blasting	18:00	21:00	18:00	21:00
Night Reduction	21:00	21:30	21:00	22:00
Cleaning	21:30	04:00	22:00	04:30
Morning Reduction	04:00	06:30	04:30	06:30

Figure 37 provides the proposed control philosophy developed from the technical feasibility analysis, which complements the mining schedule identified in Table 15, to implement cross cut isolation on Levels 2 and 3. The aim is to isolate the cross cuts during the non-drilling shifts. Section 3.7 will discuss the results obtained during the implementation of the philosophy and the requirements for obtaining sustainable energy savings.

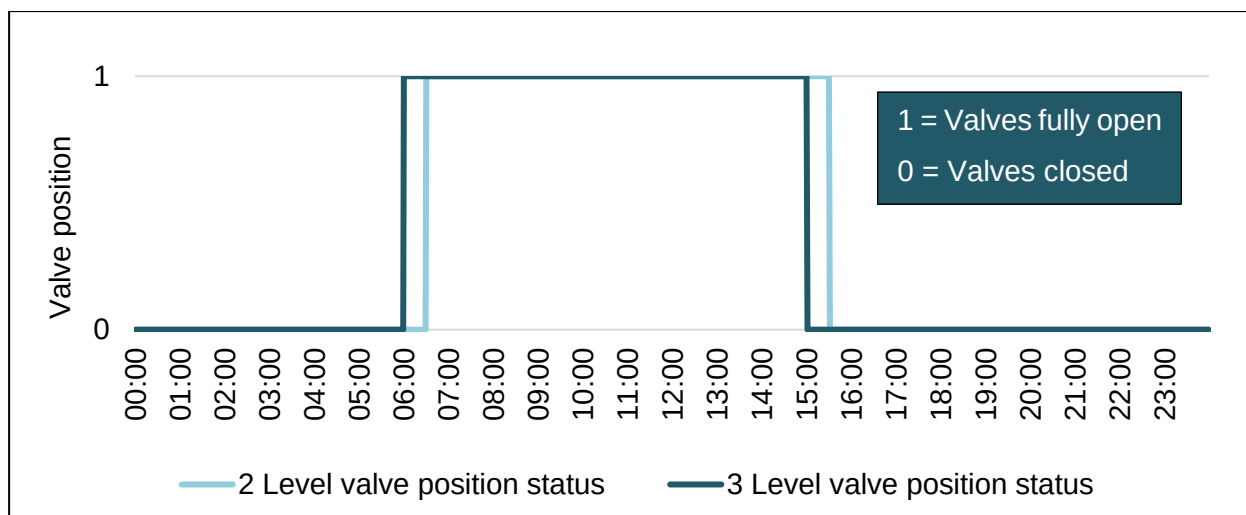


Figure 37: Cross cut isolation control philosophy for Levels 2 and 3 over a 24-hour period

3.4 Energy benefit quantification

The first step in quantifying the energy benefit for implementing cross cut isolation is to verify and validate the theoretical model used to predict what the potential CA flow reduction will be. The model will be developed, according to the process discussed in Section 2.4, for Levels 2 and 3. The results obtained in the CA network analysis, Section 3.2, for Levels 2 and 3, will be used to validate and verify the prediction by determining the error percentage between the actual and predicted results for when cross cut isolation is implemented.

Once it is determined that the model provides an accurate prediction, the prediction will be extrapolated through developing the model for the entire shaft. The model will then allow the opportunity to quantify the potential energy benefit for when cross cut isolation is implemented across the shaft.

3.4.1 Developed theoretical model

Step 1: Obtain actual compressed air data

CA flow and pressure data:

During the course of this study, an artificial demand side management initiative was implemented in the form of level control valves to address the CA wastage. This entailed replacing the isolation valves with control valves. Additionally, all measuring instrumentation was replaced with new mass flow meters and pressure transmitters. Approximately 6 months of historic CA flow and pressure data, originating from the new flow meters and pressure transmitters, was collected from the mine's historian for Levels 2 and 3.

Identified mining shift schedule:

Refer to Table 15 in Section 3.3.3.

Step 2: Identified mining crews

Table 16 provides a summary of the different mining crews and number of the different mining crews active on Levels 2 and 3. Total Merensky and Total Chrome represent both the North and South drive half-levels. The names and abbreviations used for the different mining crews in Table 16 is provided as follows:

- Stoping crew
- Ledging crew
- Re-development crew (Re-Dev)
- Flat end development crew (Flat-Dev)
- On reef development crew (On reef)
- Refuge bays (Ref-Bay): Refers to the number of active refuge bays
- Flat-end development cleaning crew (cleaning)

Table 16: Planned MRM crews for Level 2 and 3

Half-Levels	Stoping	Ledging	Re-Dev	Flat-Dev	On reef	Ref-Bay	Cleaning
Planned crews for 2 Level							
Total Merensky	9	1	6	2	6	8	2
Total Chrome	8	4	8	2	5	8	2
Planned crews for 3 Level							
Total Merensky	6	2	6	2	4	8	2
Total Chrome	5	3	7	2	5	8	2

Step 3: Equipment used per mining crews

Appendix D provides a detailed breakdown of the various equipment used by each of the mining crews listed in Table 16. This breakdown also includes the consumption data ,i.e. the flowrates at the various operating pressures as specified by the Original Equipment Manufacturer (OEM) [1], and the utilisation percentage factor for each piece of equipment. These utilisation percentage factors were determined through underground audits and by consultation with the relevant engineering and mining personnel on B Shaft.

Step 4: Calculated theoretical flow profiles

Figure 38 and Figure 39 present the developed theoretical flow profile, shown as the dark blue line, for both Levels 2 and 3, respectively. The theoretical flow profiles were developed in accordance with the procedure discussed in Section 2.4.1.

The theoretical flow profiles of both levels are compared with the baseline flow profiles, shown as the light blue line. These baseline flow profiles were developed according to the criteria framework as discussed in Section 3.4.2.

The difference between the baseline and theoretical flow profiles in the non-drilling shifts represents the predicted potential flow reduction when cross cut isolation is implemented. The half-level baseload test analysis flow data is shown as the cross cut isolation test flow data, presented as the dotted black line. Note that the gap between the actual and theoretical flow profiles in the drilling shift represents the CA wastage consumption during this shift.

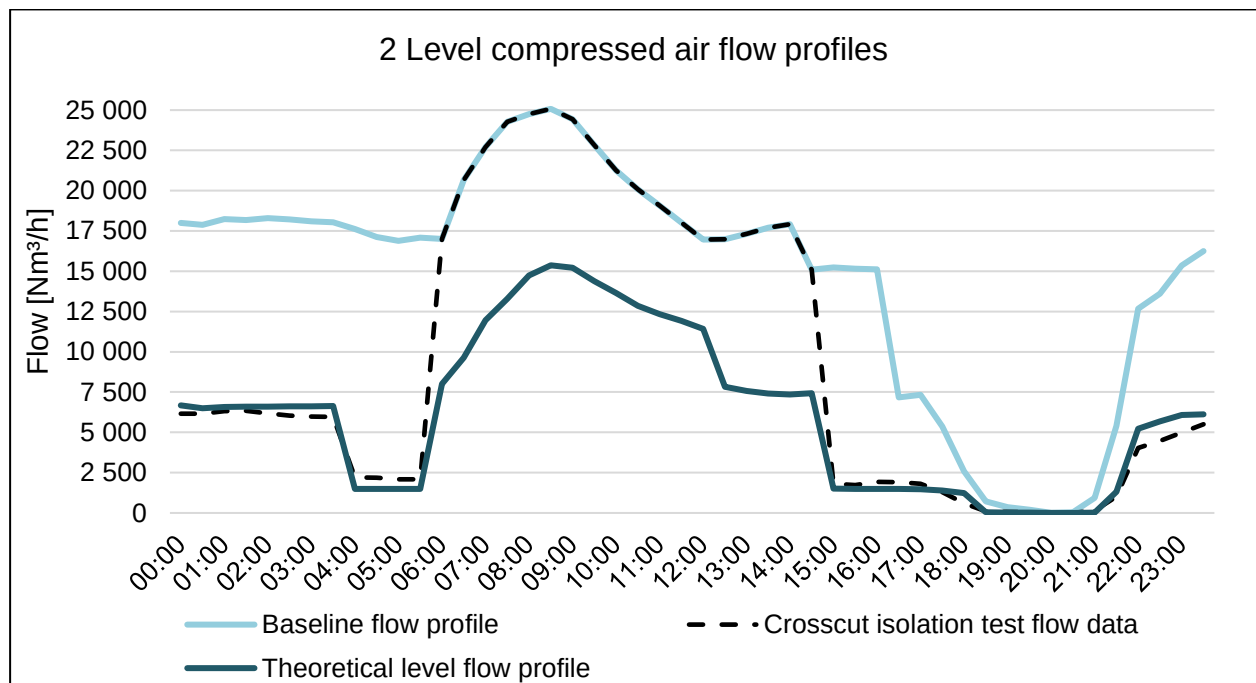


Figure 38: Theoretical flow profile of 2 Level vs the baseline and baseload result flow profile

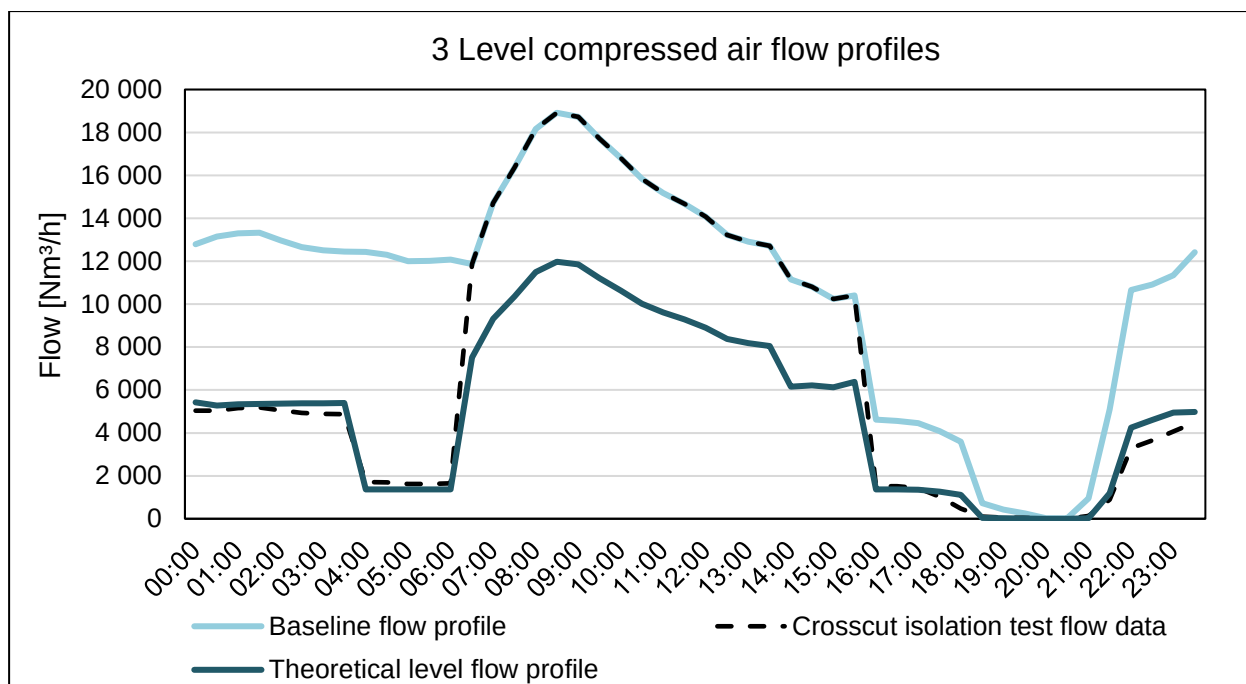


Figure 39: Theoretical flow profile of 3 Level vs the baseline and baseload result flow profile

3.4.2 Quantifying the potential flow reduction for cross cut isolation

Baseline flow profile

As mentioned in Section 2.4.2, the flow baseline will be used to quantify the energy saving brought about the implementation of cross cut isolation, and in this case what the theoretical model predicts. Using the International Performance Measurement and Verification Protocol (IPMVP) framework [72], as presented in Table 9, the baselines were calculated by addressing the criteria as follows:

Measurement boundary:

The new mass flow meter installed on the level, as mentioned in Section 3.4.1, was assigned as the flow measurement boundary used to develop the flow baseline. The newly installed pressure transmitter on the level was used as the pressure measurement boundary that was used in all of the theoretical model calculations. The purpose of the level flow baselines will mainly be to verify the effect of the two implemented control strategies on the CA network in Section 3.6.

Furthermore, the surface flowmeter and pressure transmitter will be assigned as the flow and pressure measurement boundary when the energy benefit quantification across the shaft is calculated.

Selection of the measurement period

As mentioned in Table 9, operational changes need to be taken into consideration when the baseline is developed. However, the level control valve, as mentioned in Section 3.4.1, was the only major operational change that had been introduced.

For the energy benefit quantification, weekday, Saturday and Sunday baseline flow profiles will be developed by using the surface flow meter and pressure transmitter. The maximum amount of available data, backdated to the most recent system change, i.e. the implementation of the level control valves, will be used to develop the baseline. The baselines are therefore developed for a full 6-month period.

For the purpose of verifying the theoretical model, a weekday baseline flow profile will be developed to visually illustrate the effect of isolating cross cut when compared with the half-level baseload flow profiles, as shown in Figure 38 and Figure 39. This baseline flow profile is developed for a full 6-month measuring period to account for any operational changes.

Adjustment methods:

Due to the direct correlation between the active CA end-users and the CA consumption, it was decided that the peak scaling or drill shift energy neutral method will be used to adjust the baseline according to system changes experienced, as discussed in Appendix B. This baseline scaling method will be used to verify the effect of the two implemented control strategies on the CA network, as presented in Section 3.6.

3.4.3 Model verification and validation

As mentioned in Section 2.4.3, the theoretical model is verified through determining whether or not the model accurately represents its predicted results. When comparing the half-level baseload test analysis flow profiles with the predicted theoretical flow profiles, for both Figure 38 and Figure 39, similar profile trends are observed.

The theoretical model is validated through quantifying the error percentage between the half-level baseload test analysis flow profiles and the predicted results from the theoretical model. This error percentage, which represents the discrepancy between the exact value (half-level baseload analysis flow profiles) and the approximation (theoretical predicted flow), is calculated and presented in Table 17. The percentage error between the measured flows and the modelled flows for Levels 2 and 3 were calculated at 4,92% and 4,89%, respectively. These small percentage errors indicate that the theoretical model can be regarded as fairly accurate.

Table 17: Model validation calculations

	2 Level analysis			3 Level analysis		
Mining shift	Predicted percentage theoretical flow reduction	Experimental percentage flow reduction achieved	Error percentage	Predicted percentage theoretical flow reduction	Experimental percentage flow reduction achieved	Error percentage
Drilling	Excluded – cross cut isolation is not implemented		[-]	Excluded – cross cut isolation is not implemented		[-]
Blasting	Excluded – all level valves are closed		[-]	Excluded – all level valves are closed		[-]
Post-drilling	Excluded – cross cut isolation is not implemented		[-]	Excluded – cross cut isolation is not implemented		[-]
Afternoon reduction	72%	76%%	5,26%	70%	74,18%	5,63%
Night reduction	76,5%	81%	5,55%	77,2%	82,5%	6,42%
Cleaning	59%	62%	4,84%	55,86%	62,71%	4,88%
Morning reduction	90,53%	87%	4,06%	88,6%	86,36%	2,63%
Average error percentage			4,92%	Average error percentage		4,89%

3.4.4 Energy savings benefit quantification

With confidence in the theoretical model's prediction, the potential energy savings benefit can be quantified through determining the total flow reduction resulting from cross cut isolation being implemented across the shaft. The potential flow reduction is calculated by comparing the shaft's baseline flow profile with the extrapolated theoretical model, which represents the predicted flow profile for when cross cut isolation is implemented.

The model was calculated according to the shaft's Mineral Resources Management (MRM) planned crews, equipment, and level mining schedules across the shaft. Figure 40, Figure 41 and Figure 42 present the potential flow reduction that can be achieved for weekdays, Saturdays, and Sundays, respectively. The difference between the baseline and theoretical flow profile (shown as the green area) represents the potential flow reduction, as shown in the figures.

As discussed in Appendix B, maintenance-related work is generally done on Sundays when the minimum number of CA-related mining activities are conducted. The level valves are therefore generally controlled on life-sustaining pressure (200 kPa), to supply the refuge bays throughout the course of the day. This is done to minimise CA wastage. However, mining activities start from approximately 9 pm when the cleaning shift commences, as shown in Figure 42.

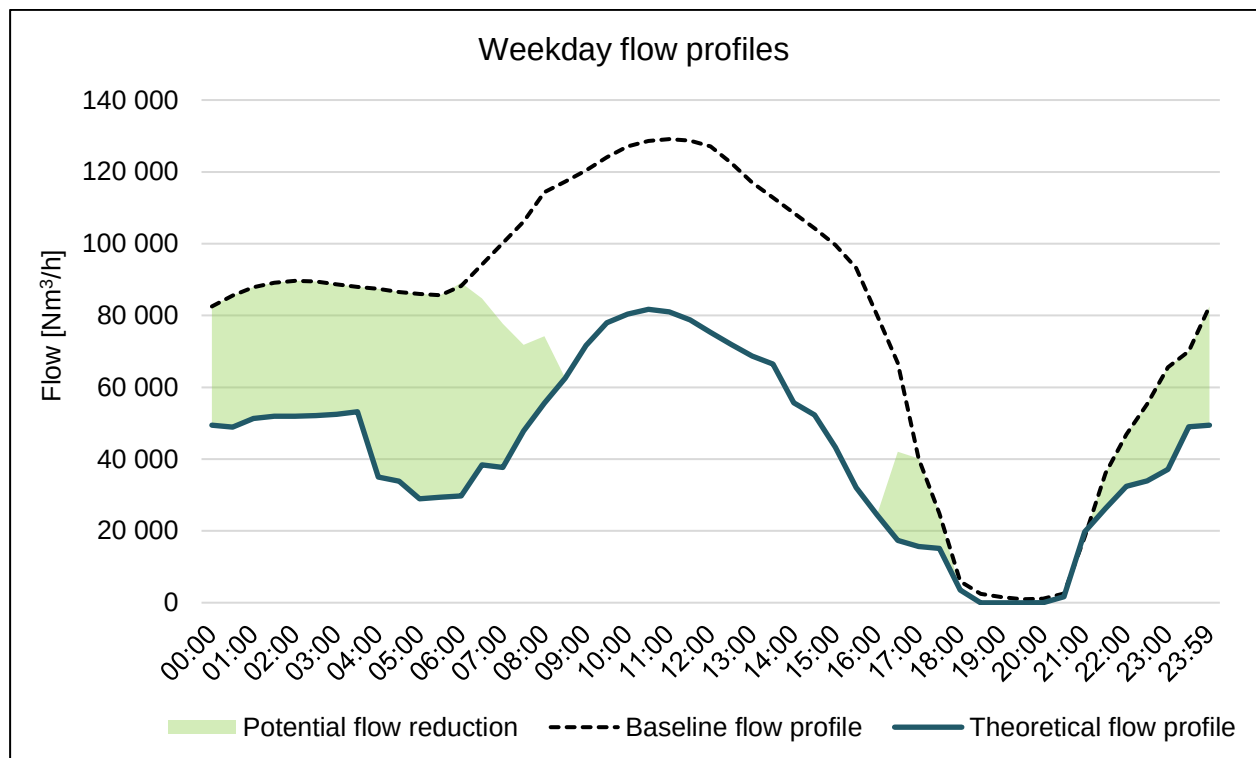


Figure 40: Weekday profile when the cross cuts are isolated during the non-drilling shifts

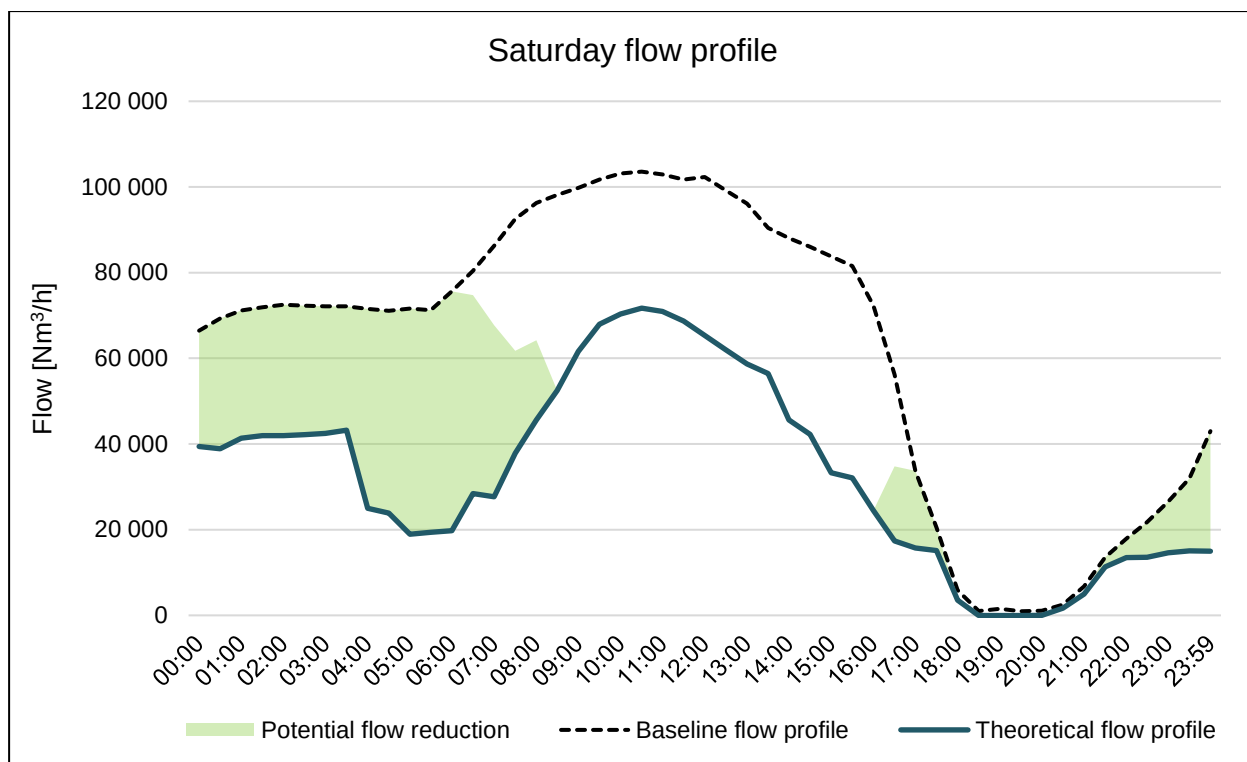


Figure 41: Saturday profile when the cross cuts are isolated during the non-drilling shifts

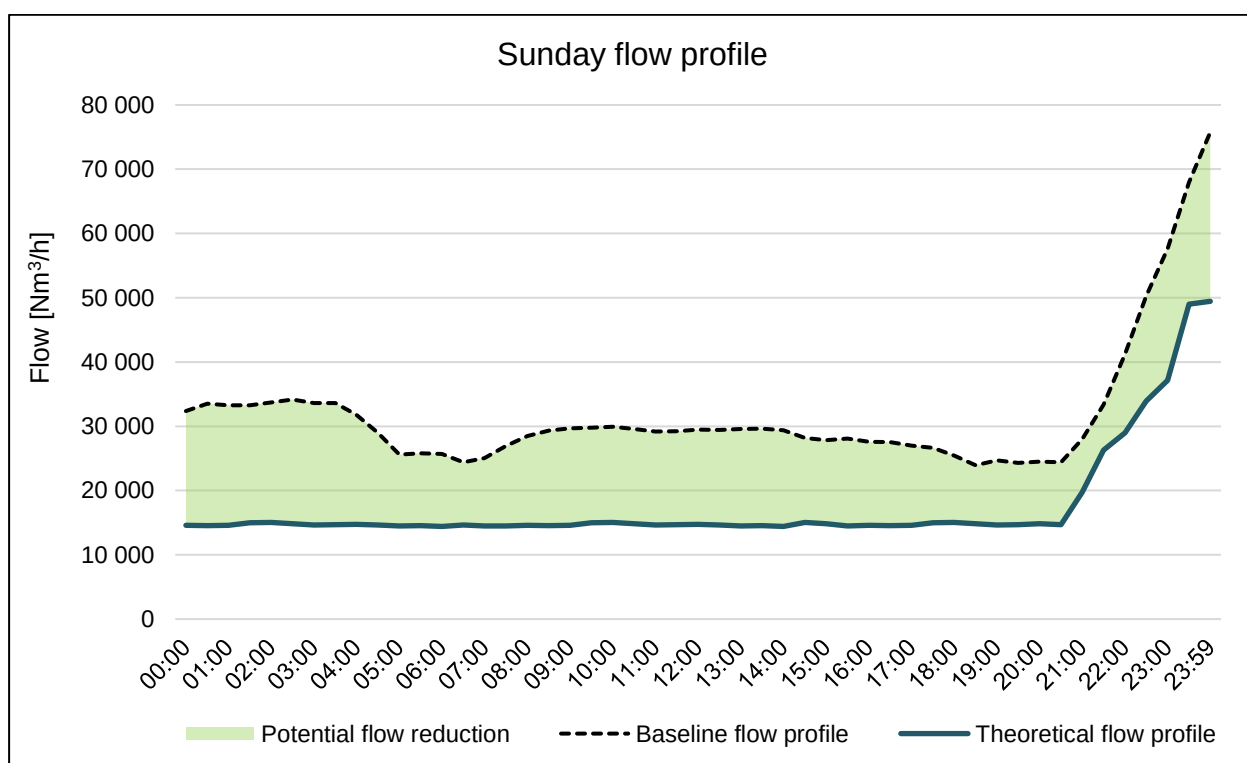


Figure 42: Sunday profile when the cross cuts are isolated

Compressed air power savings calculations

As discussed in Section 2.4.4, in order to determine the power savings for the potential flow reduction, the specific power [kWh/Nm³] of the CA network must be calculated. Table 18 gives the number of VK50 and VK32 compressors on the CA ring, as well as the average power consumption and discharge flowrates. Using the average power and the average flow, the specific power for the VK32 and VK50 compressors is calculated in Table 18.

Table 18: Compressors on South Ring

Compressor	Number on CA ring	Average power [kW]	Average flowrate [Nm ³ /hr]	Specific power [kWh/Nm ³]
VK32	5	2,751	26,100	0.1054
VK50	6	4,760	48,000	0.0992
Total				0,102

Table 19 provides a summary of the average daily power saving and daily energy saving that can be achieved according to the potential flow reductions illustrated in the weekday, Saturday, and Sunday flow profiles. The weekday profile identified an average potential flow reduction of 50% outside of the drilling shift, when compared with the baseline profile. This reduction relates to a potential daily energy saving of 43,3 MWh. To put this energy impact into perspective, the level valve initiative only allowed for a daily energy saving of 25 MWh as a result of reducing the CA consumption by 20%. Therefore, an additional 43,3 MWh can be achieved when implementing cross cut isolation. The Saturday profile identified a potential flow reduction outside of the drilling shift of approximately 48%, which therefore relates to an additional daily energy saving of 35,9 MWh. Appendix F provides a sample calculation that explains how these energy savings are calculated from the expected flow reduction.

The biggest energy impact achieved by the level control valves was on Sundays. This was due to the fact that the shaft was only supplied with life-sustaining pressure (200 kPa) throughout the course of the day until the cleaning shift commenced. This resulted in an average energy reduction of 60 MWh across the entire 24-hour period, when compared with the initial baseline. However, as shown in the potential flow reduction of Figure 42, an additional energy saving of 34,2 MWh can be achieved in the event of isolating the cross cuts on Sundays.

Table 19: Potential power and energy savings on weekdays, Saturdays, and Sundays

	Potential average daily power saving	Potential daily energy saving
Weekday	1,8 MW	43,3 MWh
Saturday	1,5 MW	35,9 MWh
Sunday	1,43 MW	34,2 MWh

3.5 Financial feasibility

The Eskom 2021/2022 Megaflex TOU tariff structure, as presented in Appendix C, is used to calculate the annual financial saving of the potential energy impact presented in Table 19. The variables considered for the cost calculations are presented in Table 20.

Table 20: Seasonal costs and days

Cost calculation variables	Winter (High demand season)	Summer (Low demand season)
Season Start	2021/06/01	2021/09/01
Season End	2021/08/31	2022/05/31
Total Weekdays (Holidays excl.)	64	188
Total Saturdays	13	37
Total Sundays	13	37

The expected potential energy reduction could result in a financial saving of approximately R12-million per annum on B Shaft's weekday CA consumption profile. This means a daily energy saving of R38 400 during the low demand season, and R76 000 during the high demand season. Furthermore, the annual financial saving for the Saturday and Sunday CA consumption profiles is approximated at R1,47-million and R1,3-million, respectively. Therefore, the implementation of cross cut isolation across the entire shaft could result in a total financial saving of approximately R14,8-million per annum.

3.6 Implementation and verification of cross cut isolation on the CA network

The implementation methodology, as discussed in Section 2.6, to implement and verify cross cut isolation, is presented in Figure 43. This section in Chapter 3 will address steps number 3, 4 and 5 in the methodology, as shown in the figure.

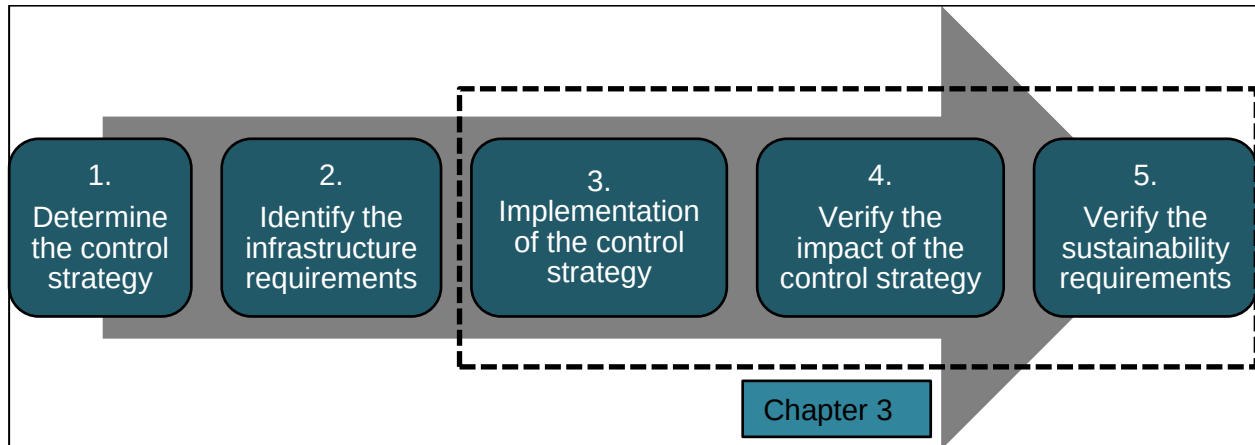


Figure 43: Implementation methodology to verify cross cut isolation

The two control strategies, namely manual and automatic control, were implemented and are presented as two separate case studies. The methodology presented in Figure 43 was applied to both strategies for the implementation and verification of the initiatives. The main objective of this section is to verify the sustainability requirements to effectively implement cross cut isolation with the goal of obtaining sustainable energy savings.

3.6.1 Case study 1: Implementation of manual cross cut isolation

The manual cross cut isolation implementation strategy, as discussed in Section 2.6.1, was implemented on 3 Level of B Shaft. Mining personnel among the different crews were identified and given the responsibility of closing their respective manual cross cut isolation valve after each drilling shift. The same appointed personnel were then responsible for reopening their valves at the start of the next drilling shift.

As mentioned in Section 3.4.1, the newly installed level mass flowmeter and pressure transmitter were used as the flow and pressure measurement boundary to develop the baseline. The maximum amount of available data backdated to the most recent system change was used to develop the baseline. Finally, the initiative was implemented and monitored over a period of 4 months.

During this 4-month implementation period, a 19,5% flow reduction was achieved across the 24-hour flow profile, when comparing the scaled baseline and the actual flow profile, as shown in Figure 44 (a). The actual flow profile represents the actual measured data over the 4-month implementation period. This flow reduction resulted in an average energy saving of 4,8 MWh over the 24-hour weekday period.

However, when comparing the actual flow profile with the theoretical flow profile, as shown in Figure 44 (b), there is still significant scope to further reduce the CA consumption by approximately 40%. This potential flow reduction therefore relates to an additional average energy saving of 5.5 MWh across the 24-hour weekday period.

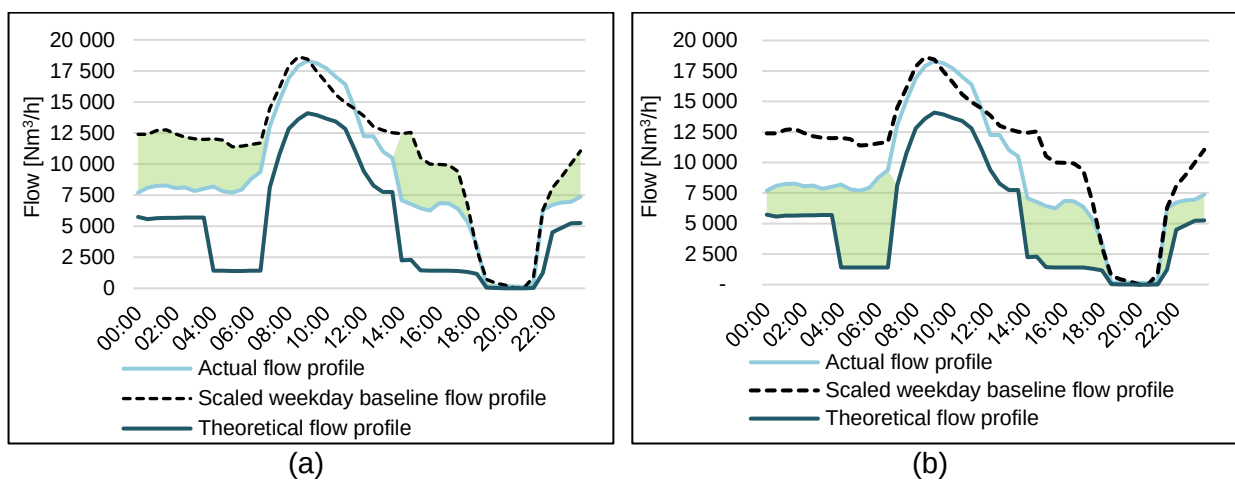


Figure 44: (a) Weekday flow profile highlighting the impact achieved from manual cross cut isolation, **(b)** The remaining flow that can be reduced if the initiative's sustainability is improved

Further investigation into the remaining flow, as shown in Figure 44 (b), revealed the following:

1. Some of the cross cut isolation valves broke during the implementation phase of the initiative. More specifically, the handles on the valves broke. The mining personnel responsible for the valves failed to report these issues which ultimately resulted in a loss of energy savings.
2. Some valves were not easily accessible, i.e. the mining personnel required ladders to reach the valves. This issue added to the lack of cooperation as the personnel were required to exert additional effort to close these valves. In conjunction to this, it was identified that some of the personnel were in a rush to leave the working areas. This led to valves not being fully isolated, which resulted in CA leaking through to the stopping areas.
3. It was frowned upon by the mining personnel to isolate the cross cuts as they were subsequently unable to ventilate with CA in the stopping areas. This was identified as the main issue with regards to sustainability. Temperature measurements in the working areas identified that the temperatures were in an acceptable range and that there is no need for CA

ventilation. This highlights the culture that exists among the mining personnel to ventilate with CA, regardless of the working environment temperature. Therefore, further research on how to effectively address this culture of ventilating with CA is recommended.

Figure 45 (a) and (b) present consumption data of two specifically chosen days that support the above-mentioned points 2 and 3. The figure compares the actual flow profile (as the light blue line) with the theoretical flow profile (as the dark blue line). This is to illustrate the significant effect that the human factor has on sustainability when implementing manual cross cut isolation. Figure 45 (a) shows that the cross cut isolation valves on the level were fully isolated during the cleaning shift, and, when comparing the theoretical and actual flow profile, it is evident that no mining activities were conducted during this shift and that the valves were closed. However, after the drilling shift the consumption increased significantly as the valves were not all isolated.

Furthermore, the same observation can be seen in Figure 45 (b), when comparing the theoretical and actual profiles. It is evident that mining activities were conducted during this shift with all the valves closed. Then again, after the drilling shift the consumption increased as the valves were not isolated. Note that the afternoon consumption in Figure 45 (b) is lower when compared with Figure 45 (a) as this is due to a lesser number of valves not isolated. This highlights the lack of cooperation from the mining personnel which ultimately compromised the sustainability of the energy savings initiative.

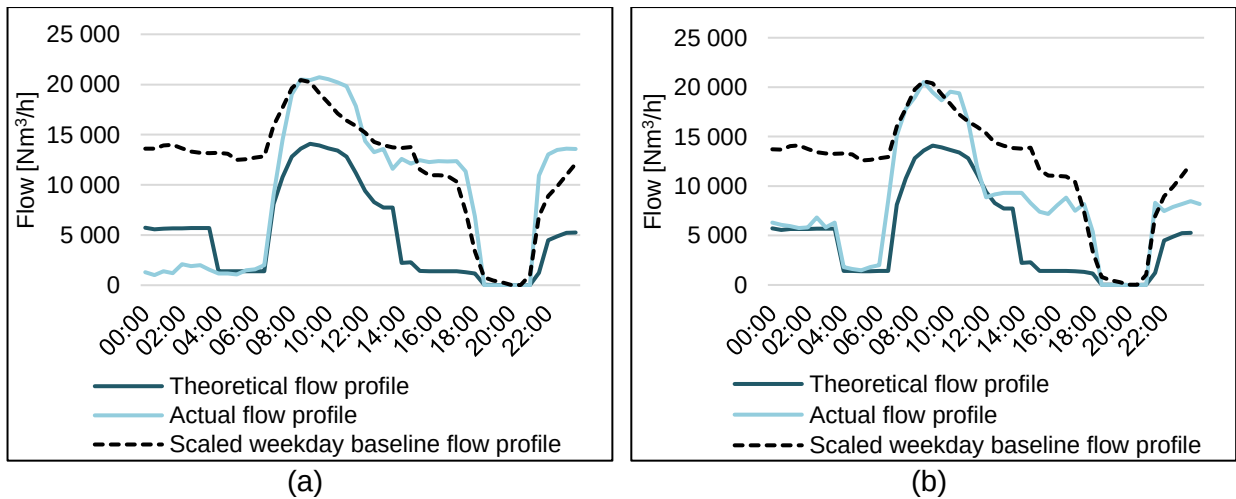


Figure 45: (a) Cross cut isolation valves were closed when no mining activities were conducted in the cleaning shift but then left open after the drilling shift, (b) Cross cut isolation valves were closed during the cleaning shift but then left open after the drilling shift

The information presented in Figure 45 (a) and (b) therefore confirms that the manual cross cut isolation control strategy is highly dependent on the cooperation of the mining personnel. Apart from promising results obtained during the implementation phase, the control strategy was unable to provide a sustainable solution. This large human factor and negligent culture added to the difficulty in managing and sustaining the performance of the initiative.

3.6.2 Sustainability requirements for the manual cross cut isolation control strategy

Before the control strategy is to be implemented, it is important to investigate the technical feasibility of implementing this strategy, as the success and sustainability of the initiative are highly dependent on the cooperation of the mining personnel. It is therefore crucial that the control philosophy proposed to the mining personnel accommodates their mining operations, schedules, and equipment, so that the initiative does not create any negative impact on the working experiences underground. Therefore, the following recommendations should be considered when the strategy is implemented:

- The valves should be easily accessible to minimise the effort for the mining personnel to open and close the valves.
- It is recommended that a manual butterfly isolation valve is used as this valve can be easily opened and closed when compared with a gate valve.

When investigating the technical feasibility, it is recommended that the stoping areas are investigated to determine if the ventilation infrastructure is up to standard. Any stoping areas that are substandard should be brought up to standard to ensure that the working areas are supplied with cool air. In addition to this, it is important to constantly monitor the ventilation in these working areas to prevent the misuse of CA when inadequate ventilation is experienced. This will essentially become the first step in addressing CA misappropriation and ensuring that no excuse will be accepted when the cross cuts are not isolated, excluding CA-related mining operations.

As mentioned in Section 3.6.1, it is recommended that half-level flowmeters are installed to cross-verify the operation of the valves and to track the performance of the control strategy. The half-level flowmeters also narrow the area of responsibility downstream of the flowmeter, which allows for specific mining personnel to be held accountable for not closing their respective valves. Holding the responsible mining personnel accountable will become important in the sustainability of the control strategy. The half-level flow metering will allow management to hold the individual shift bosses on the half-levels accountable for when there is a lack of cooperation. Under ideal

circumstances, one flow meter per cross cut will assist with identifying the exact individuals who are failing to comply.

Furthermore, the control strategy will become resource intensive when attempting to obtain sustainable energy savings. It requires constant monitoring and managing of the valves to the extent that it becomes a full-time job for the management team. Therefore, regular feedback from the mining personnel is required with regard to faulty valves. Effective communication between management and the underground mining personnel is important, as this will ensure that the project maintenance is kept up to date.

A risk was identified that mining personnel who do in fact cooperate are unaware of having faulty valves. This means that they are under the impression that the valve is closed but in reality, the valve is still leaking CA. Therefore, the responsible personnel closing the valves should conduct regular checks by opening manifolds in the cross cuts to determine if the valve is isolating effectively.

Resource management and allocation will play a vital role when the goal is to obtain maximum sustainable energy savings. This means that the respective engineering and mine managers will have to take responsibility for managing and addressing any lack of cooperation. Therefore, effective reporting systems should be in place to assist them with addressing any issues related to this control strategy. It is recommended that the engineering and mine manager assign responsibility to more than one person under them to assist with the management and monitoring of the strategy. This will simplify the overall input requirements expected from the management team. However, it will still become the responsibility of the engineering and mine manager to keep the assigned personnel accountable for their roles and tasks within the team.

In addition to effective reporting systems, awareness needs to be created among the underground mining personnel with regard to the effect of CA wastage, and, more specifically, the impact that CA misappropriation has on the production and energy performance of the shaft. Therefore, it is recommended that careful consideration is taken when deciding on what type of reports will be distributed and to whom these reports will be distributed. Awareness can be raised through the use of posters that indicate the potential impact when CA wastage is addressed and how this will positively benefit the mining crews. This will ultimately become a tool to motivate all relevant personnel to cooperate so that maximum energy savings and efficiency can be achieved.

3.6.3 Case study 2: Implementation of automatic cross cut isolation

It was noted in Section 3.6.1 that it was not possible to achieve a maximum energy saving via the manual control strategy due to the high reliance on the human factor.

The automatic cross cut isolation control strategy was therefore presented to the respective engineering and mining personnel on the shaft, and it was decided that the timer-based control strategy would not be implemented. The decision was mainly based on the lack of sustainability previously achieved, as mentioned in Section 1.5.2, and concerns from the shaft with regards to vandalism, as there is no direct line of sight on the valves. In addition to the lack of line of sight, the initiative would become extremely resource intensive due to the high maintenance requirements of maintaining each valve and timer-based unit, as personnel would regularly have to inspect each timer-based unit and valve to confirm if it is still in working condition. Thus, the strategy will once again become reliant on the human factor to achieve maximum sustainable energy savings.

It was therefore decided to install a cross cut isolation valve that is connected to the mining shaft's SCADA system to enable remote control and live monitoring. This will allow the shaft to monitor each valve for vandalism and performance, and to ultimately assist with reducing the maintenance requirements to achieve maximum sustainable energy savings. The sustainable energy savings achieved from the newly installed level valves supported this decision to connect the cross cut isolation valves to the SCADA system.

However, due to the high capital cost of implementing cross cut isolation across the entire shaft and uncertainty with regard to sustainability, the decision was made to first install a test isolation valve on a high consuming cross cut, as identified in Section 3.2, that will be connected to the SCADA. If the installation proved to be successful and sustainable, the shaft would provide the capital to expand the project to the rest of the mining levels of the shaft. Therefore the purpose of this case study is solely to evaluate the long-term sustainability of cross cut isolation when having line of sight and remote control over the valves.

Valve and actuator assembly

Figure 46 presents the valve and actuator assembly chosen for the test installation. The decision was made to install a 150 mm metal seated butterfly isolation valve with a 525 V electric actuator. The decision with regard to this chosen valve assembly was determined by the information discussed in Table 11 and Table 12 for which the following questions had to be addressed:

- What is the fail-safe application and alternatives for the valve and actuator assembly?

Rubber seated butterfly valves are known to become worn out relatively quickly, which results in the valve leaking CA. It was therefore decided to install a metal seated butterfly valve to ensure long-term sustainability and to reduce the maintenance requirements on the valve.

The electrical actuator was chosen above a pneumatic actuator due to the fact that the control of the actuator is independent of the CA supply conditions. The actuator has a manual override in the form of a gearbox-driven wheel, which allows for minimal effort to open and close the valve in the event that it is necessary to manually override the automatic valve control. The line of sight on the valve will also enable the shaft to detect whether or not the valve was manually overridden.

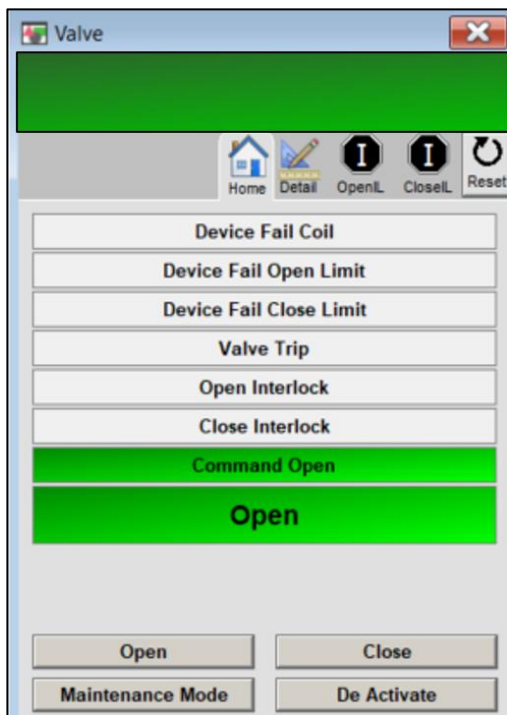
- Is the valve and actuator assembly compatible with level or surface control valves where the supply pressure varies to different pressure setpoints?

Pneumatically driven actuators are highly dependent on the supply pressure to operate efficiently and generally require a minimum operating pressure of 380 kPa. This prevented the shaft from installing pneumatic actuators, as life-sustaining pressure (200 kPa) is supplied to the shaft on Sundays which is below the minimum pressure requirement of a pneumatic actuator.



Figure 46: Cross cut isolation valve assembly

The control philosophy was programmed onto the PLC connecting the mine's SCADA system and valve assembly. The connection to the SCADA system enabled the shaft's control room operator to have remote control over the valve in the event of an emergency where CA is required in the stoping area. Figure 47 (b) shows the valve on the SCADA with the remote and valve feedback from the PLC. This information enabled the shaft to determine whether or not the valve was tampered with. Figure 47 (a) shows the user interface on the SCADA that the control room operator can use to manually open and close the valve.



(a)



(b)

Figure 47: (a) SCADA user interface for the operator to open and close the valve, (b) Valve visible on the SCADA with the remote and valve fault feedback

The newly installed level mass flowmeter was used as the flow measurement boundary to develop the baseline. The maximum amount of available data backdated to the most recent system change was used to develop the baseline. The valve was implemented and monitored over a period of 2 months.

During this 2-month implementation period, a 9% flow reduction, shown as the green area, was achieved across the 24-hour flow profile, when comparing the scaled baseline and the actual flow profile, as shown in Figure 48. This flow reduction resulted in an average energy saving of 1,6 MWh over the 24-hour weekday period. The procedure and calculations presented in Appendix F was used to determine this energy saving.

However, more importantly, when analysing the valve position feedback, it was evident that cross cut isolation occurred consistently over the 2-month monitoring period. There was an instance where the valve fault feedback indicated a problem with regard to not being able to open and close. However, because it had this feedback information, the mining shaft was able to immediately rectify the identified problem. Note that in this instance the PLC instrument lost power and the valve was therefore unable to open and close.

By effectively eliminating the reliance on the human factor, the shaft was able to obtain maximum energy savings from the implemented cross cut isolation valve. The line of sight on the valve ultimately improved the sustainability and impact of the energy saving brought about by the implemented control strategy.

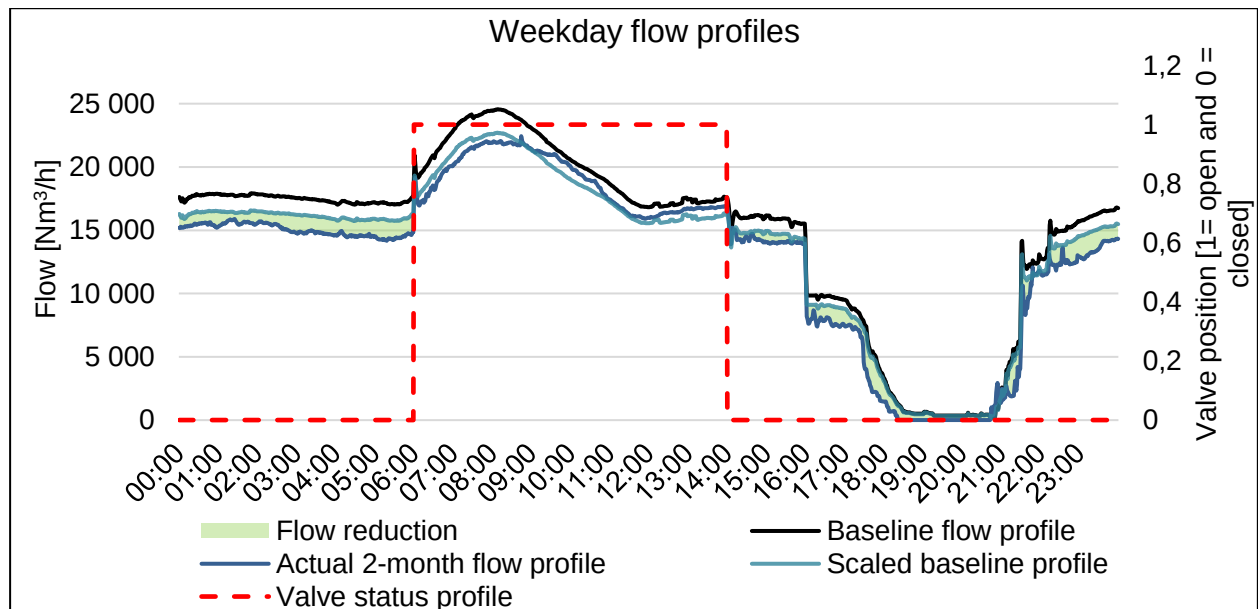


Figure 48: Flow reduction achieved from the automatic cross cut isolation control strategy

Note that the valve did, however, come with a high initial implementation cost. However, the energy saving achieved from the automatic control strategy relates to an annual cost saving of approximately R500 000. Considering the sustainable energy saving achieved from this control strategy, an estimated payback period of 5 months was calculated. Appendix G provides an explanation as to how the 1,6 MWh energy saving translates to a payback period of 5 months.

After this 5-month period the shaft would recover its initial capital investment and start making a profit with regard to energy management. This low payback period makes the implementation of this control strategy financially feasible, when considering the sustainable energy saving achieved and the potential energy saving that can still be achieved on the mining shaft when the initiative is implemented across the shaft.

3.6.4 Sustainability requirements for the automatic cross cut isolation control strategy

It is important to conduct a technical feasibility analysis before the automatic control strategy is implemented, as this control strategy completely removes the reliance on the human factor. It is crucial that the implemented control philosophy for these valves accommodate the mining operations, schedules, and equipment. If a negative impact is created on the working experience of the mining personnel, the valves will become prone to vandalism and sabotage. The valve feedback does, however, assist with identifying these issues, but it is regarded as best practice to not create any reason for the valve to be vandalised or tampered with.

When investigating the technical feasibility before implementing the control strategy, it is recommended that the stoping areas are investigated to determine if the ventilation infrastructure is up to standard. Any stoping areas that are substandard should be brought up to standard, to ensure that the working areas are supplied with cool air. This will essentially become the first step in addressing CA misappropriation as there will be no need for the personnel to ventilate with CA and no reason for the valves to be tampered with.

Having the valve feedback status is important as this will assist the management team in effectively identifying and addressing any maintenance-related work. Therefore, effective reporting systems need to be in place to simplify the management requirements when identifying and managing any maintenance-related work. These reports should be used to prioritise the maintenance-related work and assist with managing the resources responsible for the identified work.

In addition to resource management, resource allocation will become a vital part of the overall project maintenance. Resource allocation will involve identifying and assigning resources strategically to specific responsibilities in support of the main goal which is to obtain sustainable energy savings. It is therefore important to identify the role of each team member responsible for the management of the initiative. The responsibilities assigned to each member refer to the duties and tasks of their particular role in the team. By doing this the team members can be held accountable for completing the required tasks.

As mentioned in Section 3.6.2, it is recommended that half-level flowmeters are installed to cross-verify the operation of the valves and to track the performance of the control strategy. Having half-level flow meters will allow the shaft to conduct daily half-level baseload tests as the process to conduct these tests will be automated. This information can be used on a daily basis by the shaft's management team to identify the cross cuts and mining personnel responsible for the high

wastage consumption. Shaft management can therefore directly address the personnel responsible for the poor CA energy performance.

As the mining shaft develops further, the new cross cuts should be equipped with the proposed valve and actuator assembly used to implement automatic cross cut isolation. This should therefore become a standard practice among the mining operations going forward to ensure that the CA wastage is managed effectively.

The valve and actuator assembly must be robust as it will be exposed to harsh underground mining conditions. Installing a poor-quality valve and actuator assembly could result in poor valve performance, i.e. the valve starting to leak, which could ultimately jeopardise the sustainability of the initiative and its energy savings performance. It is also important to ensure that the valve is tamperproof to prevent mining personnel from vandalising or bypassing the valve without permission from the respective mining personnel.

3.7 Conclusion

In Chapter 3 the results were presented and discussed for the solution strategy identified in Section 2.1. The distribution analysis, conducted via the surface and half-level baseload tests on B Shaft, effectively quantified the wastage consumption in the cross cuts. Valuable information was obtained with regard to quantifying each category in the wastage breakdown analysis, as presented in Figure 36, which supports the need for this study to effectively address the unauthorised consumers outside of the drilling shift.

The technical feasibility analysis, as discussed in Section 3.3, did, however, identify two end-users that will be affected in the event of isolating the cross cuts. However, alternative solutions were presented and discussed, and it was therefore deemed feasible to proceed with implementing cross cut isolation.

The theoretical model was successfully verified in Section 3.4.3. With confidence in the model's predictions, the energy benefit quantification for implementing cross cut isolation was done, and the financial benefit of reducing the energy consumption was calculated.

Furthermore, the results obtained from implementing the manual and automatic cross cut isolation control strategies were presented and discussed. The successful implementation of both control strategies enabled the identification of the sustainability requirements for obtaining maximum energy savings.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

Chapter 4 presents the conclusion to the study. A summary of the main findings is provided, as well as a discussion of how the individual study objectives were achieved. The chapter ends with recommendations for future work.

4.2 Summary of the study

Chapter 1: The use of compressed air in deep-level platinum mining

Chapter 1 expanded on the usage of compressed air (CA) in deep-level platinum mining operations. Background was provided on the CA infrastructure, relevant mining operations and equipment that make use of CA.

The chapter further expanded on CA wastage, and it was identified that CA wastage can be divided into two categories, namely leaks and misappropriation. Misappropriation is a collective noun that refers to the mismanagement of CA (i.e. poor management and maintenance) and CA malpractice due to negligence (i.e. leaving manifold valves open and ventilating with CA). The impact of inefficient CA use and the effect of CA wastage on the system were discussed. It was identified that CA wastage not only reduces overall energy efficiency, but it also negatively affects underground CA production-related mining operations.

From the literature review, it was found that CA energy efficiency initiatives on deep-level mines predominately focus on matching the supply of CA with the underground demand for CA. However, these initiatives only address the symptoms caused by CA leaks and misappropriation and do not directly reduce the high underground demand. Leak management focus on reducing the CA demand, but the research identified that a large contributor to CA wastage is misappropriation, more specifically, the use of CA for ventilation purposes. Therefore, leak management does not directly address CA misappropriation, as it only highlights the areas with the large wastage consumptions.

Numerous studies suggested further investigation into expanding demand side management through isolating the stoping areas from the CA network during the non-drilling periods. A critical analysis of deep-level mine CA efficiency studies identified a research gap with regards to cross cut or stope isolation. However, it was mentioned that cross cut isolation valves are prone to vandalism and sabotage which could ultimately jeopardise the sustainability of the initiative.

Thus, a need was recognised to investigate the scope and requirements for expanding CA demand side management through cross cut isolation on a deep-level platinum mine to directly address CA misappropriation. To meet this need, the study objectives were identified as follows:

1. Quantifying the CA wastage in the cross cuts and stoping areas.
2. Determining the technical feasibility for implementing cross cut isolation.
3. Quantifying the energy savings benefit of implementing cross cut isolation.
4. Investigating manual vs automatic cross cut isolation.
5. Identifying the sustainability requirements for implementing cross cut isolation.

Chapter 2: Development of solution to expand compressed air management through cross cut isolation

The purpose of Chapter 2 was to discuss the solution strategy developed to address the need and study objectives identified in Chapter 1. The CA network analysis was identified as the first step in the solution strategy. The main objective identified in the CA network analysis was to quantify the CA wastage in the cross cuts and stoping areas by means of a distribution analysis. The methodology used to conduct a distribution analysis was presented and discussed.

The technical feasibility of implementing cross cut isolation during the non-drilling periods was identified as the second step in the solution strategy. The main purpose of this step was to determine the feasibility requirements to effectively implement cross cut isolation in the non-drilling periods whilst ensuring that CA-related mining operations are not negatively affected. The strategy developed to determine the technical feasibility analysis was presented.

The energy benefit quantification for implementing cross cut isolation was identified as the third step in the solution strategy. The quantification of the energy benefit was determined by means of a theoretical model which predicted the energy efficiency impact of isolating the cross cuts during non-drilling periods. The methodology used to develop such a model was presented and discussed in conjunction with the validation strategy and the prediction of the model.

The final step identified in the solution strategy was to implement and test manual and automatic cross cut isolation. The methodology and operational requirements to implement both these strategies was identified and discussed. Thereafter, the method used to validate the energy impact and sustainability of the two control strategies was presented and discussed.

Chapter 3: Results

The solution strategy to expand CA management through cross cut isolation, as developed in Chapter 2, was applied to a case study. A deep-level platinum mining shaft in South Africa was used as a case study. The aim of Chapter 3 was to address each sequential step identified in the solution strategy.

The first step in the strategy was to conduct an in-depth CA distribution analysis on the case study's CA network. The shaft baseload tests conducted over a period of 12 months indicated that up to 74% of the mining shaft's total CA consumption is attributable to wastage. Levels 2 and 3, the two highest consuming levels, were then used as the next case study to investigate which mining sections in the haulages are responsible for this high wastage consumption. The results obtained from the half-level baseload tests identified that on average 85% of the levels' wastage consumption is located in the cross cuts. It was noted during the half-level baseload tests that, as a result of isolating the cross cut and reducing the CA flowrate, a pressure increase of up to 20 kPa was achieved as a result of eliminating the dynamic pressure drop caused by the high flowrate. This highlights the additional production benefit that comes with cross cut isolation as a result of increasing the operating pressures for the cleaning shift.

The distribution analysis and visual audits conducted in the stoping areas provided the opportunity to effectively quantify and categorise the CA wastage. It was identified that CA misappropriation is responsible for approximately 70% of the total wastage consumption in the cross cuts, and that leaks were responsible for the remaining 30%. This information ultimately supported the need for the study to isolate the cross cuts from the CA network in order to address the wastage issue brought about by CA misappropriation.

The next step in the strategy was to determine if the implementation of cross cut isolation is technically feasible, as it is important to ensure that no production-related mining activities are going to be affected. The technical feasibility analysis identified two end-users, namely air whistles and water pumps, that will be affected in the event of isolating the cross cuts. Alternative solutions were identified which ultimately enable the shaft to proceed with the implementation of cross cut isolation. The mining shift schedules and consumers identified in the technical feasibility analysis were then used to determine the control philosophy which will be used to implement both the manual and automatic control strategies.

The third step in the strategy was to develop a theoretical model that predicted the energy impact of implementing cross cut isolation. The model was verified using two case studies on which half-level baseload tests were conducted. The model was then validated by comparing the theoretical

and actual flow reduction, achieved during the half-level baseload tests of the two case studies. The model validation highlighted that the flow reduction is predicted to within an error percentage of less than 5%.

With confidence in the model's prediction, the model was applied across the entire case study shaft. The energy benefit quantification identified that an energy saving of approximately 43,3 MWh can be achieved daily over the 24-hour weekday mining profile when compared with the baseline and theoretical flow profile. This is as a result of reducing the total CA consumption across the 24-hour period by approximately 50%. The model also identified that an energy benefit of approximately 35,9 MWh and 34,2 MWh could be achieved over the 24-hour period for Saturdays and Sundays, respectively.

By using the Eskom Megaflex TOU tariff structure, a potential financial saving was calculated at approximately R14,8-million per annum when cross cut isolation is implemented. However, when considering the life of mine for this particular shaft, which is estimated at 20 years, the cumulative financial saving can be extrapolated to R296-million, excluding any Eskom tariff increases.

Finally the two control strategies identified in Section 2.6, namely manual, and automatic cross cut isolation were implemented on the case study. The implementation of these two strategies enabled the study to determine the sustainability requirements for the implemented strategies in order to achieve maximum and sustainable energy savings.

The implemented manual cross cut isolation control strategy managed to achieve a total average CA flow reduction of 19,5% across the daily 24-hour weekday profile. However, this control strategy was unable to achieve maximum sustainable energy savings as there was still potential to further reduce the total CA consumption by an average of 40%. This means that a daily energy saving of approximately 5.5 MWh across the 24-hour weekday profile was lost. The manual control strategy is highly dependent on the cooperation of the mining personnel and was therefore unable to provide a sustainable solution.

The sustainability requirements for this strategy to achieve maximum energy savings was therefore successfully identified and discussed. However, the large human factor and negligent culture contribute significantly to the difficulty of managing and sustaining the performance of this control strategy. It can therefore be concluded that this strategy comes with high project maintenance and resource management requirements when attempting to achieve sustainable energy savings.

It was noted that the manual control strategy was unable to provide a sustainable solution and it was therefore decided to install a cross cut isolation valve that was connected to B Shaft's SCADA. It was decided to install a 150 mm metal seat butterfly isolation valve with an electric 525V actuator. However, due to the high capital cost of implementing this valve assembly across an entire level, the decision was made to first install a test isolation valve on a high-consuming cross cut to determine its sustainability and impact.

By effectively eliminating reliance on the human factor, the shaft was able to obtain a sustainable maximum daily energy saving of approximately 1,6 MWh over the 24-hour weekday profile. A payback period of 5 months was calculated on the initial capital investment to obtain the valve and actuator assembly. This low payback period makes the implementation of this control strategy financially feasible, when considering the sustainable energy saving achieved and the potential energy saving that can still be achieved when the initiative is implemented across the shaft.

It is evident that without constant feedback with regard to the status of each valve, the sustainability requirements in terms of project maintenance become increasingly more difficult. The implementation of an automated control philosophy is therefore preferred to eliminate the human error in order to maximise the energy savings and the sustainability of the initiative.

4.3 Meeting the required study objectives

Objective 1: Quantifying the CA wastage in the cross cuts and stoping areas

The first study objective was successfully addressed, as an accurate quantification of the wastage consumption in the cross cuts was determined. Several half-level baseload tests were conducted across six different half-levels and the results determined that the cross cuts are responsible for approximately 85% of a mining level's CA wastage consumption.

Objective 2: Determining the technical feasibility for implementing cross cut isolation

The second study objective was successfully addressed, as the implementation requirements of effectively implementing cross cut isolation were identified. Several authorised CA consumers which are present during the cleaning shift were noted. These consumers would prevent the implementation of cross cut isolation. However, alternative solutions to convert these consumers were presented so that the technical feasibility requirements could be accomplished, irrespective of the mining operation in question.

Objective 3: Quantifying the energy savings benefit of implementing cross cut isolation

The third study objective was successfully addressed by means of developing a theoretical model which approximated the CA consumption of all the authorised CA consumers. The theoretical model was then compared with actual flow data and the potential flow reduction was determined. The energy impact of the potential flow reduction highlighted by the theoretical model was then quantified, therefore quantifying the potential energy saving of cross cut isolation.

Objective 4: Investigating manual vs automatic cross cut isolation

The fourth study objective was successfully addressed by means of implementing both control strategies. The implementation of manual cross cut isolation revealed that a large portion of energy savings was lost due to high reliance on the human factor.

The implementation of automatic cross cut isolation removed reliance on the human factor and improved the sustainability and overall energy impact of the initiative.

Objective 5: Identifying the sustainability requirements for implementing cross cut isolation

The fifth study objective was successfully addressed by identifying the sustainability requirements needed to ensure the success of both cross cut isolation strategies. The critical components for ensuring the sustainability for both manual and automatic cross cut isolation were identified and discussed accordingly.

4.4 Recommendations for future work

The following opportunities for future work were identified during the scope identification for expanding demand side management through cross cut isolation in the deep-level platinum mining industry:

- The distribution analysis conducted in this study effectively quantified the wastage consumption in the cross cuts. The results obtained from this analysis indicated that misappropriation, more specifically self-ventilation using CA, is responsible for approximately 80% of the total wastage consumption on the shaft. Further research is recommended on how to effectively and sustainably address the negligent culture of ventilating with CA.
- There is scope to expand this study to include deep-level gold mines. It is therefore recommended that this solution strategy is applied to the gold industry in order to determine the scope of expanding CA management through implementing cross cut isolation valves.

- Automatic cross cut isolation was only implemented on a single cross cut. There is scope to expand this control strategy for an entire level or shaft. In the event of this happening, follow-up research should be done to assess the sustainability and energy impact thereof.
- If automatic cross cut isolation is implemented, daily half-level baseload tests can be conducted. This can be used as a reporting tool to identify and monitor the CA wastage in the cross cuts, if the necessary measuring infrastructure is in place.
- When comparing the theoretical model's flow profile with the actual CA data obtained from the case study shaft, it is evident that there is scope to reduce the CA wastage in the drilling shift. It is therefore recommended, for future work, that initiatives are identified to address the wastage consumption during the drilling shift as this will come with a service delivery benefit.
- The developed theoretical model can be used in the mining industry to monitor the CA wastage via effective reporting, if the necessary measuring infrastructure is in place. This reporting strategy should be considered for future work and initiatives.
- The half-level baseload test methodology, as discussed in Section 2.2.2, can be expanded, and adapted for the purpose of identifying areas with high CA ventilation. This can be used as an auditing tool to identify mining areas with substandard ventilation.

BIBLIOGRAPHY

- [1] J. N. de la Vergne, *Hard Rock Miner's Handbook*. 5th ed. Alberta Canada: Stantec Consulting, 2014, pp. 178-185.
- [2] P. Fraser, "The energy and water required to drill a hole," *The Southern African Institute of Mining and Metallurgy*, The 4th International Platinum Conference, Platinum in transition 'Boom or Bust' vol. The Southern African Institute of Mining and Metallurgy, 2010.
- [3] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, "A review on compressed-air energy use and energy savings," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1135-1153, 2010.
- [4] A. M. van Tonder, "Sustaining compressed air DSM project savings using an air leakage management system " Master's dissertation, North West University, Potchefstroom, 2010.
- [5] D. du Plooy, P. Maré, J. Marais, and M. J. Mathews, "Local benchmarking in mines to locate inefficient compressed air usage," *Sustainable Production and Consumption*, vol. 17, pp. 126-135, 2019.
- [6] United States Department of Energy, *Improving compressed air system performance - A sourcebook for industry*. 3rd ed. Washington D.C: U.S. DOE, 2014.
- [7] H. Hernandez-Herrera *et al.*, "Energy Savings Measures in Compressed Air Systems," *International Journal of Energy Economics and Policy*, vol. 10, pp. 414-422, 2020.
- [8] L. Zietsman, "Novel solutions for compressed air demand management on deep-level mines " PhD thesis, North West University Potchefstroom, 2020.
- [9] E. Cabello, J. José, A. Sagastume Gutiérrez, V. Sousa Santos, and M. J. Cabello Ulloa, "Energy management of compressed air systems. Assessing the production and use of compressed air in industry," *Energy*, vol. 213, p. 118662, 2020.
- [10] H. J. Groenewald, "Developing a framework for managing compressed air in the Platinum Group Metal Mining Industry in South Africa," MBA thesis, North West University, Potchefstroom, 2020.
- [11] Eskom, *Tariffs & Charges 2021/2022*. South Africa, 2021.
- [12] P. Mitchell, "Top 10 business risks and opportunities – 2020," Ernst & Young, 2020.
- [13] G. Ryan, "Energy management by platinum companies in South Africa: exploring mitigation strategies for reducing the impact of electricity price increases," presented at the International Platinum Conference, "Platinum–Metal for the Future," Southern African Institute of Mining and Metallurgy, Sun City, 2014.
- [14] J. A. Bohlmann and R. Inglesi-Lotz, "Analysing the South African residential sector's energy profile," *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 240-252, 2018.

- [15] E. Bellos, "Sustainable energy development: How can the tension between energy security and energy transition be measured and managed in South Africa?," *Journal of Cleaner Production*, vol. 205, pp. 738-753, 2018.
- [16] P. de Villiers, "Reducing deep-level mine refuge bay compressed air consumption," Master's dissertation, North-West University, Potchefstroom, 2019.
- [17] W. Booysen, "Reducing Energy Consumption on RSA Mines Through Optimised Compressor Control " Master's dissertation, North West University, Potchefstroom, 2010.
- [18] Atlas Copco. "What Compressor Size do I Need?" <https://www.atlascopco.com/en-za/compressors/wiki/compressed-air-articles/sizing-an-air-compressor> (accessed July).
- [19] Y. A. Çengel and M. A. Boles, *Thermodynamics : An Engineering Approach*. 6th ed. New York: McGraw-Hill Higher Education, 2008.
- [20] B. R. Munson, T. H. Okiishi, W. Huebsch, and A. P. Rothmayer, *Fluid Mechanics*. Singapore: John Wiley & Sons (Pty.) Ltd, 2013.
- [21] C. J. R. Kriel, "Modernising underground compressed air DSM projects to reduce operating costs," Master's dissertation, North West University, Potchefstroom, 2014.
- [22] R. Joubert, "Cost and time effective DSM on mine compressed air systems " Master's dissertation, North West University, Potchefstroom, 2010.
- [23] L. Liebenberg, D. H. Velleman, and W. Booysen, "A simple demand-side management solution for a typical compressed-air system at a South African gold mine," *Journal of Energy in Southern Africa*, vol. 23, pp. 20-29, 2017.
- [24] C. Cilliers, "Benchmarking electricity use of deep-level mines," PhD thesis, North West University, Potchefstroom, 2016.
- [25] G. P. Heyns, "Challenges faced during implementation of a compressed air energy savings project on a gold mine," Master's dissertation, North West University, Potchefstroom, 2014.
- [26] J. Vermeulen, "Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems," PhD thesis, North West University, Potchefstroom, 2018.
- [27] J. H. Marais, "An integrated approach to optimise energy consumption of mine compressed air systems," Ph.D. thesis, Electrical Engineering, North-West University, Potchefstroom, 2012.
- [28] J. Jonker, "Automated mine compressed air control for sustainable savings," Master's dissertation, North West University, Potchefstroom, 2016.
- [29] A. Hassan, K. Ouahada, T. Marwala, and B. Twala, "Optimization of the compressed air-usage in South African mines," in *IEEE Africon '11*, 2011, pp. 1-6.
- [30] C. J. Oosthuizen, "A compressed air cost savings identification model for deep-level mines," Master's dissertation, North West University, Potchefstroom, 2019.

- [31] B. Pascoe, "Improving mine compressed air network efficiency through demand and supply control " Master's dissertation, North West University, Potchefstroom, 2017.
- [32] M. Q. W. Jones, "Virgin rock temperatures and geothermal gradients in the Bushveld Complex," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, pp. 671-680, 2018.
- [33] H. Harraz, *Underground mining Methods*. 2010.
- [34] S. J. Bester, D. Le Roux, and D. Adams, "The effect of compressed air pressure on mining production and energy demand," in *Proceedings of the 10th Industrial and Commercial Use of Energy Conference*, 2013, pp. 1-4.
- [35] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," Master's dissertation, North West University, Potchefstroom, 2017.
- [36] S. J. Cloete, D. F. Le Roux, and B. R. T, "Reducing compressed air wastage by installing new technology in underground mines," in *2013 Proceedings of the 10th Industrial and Commercial Use of Energy Conference*, 2013, vol. 10th, pp. 1-6.
- [37] S. Rupprecht, "Conventional loading techniques for flat end development," in *The Southern African Institute of Mining and Metallurgy*, Johannesburg, 2013, pp. 1-12.
- [38] M. B. Revuelta, *Mineral resource extraction*. 1st ed. (Mineral Resources – From Exploration to Sustainability Assessment). Madrid Spain: Springer International Publishing AG, 2018, pp. 381-414.
- [39] S. J. Fouche, "Improving efficiency of a mine compressed air system," Master's dissertation, North West University, Potchefstroom, 2017.
- [40] (2017). *Learners/Examiners Guide for the Assessment and Certification of Blasting Certificate Holders for Scheduled Mines*.
- [41] A. J. A. White, N. C. Joughin, and N. G. W. Cook, "Improvements in stope drilling and blasting for deep gold mines," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 75, no. 6, pp. 139-150, 1975.
- [42] A. G. Du Plessis, D. G. Wymer, and N. C. Joughin, "Equipment alternatives for stoping in gold mines," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 89, no. 12, pp. 387-394, 1989.
- [43] A. Meek, "A critical comparison between a compressed air driven rocker arm shovel and a track-bound non-throw loader," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 109, pp. 217 - 221, 2009.
- [44] Boart Longyear, "S250 rock drill – Rock drill & blast equipment and technical overview," Utah, USA, 2012.
- [45] L. Padachi, G. D. Bolt, M. Kleingeld, J. Marais, and P. E. Mathews, "Energy efficiency through the integration of compressed air supply control with air network demand control," *Eskom Demand Side Management and North West University*, vol. 1, pp. 1-4, 2009.

- [46] C. Krogscheepers and S. Gossel, "Input cost and international demand effects on the production of platinum group metals in South Africa," *Resources Policy*, vol. 45, 2015.
- [47] I. T. Program, "Energy Tips - Compressed Air " *Compressed air tip sheet* vol. 3, 2004.
- [48] B. D. Horbaniuc, "Refrigeration and Air-Conditioning," in *Encyclopedia of Energy*, C. J. Cleveland Ed. New York: Elsevier, 2004, pp. 261-289.
- [49] F. W. Schroeder, "Energy efficiency opportunities in mine compressed air systems," Master's dissertation, North West University Potchefstroom, 2009.
- [50] R. Foss, "Optimizing the Compressed Air System," *Energy Engineering - ENERG ENG*, vol. 102, pp. 49-60, 2005.
- [51] T. Nehler, R. Parra, and P. Thollander, "Implementation of energy efficiency measures in compressed air systems: barriers, drivers and non-energy benefits," *Energy Efficiency*, vol. 11, 2018.
- [52] J. H. Marais, "An integrated approach to optimise energy consumption of mine compressed air systems " PhD thesis, North West University, Potchefstroom, 2012.
- [53] L. N. Zietsman, J. H. Marais, and W. Schoeman, "A Practical Method for Compressed Air Leak Localisation in Deep-Level Mines," presented at the AIUE Proceedings of the 17th Industrial and Commercial Use of Energy (ICUE) Conference, Cape Town, 2019.
- [54] J. H. Marais, M. Kleingeld, and J. F. van Rensburg, "Simplification of mine compressed air systems," in *2013 Proceedings of the 10th Industrial and Commercial Use of Energy Conference*, 2013, pp. 1-8.
- [55] A. van Tonder, "Sustaining compressed air DSM project savings using an air leakage management system," in *2011 Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy*, 2011, pp. 133-137.
- [56] J. Neale and P. Kamp, "Compressed air system best practice programmes: What needs to change to secure long-term energy savings for New Zealand?," *Energy Policy*, vol. 37, pp. 3400-3408, 2009.
- [57] W. G. Shaw, J. H. Marais, J. H. van Laar, C. Cilliers, and J. A. Stols, "Analysing demand and supply projects on a mine compressed air system," presented at the AIUE Proceedings of the 17th Industrial and Commercial Use of Energy Conference 2019, , The Riverclub Cape Town, 2020.
- [58] C. J. R. Kriel, J. H. Marais, and M. Kleingeld, "Modernising underground compressed air DSM projects to reduce operating costs," in *2014 International Conference on the Eleventh industrial and Commercial Use of Energy*, South Africa, 2014, pp. 1-6.
- [59] J. van Rensburg, A. Botha, and G. Bolt, "Energy efficiency via optimisation of water reticulation in deep mines," in *2011 Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy*, 2011, pp. 124-132.
- [60] M. Kleingeld and J. H. Marais, "A high level strategy plan for reducing a mine group's dependence on compressed air," presented at the The 7th Conf. on the Ind. and Commer. Use of Energy (ICUE), 2010.

- [61] A. J. M. van Tonder, G. Bolt, and J. F. van Rensburg, "Compressed air alternative solutions: Challenges encountered in deep level mining," in *The 7th Conf. on the Ind. and Commer. Use of Energy (ICUE)*, Cape Town, 2012, pp. 20-25.
- [62] A. de Coning, "Sustained energy performance on compressed air systems for expanding gold mines," Master's dissertation, North West University, Potchefstroom, 2013.
- [63] H. J. van Staden, J. I. G. Bredenkamp, and J. H. Marais, "Improving sustainability of previously implemented energy savings strategies on mine compressed air systems," in *2017 International Conference on the Industrial and Commercial Use of Energy (ICUE)*, 2017, pp. 1-6.
- [64] Wika. "Process transmitters." WIKA Alexander Wiegand SE & Co. KG. https://www.wika.co.za/products_process_transmitters_en_co.WIKA (accessed 10 October).
- [65] C. Instruments. "Proven flow meters and flow measurement devices for compressed air and gas." <https://www.cs-instruments.com/za/products/l/flow-meter> (accessed 10 October).
- [66] N. Benton, P. Burns, J. Zahlan, and C. Kurnik, *The Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures*. California, San Francisco: Nextant Inc, 2017.
- [67] Y. Ming, "Air compressor efficiency in a Vietnamese enterprise," *Energy Policy*, vol. 37, pp. 2327-2337, 2009.
- [68] RSA Department of Mineral Resources, "Surveying, mapping and mine plans," *Mine Health and Safety Act (Act No. 29 of 1996)*, vol. 29, 2011.
- [69] B. Friedenstien, C. Cilliers, and J. van Rensburg, "Simulating operational improvements on mine compressed air systems," *South African Journal of Industrial Engineering*, vol. 29, pp. 69-81, 2018.
- [70] L. A. Meijsen, J. F. van Rensburg, and W. Booysen, "Verification procedures to ensure consistent energy metering," in *The 13th Conf. on the Ind. and Commer. Use of Energy (ICUE)*, 2015.
- [71] W. Booysen, "Measurement and verification of industrial DSM projects," PhD thesis, North West University, Potchefstroom, 2014.
- [72] Efficiency Valuation Organization, *International Performance Measurement and Verification Protocol (Concepts and Options for Determining Energy and Water Savings)*. Toronto, Canada: EVO-world, 2012.
- [73] B. Thacker, S. W. Doebeling, F. Hemez, M. Anderson, J. E. Pepin, and E. Rodriguez, "Concepts of Model Verification and Validation," Southwest Research Institute, California, 2004.
- [74] A. M. Law and D. M. Kelton, *Simulation Modeling and Analysis*. 3rd ed. Singapore: Mcgraw-Hill Inc, 1999.

- [75] K. Sotoodeh, "Why Are Butterfly Valves a Good Alternative to Ball Valves for Utility Services in the Offshore Industry?," *American Journal of Industrial Engineering*, vol. 5, 2018.
- [76] Auma. "Actuators SA and SAR." <https://www.auma.com/en/products/multi-turn-actuators/actuators-sa-and-sar/> (accessed August).
- [77] V. a. Automation. "ACTREG - RP Pneumatic valve actuators." <https://valve.co.za/product/actreg-rp-series-pneumatic-valve-actuators/> (accessed January).
- [78] Mine Health and Safety Council, "Mine Health and Safety Act 29 of 1996 and Regulations," South Africa, Act 29, 2018.
- [79] D. F. Wood, "Shotcrete in underground hard rock mines," *Underground support systems*, vol. 35, pp. 1-6, 1987.
- [80] R. Moseme, P. J. Foster, R. L. Demana, and S. M. Rupprecht, "Investigation into the causes of accidents on scraper systems in the Gold and Platinum mining sectors," Safety in Mines Research Advisory Committee, Pretoria, 2003.
- [81] R. d. Giacomo, "Winch Safety Signalling Systems," in "Mining Equipment Manufacturers of South Africa," Mine Health and Safety Council, Johannesburg, 2021. [Online]. Available:
- [82] J. H. Marais, M. Kleingeld, and J. F. van Rensburg, "Challenges in the scaling of energy savings baselines on mine compressed air systems," in *The 9th Conf. on the Ind. and Commer. Use of Energy (ICUE)*, South Africa, 2011, pp. 88-92.

APPENDIX A: COMPRESSED AIR FLOW NORMALISATION CALCULATION

The ideal gas law is used to normalise a flowrate, at a specific pressure, to a specific pressure setpoint. The controlled molar flow can be estimated with the assistance of the pressure ratio, as derived in Equation 1 to Equation 5.

$$\frac{P}{n} = \frac{RT}{V}$$

Equation 1: Ideal gas law

$$\frac{P_{historic}}{n_{historic}} = \frac{RT}{V}$$

Equation 2: Ideal gas law -historical

$$\frac{P_{set-point}}{n_{controlled}} = \frac{RT}{V}$$

Equation 3: Ideal gas law -controlled molar flow

$$\frac{P_{set-point}}{n_{controlled}} = \frac{P_{historic}}{n_{historic}}$$

Equation 4: Ideal gas law -equivalence

$$n_{controlled} = \frac{P_{set-point}}{P_{historic}} n_{historic}$$

Equation 5: Controlled airflow

The molar flow is equivalent to the nominal flow used in the calculations because the volumetric flow is normalised to constant pressure and temperature. Thus, the pressure ratio can be used on the volumetric flow, as indicated by Equation 6 and Equation 7.

$$n = \frac{P_{constant} V_{normalised}}{R_{constant} T_{constant}}$$

Equation 6: Ideal gas law

$$n = Constant * V_{normalised}$$

Equation 7: Normalised volumetric flow's equivalence to molar flow

APPENDIX B: BASELINE FLOW PROFILES AND DRILL SHIFT ENERGY NEUTRAL ADJUSTMENT METHOD

Historic CA data is used to develop project baselines which will consist of the average weekday, Saturday, and Sunday flow profiles. The reason for this is that the flow profiles differ for the different days of the week on a mining shaft. Generally, on Sundays, maintenance-related work is conducted with no production-related activities. Figure 49 gives an example of the different flow baselines for each day of the week. Note that these baselines are developed from actual data obtained from a deep-level platinum mining shaft in South Africa.

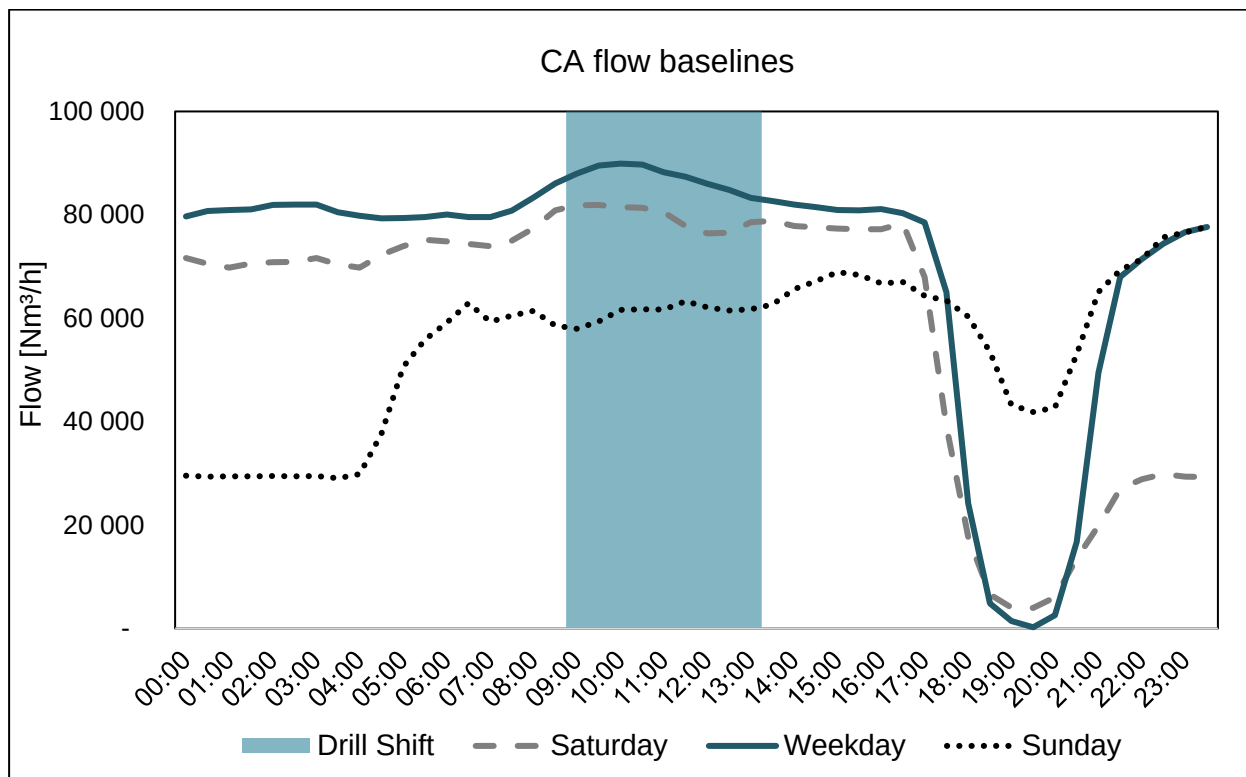


Figure 49: Example of CA flow baselines for weekdays, Saturday, and Sunday

Internal changes, such as a production increase, could affect the measurement of the project's performance. However, in order to measure the initiative's performance accurately, the effect of system changes that occurred (not as a result of the cost saving initiative) should be excluded from the performance measurements [8]. Therefore, baseline adjustments are required to allow for changes in conditions between baseline periods and the performance measurement periods. Note that any baseline adjustment should be implemented in accordance with the International Performance Measurement and Verification Protocol (IPMVP) [72].

The peak scaling or drill shift energy neutral method will be used to adjust the baseline according to system changes experienced [26]. The concept of drill shift energy neutrality is to ensure that an adjusted compressed air system baseline is representative of what would actually have happened during a performance assessment period. It was mentioned in Section 1.2.1 that energy saving initiatives that will change the system's profile during the drilling shift are not allowed as this will directly affect the mine's production performance.

This energy neutral baseline adjustment method will ensure that the baseline is adjusted in accordance with increased or decreased production. This is due to the fact that the energy consumption of the compressors directly correlates with the production during the drilling shift [82]. Note that no adjustments will be made on Sundays as there are no production-related activities conducted on the mining shafts.

The baseline will be adjusted by means of a Service Level Adjustment (SLA) factor. The SLA represents the ratio between the energy consumption during the drilling shift of the measurement period and the baseline. The following formula will be used to calculate the SLA, as given by Equation 4.

$$SLA = \frac{E_A}{E_B} \quad (4)$$

Equation 4: SLA calculation [82]

Where,

E_A = The total measurement period energy consumption in the drill shift

E_B = The total baseline period energy consumption in the drill shift

The baseline will be multiplied by the SLA factor to obtain the adjusted baseline according to the formula below:

$$Adjusted\ Baseline = Baseline \times SLA$$

- **SLA = 1** (The baseline will remain unadjusted.)
- **SLA > 1** (The baseline will be adjusted higher by multiplying the baseline with the SLA)
- **SLA < 1** (The baseline will be adjusted lower by multiplying the baseline with the SLA)

Figure 50 shows an example of scaling the weekday baseline profile, as presented in Figure 49, where the energy consumption of the measurement period in the drill shift was lower than the weekday baseline. Thus, the SLA is less than 1 and the baseline was adjusted lower.

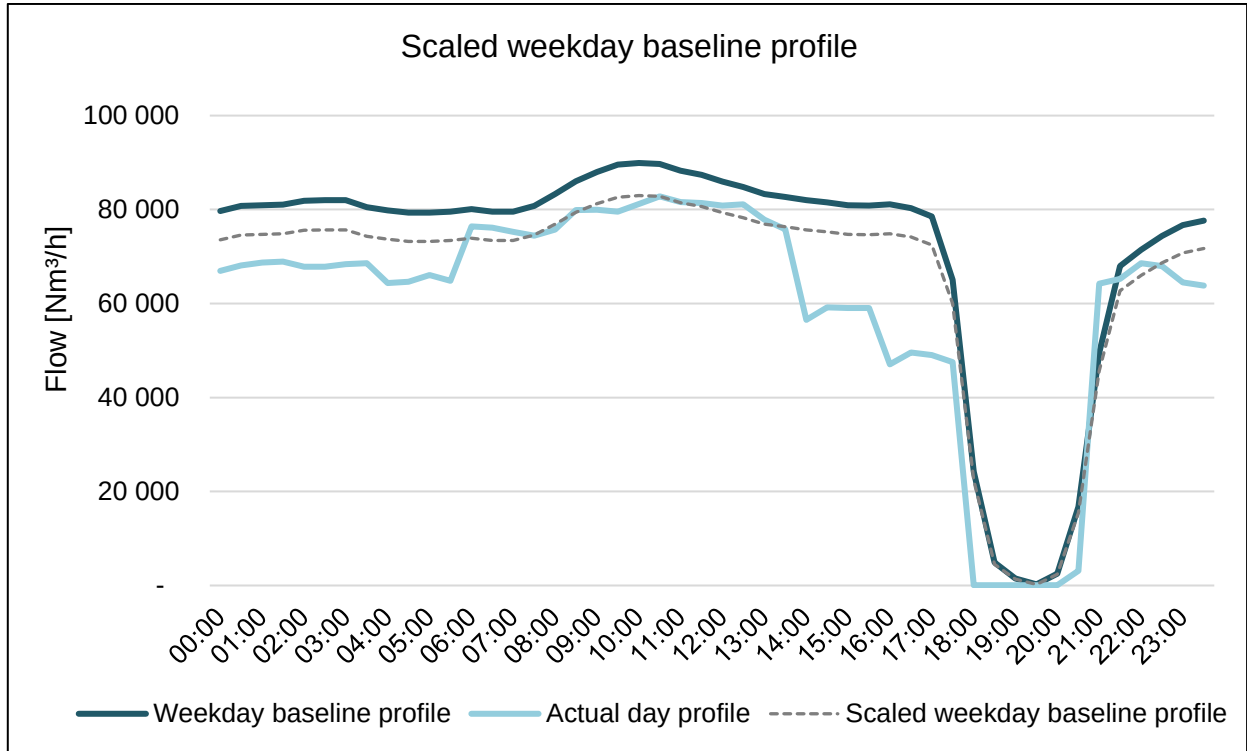


Figure 50: An example of scaling a baseline profile

APPENDIX C: ESKOM MEGAFLEX TOU TARIFF STRUCTURE

The mining industry generally operates on the Eskom Megaflex tariff structure, which is a time-of-use (TOU) tariff structure [11]. This TOU tariff structure operates on the principle that the consumer is charged for the electrical power consumed at different tariff rates which is determined during the time period of power consumption. This time period for the Megaflex TOU tariff structure can be divided into three categories, namely off-peak, standard, and peak period, as shown in Table 21.

Table 21: Eskom Megaflex TOU tariff table 2021/2022 (c/kWh) [11]

	Summer Tariff Low demand season			Winter Tariff High demand season		
	Weekday [c/kWh]	Saturday [c/kWh]	Sunday [c/kWh]	Weekday [c/kWh]	Saturday [c/kWh]	Sunday [c/kWh]
00:00	74,65	74,65	74,65	83,72	83,72	83,72
01:00	74,65	74,65	74,65	83,72	83,72	83,72
02:00	74,65	74,65	74,65	83,72	83,72	83,72
03:00	74,65	74,65	74,65	83,72	83,72	83,72
04:00	74,65	74,65	74,65	83,72	83,72	83,72
05:00	74,65	74,65	74,65	83,72	83,72	83,72
06:00	108,37	74,65	74,65	426,94	83,72	83,72
07:00	150,12	108,37	74,65	426,94	140,58	83,72
08:00	150,12	108,37	74,65	426,94	140,58	83,72
09:00	150,12	108,37	74,65	140,58	140,58	83,72

10:00	108,37	108,37	74,65	140,58	140,58	83,72
11:00	108,37	108,37	74,65	140,58	140,58	83,72
12:00	108,37	74,65	74,65	140,58	83,72	83,72
13:00	108,37	74,65	74,65	140,58	83,72	83,72
14:00	108,37	74,65	74,65	140,58	83,72	83,72
15:00	108,37	74,65	74,65	140,58	83,72	83,72
16:00	108,37	74,65	74,65	140,58	83,72	83,72
17:00	108,37	74,65	74,65	426,94	83,72	83,72
18:00	150,12	108,37	74,65	426,94	140,58	83,72
19:00	150,12	108,37	74,65	140,58	140,58	83,72
20:00	108,37	74,65	74,65	140,58	83,72	83,72
21:00	108,37	74,65	74,65	140,58	83,72	83,72
22:00	74,65	74,65	74,65	83,72	83,72	83,72
23:00	74,65	74,65	74,65	83,72	83,72	83,72

Legend	Off-peak period	Standard period	Peak period
---------------	------------------------	------------------------	--------------------

The tariff rates differ according to the time of day, day of the week, and the season of the year, and are based on the cost of generating electricity during these periods. The aim for the different tariff periods is to encourage consumers to reduce their power consumption during the peak demand period. The reason behind this is to alleviate the strain placed on the generating system during the peak demand periods [59].

APPENDIX D: EQUIPMENT USED BY THE VARIOUS CREWS AND THEIR RESPECTIVE UTILISATION FACTORS

Consumptions		
Equipment	Consumption [CFM]	Consumption [CMH]
Rock-drill (S215)	180	305,8218
Roof-bolter	180	305,8218
Water pump	22	37,37822
Cheetah saw	18	30,58218
Jackpot pump	5	8,49505
Loader (B56)	600	1019,406
Loader (Anfex)	5	8,49505
Rock-drill (S25)	250	424,7525
Air whistle	2	3,39802
S36 machine	250	424,7525
Cement pump	750	1274,2575
Techno post	12	20,38812
Refuge bay	20	33,9802
Chutes	50	84,9505
Air hoist	150	254,8515
Diamond drill	300	509,703

Stopping crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm ³ /h]
Rock-drill (S215)	305,8218	0,7	4	856,30104
Roof-bolter	305,8218	0,7	1	214,07526
Water pump	37,37822	0,9	1	33,640398
Cheetah saw	30,58218	0,7	1	21,407526
Loader (Anfex)	8,49505	0,6	1	5,09703
Air whistle	3,39802	0,05	3	0,509703
Total			11	1131,030957

Ledging crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm³/h]
Rock-drill (S215)	305,8218	0,7	4	856,30104
Roof-bolter	305,8218	0,7	1	214,07526
Water pump	37,37822	0,9	1	33,640398
Cheetah saw	30,58218	0,7	1	21,407526
Loader (Anfex)	8,49505	0,6	1	5,09703
Air whistle	3,39802	0,05	3	0,509703
Total			11	1131,030957
Cleaning crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm³/h]
Water pump	37,37822	0,8	1	29,902576
Loader (B56)	1019,406	1	1	1019,406
Diamond drill	509,703	0,7	1	356,7921
Air whistle	3,39802	0,05	2	0,339802
S36 machine	424,7525	0	0	0
Cement pump	1274,2575	0,6	1	764,5545
Total			6	2170,994978
Flat Development crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm³/h]
Water pump	37,37822	0,9	2	67,280796
Loader (Anfex)	8,49505	0,6	1	5,09703
Rock-drill (S25)	424,7525	0,6	1	254,8515
Total			4	327,229326
Auxiliary crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm³/h]
Cheetah saw	30,58218	0,7	1	21,407526
S36 machine	424,7525	0,6	1	254,8515
Cement pump	1274,2575	0,6	1	764,5545
Total			3	1040,813526

Re-development crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm ³ /h]
Rock-drill (S215)	305,8218	0,7	2	428,15052
Water pump	37,37822	0,9	2	67,280796
Loader (B56)	1019,406	0,4	1	407,7624
Loader (Anfex)	8,49505	0,6	1	5,09703
Air whistle	3,39802	0,05	1	0,169901
S36 machine	424,7525	0,6	1	254,8515
Total			8	1163,312147
On reef development crew				
Equipment	Consumption [CMH]	Utilisation	Amount	Consumption [Nm ³ /h]
Rock-drill (S215)	305,8218	0,7	2	428,15052
Water pump	37,37822	0,9	1	33,640398
Air whistle	3,39802	0,05	1	0,169901
Total			4	461,960819

APPENDIX E: HALF-LEVEL BASELOAD TEST RESULTS

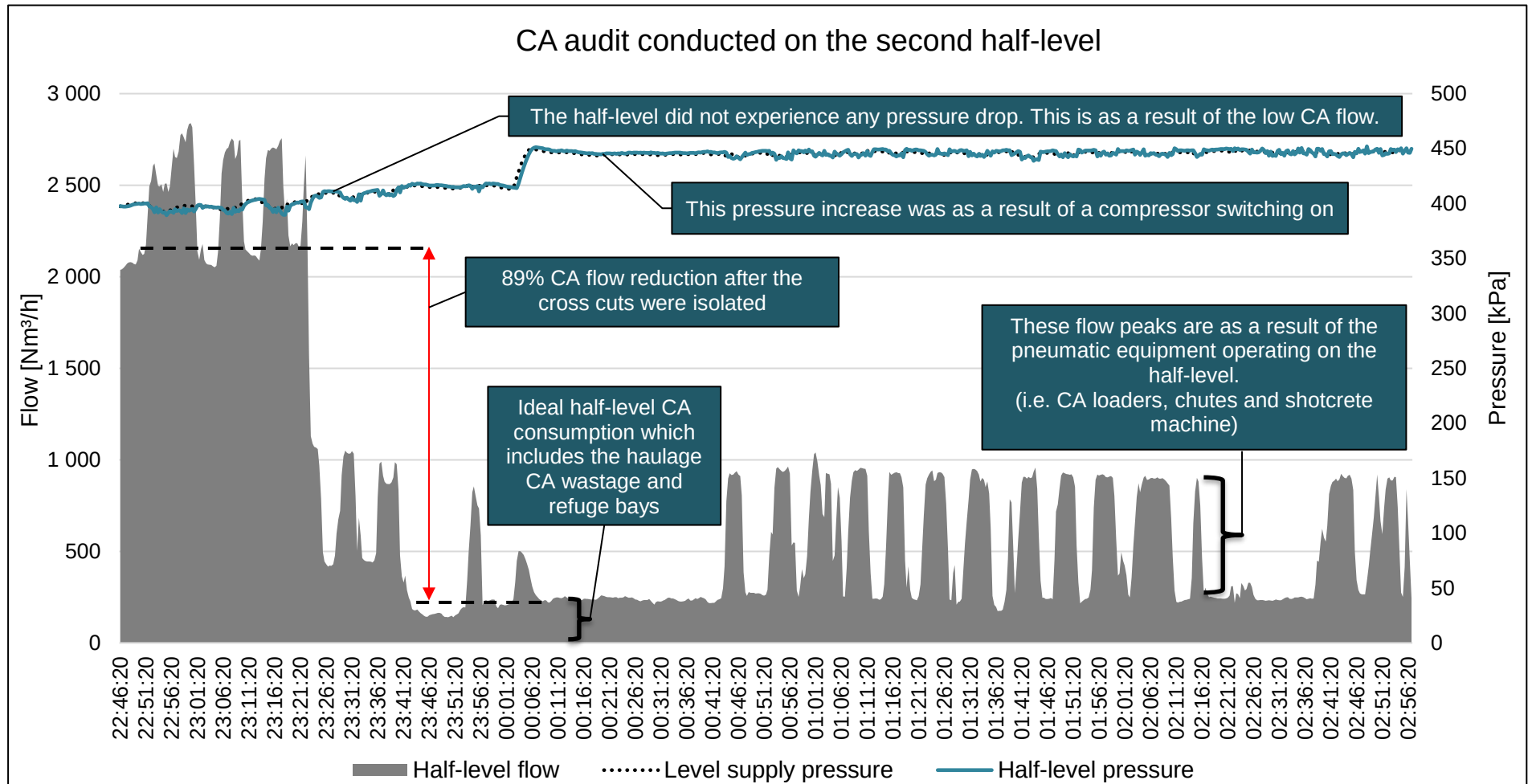


Figure 51: Flow and pressure profile obtained during the CA audit on half-level number 2

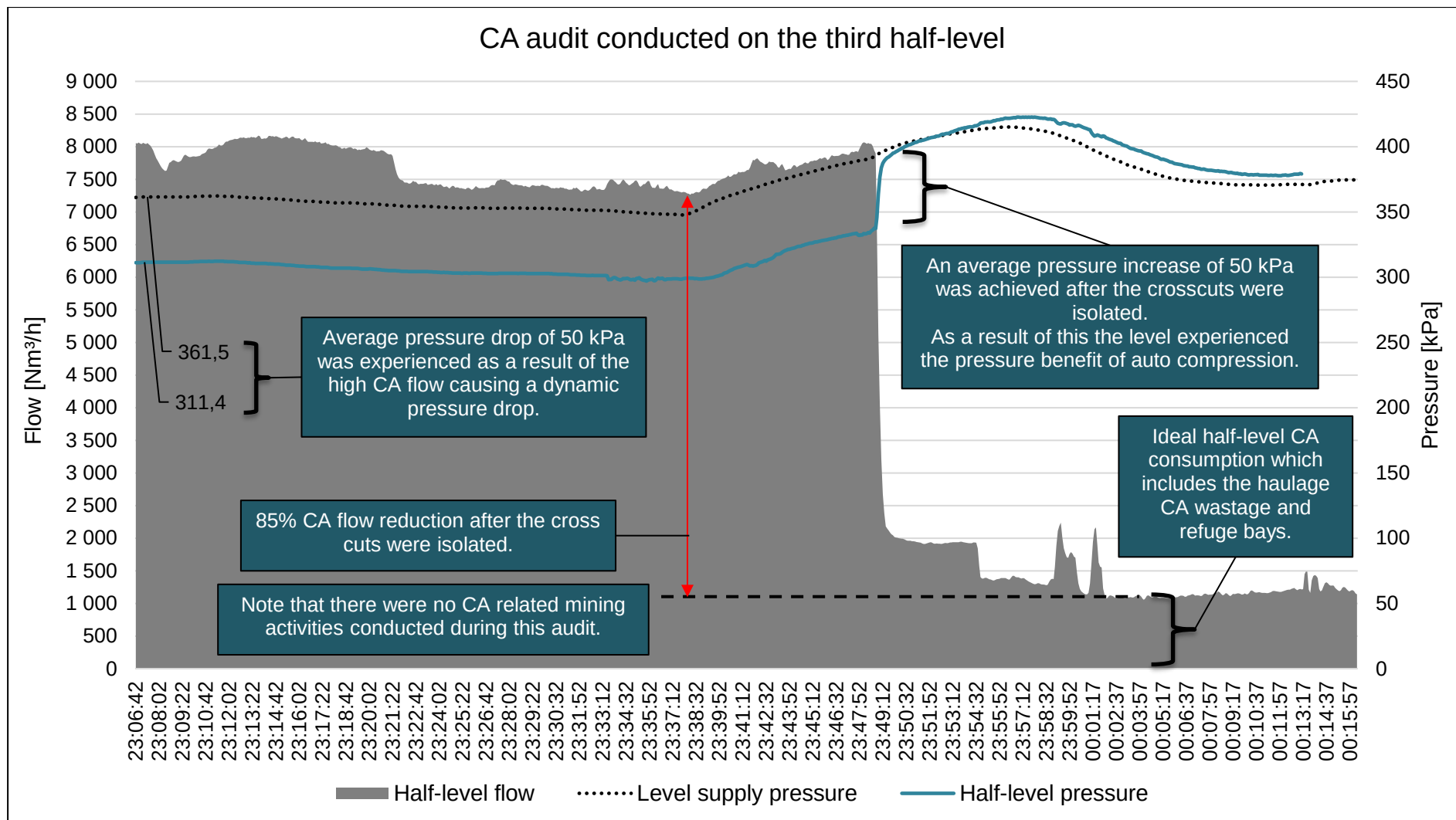


Figure 52: Flow and pressure profile obtained during the CA audit on half-level number 3

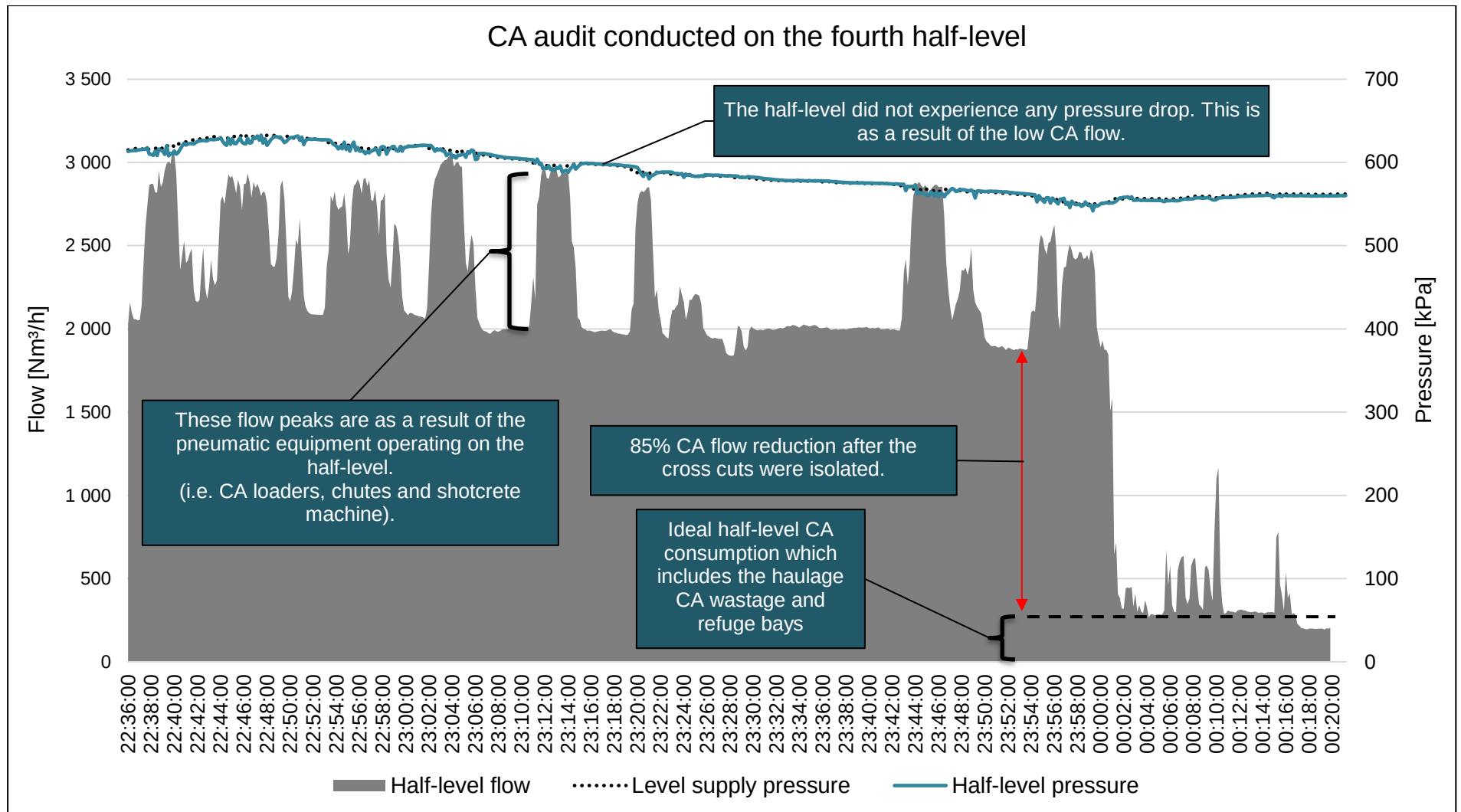


Figure 53: Flow and pressure profile obtained during the CA audit on half-level number 4

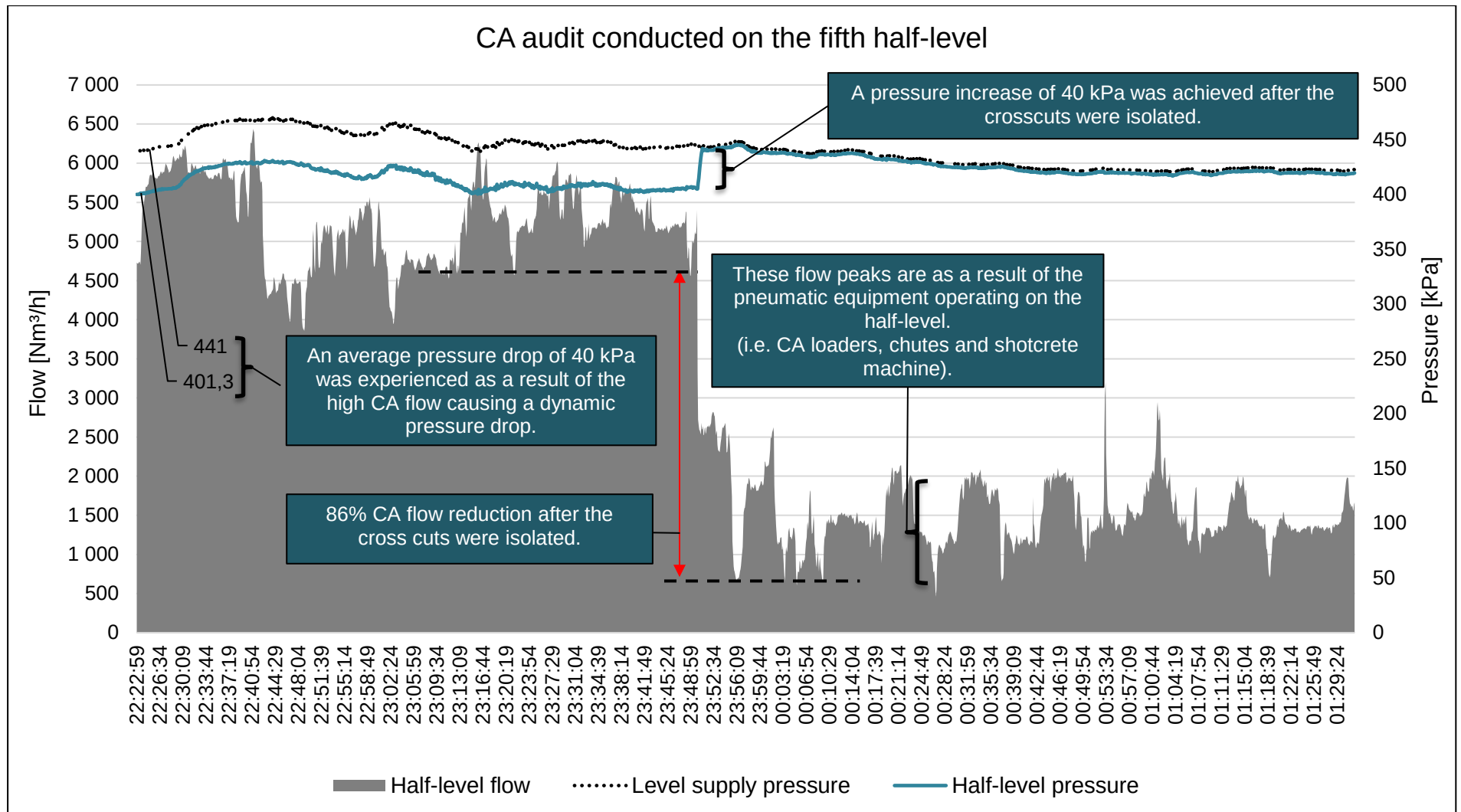


Figure 54: Flow and pressure profile obtained during the CA audit on half-level number 5

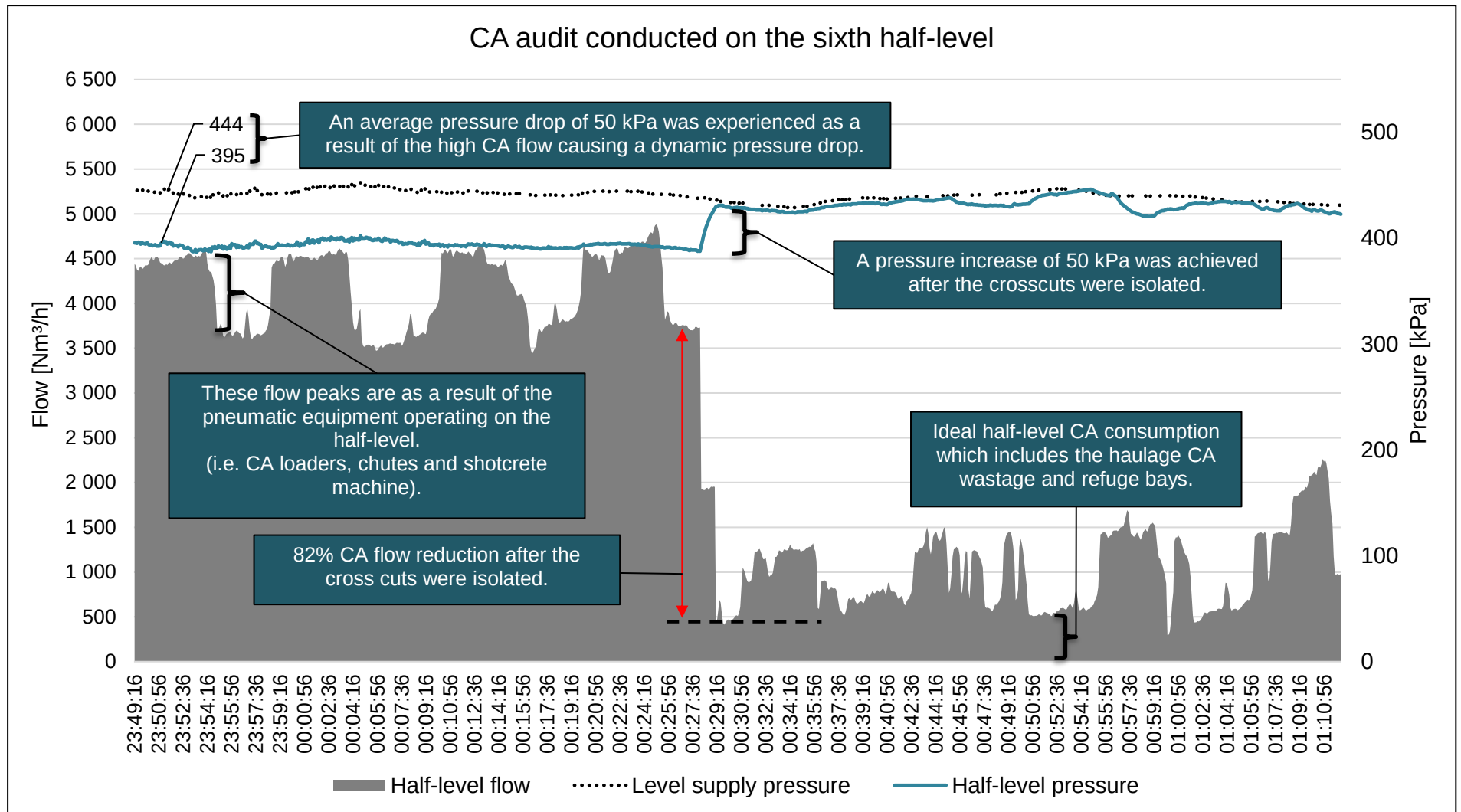


Figure 55: Flow and pressure profile obtained during the CA audit on half-level number 6

APPENDIX F: EXPLANATION OF THE ENERGY AND FINANCIAL SAVING CALCULATION

A theoretical model is used to predict the potential energy reduction of implementing cross cut isolation on a deep-level mine's compressed air (CA) network. In essence, the developed theoretical model is used to predict what the potential flow reduction is when the cross cuts on a mining shaft are isolated. This potential flow reduction can then be translated to an energy saving, which is then used to determine the financial feasibility of implementing cross cut isolation.

Table 22 presents an example of the calculations done for the weekday flow profile to determine the potential power saving brought about by the reduction in flow as a result of implementing cross cut isolation. For illustration purposes, to show how the calculations are done, the data during the time period of 05:00 to 08:30 are presented. The energy saving calculations are done as follow:

1. The half-hourly averaged data used for the weekday theoretical CA flow profile, as shown in Figure 40, is presented in Table 22 for the time period of 05:00 to 08:30. The procedure and calculations to develop this theoretical model are discussed in Section 3.4.
2. The half-hourly averaged data used for the weekday baseline CA flow profile, as shown in Figure 40, is presented in Table 22 for the time period of 05:00 to 08:30. The procedure to develop the baseline flow profile is discussed in Section 3.4.2.
3. Next, the potential flow reduction is calculated by subtracting the theoretical flow profile data from the baseline flow profile data for each half-hourly increment. As a result of this a 24-hour potential CA flow reduction profile, as shown in Figure 40, will be calculated in half-hourly increments.
4. The next step is to calculate the half-hourly power saving brought about the potential flow reduction. This is done by multiplying the potential flow reduction with the calculated specific power [kWh/Nm³] of the CA network, as presented in Table 18.

Table 22: B Shaft's compressed air half-hourly power saving calculations for the weekdays

Weekday calculations				
Time	Theoretical flow profile	Baseline flow profile	Potential flow reduction	Power saving from the flow reduction [kW]
05:00	28 979	85 980	57 002	5 814
05:30	29 372	85 639	56 268	5 739
06:00	29 764	88 223	58 458	6 052

Weekday calculations				
Time	Theoretical flow profile	Baseline flow profile	Potential flow reduction	Power saving from the flow reduction [kW]
06:30	38 415	94 180	55 766	4 724
07:00	37 680	100 136	62 456	4 083
07:30	47 875	106 108	58 234	2 439
08:00	55 600	114 332	58 732	1 897
08:30	62 513	117 256	0	0

Table 23 provides a summary of the half-hourly potential power savings from 05:00 to 08:30 for a weekday, Saturday, and Sunday. Note that the above-mentioned procedure was used to determine the power savings for weekday, Saturday, and Sunday flow profiles, as presented in Table 23. Furthermore, the daily energy saving [kWh] for a weekday, Saturday, and Sunday is calculated using the following equation:

$$\text{Daily energy saving [kWh]} = \frac{\text{Sum of the 24hour power saving in half hourly increments}}{2}$$

Finally, the average daily power saving is calculated using the following equation:

$$\text{Average daily power saving [kW]} = \frac{\text{Energy saving [kWh]}}{24 \text{ hours}}$$

Table 23: B Shaft's compressed air power saving for weekdays, Saturdays, and Sundays

Power savings in kW			
Hour of day	Weekday	Saturday	Sunday
05:00	5814	5367	1133
05:30	5739	5294	1152
06:00	6052	5698	1153
06:30	4724	4724	996
07:00	4083	4083	1075
07:30	2439	2439	1274
08:00	1897	1897	1417
08:30	0	0	1509

Power savings in kW			
Hour of day	Weekday	Saturday	Sunday
...	...	...	...
Daily energy saving [kWh]	43 337	35 905	34 233
Average daily power saving [kW]	1806	1496	1426

The next step is to calculate the financial saving brought about the potential power reduction. Using the Eskom 2021/2022 Megaflex TOU tariff structure, as presented in Appendix C, the annual financial saving of the potential energy impact presented in Table 23 can be calculated by using the following equation for each of the half-hourly increments:

$$\text{Half hourly cost saving [Rand]} = \frac{\text{Energy saving [kWh]} \times \text{tariff rate [cents/kWh]}}{100}$$

Note that the reduction in CA flow, resulting from implementing cross cut isolation, reduces the total active energy consumption (kWh). Therefore, all the components determined by the energy consumption to calculate the electricity tariff will be affected. Table 24 presents the calculated cost saving for the potential power reduction in half-hourly increments for a weekday, Saturday, and Sunday using both the summer and winter tariffs.

Table 24: Cost savings for both summer and winter tariffs

Time	Cost Saving – Summer Tariff			Cost Saving – Winter Tariff		
	Summer Tariff	Summer Tariff	Summer Tariff	Winter Tariff	Winter Tariff	Winter Tariff
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
...	...	...	...	...	...	...
05:00	R4 340,31	R4 006,49	R845,90	R4 867,66	R4 493,28	R948,68
05:30	R4 284,42	R3 951,79	R859,83	R4 804,98	R4 431,93	R964,30
06:00	R6 558,36	R4 253,29	R860,51	R25 837,65	R4 770,06	R965,06
06:30	R5 119,53	R3 526,56	R743,78	R20 169,16	R3 955,03	R834,15
07:00	R6 128,70	R4 424,24	R802,47	R17 429,97	R5 739,23	R899,97
07:30	R3 662,09	R2 643,62	R951,12	R10 414,96	R3 429,37	R1 066,68
08:00	R2 847,62	R2 055,66	R1 058,11	R8 098,60	R2 666,65	R1 186,67
08:30	R0,00	R0,00	R1 126,21	R0,00	R0,00	R1 263,04
...	...	...	...	...	...	...

Time	Cost Saving – Summer Tariff			Cost Saving – Winter Tariff		
	Summer Tariff	Summer Tariff	Summer Tariff	Winter Tariff	Winter Tariff	Winter Tariff
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Total	R 38 523,32	R 28 222,76	R 25 555,26	R 76 196,61	R 32 453,44	R 28 660,23

Finally, the total savings for weekdays, Saturdays, and Sundays, as presented in Table 25, are calculated using the following equations:

$$\text{Average daily savings [Rand]} = \text{Total as presented in Table 24}$$

$$\text{Winter saving [Rand]} = \text{Average daily winter saving} \times \text{total number of workdays in winter}$$

$$\text{Summer saving [Rand]} = \text{Average daily summer saving} \times \text{total number of workdays in summer}$$

$$\text{Total saving [Rand]} = \text{Summer saving} + \text{winter saving}$$

Table 25: Summary of the total weekday, Saturday, and Sunday cost savings

Weekday Savings			
Average daily summer savings	R38 523,32	Average daily winter savings	R76 196,614
Summer savings	R7 242 384,41	Winter savings	R4 876 583,298
Per month summer savings	R804 709,38	Per month winter savings	R1 625 527,766

Total Weekday savings	R12 118 967,70
------------------------------	-----------------------

Saturday Savings			
Average daily summer savings	R28 222,76	Average daily winter savings	R32 453,441
Summer savings	R1 044 242,21	Winter savings	R421 894,730
Per month summer savings	R116 026,91	Per month winter savings	R140 631,577

Total Saturday savings	R1 466 136,94
-------------------------------	----------------------

Sunday Savings			
Average daily summer savings	R25 555,26	Average daily winter savings	R28 660,231
Summer savings	R945 544,56	Winter savings	R372 583,001
Per month summer savings	R105 060,51	Per month winter savings	R124 194,334

Total Sunday savings	R 1 318 127,56
-----------------------------	-----------------------

APPENDIX G: EXPLANATION OF THE PAYBACK PERIOD CALCULATION

Using the same calculation methodology as discussed in Appendix F, the potential flow reduction, as shown in Figure 48, was calculated by dividing the “Scaled baseline profile” with the “Actual 2-month flow profile” (representing the new flow profile as a result of implementing cross cut isolation). The potential flow reduction was then multiplied by the calculated specific power [kWh/Nm³] of the CA network, as presented in Table 18, to calculate the potential power saving brought about by the implementation of the cross cut isolation valve. Table 26 presents the half-hourly calculated power saving for weekdays. For illustration purposes, to demonstrate how the calculations are done, the data during the time period of 02:30 to 06:30 are presented.

Table 26: Weekday power saving for the cross cut isolation valve

Hour of day	Weekday power saving [kW]
...	...
02:30	127
03:00	135
03:30	129
04:00	126
04:30	132
05:00	156
05:30	142
06:00	0
06:30	0
...	...
Daily energy saving [kWh]	1 678
Average daily power saving [kW]	70

The financial saving brought about by the power reduction as a result of implementing the cross cut isolation valve was then calculated using the Eskom 2021/2022 Megaflex TOU tariff structure, as presented in Appendix C. The annual weekday financial saving of the calculated power reduction is presented in Table 27. These calculations were done in accordance with the procedure discussed in Appendix F.

Table 27: Summary of the total weekday cost saving for the cross cut isolation valve

Weekday Savings				
Average daily summer savings	R1 539,73		Average daily winter savings	R2 534,441
Summer savings	R323 342,72		Winter savings	R177 410,873
Per month summer savings	R35 926,97		Per month winter savings	R59 136,958
Total weekday savings			R 500 753,60	

The payback period, which represents the time that is required to recover the initial capital investment to acquire the cross cut isolation valve, was calculated using the following equation [21]:

$$\text{Payback period [Months]} = \frac{\text{Initial capital investment [Rand]}}{\text{Compressed air saving [Rand]}} \times 12$$

With

$$\text{Initial capital investment} = R\ 180\ 000$$

$$\text{Compressed air saving} = R\ 500\ 000$$

$$\text{Payback period} = 5\ \text{Months}$$