Novel solutions for compressed air demand management on deep-level mines

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Abstract

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Mining makes a significant contribution to South Africa's economy (7.3% of the gross domestic product) and provides direct employment to more than 450 000 people. The bulk of South Africa's mineral wealth lies in deep-level platinum and gold mining. However, this industry is struggling to stay profitable. High operational costs have been identified as one of the major factors influencing profitability.

One approach to improve the profit margins of deep-level mines is decreasing electricity costs. Industrial compressed air systems are major consumers of electricity on deep-level mines. It has been estimated that 40 to 80% of the generated compressed air is wasted through leaks, thus indicating that there is significant scope for improvement.

Existing compressor electricity cost saving strategies focus on controlling the supply of compressed air which is limited to end-user requirements. Studies on underground leak reduction are limited. There is a need for methods to reduce deep-level mine compressor power consumption through the management of underground wastages.

Benchmarking models have successfully been used to identify scope for electricity savings on mine compressed air systems. Existing methods are not designed to indicate scope for underground wastage management. A novel benchmarking model has been developed to prioritise shafts based on the scope for underground demand reduction. This benchmarking model was able to improve resource utilisation by up to 57% when compared to existing benchmarking models.

Studies involving underground compressed air leak audits mostly rely on impractical comprehensive audits of an entire shaft. Leak auditing methodologies used in the potable water distribution industry were modified to be applied to mine compressed air networks. When this method was applied to a deep-level mining shaft, it reduced the auditing time by approximately 65%. An annual cost saving of R620-million is possible when the flow reduction achieved is extrapolated over 25 deep-level mines. The estimated annual resource cost to maintain this saving is R34.6-million.

The methods developed in this study were combined into one integrated method to reduce underground leaks and achieve electricity cost savings on the compressors. However, existing electricity savings quantification methods were found to be unable to accurately quantify the savings achieved on deep-level compressed air systems.

A novel savings quantification method was developed based on the parameters used in the new benchmarking model. The new method was tested on various scenarios and found to quantify the savings equally or better than existing methods and in less time. In one scenario, the new quantification method improved the quantification accuracy by up to 83%, amounting to an estimated annual savings difference of R14.5-million.

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Terminology and acronyms

Blowers	Open-ended compressed air columns used to ventilate underground working areas.
CA	Compressed Air
CA wastage	Compressed air consumers serving no purpose.
Centre gully	An on-reef tunnel created for the transportation of ore from the stopes to the loading box.
Conventional mining	Non-mechanised narrow-reef mining.
Cross cut	Small passageways connecting the haulage and stopes.
DCS	Dynamic Compressor Selectors – A control philosophy that dynamically changes the supply controls to meet the compressed air demand with the least amount of power.
Demand reduction	Reducing the demand for compressed air downstream of automated surface or underground valves.
Development	The process of creating the dedicated passageways for reaching and transporting ore from the reef to surface. This can include the shaft tunnel, haulages, cross cuts, box holes, and centre gullies. In other words, preparations for stope advancing to take place.
DI	Demand reduction indicator – Explained in Section 2.2.2
ESCos	Energy Service Companies
Half level	The reef being mined is divided into different working horizons, known as levels. The shaft column usually connects with approximately the middle of the level, thereby splitting the level in two parts. Each part of the level is referred to as a half level.

Haulage	Underground tunnels for the transportation of ore via rail from the stoping areas to the shaft. These tunnels are also used to transport personnel and services which include compressed air, water, and electricity.
ID	Inside Diameter
IDM	Integrated Demand Management
IoT	Internet of Things
kPa_g	Gauge pressure measured in kilo pascals
Loading box	Ore from the stopes is transported via the centre gully with a winch into a hole called an ore pass. The loading box is located at the bottom of the ore pass. Ore will remain in the ore pass until the loading box is opened and the ore falls into a hopper under the loading box.
Min	Minimum
MNF	Minimum Night Flow
PA	Performance Assessment. Period in which ESCos electricity cost saving performance is measured.
Peak clipping	A reduction in electricity consumption during the high electricity tariff period. Peak clipping can usually only be implemented for a certain period after which production activities will be negatively affected.
PTB	Process Toolbox – A thermal-hydraulic simulation software package specifically designed for simulating mine fluid transportation networks.
SLA	Service Level Adjustment
Station area	An area within a radius of ±100 m from the shaft. This is usually where miners wait for the lift to arrive.

Stope	The areas where the ore is being extracted or has already been extracted through drilling and blasting.
Sweeping	Sweeping process involves recovering the remaining blasted ore from working places that have been mined out.
UAVs	Unmanned Aerial Vehicles
x/c	Cross cut

Chapter 1. Compressed air in deep-level mines

1.1 Potential for compressed air improvements

1.1.1 Overview of South African mining industry

According to statistics from the United States Geological Survey (USGS), South Africa holds more than 90% of the world's Platinum Group Metal (PGM) reserves and more than 10% of the world's gold reserves [1]. When compared to other minerals mined in South Africa, gold and PGM contribute to the majority of the total mineral revenue [2].

The economy depends on this mineral wealth for growth as mining contributes to 7.3% of the country's GDP [2]–[4]. The contribution of gold and platinum to the total South African mining revenue has, however, decreased from 39% in 2017 to 35% in 2018 [2].

Reasons for the decreased gold and platinum output include increased operational costs and low mineral prices [4]–[6]. Gold and PGM producers are price takers. This means that the mined minerals have to be supplied at global market related prices [7], [8]. Adjusting the price of gold or PGMs to compensate for an increase in expenses is not an option.

Labour relations, political instability, a shortage of critical skills, and increased cost of utilities are some of the prominent risks faced by South African mining companies [2], [9]–[11]. International competitors may thus have an advantage over South African mining companies [4], [8], [9], [12]. To increase profit margins, mines can increase mineral production or decrease operational expenditure [7], [13], [14].

A decrease in the total gold and PGM production has been experienced since 2015 [15]. This may be attributed to the increased difficulty of mining these commodities [2], [9], [11], [16]. As an alternative means to show a profit, mining companies are reducing operational expenditures [8], [13]. A breakdown of the operational expenditure on a typical mine is shown in Figure 1.

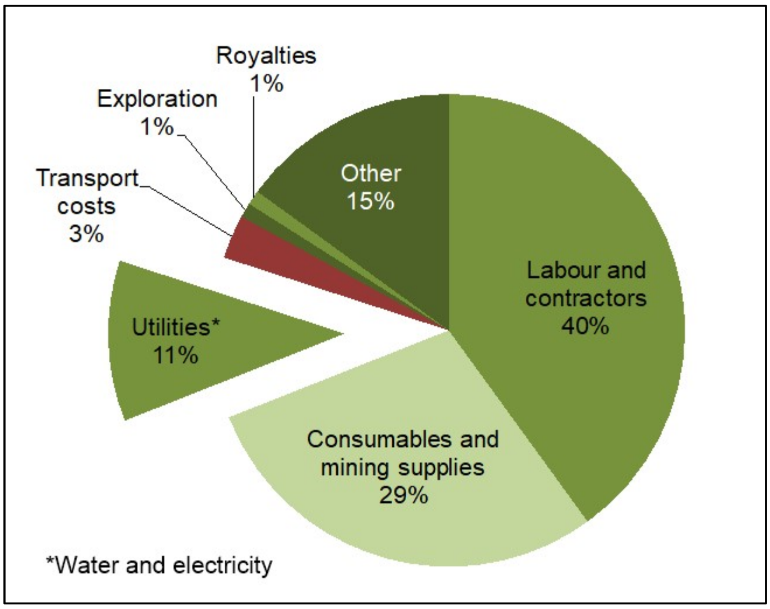


Figure 1: Typical mine operational expenditure [2]

Labour and contractors are the largest operational expense on deep-level mines, as seen in Figure 1. PGM and gold mining are labour-intensive, as conventional underground mining technologies are typically used in South Africa [7], [11], [17], [18]. Mining companies provide direct employment to more than 450 000 people in South Africa [2]. Mining thus plays an important role in providing employment in a country with a high unemployment rate [19].

Mining companies are closing non-profitable operations in an effort to decrease operating costs and increase profitability [2], [20]. Figure 2 illustrates the number of people employed by the mining industry over a 12-year period. The total number of permanent employees decreased by more than 10% over this period [2] thus adding to the growing South African unemployment rate.

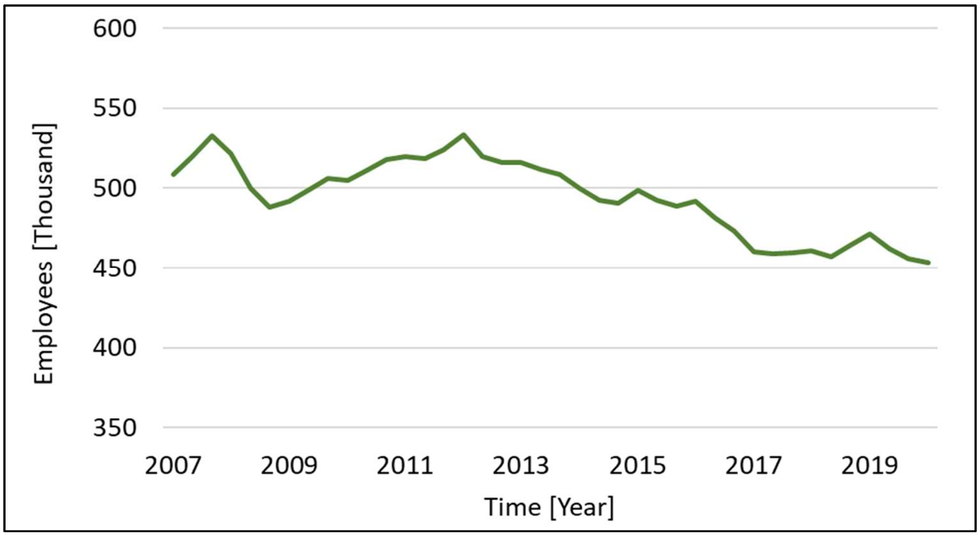


Figure 2: Number of people directly employed by the South African mining industry [2]

There is still an opportunity for reducing the electricity cost on deep-level mines to increase profits [5], [21], [22]. Utilities are the third-largest expense for the mining industry, contributing to 11% of the total operating expenditure. An analysis of one of South Africa's largest mining companies revealed that utilities can account for more than 13% of the total operational expenditure with the cost of electricity being more than 90% of the total utility cost [5], [23]. Electricity is thus a significant operational expense in the mining industry.

In March of 2019, the National Energy Regulator of South Africa (NERSA) approved a 13.87% electricity tariff increase for the April 2019 to March 2020 period [24]. Energy-intensive gold and PGM mining groups are very sensitive towards these tariff hikes [4][25]. According to a model developed by Krogscheepers and Gossel [8], a 1% increase in electricity tariffs may lead to a 2.02% decrease in mine production. This is because electricity is such an integral part of the mining value chain [8]. Increasing the price of electricity may mean that some operations become unprofitable.

As shown in Figure 2, more than 50 000 people who were permanently employed at mining companies have lost their jobs since 2007. More than 30% of these job losses could be attributed to the rapidly increasing electricity costs [4]. There is thus a need for deep-level PGM and gold mining groups to decrease electricity costs.

1.1.2 Electricity as an operational expense on deep-level mines

According to Section 1.1.1, PGM and gold mining groups are significantly affected by electricity tariff increases. Unlike the global commodity prices, energy input is a variable over which mining companies have more control. Electricity costs could be decreased to increase competitiveness in the global market [26]–[28].

Mining groups recognise the negative effect of higher-than-inflation electricity tariff increases. These companies have placed emphasis on reducing electricity costs to improve profitability [5], [11], [20]. However, decreasing the electricity cost on deep-level gold and PGM mines is not an easy task as energy-intensive machinery is required to continue with mining operations.

A breakdown of electricity-consuming systems on a typical deep-level mine is illustrated in Figure 3. Mining processes are the highest electricity consumers. These electricity consumers consist of numerous electricity consuming units such as booster fans, conveyor belts, and battery-powered locomotives. Electricity cost saving initiatives on larger units, such as surface extraction fans and compressors, are preferred [18] as these units are easier to monitor and manage.

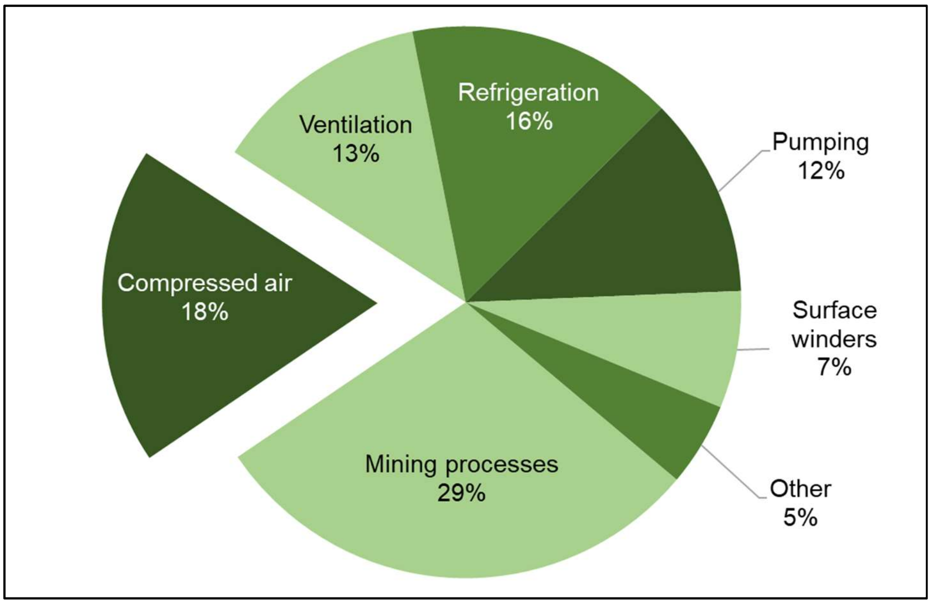


Figure 3: Electricity consumption breakdown of a typical deep-level mine (Adapted from [13])

According to Figure 3, 18% of the total electricity consumption can be attributed to the generation of Compressed Air (CA). However, this value can increase up to 50% [14], [29]. Reducing the energy consumption of deep-level mine CA systems could significantly help the mine to stay economically viable [22].

1.1.3 Deep-level mine compressed air systems

Compressed air end-users

CA is an easy-to-use, versatile, and relatively safe medium to transfer energy from the point of generation to the point of use. This explains the extensive use of this medium in the deep-level mining environment [30]–[35]. CA is normally generated by multiple compressors located on the mine. The generated CA is distributed to the various end-users on a shaft.

CA is used to operate a variety of equipment required for the blasting process (mining). The equipment used is usually specific to the tasks that need to be performed in a mining shift [30], [36], [37]. When discussing CA end-users, it is thus important to understand the mining cycle. Deep-level mines typically work in a 24-hour cycle consisting of three distinct shifts [16]. These are:

<u>Drilling shift:</u> In conventional mining, drill rig operators are used to drill holes into the stope face with the use of pneumatic drills [16].

Blasting shift: Explosives are inserted into the holes that were drilled during the drilling shift and detonated. No mining personnel are allowed in the working areas during the blasting shift [16], [38].

Support and sweeping shift: The blasted area is declared safe and support is inserted. Blasted ore is hauled from the stope face to the loading box with the use of winches [39].

A typical daily mining cycle on a deep-mine is displayed in Figure 4.

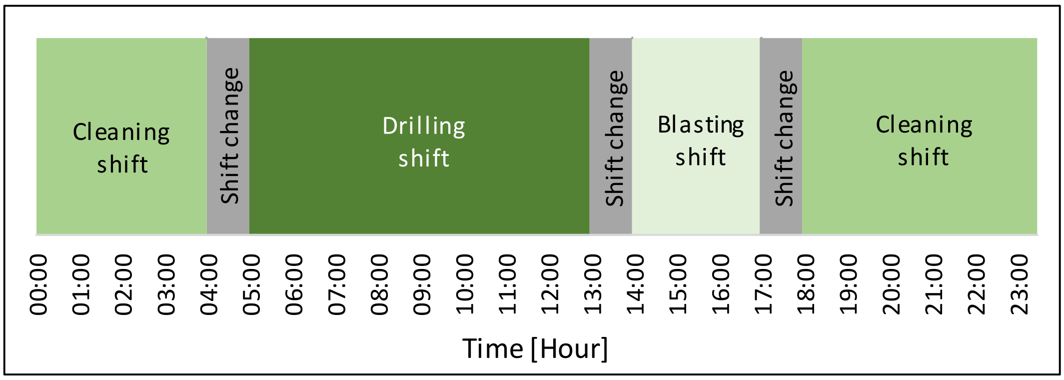


Figure 4: Daily shift cycle on a typical deep-level mine

Figure 4 shows periods between the shifts, known as changeover periods. During these periods, mining personnel from the previous shift are transported to surface while personnel working during the next shift is transported underground. Some personnel must travel up to 10 km by foot to reach the working area [11], [16], [40].

As described above, different tasks are performed during each of the mining shifts [30]. Specialised machinery is required to perform these tasks. For this study, focus will only be placed on the pneumatic machinery used throughout a typical mining cycle. Details on some typical CA end-users follow below:

Pneumatic drills:

Shift: Drilling shift [30]

Required pressures 450 – 620 kPa_g [30], [41], [42]

CA flow requirements: 0.12 kg/s [41]

Description: Pneumatic drills are used to drill holes into the rock for inserting explosives [16].

Pneumatic loading boxes (chutes):

Shift: Drilling and sweeping shifts [30], [32]

Required pressures: 400 – 500 kPa_g [30], [32], [37], [42]

CA flow requirements: 0.004 – 0.1 kg/s [16]

Description: Blasted ore from the stopes are scraped to the box holes where it falls to the loading box. The loading box is opened using CA to let the ore fall into a track-bound hopper. Unlike pneumatic drills which are nearly in constant operation, the loading boxes are only used for short periods when ore handling is required. There are also much less loading boxes in operation when compared to drills [30].

Pneumatic loaders (rock shovels):

Shift: Cleaning shift [30]

Required pressures: 350 – 450 kPa_g [30], [42], [43]

CA flow requirements: 0.8 kg/s [43]

Description: Pneumatic loaders are track-bound machinery used to transfer waste rock from the development areas into a track-bound hopper car. CA is used to pivot the loader arms to catapult ore into the hopper and to move the machine forward and backwards to scoop the waste [43]. There is usually only one pneumatic loader located per half level.

Refuge bays:

Shift: All shifts [30]

Required pressure: 150 – 200 kPa_g [37], [42]

CA flow requirements: < 0.06 kg/s[1]

Description: Mines are legally required to provide places of safety for emergency events, such as fires. These places of safety are known as refuge bays [44]. Furthermore, breathable air should constantly be supplied to the refuge bay [45]. CA could be used to

[1] CA is constantly supplied to the refuge bay through a hole in the column with a diameter smaller than 5 mm. In the event of an emergency, the CA valve in the refuge bay is opened.

ventilate refuge bays as it is breathable and non-toxic. The constant flow of CA also results in the air pressure of the refuge bay being higher than the surrounding areas [46]. Harmful gasses can thus not enter the refuge bay.

All end-users mentioned above are usually connected to one CA network. The supply pressure should thus always be sufficient for the end-user component with the highest pressure requirements to function properly [30], [34], [36], [47]. Low pressure may lead to a loss of production and time [48]. A graph of a typical daily pressure requirement profile and equipment with the highest pressure requirements for the specific period of the day are displayed in Figure 5.

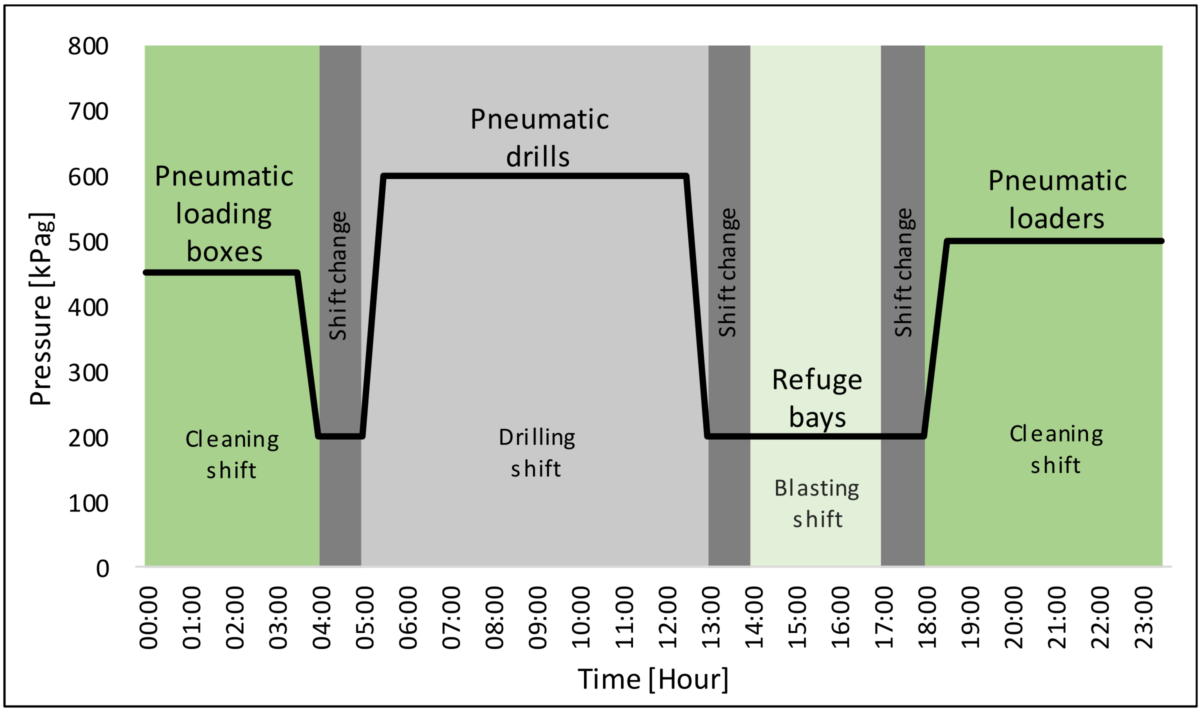


Figure 5: Underground compressed air pressure requirement profile

Compressed air generation

Deep-level mining shafts generally require a high volume of CA between 400 and 600 kPa_g. Multi-stage centrifugal compressors are typically used as these machines meet the CA needs of deep-level mines [34], [36], [47], [49]. These machines are easy to operate and maintain due to the mechanical simplicity.

A centrifugal compressor motor can have a rated power of up to 15 MW [30], [32], [36]. Various combinations of these machines could be operated in parallel to accommodate the flow and pressure requirements of different shafts [50]. Multiple compressors are usually housed in a building known as a compressor house. A typical surface layout of compressors on a deep-level mine is displayed in Figure 6.

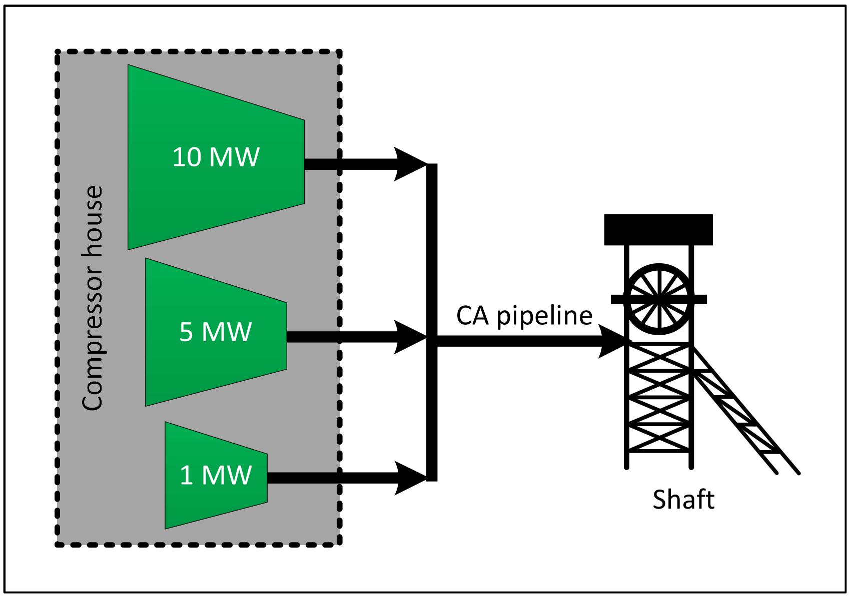


Figure 6: Compressors configured in parallel

Most deep-level mines have a combination of base load and trimming compressors. Base load compressors are usually operated at full capacity to maintain the CA pressure above a minimum set point. Trimming compressors are used to increase the supply in periods of higher demand [34], [47], [51].

Centrifugal compressors are categorised as dynamic compressors as these compressors can regulate the flow to the system by means of mechanisms which include inlet guide vanes and blow-off valves [34], [39], [47], [52].

Distribution of compressed air

CA generated by the centrifugal compressors is distributed via an uncomplicated network of above-ground steel columns. The diameter of these columns range from 150 to 700 mm and are connected in 9 m sections [12], [30], [32].

CA columns are used to connect various compressor houses and shafts. This connection is often referred to as a CA ring and could be used to match the supply and demand on various shafts [18], [30], [50], [53]. In some instances, the network of two shafts may also be connected underground [54]. A diagram of a typical deep-level mine surface CA ring is displayed in Figure 7.

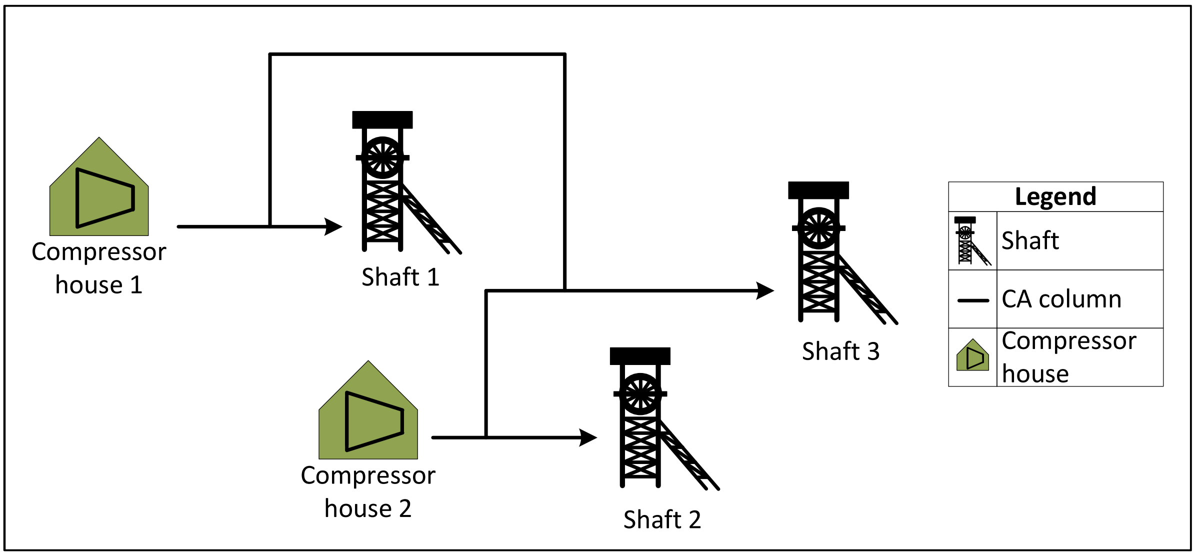


Figure 7: Surface compressed air ring

At the shaft, the CA is channelled to underground. A shaft could extend up to 4 km downwards to the deepest level [18]. There are usually multiple underground levels connected to the shaft. These levels further extend into sub-levels, called half levels, which will also be referred to as haulages. Haulages act as a route for transporting ore, services (CA, water, and electricity) and people. Figure 8 shows a diagram of the typical route followed by the CA from the compressors to underground.

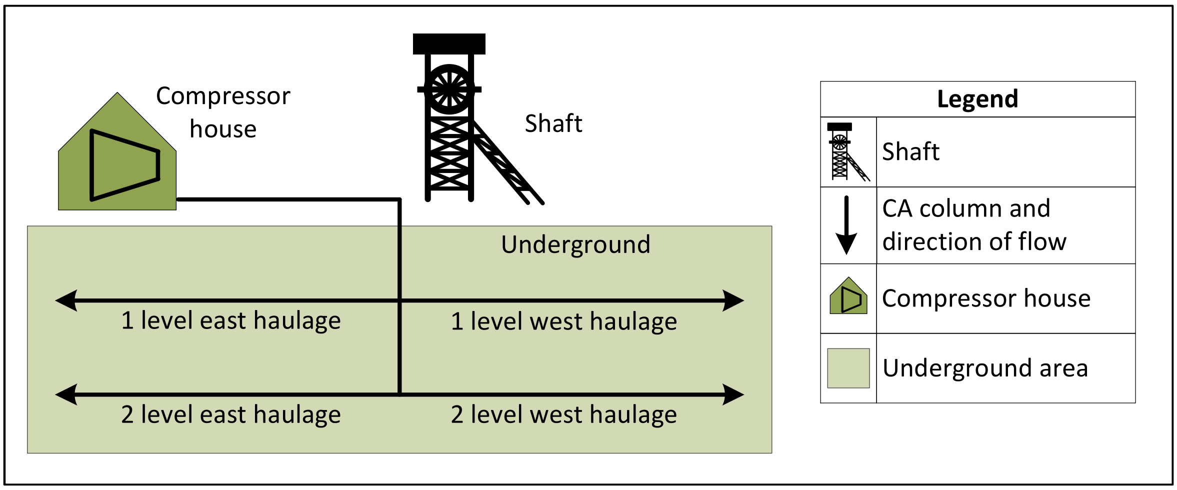


Figure 8: Simplified diagram of an underground compressed air layout

From the half level haulage, the passageways branch off further to what are known as cross cuts. The cross cut is a small passageway going to the working areas, also known as stopes. Service pipes and a ladder can be found entering the cross cuts.

Ore from the working areas is transported to the haulage via loading boxes located in the roofs of the haulages. Ore from new areas under development is scooped onto the track-bound hoppers with the use of the pneumatic loaders as described previously. A simplified diagram of a haulage CA network is displayed in Figure 9.

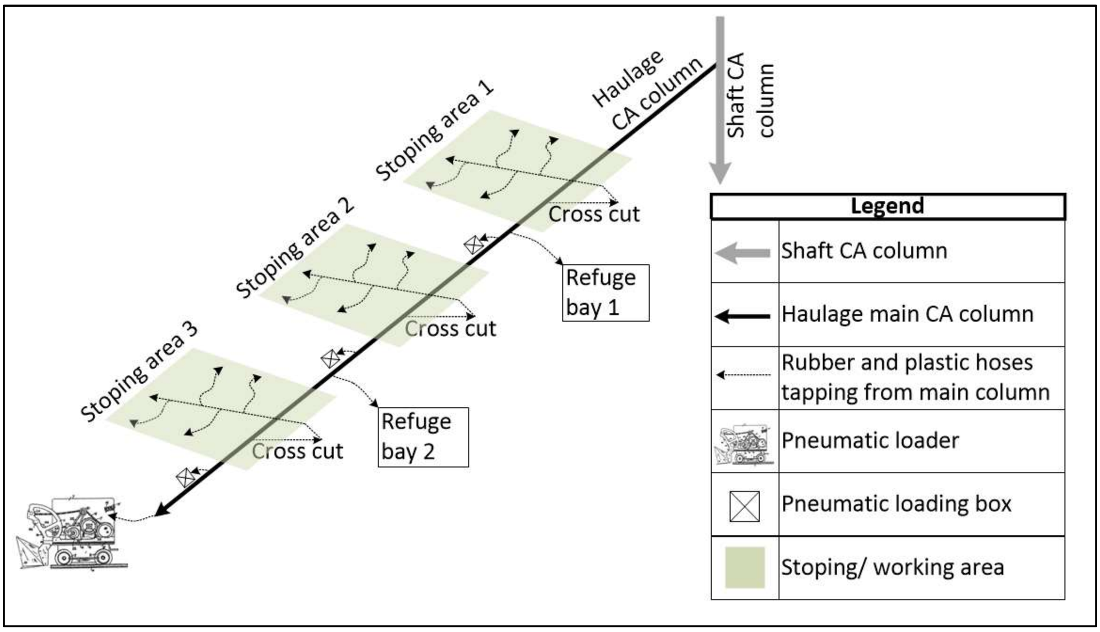


Figure 9: Haulage compressed air network (Adapted from [46])

The CA column follows the haulage traveling ways from the shaft until it reaches the point of use at the stoping areas. The working areas are usually the furthest points from the surface compressors. Stoping and development normally occurs near the end of the half level due to the depletion of ore reserves closer to the shaft [55]. This could be as far as 10 km from the CA supply point [16]. The CA is channelled to the stoping areas via plastic and rubber pipes as indicated in Figure 9. The top view of a simplified stope layout is displayed in Figure 10.

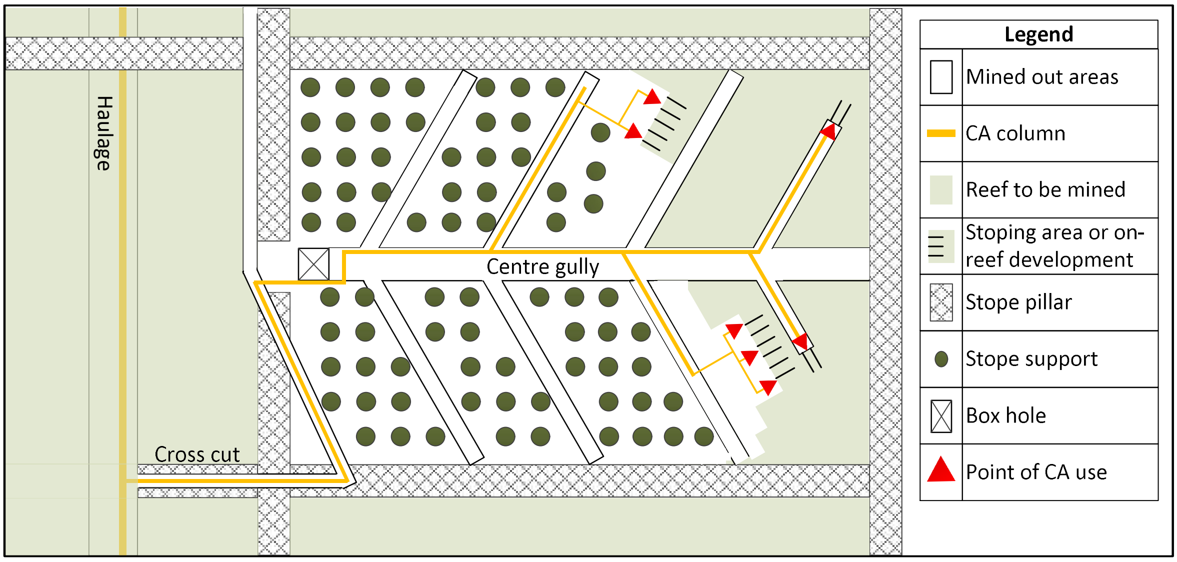


Figure 10: Top view of a simplified stope layout (Adapted from [56])

The yellow line in Figure 10 indicates how the CA is channelled from the haulage through the cross cut and into the stoping area [57]. The pipe sizes tend to decrease as it extends further from the shaft [39]. Quick clamp-on pipes are used to channel the CA in the working areas due to the dynamic nature of the stoping areas [29], [39], [58]. In the stopes, the CA is channelled by means of a plastic pipe following a centre gully where it then branches to the stope face or the on-reef development areas.

Near the development or stoping areas, the CA equipment is connected to the plastic pipe with a flexible rubber hose. A manifold with multiple connections is located at the stope face where drilling occurs. Here, multiple CA equipment could be connected to the manifold.

Underground gold and platinum (PGM) mines usually practice narrow-reef mining methods, hereafter referred to as conventional mining, and will thus share a similar layout to the one indicated in Figure 10 [11], [38], [39], [59]. Photos of rubber hoses connected to a common manifold are illustrated in Figure 11.

Figure 11: Rubber pipes connected to a compressed air common manifold

The underground dynamics could also have an influence on the CA consumption and wastage [31], [39]. Extension of these networks increases the likelihood of CA wastage and increases the difficulty in supplying the services to the point of use [8], [16], [32], [42], [55].

1.1.4 Compressed air mismanagement

In Section 1.1.3 the different CA consumers used in the mining cycle were discussed. A constant baseload of flow is required to deliver the desired pressure to the end-users [21], [33]. These end-users, however, need to share the CA with other unauthorised consumers which include pipe leaks and CA used for ventilation purposes.

A graph illustrating the total shaft CA consumption and the simulated CA consumption by authorised mining equipment on a typical deep-level mining shaft can be seen in Figure 12. Only the major authorised CA consumers are indicated in Figure 12. The consumption of pneumatic loading boxes was assumed to be negligible.

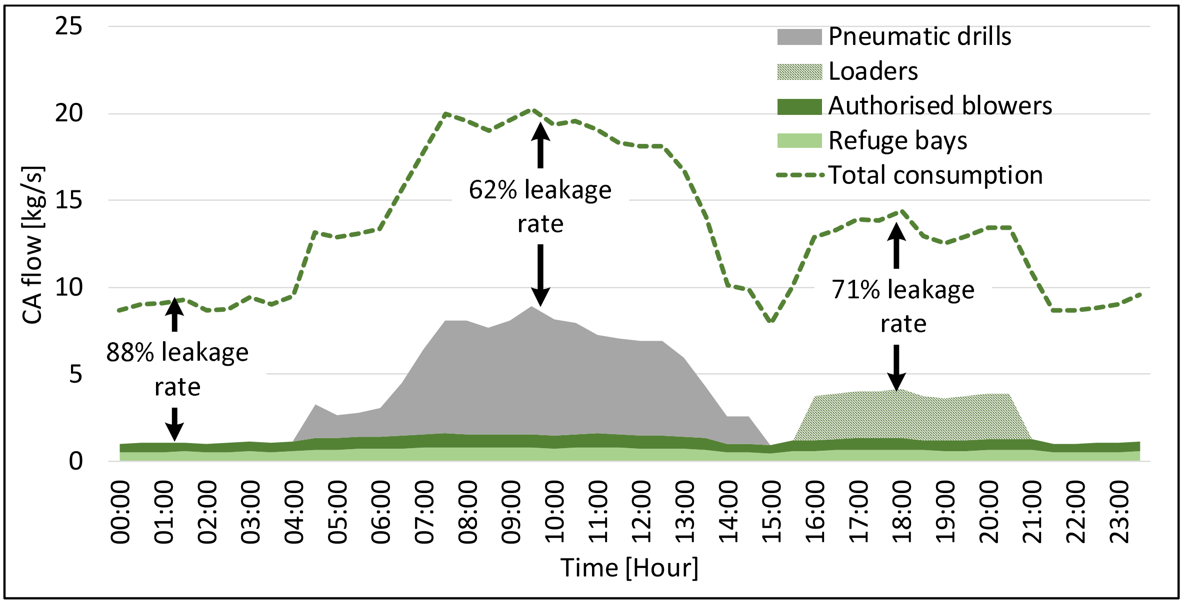


Figure 12: Typical compressed air consumption of authorised and unauthorised end-users

The maximum shaft CA consumption on a typical weekday occurs for a ± 6-hour period, as illustrated in Figure 12 [16], [30], [50], [60]. As mentioned in Section 1.1.3, this period is known as the morning or drilling shift. Numerous pneumatic drills, together with other pneumatic equipment, are operated during this period. The combined CA flow requirements of these equipment are significantly higher than the requirements outside the drilling shift.

According to the data in Figure 12, there is an average difference of 75% between the total shaft CA consumption and the authorised consumers. The baseload CA consumption required by the shaft to maintain the desired pressure can mainly be attributed to leaks [21], [29], [31], [33], [46], [57].

Exposure to the harsh environment underground results in the deterioration of compressed air infrastructure [35], [40]. High moisture and temperature results in corrosion, while rock falls and heavy machinery can result in punctured columns. Studies found that unintentional leaks also often occur at the flanges and other connections [32], [33], [61] [36]. A photo of a flange leak and a rusted column is shown in Figure 13.

Figure 13: Compressed air flange leak and rusted column

As mentioned previously, the CA network will expand to accommodate the shaft expansion. Larger networks thus result in more connections and pipe area which increases the potential for leak formation. In addition, the larger network results in more unknown areas where the compressed air could be lost and increases the area of the column where potential leaks can form. The dynamics and expansion of the underground network over time has been linked to increased use and inefficiencies [36], [44], [57], [62].

There is often no structure to how the CA system is constructed and little to no people fully know the underground distribution network [30], [39], [63]. The size and age of the network on a typical shaft adds to the difficulty in analysing the system and planning for future expansion [30], [47], [64], [65].

Apart from natural causes, such as rust, CA wastage could also occur due to negligence [32], [39]. As previously mentioned in Section 1.1.3, CA is easy to use and scalable. However, these advantages increase the probability of wastage [30], [34], [47], [49], [66] Studies also found major leaks in the inactive areas that were supposed to be sealed off from the CA system [16], [34], [40], [46], [54], [67]. Apart from negligence, unauthorised airflow in inactive areas can be the result of illegal mining activities [47].

Employees working in hot environments, such as factories and underground, use the easily accessible CA to cool themselves. To make matters worse, negligent personnel leave the hose open, even when there is no one present [30], [32]–[34], [68]. This could also explain why one of the major areas where leaks are found is the stoping area [29], [57], [69]. Fans or special CA-reducing nozzles should rather be used for this purpose [42], [49], [51].

Repairing all CA leaks is not realistic. Studies suggest that an acceptable leakage rate is 10–15% of the total consumption [32]–[34], [48], [49], [70]. A leakage rate of 86% of the total consumption has been recorded on an CA system of a factory [33]. Deep-level mines are no exception as it is approximated that only 10% of the CA consumption is used for underground pneumatic drilling which can directly be related to production [29]. According to Nehler, large potential remains for reducing wasted on large industrial CA systems [60].

Apart from leaks, excessive pressure drop is another problem that comes with using CA as an energy carrying medium. Sometimes, mining personnel use CA materials that are easily accessible. This culture of using what is available often leads to restrictions in the system leading to excessive pressure drops [39], [65]. Additional energy is used to supply CA at a higher pressure to accommodate for pressure losses [49], [53], [57], [71]. An acceptable pressure drop from the point of supply to the point of use is less than 10% [49].

1.2 Energy efficiency on deep-level mine compressed air systems

1.2.1 Preamble

In the previous section, it was identified that there is significant scope for wastage reduction on deep-level mine CA systems. Solutions to leak management presented by various studies in the deep-level mining and non-mining industry is investigated in this section. The purpose of this section is to evaluate available technologies for electricity cost savings on deep-level mining and identify drivers that will motivate energy efficiency on deep-level mine CA systems.

1.2.2 Existing leak management methods on deep-level mines

Decreased leakage rate through compressor control

Large, inefficient CA systems are common on deep-level mines. These systems were installed when the price of electricity was low when compared to other expenses. There was thus little need for systems to be energy efficient [48], [62]. Deep-level mines also typically have a large spare installed capacity of CA to avert the risk of production loss and accommodate the future expansion of the mine similar to other industries [63], [66]. Once installed, deep-level mine CA systems tend to be operated at maximum capacity [50], similar to ventilation systems [55].

Deep-level mines operate on a 24-hour shift cycle, as mentioned in Section 1.1.3. CA flow and pressure demands vary with each of the shifts. There is an estimated 6-hour period where the pressure requirement is at its highest to supply the rock drills with enough pressure. Electricity cost saving initiatives on the compressors are usually not allowed during the drilling shift as it is believed that it will have a negative influence on the shaft production [48], [72], [73].

Constantly operating the compressors at full load will result in excess CA pressure during the low-demand shifts [30], [40], [60], [73]. The rate of leakages increases with an increase in pressure [30], [61], [74], [75]. Reducing the system pressure during the low-demand shifts will mean that less CA is wasted through existing leaks. The compressor load could thus be reduced as less CA needs to be generated.

Although controlling the compressors does not reduce the size or number of leaks underground, it does treat the symptoms of the leaks [30], [33], [34], [36], [74]. The purpose of compressor control is to meet the supply and demand of the CA [36], [42], [50]. Electrical energy reduction could thus be achieved through supply management without affecting mine production.

As mentioned in Section 1.1.3, compressors have certain mechanisms to reduce the CA supply. These include the guide vane and blow-off valve. Throttling the CA flow can, in turn, result in electricity cost savings. The compressor efficiency is, however, negatively impacted when throttling a compressor [71], [75].

Ideally, compressors should be stopped as it will result in more energy efficiency savings than operating the compressor at partial load [36], [67], [69]. Some of the compressors typically found on deep-level mines are more than 40 years old. The throttling capabilities of these compressors are sometimes very poor resulting in low supply-side management savings [52], [53].

Stopping compressors comes with various setbacks. Compressors are put through high mechanical strain when started up [65], [76]. Mining personnel are concerned that the high strain can cause increased wear and even breakdowns which may result in production loss [52], [64], [65], [75]. Mining personnel are usually more open to the idea of stopping and starting the smaller trimming compressors as production can continue if these compressors break down [73].

Reducing the compressor pressure set point or stopping the compressor to match the supply with the demand of the end-users is generally a low-cost method to significantly reduce the compressor electricity consumption [30], [63], [71]. However, electricity cost savings are limited to the minimum demand of the CA end-users.

Improved compressor control can be achieved by using sophisticated compressor control systems, called Dynamic Compressor Selectors (DCS). These control systems can select the more suitable compressors to operate, based on compressor efficiency, demand, and compressor location [30], [36], [77]. DCS can also change the set-point pressure to meet the end-user demand [16], [75].

Throttling and isolation

As mentioned in Section 1.1.3, all end-users are normally connected to a common CA ring. The entire ring must be pressurised to meet the needs of the end-user with the highest pressure requirements. There are some sections which will thus be oversupplied [37], [44], [48]. The leakage rate and thus the electricity consumption of the compressors will increase with an increase in ring pressure. Valves are used as a solution to this problem [44].

There are various areas which can be isolated or throttled on deep-level mines. Surface bypass valves are used to throttle the flow of CA to a shaft to meet the pressure requirements [32], [33], [44], [76]. Underground level valves further decrease the demand of CA by meeting the unique needs of the underground levels [30], [37], [40].

Timer based isolation valves, installed near the working areas, are used to further decrease the demand for CA by isolating the working areas when CA is not needed [37], [42], [48] However, installing valves come with a high initial capital investment [44].

Conventional leak auditing and repair on deep-level mines

Controlling the supply of CA to the consumers through methods such as compressor or valve control, as discussed earlier, will be referred to as supply-side management. Changes to the consumers, such as leak repairs and adding additional drills, will be referred to as demand-side management. The consumption graph depicted in Figure 12 was adapted to illustrate the effect of supply- and demand-side management on the authorised and unauthorised consumers in Figure 14.

When reducing the shaft CA consumption through supply-side management, the consumption of both the authorised and unauthorised consumers are affected, as seen in Figure 14. The consumption ratio of both these consumers remains unchanged. Supply-side management only treat the symptoms of leaks and can only do this up to a certain extent until the performance of the end-users is negatively affected [66], [70].

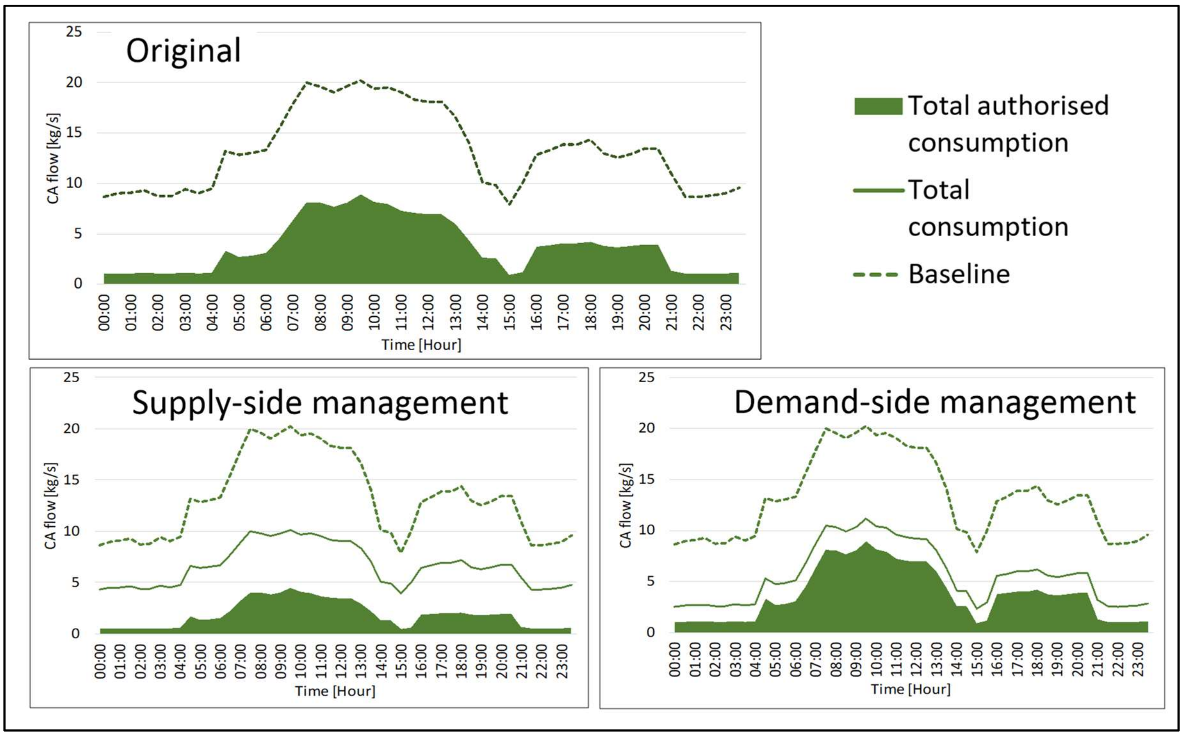


Figure 14: Difference between demand- and supply-side management

Demand-side management initiatives will typically involve the repairing of CA leaks. As seen in Figure 14, reducing the total shaft consumption does not mean that the consumption of the authorised consumers needs to be reduced as with supply-side management. The obvious solution to effectively address most of the problems associated with CA, such as the high cost of generation, is to reduce the demand by repairing leaks [30], [44], [64], [69].

One study claims that demand management (leak repair and CA alternatives) can result in up to 70% of the total energy saved on a system with the balance being supply-side management (compressor and valve control) [63]. Energy managers can thus lose out on a large part of the CA system savings potential if leak management is avoided.

Leak repair is considered a small change to the CA system which requires little investment to realise substantial benefits [35], [63], [66]. Mining personnel are generally more motivated to implement leak management solutions when compared to implementing supply-side management initiatives.

As mentioned previously, CA systems on deep-level mines are intrinsically large and very complex [32]. Repairing all the underground leaks is thus not realistic [31]. In addition to the large network, CA leaks are not easy to find visually when compared to other fluids like water and steam [32], [33]. Auditors may thus have to enter dangerous areas of the mine to detect leaks if visual or audible methods of leak detection are used.

Energy managers frequently resort to comprehensive audits which involve visual inspections of the entire CA system to locate leaks [12], [16], [21], [32], [33], [35], [40]. Using conventional leak detection methods are resource-intensive and impractical, especially when conducted on a CA system as large as that of a deep-level mine [31], [32], [53], [73].

Of all the steps in the electricity cost savings potential determination, audits of the underground CA system requires the most time [72]. In one study, it took four auditors three months to conduct a comprehensive audit of an entire shaft [31]. Stopes, which were found to be one of the areas where most of the wastage occurs, are also often avoided in such comprehensive audits [32], [37].

It has been determined that 80% of CA wastages that were repaired were the result of repairing 20% of the leaks [31], [32]. Fewer resources would be required if an audit method can be developed to identify the largest leaks without the need for a comprehensive audit of the entire shaft.

Identified leaks are not always easy to repair and may require planned maintenance [40]. The mining company will normally provide the resources for the leak repair. Once a leak is found, good practice would be to prioritise the leaks for repair in an attempt to maximise the effect of the resources [14], [78].

Leaks are normally prioritised based on rate of CA flow through the leak. The leakage rate through an opening in the column can be determined by substituting the hole size and line pressure into an empirical equation such, as Equation 1 [12], [34], [79], or by using graphs of experimental data [80].

$$\dot{m} = C_{discharge}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}\left(\frac{P_{line}}{RT_{line}}\right)A\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \tag{1}$$

Where:

$\dot{m}$ =	Mass flowrate of CA [kg/s]
$C_{discharge}$ =	Discharge coefficient [0.6 for a hole with sharp edges]
k =	Air specific heat ratio [Assumed value = 1.4]
P_{line} =	Pressure in the CA column [kPa_g]

R = Gas constant [0.287 kJ/kg·K]

T_{line} = Temperature in the CA column [K]

The difficulty in using Equation 1 comes when determining the size of the hole. Leaks through opening in the CA column come in all shapes and sizes [81]. Many leaks are typically in the form of flange leaks of which it is difficult to find the leakage rate with this equation [40], [49]. In some cases, the leak flowrate is determined with subjective methods such as listening or feeling [32], [40], [61], [67], [82].

The effect of repairing a leak is often solely done with the use of Equation 1, by relating the leakage rate directly to the compressor electricity consumption and thus cost saving [39]. Auditing committees and the client are often left dissatisfied with the effect of the leak repair [30], [32], [40], [68].

In one deep-level mine CA leak-reduction case study, less than 25% of the expected energy savings was achieved [68]. Repairing leaks has a dual positive effect on the system [40]. Firstly, it reduces the consumption, and secondly, the column pressure drop reduces which results in a higher pressure at the column end. Figure 15 graphically illustrates what happens when a leak is repaired on a CA column.

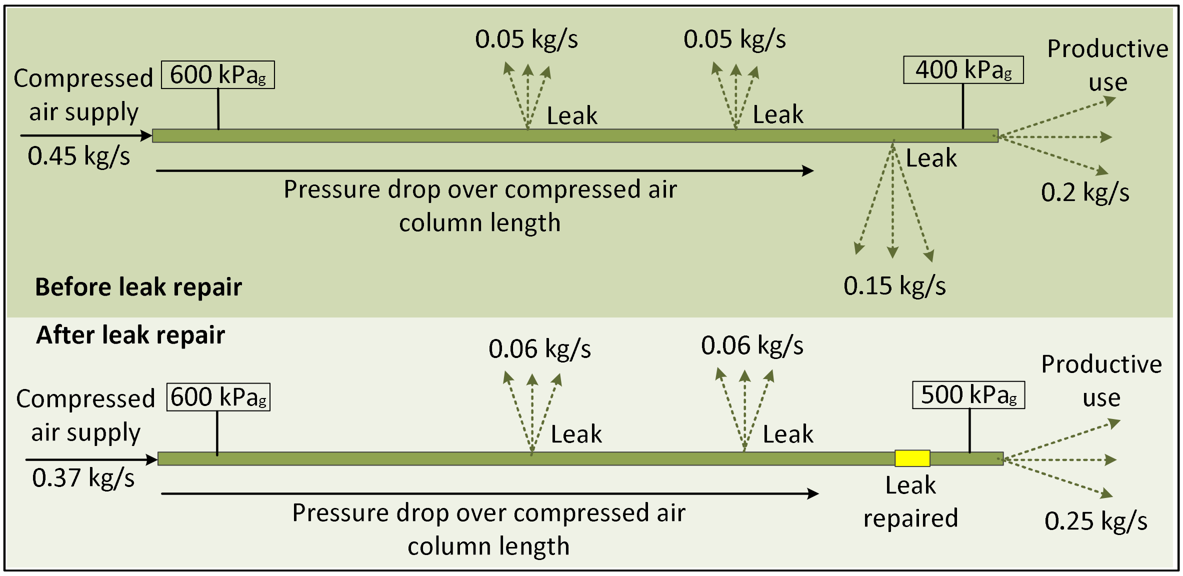


Figure 15: Effect of leak repair on a compressed air column (Adapted from [51])

A CA column with various leaks is graphically illustrated in the upper block of Figure 15. The column is supplied with 0.45 kg/s of CA at 600 kPa$_g$. Pressure losses over the column and leaks result in only 0.2 kg/s of the supplied CA reaching the end-user at a pressure of 400 kPa$_g$. The bottom block displays the same column after the 0.15 kg/s leak in the upper block was repaired.

Repairing the leak in Figure 15 resulted in a decreased CA consumption which, in turn, will result in an increased column pressure according to the Darcy-Weisbach equation (Equation 2) [83]. The leakage rate through existing leaks will increase with an increase in the column pressure according to Equation 1 [30]. This explains why repairing a 0.15 kg leak only resulted in a 0.08 kg/s reduction in consumption.

$$\Delta P = f\left(\frac{\rho V^2}{2D}\right)L \qquad (2)$$

Where:

ΔP =	Pressure drop over pipe length (L) [kPa]
f =	Frictional factor. Calculated with the Moody diagram [84] [Dimensionless]
ρ =	Fluid density [kg/m³]
V =	Mean velocity of the fluid [m/s]
D =	Pipe inside diameter [m]
L =	Length of pipe under investigation [m]

Other leaks in the CA column should thus also be taken into consideration when using Equation 1. Simulation packages, which will be discussed in Section 1.2.5, can be used as a solution to this complex problem.

Benchmarking models for shaft compressed air consumption

As mentioned previously, leaks should be prioritised to make effective use of the given resources. Similarly, audits should be conducted on the shafts that show the highest potential for CA efficiency improvements [18], [21]. Some studies simply select the highest electricity consuming shafts as it is reasoned that more savings can be achieved on these shafts when compared to lower electricity consuming shafts [53].

Benchmarking is a powerful tool used when implementing energy efficiency initiatives [85]. A study done by Oosthuizen proved that fewer resources are required to identify compressor energy reduction potential through benchmarking models when compared to conventional energy audits [72]. Benchmarking involves comparing the actual performance of an entity to that of a reference performance [86], [87]. Benchmarking can be used to [14], [18], [85]:

- Identify scope for electricity cost saving potential,
- Provides a standard with which shaft CA consumption can be measured against, and
- Shaft budgeting purposes.

Multiple studies have been done on benchmarking deep-level mine CA systems. A short summary of existing benchmarking models is listed below:

- Compressor energy consumption and shaft production [14].
- Compressor energy consumption, ore mined, and mining depth [18].
- Comparing the energy consumption ratio of the peak drilling shift to the blasting shift [21], [72].
- Mining level CA consumption and production [16], [31].

Data for benchmarking should be readily available to allow for continuous benchmarking [18]. A popular KPI used in benchmarking mine CA systems is the compressor energy intensity which uses readily available production data [21], [88]. The energy intensity of a shaft can be calculated with Equation 3 [14].

$$I = \frac{E}{P} \tag{3}$$

Where:

I =	Shaft compressor energy intensity [MWh/ tonne]
E =	Monthly compressor energy consumption [MWh]
P =	Mass of ore mined for the month [kilo tonnes]

Mines that show a large production output could give a false indication of being energy efficient [14], [53], [72]. The graph in Figure 16 is a benchmarking case study done on multiple shafts.

The energy savings potential in Figure 16 is determined by comparing the CA intensity of the shafts. Mines E and F were singled out for being the largest compressor energy consumers. The case study was conducted on Mine E, as it was a “smaller mine” when compared to Mine F, thus having more scope for improvement [14].

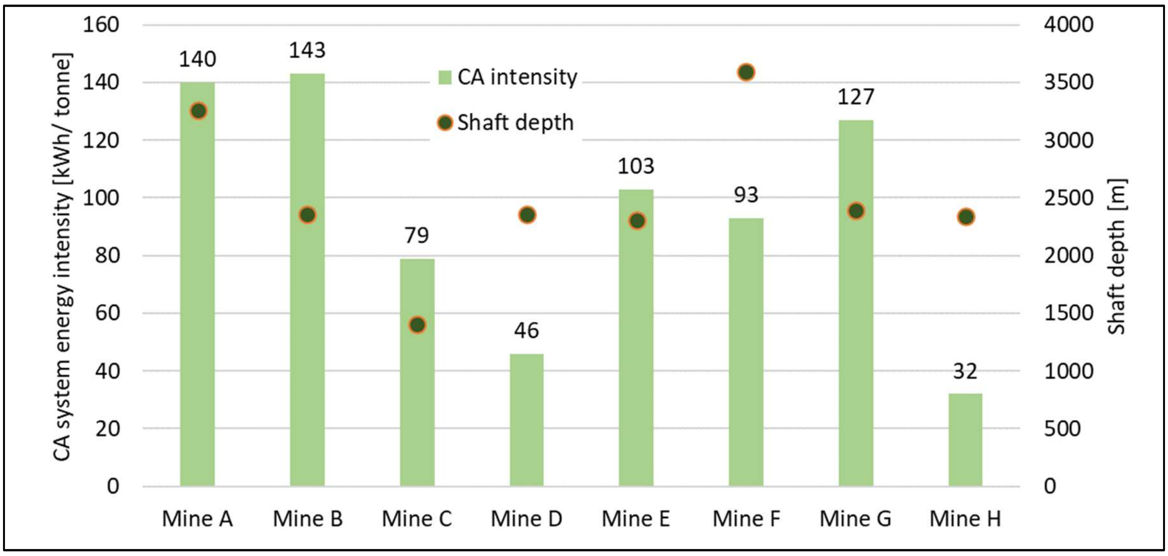


Figure 16: Shaft benchmarking with compressor energy intensity and shaft depth (Adapted from [14])

An updated benchmarking model to the model of Van der Zee was created by Cilliers [18]. In addition to the shaft production that was included by Van der Zee, Cilliers included the shaft depth and season into a model which can be used to predict the required compressor energy consumption. The model created by Cilliers is given in Equations 4 and 5. The model in Equation 4 has an R^2 value of 0.792 while the model in Equation 5 has an R^2 value of 0.861 [18].

$$E_{summer} = -269.82 + 1.69D + 28.55P \tag{4}$$

$$E_{winter} = 406.76 + 0.78D + 54.16P \tag{5}$$

Where:

E_{summer} = Monthly required compressor energy in the summer [MWh]

E_{winter} = Monthly required compressor energy in the winter [MWh]

D = Shaft depth [m]

P = Mass of ore mined for the month [kilo tonnes]

Existing benchmarking models for deep-level mines discussed in this section give energy managers an indication of the amount of energy that can be saved on the shaft by implementing a combination of demand- and supply-side initiatives. Separating the potential for supply- and demand-side management could help energy managers to allocate resources.

Integration of savings methodologies

As discussed previously, CA leak audits and repairs often end in disappointment as the potential savings from repairing leaks is often overestimated. Repairing a leak typically results in an overall increase in the system pressure and a decrease in flow which is not always equal to the leakage rate of the repaired leak, as explained in Figure 15.

An integrated approach of the above-mentioned leak management solutions is required to increase the benefit of electricity cost savings from leak repair [13], [16], [30], [31], [49], [54], [65], [66]. CA can be oversupplied and electricity wasted if an integrated approach is not implemented.

The integrated approach involves a simple, four-step process. As mentioned before, changing the compressor control to achieve electricity cost savings on a deep-level mine is considered as the “low hanging fruit” of CA system savings. This is followed by isolating end-users with high pressure demand from the system.

The final step of the integrated approach is underground leak repair which is often left until last due to the implementation difficulty. Underground leak repair was not included in the diagram of Marais [30], but was later included by van der Zee [14]. A diagram of the integrated approach is displayed in Figure 17.

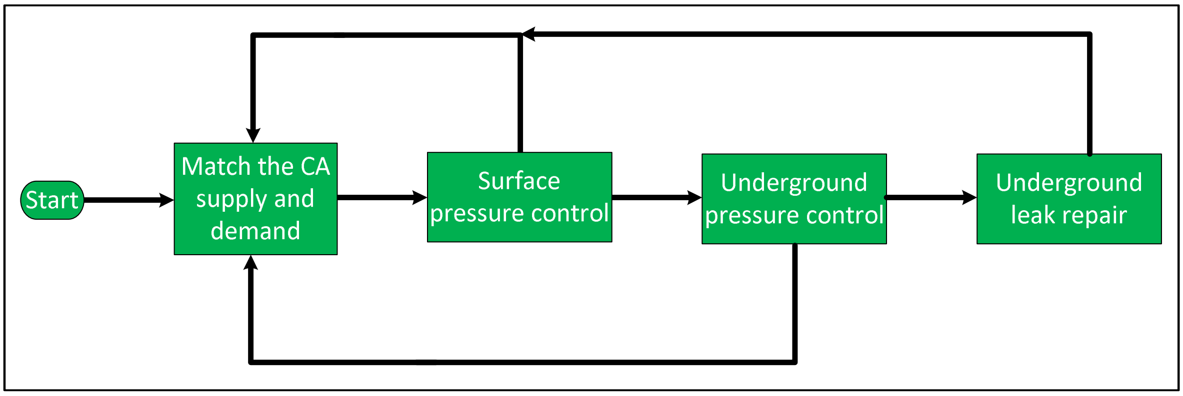


Figure 17: Diagram of an integrated compressor energy savings approach (Adapted from [14] and [30])

As seen in Figure 17, after completing one of steps two to four, the user is again directed to the first step which involves matching the supply and demand through compressor control [40]. If this step is avoided, CA reduction on the demand-side may be blown off into the atmosphere through the compressor blow-off valve. However, CA can still be wasted even if good supply-side management practices are implemented.

Deep-level mine compressors typically have limited throttling capabilities. Demand-side management can result in the air supply being blown off into the atmosphere if the shaft demand is not sufficiently reduced for a compressor to be stopped [21], [30], [47] Valve control and leak repair can thus be of little to no use when the compressor throttling limitations are reached [34], [64], [66].

Critical analysis of deep-level mine compressed air efficiency studies

Numerous deep-level mine CA leak management initiatives have been discussed in this section. These initiatives are listed and individually evaluated in Table 1. Shortcomings in existing studies and suitable leak management methods will be highlighted in this evaluation.

Table 1: Summary of CA savings initiatives on deep-level mines

Ref.	Supply-side management	Leak auditing	Bench-marking	Shortcomings
[50]	✓	-	-	No underground leak repair initiative.
[18]	Limited	-	✓	Focus on benchmarking of compressor power.
[39]	-	✓	-	Prioritised levels and cross cuts with the use of pressure loggers. Numerous loggers were required to complete the exercise. Using 10 kPa interval pressure loggers were found to be inaccurate [16].
[47]	✓	-	-	Focus on compressor and valve control.
[89]	✓	-	-	Development of an improved compressor control philosophy.
[44]	✓	-	-	This study mostly deals with CA valve control.
[31]	-	✓	✓	Prioritised levels based on production. Required the auditors to search for leaks in pipe columns that can be 10 km in length. This method could not be used on non-production levels.

Ref.	Supply-side management	Leak auditing	Bench-marking	Shortcomings
[40]	✓	✓	-	Although this method prioritised a section of the mine for leak auditing it still involved resource-intensive audits of the entire section.
[75]	✓	-	-	A dynamic compressor selector was developed.
[64]	✓	-	-	The method developed and the case studies on which the method was implemented is focused on supply-side management.
[30]	✓	✓	-	The leak auditing methodology involved a detailed audit of the entire CA system.
[32]	-	✓	-	The leak auditing methodology involved a detailed audit of the entire CA system.
[54]	✓	-	-	Electricity cost savings through compressor and valve control. No focus on reducing underground leaks.
[53]	✓	-	-	This study only focused on cost-effective compressor and valve control.
[29]	-	✓	-	A new technology to reduce CA wastage in the stoping areas. No method of identifying where the wastages are.
[21]	Limited	-	✓	A benchmarking model based on the CA energy profile. However, this model is limited to the Eskom evening peak period [72].
[77]	✓	-	-	This study focused on the isolation of certain parts of the CA system.
[37]	✓	-	-	Underground automated valve control was used to reduce the CA consumption of a shaft.
[69]	✓	Limited	-	This study focussed on compressor and valve control and had limited information on underground leak detection methods.
[65]	✓	-	-	A new controller for efficient compressor control was developed.
[71]	✓	-	-	Focused on compressor control.

Ref.	Supply-side management	Leak auditing	Bench-marking	Shortcomings
[36]	✓	-	-	Focused on compressor control.
[14]	Limited	-	✓	Benchmarking deep-level mine production with compressor energy consumption.
[52]	✓	-	-	A new mechanism to replace inefficient guide vanes for compressor supply-side management.
[76]	✓	-	-	This study deals with the typical challenges faced when implementing supply-side management initiatives on a deep-level mine CA system.
[72]	Limited	Limited	✓	A benchmarking model for deep-level mine CA systems using the electricity consumption profile of the compressors.

According to Table 1, most methodologies focus on reducing CA leakage rates with compressor or valve control. If all the control infrastructure is in place, these methodologies require minimal alterations to achieve significant savings on a CA system. Automated control methodologies on deep-level mine CA systems are, however, limited to the end-user requirements.

Leak auditing on deep-level mine CA systems have received little attention, as can be seen in Table 1. Existing methodologies are limited to audits of the entire CA system, or at best, identifying inefficient levels. These methodologies are resource-intensive and ineffective in the identification of leaks.

1.2.3 Challenges to energy efficiency measures on compressed air systems

Alternatives to compressed air

CA has been identified as a very inefficient energy carrying medium [34], [51], [68]. When compared to other energy carrying mediums on deep level mines, CA is the most inefficient energy carrying medium according to Table 2 [46]. It has been recommended that industries move away from CA as an energy carrying medium [42], [51].

Table 2: Efficiency of energy-carrying mediums for stope drilling [46]

Drilling % energy delivered to point-of-use	Compressor or pump efficiency	Distribution efficiency	Energy left after leaks	Efficiency of drill	Overall efficiency
Compressed air	58%	75%	18%	24%	**2%**
Oil electro-hydraulic	80%	80%	100%	36%	**23%**
Hydropower-pumped	85%	80%	95%	31%	**20%**
Hydropower-gravity	96%	89%	90%	31%	**24%**
Electric drill	100%	90%	100%	35%	**31%**

Electricity is the most efficient energy carrying medium according to Table 2. Replacing pneumatic equipment with electric equipment, such as electric rock drills, has been proposed [90]. The electric rock drills proved to have lower maintenance when compared to CA drills. Replacing pneumatic drills with electric drills is, however, very costly [90].

Hydraulic technology has been implemented successfully on various deep-level mines in South Africa. Hydraulic loading boxes and drills, to name a few, have eliminated the need for high CA pressure [46]. Apart from the increased energy efficiency, it also does not create an uncomfortable and unsafe environment, as it does not produce mist and has a lower noise emission than pneumatic drills [46], [48].

On a complete hydraulic mine, CA is still required to provide breathable air to the refuge bays [29], [42]. Partial conversion to hydraulic technology could lead to electricity cost savings on the compressors, but still comes with a high initial capital cost [29], [42], [46].

Although hydraulic and electric technologies outperform pneumatic technologies when it comes to energy efficiency, the equipment is more expensive. Replacing the existing CA system will also prove to be a challenging task due to the high capital requirements and resistance to change [32], [39], [46], [48], [71].

Optimisation of existing CA systems should be pursued as far as possible [29]. As an example, the pneumatic cylinders on loaders could be replaced by larger cylinders to reduce the need for high pressure [30], [42], [48]. Leak repair has also been proven to have a much better payback period when compared to replacing or adapting pneumatic equipment and is the preferred solution to deep-level mine inefficiencies [39].

Existing instrumentation

Prior to 2015, ESCos received funding from Eskom, South Africa's state owned electricity provider, to implement electricity cost saving projects on industries such as deep-level mines [30], [54], [75], [91]. This funding could be used to purchase infrastructure which assisted in the electricity cost saving efforts [71], [92]. Since 2015, funding provided by Eskom for Integrated Demand Management (IDM) initiatives has been reduced. ESCos now need to find innovative ways to use existing infrastructure to obtain electricity cost savings [13], [21], [93].

Automated valves installed on CA columns are used to control the flow in a network. Some uses of valves include the isolation of areas where maintenance is required and the channelling of available CA to the areas where it is needed most. Similar to the distribution network discussed in Section 1.1.4, valves are also subjected to the harsh underground environment which causes damage [30], [37], [40], [44]. Leaking valves mean that it is difficult to channel CA where it is required.

To complement the automated valve operation, measurement instrumentation is installed. Properly functioning measurement instrumentation could prove to be very valuable to energy efficiency initiatives [13], [75]. These instruments give mining personnel and auditors the ability to better understand and control the CA system [21], [31], [40], [94], [95]. In some cases, a lack of instrumentation may also mean that an energy efficiency project cannot be implemented [37], [75], [96].

Instrumentation comes with high initial capital cost [14], [37] meaning that it will sometimes only be installed if absolutely necessary [36]. Like the CA piping network and valves, the little instrumentation found on some mines is also subjected to the harsh underground environment, meaning that regular maintenance is necessary for the equipment to function properly [40], [73], [75]. Poorly instrumented shafts are common because understanding the CA system is a low priority for mining personnel [12], [13], [39], [44], [97].

Communication mediums, usually in the form of communication cables, are required to send information to and receive information from underground instrumentation. For cost and maintenance reasons, instrumentation is rarely found outside a 500 m radius from the shaft. It was mentioned previously that CA columns can extend as far as 8 km from the shaft. CA information is thus limited to the station area [53], [94]. Proxy metering techniques can be used as a solution to obtain the necessary measurements. With proxy metering, available data can be used to calculate the desired parameter [98].

Benefit quantification

When implementing an electricity cost saving initiative, it is important to quantify the benefit of the initiative for purposes such as ESCo compensation and future project planning. Quantification of the electrical cost reduction resulting from the project is usually done by comparing the power consumption of the system before the implementation of the initiative, known as the baseline, with the post-project implementation power profile [34], [95], [99].

The baseline power profile is developed from data collected before the implementation of the electricity cost saving initiative. Before this data can be collected, the boundaries of the project should be identified. The electrical consumers encapsulated in this boundary will determine the baseline power profile and how the impact of the project will be measured [99], [100].

External changes (e.g. weather) and internal changes (e.g. increase in operations) affect the measurement of the project performance. For accurate performance measurement the effect of system changes that occurred not as a result of the cost saving initiative should be excluded from the performance measurement. The baseline needs to be adjusted by means of a Service Level Adjustment (SLA) method to exclude the effect of external changes [62], [99], [101]. A SLA method will also keep the baseline relevant for a longer period [62]. Figure 18 illustrates how savings are quantified with an SLA method.

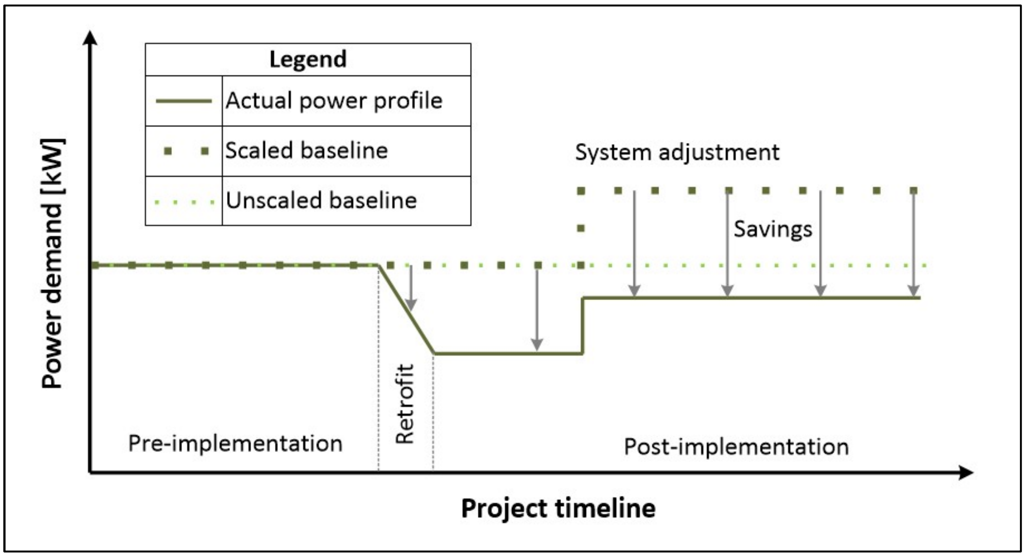


Figure 18: Service level adjustment example (Adapted from [96] and [100])

From the graph in Figure 18, the system retrofit resulted in electricity cost savings. During the initial period after the retrofit, there was no difference between the baseline and the unscaled baseline. A system adjustment, however, resulted in an increased power consumption. The scaled baseline accounted for the system adjustment by predicting what the power profile would have been if no electricity cost savings initiative was implemented [96], [100]. Equation 6 is used to calculate the project impact.

$$Project\ impact = Adjusted\ baseline - \ Actual \tag{6}$$

Measurement and Verification (M&V) teams will choose an SLA method based on the influence of different factors on the system energy consumption [96]. The power consumption of a residential area may, for example, be influenced by the number of houses or the ambient conditions. In some cases, however, the system being improved is very simple and requires no adjustment [99], [100].

Deep-level mine CA systems are typically complex and undergo frequent non-project related changes which affect the system operation [37], [53], [72]. SLA methods are needed to accurately quantify the electricity cost savings [101]. Popular SLA methods for deep-level mine CA systems involve relating production output (tonnes of ore mined in a specified period) to compressor power consumption [62], [101]–[103].

Using a SLA method of production and compressor power consumption is not recommended as there is typically a poor correlation between production and compressor energy consumption [62], [99], [101]. Incorrect compressor electricity cost savings can thus be calculated with such a model. A graph showing the correlation between production and compressor electricity consumption of five shafts (three platinum and two gold mining shafts) is illustrated in Figure 19.

Shaft O has the highest correlation between compressor energy consumption and production of the shafts in Figure 19. However, the R^2 value of this shaft was only 0.21 which indicates a poor correlation. Also noticeable in the graphs of Figure 19 is the near-horizontal slopes of the shaft regression lines. This indicates that the energy consumption of shafts barely changes with a change in production. An explanation for this occurrence can be the prominent CA baseload consumption typical to deep-level mining shafts as discussed in Section 1.1.4.

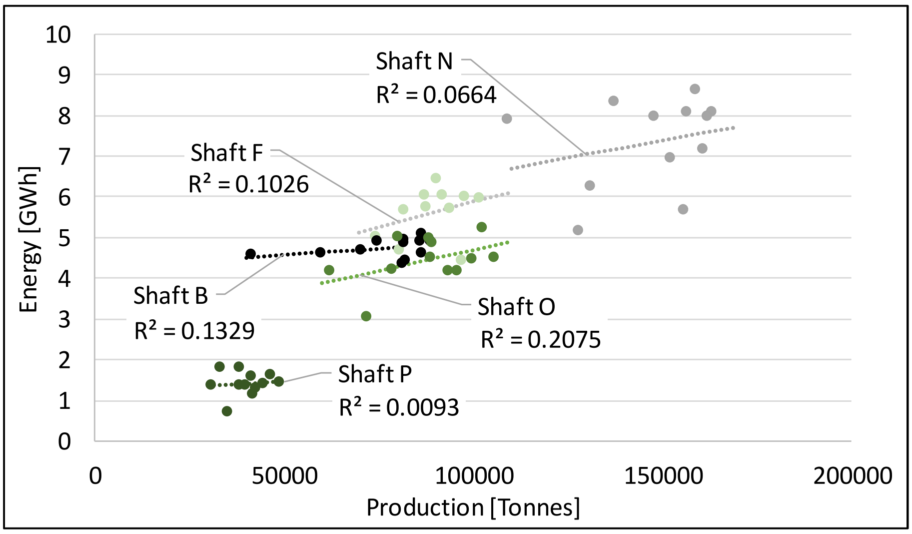


Figure 19: Monthly shaft compressor energy consumption versus tonnes produced

An alternative to directly correlate compressor energy consumption to shaft production is the peak scaling SLA method. Peak scaling is an indirect method of using production to quantify the energy savings achieved on a CA system. As mentioned in Section 1.1.4, the CA and thus electrical energy consumed during the drilling shift is more closely related to the shaft production [21], [29], [62].

The idea behind the peak scaling is to link the average drilling shift compressor electricity consumption to production. Compressor electrical data is less sensitive and easier to obtain when compared to shaft production data [21]. Peak scaling involves adjusting the baseline to match the peak drilling shift power consumption of the improved power profile [101]. An example graph of the peak scaling SLA method being implemented on Shaft F is presented in Figure 20.

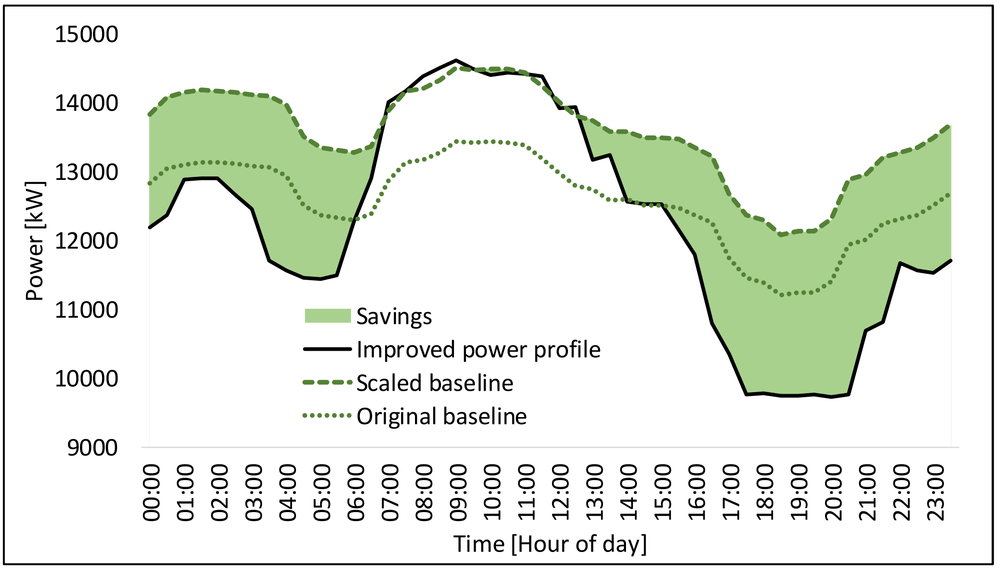


Figure 20: Peak baseline adjustment example graph

The project impact (savings) illustrated as the green area in Figure 20 can be calculated with Equations 7 to 9.

$$PI_i = BS_i - IP_i \tag{7}$$

$$BS_i = SF \times BO_i \tag{8}$$

$$SF = \frac{IP_A}{BP_A} \tag{9}$$

Where:

PI_i = Project impact for hour i [kW]

BS_i = Scaled baseline power for hour i [kW]

IP_i = Improved profile power for hour i [kW]

SF = Scaling factor

BO_i = Original baseline power for hour i [kW]

IP_A = Average power consumption of the improved power profile during the drilling shift (typically from 07:00 to 13:00) [kW]

BP_A = Average power consumption of the original baseline during the drilling shift [kW]

Apart from being related to production, which is a poor predictor of compressor electricity consumption, the peak scaling SLA method is also not able to accurately predict the savings of an all-day energy efficiency improvement on the compressors. An all-day efficiency improvement will result in less energy being used during the peak drilling shift thus resulting in a lower adjusted baseline [101].

On analysis of historic Eskom IDM projects, which related the compressor electricity consumption to production, it was found that the SLA method of deep-level mine CA systems had to be changed to accommodate for an increase in the shaft demand [104], [105]. One of the reasons for the increase in demand includes an expansion in the operations. There is thus a need to find a non-production related SLA method [101].

Energy efficiency measures could also yield additional benefits which exclude electricity cost savings. These benefits are referred to as non-energy benefits and can include improvements in a facility's production performance. Quantifying these benefits can aid in motivating mining personnel to participate in energy efficiency projects [59], [60], [66].

In Section 1.2.2 it was mentioned that CA leak repairs can result in increased pressure and decreased consumption. Some leak repair initiatives have resulted in disappointing electricity cost saving [30], [32]. As with numerous other efficiency studies, the increases in pressure resulting from the leak repairs have not been quantified [30], [32], [60]. The improvement in pneumatic equipment performance could thus not be estimated.

Pneumatic equipment tends to underperform when operated at lower than the recommended pressure, as mentioned in Section 1.1.3. Drill rig operators need to drill a fixed number of holes each day to meet production targets. If the drilling task is not completed due to underperforming pneumatic equipment, the explosives cannot be inserted for blasting, resulting in production loss [39].

The graph in Figure 21 shows how the drill penetration rate can increase with an increase in CA pressure. Increased system pressures can thus have a positive impact on mine production [31], [40], [57].

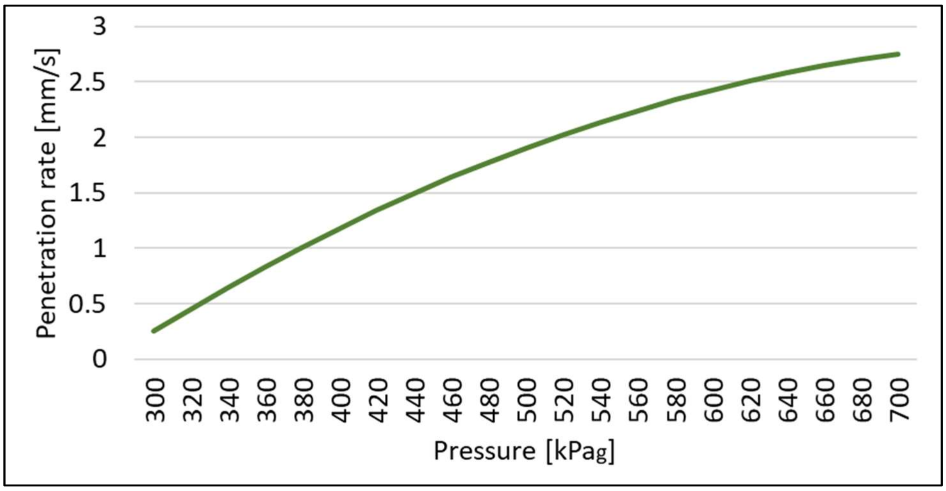


Figure 21: Influence of compressed air pressure on the penetration rate of a typical pneumatic drill[2] [106]

From the information above, non-energy benefits can play an important role in motivating mining personnel to implement energy efficiency projects. In some cases, it may be the deciding factor on the implementation of a project. These benefits must thus be quantified, preferably in monetary terms, to further motivate the implementation of the project.

[2] Chosen drill bit size = 30 mm; Force exerted on the bit-rock interface = 500 N

Quantifying some non-energy benefits are, in some cases, very difficult. There are multiple factors, other than an increase in CA pressure, which can complicate the quantification of non-energy benefits [57], [59]. One study investigated the non-energy benefits from improving a deep-level mine ventilation system. The non-energy benefits could, at best, be quantified by surveying experts on what they think the benefits will be [59].

Underground safety

The mining environment is known to be unsafe. Most of the documented incidents on South African mines occurred at deep-level platinum and gold mines. In 2017, 39 fatalities and 1018 injuries occurred on gold mines while 28 fatalities and 1156 injuries occurred on platinum mines.

Combined, platinum and gold mines account for 76% of the fatalities and 82% of the injuries on South African mines [107]. As mentioned previously in Section 1.1.3, CA is extensively used all over the mine. Auditors are exposed to the dangerous underground environments when conducting audits.

Figure 22 displays the South African mining safety statistics. According to the pie chart in this figure, most of the incidents occurred underground. When analysing the underground safety statistics, most of the incidents occurred near the stope face [46], [56], [107]. As mentioned in Section 1.1.4, the stoping area is also known to have the highest CA wastage rate.

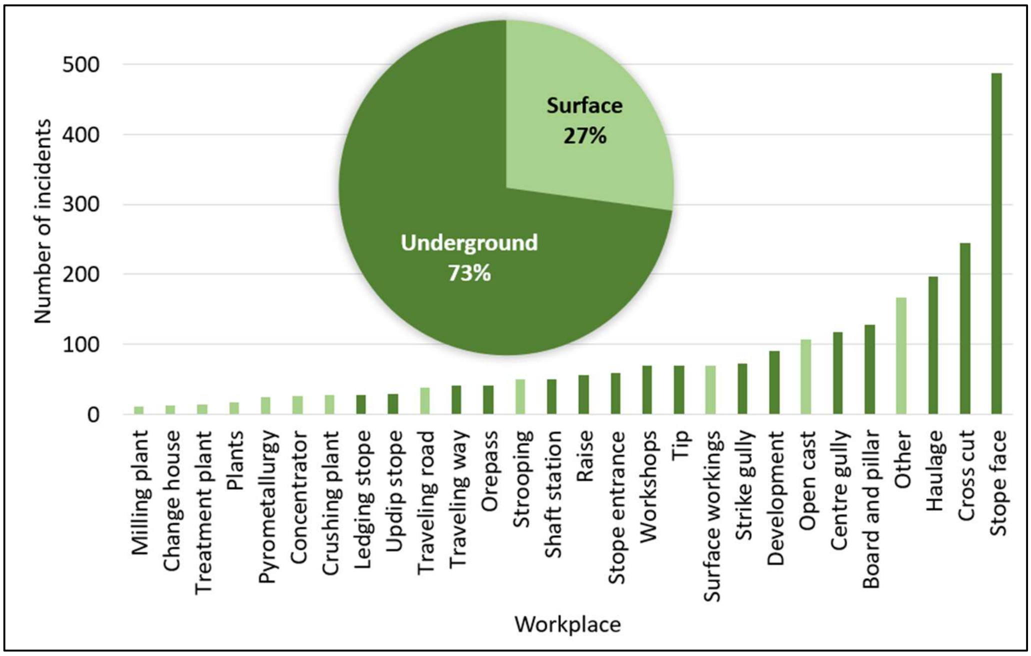


Figure 22: South African mine safety incident statistics 2017 [107]

For the auditors to reach the stopes, they must first go through various other areas such as the haulage, cross cut, centre gully, and board and pillar which hold various safety risks. People working in these areas every day are more familiar with the dangers in these areas when compared to the auditors which need to cover a large range of the underground mining areas. Safety should thus also be kept in mind when developing a CA auditing methodology.

Mining priorities

After a drastic decrease in the ESCo funding provided by Eskom mentioned previously, ESCos are now mostly, if not completely, reliant on mine resources to implement electricity cost saving initiatives. It is, therefore, important to understand the perception of mining personnel with regards to energy efficiency [108]. This will assist in motivating mining personnel to dedicate resources to assist with energy efficiency initiatives.

One of the main barriers to energy efficiency in a company is the priorities of the company. The core business of deep-level mining in South Africa is precious metal production. Resources are thus often only focused on meeting production targets [29], [66], [75], [97].

Mining companies may be motivated by the financial benefits of energy efficiency initiatives [12], [30]. However, capital expenditure required for these initiatives is often withheld when markets are not good [8], [13]. Similar to other production industries, services, such as CA, will often only receive attention when it starts to have a negative impact on production [35].

Underground CA systems are complex. A knowledge of the entire system is required to sufficiently address inefficiencies. Historically, some mining companies appointed dedicated teams with the sole responsibility to understand and maintain the system [39]. Large-scale retrenchments, as mentioned in Section 1.1.1, have made it difficult for dedicated personnel to be appointed [32].

CA infrastructure responsibilities are usually delegated to the mining and engineering workers responsible for the specific area [63]. This raises a problem as there is often a lack of communication between different sectors in a company [108]. A complete knowledge of the underground CA system is thus rarely obtained.

In the pursuit to completely understand a deep-level mine CA system, skilled workers are often required. However, one of the main issues faced by South African mines is a shortage of skills. These skills are required for the successful implementation of energy efficiency initiatives [109].

With a lack of knowledge, industrial companies usually tend to develop their own truths regarding energy efficiency [36], [48], [65], [108]. Personnel, such as managers who do have the technical skills to manage CA systems, are often flooded by the amount of resources they have to manage [97], [109].

1.2.4 Non-mining leak management solutions

Apart from the deep-level mining industry in South Africa, CA is also extensively used in other industries around the world. The problem of leaks is also not limited to CA systems. Leaks also lead to losses in other large pressurised fluid distribution systems such as gas, oil, and water [81]. Similar techniques applied to these systems may also prove to be applicable to the deep-level mine CA systems.

Losses incurred on systems, such as natural gas and oil pipelines, hold severe consequences not only financially, but also environmentally [78], [81], [110]–[115]. As an example, a leak on a natural gas pipeline can pollute the environment, while water leaks can result in damages to surrounding infrastructure.

Monitoring the leaks on pressurised fluid systems, which exclude CA systems, can thus be more crucial than leak detection on CA systems. It is thus argued that technologies on fluid transportation systems such as oil, water, and natural gas is better developed than that of deep-level mine CA systems. These advanced methods could thus hold a solution to improved leak monitoring [116].

Before the leaks can be repaired, it must first be found, quantified, and prioritised [31], [39], [40], [63], [110]. As mentioned in Section 1.2.2, this is mainly done with conventional walk-through audits of an entire underground CA network. This can be a dangerous, resource-intensive method to locate leaks. The need for a leak detection solution without the need to patrol an entire fluid network has also been identified in the non-mining industry [16], [110], [113], [117], [118].

There are various leak detection techniques used in the non-mining industry. Like deep-level mines, patrolling fluid distribution networks is a popular method used in the non-mining industry [33]. CA networks of non-mining industries are generally smaller than that of a deep-level mines [30], [73]. Conducting walk-though audits on these small systems is regarded more feasible. A method is required to localise the largest leaks to a manageable region on a system as large as that of a deep-level mining CA system [31].

Oil and gas are distributed in piping networks that can have a total length of more than 100 km [119], [120]. Pressure and/or flow sensors are installed on certain intervals over the length of the pipeline to determine the location of a leak via a mass balance or irregular pressure drop [119], [121]. Installing the equipment over a smaller interval will result in more accurate leak locating but will be more expensive [114]. A diagram of sensors installed over a pipe length is shown in Figure 23.

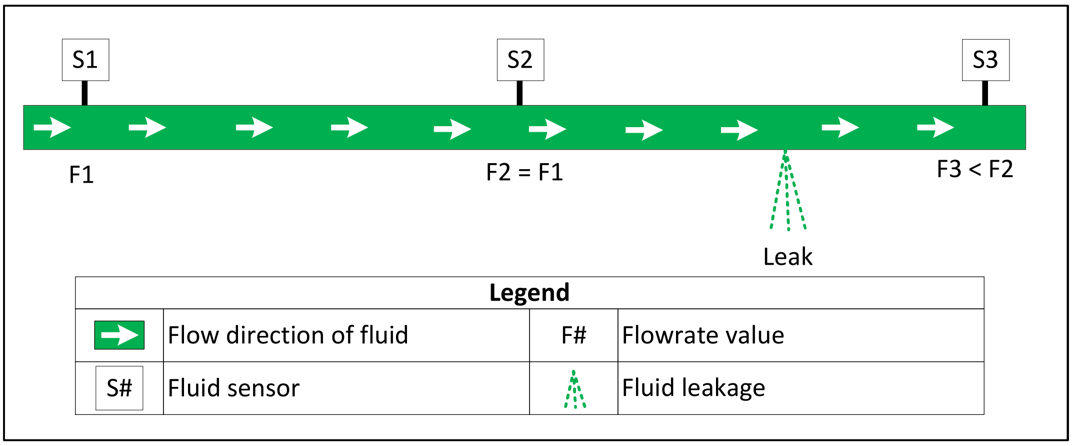


Figure 23: Incremental fluid sensor installation

As seen in Figure 23, localising the leak to a certain segment of the pipe can be done by simply determining if the flow downstream of the pipe is less than the upstream flow. Like oil and gas distribution networks, water distribution networks also need to transport water over kilometres of piping length. However, water distribution networks are generally more complicated and need more complex leak analysis techniques.

When a pipe bursts in a water distribution network, pressure waves are emitted from the location of the burst which then propagates through the network as illustrated in Figure 24 [114]. In complex water distribution networks measurement devices, such as acoustic emission sensors and pressure loggers installed in strategic arrays, can measure the disturbances in the pipeline.

The data from the acoustic emission sensors and complex algorithms are used to calculate the approximate location and sometimes severity of the pipe burst [122]–[124]. This method allows auditors to quickly detect a pipe burst and send out a crew of people to repair the leak.

Step-testing is a manual method used to localise an area where potential leaks can be found [118], [125]. These tests involve installing a flowmeter upstream of the area being tested and then isolating certain areas one by one to determine which areas have the largest leakage rate.

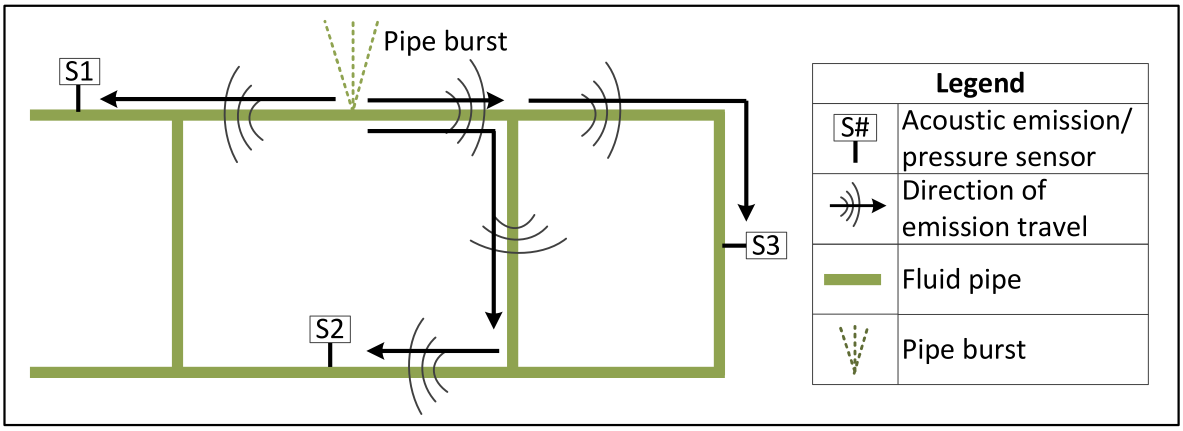


Figure 24: Pressure wave propagation through a fluid system (Adapted from [123])

Minimal instrumentation is required to conduct step-testing audits, as the auditors use the existing isolation valves on the network and a flowmeter. Figure 25 illustrates an example of a water distribution network. Step-testing can typically be done by installing a flowmeter at the water source and isolating each region one by one to determine which region has the highest leakage rate.

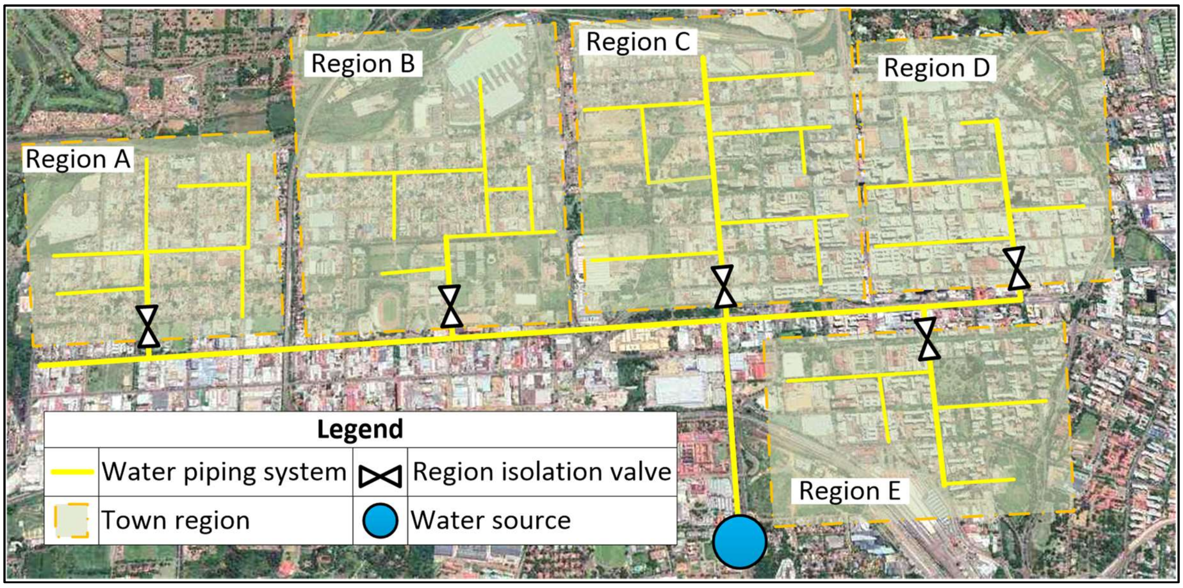


Figure 25: Area isolation valves on a fabricated water distribution network[3]

Figure 26 displays the flow meter results of a step-testing audit that was conducted in a residential area between 00:00 and 02:30 in the morning, which is known as the Minimum Night Flow (MNF) period which will be discussed later in this Section 2.2.2. In this case study, various valves were closed at different times. This resulted in a gradual decrease in

[3] Background image obtained from Google Earth 2019

the water flow. With this data, the auditors were now able to isolate the leaks to specific areas [126]. A more in-depth discussion on the step-testing method will follow in Section 2.3.3.

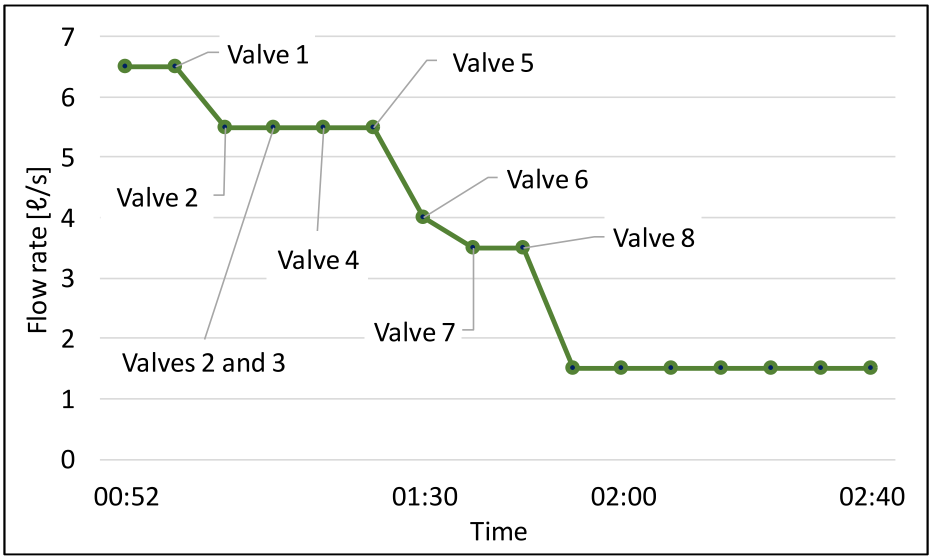


Figure 26: Results from a step-testing audit (Adapted from [126])

CA leak auditing and repair should continuously be implemented to maintain the system efficiency [32], [48]. This, together with other inherent characteristics of deep-level mine CA systems and the challenges this industry currently faces, should be considered when deciding on a leak auditing technique. An ideal leak management solution for deep-level mines should meet the following criteria:

- Cost-effective,
- Localisation of leaks, and
- Quantification of the identified leaks.

There are various requirements which leak detection systems must meet in the non-mining industry. Some of these requirements are not critical for deep-level mine CA systems. As an example, instantaneous leak detection is not critical. Furthermore, some of the leak detection methods used in the non-mining industry cannot be applied to deep-level mine CA systems. Gas pipelines, such as that of CA pipelines, are known to have a poor signal-to-noise ratio. Leak detection through the installation of an array of measurement instrumentation should preferably only be implemented on liquid distribution networks [127].

Some leak detection methods will work better than others for certain applications [110], [124]. An assessment of the existing leak detection and quantification methods, some of which were also mentioned in this section, was done in Table 3. The following criteria were used to evaluate the leak detection methods:

A – Leak localisation

B – Quantification of fluid being wasted

C – Cost-effectiveness of method being used

Table 3: Evaluation of non-mining leak management solutions

Ref.	Method	A	B	C	Discussion
[34] [63] [67]	Walk-through audit	✓	✓	-	A very resource-intensive way to find leaks on a system as large as a deep-level mine CA system. Exact location and magnitude of leaks can, however, be determined with this method.
[113] [115] [123] [122] [128]	Installing an array of sensors	✓	Ltd.	-	This method is more suitable to use in complex systems, such as water distribution networks, to instantaneously know the location of a leak and avoid environmental and property damage. This method also often does not allow the quantification of the leak. It also involves solving complex equations.
[114] [119] [120]	Installing sensors over certain intervals of the pipeline	✓	✓	-	Not cost-effective to install measurement instrumentation in increments over the entire length of all the deep-level mine CA columns.
[33] [34] [39] [49] [61] [80] [118] [125]	Localisation and quantification involving area-specific drop testing	✓	✓	✓	Minimal equipment is required to conduct these tests. However, it will be difficult to quantify the leaks on specific areas with this method because it is difficult to obtain the pipe volume in the area being investigated.
[112] [113] [117] [121] [129]	Sensor installation at the start and end of the pipeline	✓	✓	-	These methods are more suitable for the detection and localisation of instantaneous leaks in an unsteady state system. It will not be cost-effective to implement such a leak detection system on deep-level mines.

Ref.	Method	A	B	C	Discussion
[118] [125] [130] [126] [131]	Step-testing	✓	✓	✓	Step-testing is a very simple method to localise leaks to a manageable area using existing infrastructure. This method tends to be faster than comprehensive audits of an entire fluid system and can quantify the amount of fluid being wasted.

According to the leak detection methods listed in Table 3, there are only two methods which fulfil all the criteria of an ideal deep-level mine CA leak detection method. These are step-testing and pressure drop testing. Leak localisation through pressure drop testing is, however, difficult as it requires that the auditors should know the CA network volume. This may require a comprehensive audit of the system.

Numerous fluid leak detection methods investigated involve the widespread installation of instrumentation which will require a high initial capital investment. Complex optimisation models are then required to instantaneously identify the leak location. In some cases, the magnitude of the identified leaks cannot be calculated, unless the data is analysed with more complex analysis methods [78].

Studies done in 2009 and 2011 found that complex optimisation models are rarely implemented in practice [33], [87], [108], [125]. Recent case studies by a leading company in water distribution system leak detection services show that uncomplicated methods, such as step-testing, are still used to identify leaks [126], [130], [131].

1.2.5 Energy efficiency drivers

Step by step method

It has been proven that energy efficiency projects perform better when mining personnel take responsibility for the projects instead of relying on outsourcing [12], [32], [63], [69]. There are limited skilled mining personnel that often do not have the time nor resources to investigate and implement energy efficiency initiatives [13], [48].

As mentioned in Section 1.1.1, the mining industry has significantly reduced the number of permanent employees. These redundant labourers generally have limited skills [17], [65]. Knowledge gained from the ESCos could be carried over to these personnel to improve the energy efficiency of their shaft [63], [108]. Training redundant mining personnel to follow an energy management plan can improve job security and be of benefit to the mining industry [17].

The development of an energy management plan is important when implementing energy efficiency initiatives [13], [87], [132]. Deep-level mines rarely have such plan [32], [39], [48], [70]. Systems, such as CA systems, are generally only dealt with when a breakdown is issued. Following a step by step method to energy management compiled by experts, such as ESCos, will assist the new auditors to come to conclusions that are similar to that of experts [31].

Leak awareness

Energy efficiency initiatives are often restricted by information barriers. Efforts in leak management will, most likely, not occur if no one is aware of the problem or how to solve the problem [66], [68]. Raising awareness of energy wastage is one of the first steps to improving the energy efficiency of a company [13], [27].

The importance of addressing information barriers is also recognised in the ISO 50001 standard for energy management [13]. Creating awareness through reporting and training could alleviate these barriers [12], [18], [28], [39].

For a report to be generated, data on the CA system is first required. Value can be gained from the reports if in the hands of people who can understand the information in the report and who are in the position to act on the information [12], [48].

It was found that actions will follow soon after reports were given to competent mining personnel [32], [87], [94]. Figure 27 displays the effect on a mine cooling system after a report informed the general manager and group engineer of problems on this system. The cold dam temperature decreased which resulted in improved service delivery to the underground mining personnel.

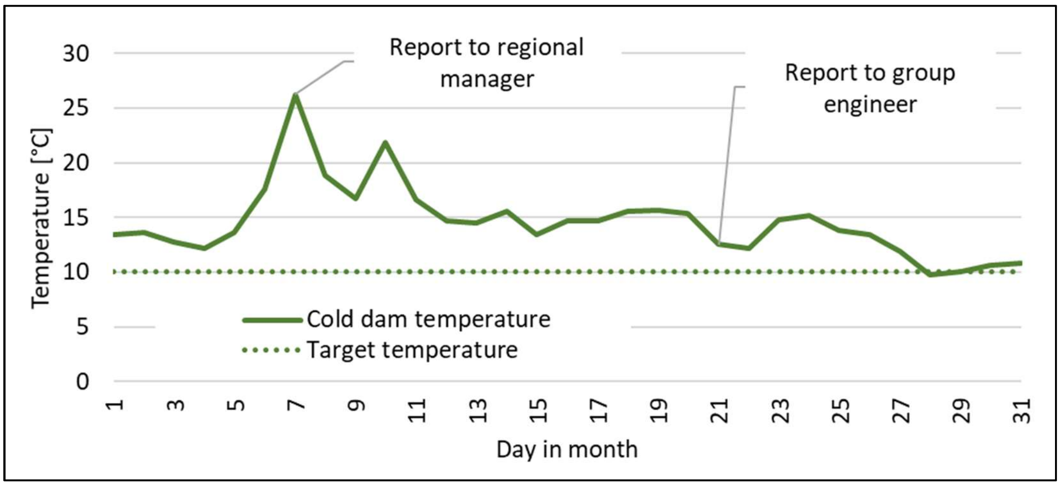


Figure 27: Effect of reporting on the cooling dam temperature of a deep-level mine [94]

CA is mainly used by mining personnel, such as rock drill-, loader-, and loading box operators. These mining personnel generally do not receive reports with regards to CA energy efficiency. Uneducated mining personnel will be unable to understand the report [94], while other more competent personnel may not be willing to change in the way they use CA. Vocational training can thus result in improved awareness of energy efficiency and lead to a culture of waste minimisation on a deep-level mine [27], [33], [35], [108].

Simulation

Underperforming energy efficiency projects could be avoided with better planning and execution. A simulation of a CA network acts as a powerful tool to energy efficiency audits as it can assist in the planning of the energy efficiency project [28], [87]. Instead of testing a scenario on a CA network, the scenario could rather be simulated by using a computer model [64]. Other benefits of using a simulation include:

- Scope identification,
- CA system design improvements,
- A reduction in the implementation period, and
- Cost-effective use of resources.

CA simulations involve solving complex mathematical equations [112]. Simulation packages reduce the time and complexity of constructing a CA system simulation by incorporating the mathematical models into one user-friendly platform. There are various available simulation packages which could be used to simulate deep-level mine CA systems [39].

Constructing and using a simulation of a deep-level mine CA system does not come without its difficulties. Although the simulation packages have made it easier for the users to construct a simulation, there are still some basic skills and knowledge the user requires [28], [65]. Even with the basic skills, it is a time-consuming process to construct and calibrate the simulation [16], [21], [73].

Obtaining enough data to construct a well-defined deep-level mine CA system simulation may also be very difficult and time-consuming [30]. Multiple studies have thus created methods to avoid the use of simulations [21], [30], [64], [72], [73].

New technology

Labour relations has been identified as one of the major challenges faced by South African mines in Section 1.1.1. Implementing new technologies in the underground mining environments has the potential to improve energy audits [133] through, for example, avoiding labour intensive leak audits by automating CA leak detection. Risks to the safety of auditors can also be avoided, as the need to enter dangerous areas, such as the stopes mentioned in Section 1.2.3, is avoided [134], [135].

One method to automate leak detection would be the installation of more CA measurement instrumentation in areas, such as the stopes. It was, however, discussed in Sections 1.2.4 and 1.2.3 that the installation of more instrumentation would be capital intensive and thus avoided by the struggling South African mines. Additionally, the instrumentation would frequently need to be uninstalled and installed in the new working areas due to the dynamic nature of underground mines.

Advances in portable sensors and Unmanned Aerial Vehicles (UAVs) have allowed auditors to remotely take measurements in hard-to-reach and/ or dangerous areas. In one study, UAVs have been used to detect CA leaks with portable acoustic sensors on an experimental setup of industrial CA columns [134], while in another study, UAVs mounted with multi-spectral and thermal imagers have been used to detect geological discontinuities in an underground mine [135].

Similar problems faced with using UAVs and CA instrumentation in the intricate underground environment is the harsh underground conditions which can damage the equipment and communicating with the equipment [135]. A study done by Singh et al. investigated possible solutions to communicate with devices underground using the Internet of Things (IoT). One of the concepts mentioned in this study was for the devices to first log the data and then, when capable, transmit it to a base station for further processing [133].

1.3 Problem statement and study objectives

Deep-level mine compressed air energy efficiency studies predominantly focussed on supply-side management (compressor and automated valve control) [30]. Supply-side management is limited to end-user pressure requirements [47]. Demand-side management initiatives, such as leak identification and repair, have been neglected as it is complex and resource-intensive [16].

Existing leak management strategies either require intensive audits or a widespread installation of measurement instrumentation. These approaches are resource-intensive and therefore not viable for the struggling South African deep-level mining industry [40], [80]. Innovative approaches are required to cost-effectively prioritise, identify, and reduce the compressed air consumption on deep-level mines in order to achieve electricity cost savings.

The following objectives have been defined to address the identified needs:

Study objective 1

Develop, verify, and validate a method to prioritise deep-level mining shafts for compressed air and electricity demand reduction.

Study objective 2

Develop and apply improved auditing techniques for underground leak localisation. These techniques should enable auditors to find wastages in a shorter amount of time and in a safer manner when compared to conventional auditing methods.

Study objective 3

Develop and apply an integrated methodology to prioritise, audit, and achieve electricity cost savings on deep-level mine compressed air networks.

Study objective 4

Create, verify, and validate an improved compressor energy savings quantification method. The new method should also be able to accurately predict the impact of electricity cost saving initiatives on deep-level mine compressed air systems.

1.4 Novel contributions

1. A novel benchmarking model to prioritise deep-level mine compressed air systems for demand reduction

Problem statement:

There are several deep-level mining operations in South Africa. Each of these operations typically has multiple shafts. ESCos have limited resources to audit these shafts. Simple estimation methods are required to assess the potential for electricity cost-saving projects on deep-level mines [30], [64]. There is a need for a benchmarking model to prioritise shafts for compressed air demand reduction.

Shortcomings to existing research:

Existing benchmarking models determine the potential for compressor electricity cost savings with calculated indicators which consist of production data [14], [18], [31] or the compressor power profile [21], [72]. These benchmarking models cannot isolate demand-side[4] from supply-side[5] initiatives for energy efficiency potential. There is a need for a benchmarking model which can be used to prioritise shafts for underground compressed air demand reduction.

Study contribution:

A new benchmarking model will be developed to prioritise shafts for underground compressed air demand reduction. This will be done by using the length of the active underground compressed air network together with the compressed air consumption during the low-demand periods. Shafts with higher compressed air consumption per length of active pipe will be prioritised for demand reduction.

2. An improved audit method for deep-level mine compressed air systems using flowmeters

Problem statement:

Deep-level mines have extensive compressed air networks. It is not always possible to install instrumentation for identifying and measuring leaks due to the ever-changing

[4] Electricity cost savings potential through CA wastage reduction
[5] Electricity cost saving potential through compressor and/or valve control

conditions underground combined with capital expense restrictions. Manual audits of entire compressed air networks are resource-intensive and unsafe.

Shortcomings of existing research:

Existing techniques to identify compressed air leaks either involve tedious audits of the entire compressed air networks that are resource-intensive [30], [32], [40], or benchmarking models which indicate major leak areas too broadly [18], [21], [31]. There is thus a need to develop a technique to safely localise leaks to manageable areas.

Study contribution:

A new audit technique will be developed which will not only localise leaks to a manageable area but will also indicate the leak flowrate for prioritisation. The new audit method reduces the need for audit personnel to enter dangerous areas.

3. An innovative procedure to localise compressed air leakages with limited compressed air flow measurement points

Problem statement:

Compressed air flow is an essential parameter to deep-level mine compressed air audits. Limited measurement points for insertion-type compressed air flowmeters have been identified as a barrier to audits. Implementing the localisation technique mentioned in the second novel contribution will thus not be possible without flow measurement points. Alternative methods are required to conduct compressed air audits on areas with limited measurement points.

Shortcomings of existing research:

Existing research attempts to quantify the compressed air leakages by installing inexpensive pressure loggers at certain increments over the length of a pipe [16], [39]. These methods are time consuming and inaccurate [16].

Study contribution:

A new procedure will be developed to estimate compressed air flow into the working area on a level with limited flowmeter measurement points. The method will require an estimation of the compressed air flow and a pressure logger installed at the end of the column. A thermo-hydraulic simulation and newly-developed mathematical model will be used to calculate the flow into each working area.

4. A new, integrated process to reduce the compressed air consumption of deep-level mines

Problem statement:

A clear, step by step process is required to effectively implement electricity cost saving initiatives on deep-level mine compressed air systems [13], [109].

Shortcomings to existing research:

Standard leak identification methods often involve intensive audits of the entire compressed air network [30], [32], [40]. These audits are also often haphazardly conducted without a clear structure. Valuable resources, such as time, employees, and money are wasted through such audit methods. There is thus a need for a structured approach to leak audits.

Study contribution:

This contribution combines the abovementioned contributions into one simple, step by step, process for effective and efficient electricity cost reduction on deep-level mine compressed air systems.

5. A new model for accurate savings quantification of energy efficiency initiatives on deep-level mine compressed air systems

Problem statement:

Service level adjustment methods are used to calculate the cost savings impact of energy efficiency projects. The effect of non-project operational changes should be disregarded from the impact calculation. Compressed air networks are constantly being adapted to meet the mining production requirements. These changes influence the power consumption of surface compressors. Accurate service level adjustment methods are needed when quantifying electricity cost savings on deep-level mine CA systems.

Shortcomings of existing research:

Existing service level adjustment methods for deep-level mine compressed air systems use peak electricity consumption or production data to calculate a scaling factor. These methods fail to accurately calculate the impact of electricity cost saving initiatives on deep-level mine compressed air systems.

Study contribution:

A new and improved service level adjustment method (savings quantification method) for deep-level mine compressed air systems will be developed. This method will be based on the size of the active underground network.

1.5 Thesis outline

Chapter 1

Chapter 1 consists of a brief overview on deep-level mine compressed air systems in South Africa. This will be followed by a literature study on methods to reduce the electricity consumption on mine compressed air systems. The overview and literature study in this chapter are used to formulate the problem statement and objectives.

Chapter 2

Methods to address the needs that were identified in Chapter 1 will be developed in Chapter 2. The chapter will start with a method to identify scope and prioritise shafts for compressor electricity reduction on deep-level mines. Prioritised shafts could then be audited with the newly-developed auditing methods. The chapter is concluded with a management strategy for energy efficiency initiatives on deep-level mines.

Chapter 3

Verification and validation of the developed methods are done in Chapter 3. The integrated methodology, which include prioritisation and auditing, is tested. The benchmarking and energy saving quantification methods are applied to real-world case studies. Outputs of these methods are compared to existing methods.

Chapter 4

A summary of this study is presented in this chapter. Recommendations for further work are listed at the end of Chapter 4.

Chapter 2. Development and verification of demand management strategies

2.1 Introduction

In Chapter 1, it was found that up to 86% of generated Compressed Air (CA) in industrial systems is wasted. Identifying these leaks on a CA system as large as that of a deep-level mine is not a simple task. A need was identified for methodologies to address these inefficiencies.

This chapter will present methodologies to identify, quantify, and achieve cost savings and/or service delivery improvements through underground CA leak repairs and compressor control. These methodologies will be integrated into one procedure for achieving electricity cost savings on deep-level mine compressors.

2.2 Auditing opportunity identification

2.2.1 Preamble

According to **Objective 1** of this study, a method needs to be developed to prioritise shafts for demand reduction. In this section, methods will be developed to identify potential for electricity reduction through underground demand management on deep-level mine CA systems. The first method involves determining the potential for underground demand reduction using a newly-developed benchmarking model.

Regardless of the demand reduction potential identified with the benchmarking model, the electricity reduction limitations of the shaft compressors should be considered. It is recommended that energy managers only initiate underground audits if there is enough potential for reducing the underground CA demand and satisfactory electricity savings can be achieved.

2.2.2 Benchmarking using underground compressed air network size

As mentioned in Section 1.2.2, benchmarking is used as a tool to identify scope for electricity cost saving initiatives. Existing benchmarking models are limited in enabling auditors to determine scope for CA demand reduction on deep-level mines. In this study, benchmarking models used for potable water distribution networks wastage audits were adapted to be used on deep-level mine CA networks.

Potable water distribution leak auditors typically use the Minimum Night Flow (MNF), as also discussed in Section 1.2.4, when conducting wastage measurements. The MNF give the auditors a better indication of the amount of water leaked as only a small amount of the water is assumed to be used for productive purposes, while the rest of the water is consumed by leaks [125], [132].

Like potable water distribution networks, deep-level mines also have periods of low consumption. According to Figure 12 in Section 1.1.4, the least amount of CA is required during the blasting and the sweeping shifts. A comparison between the flow profile of a water distribution network and a typical deep-level mine CA system is displayed in Figure 28.

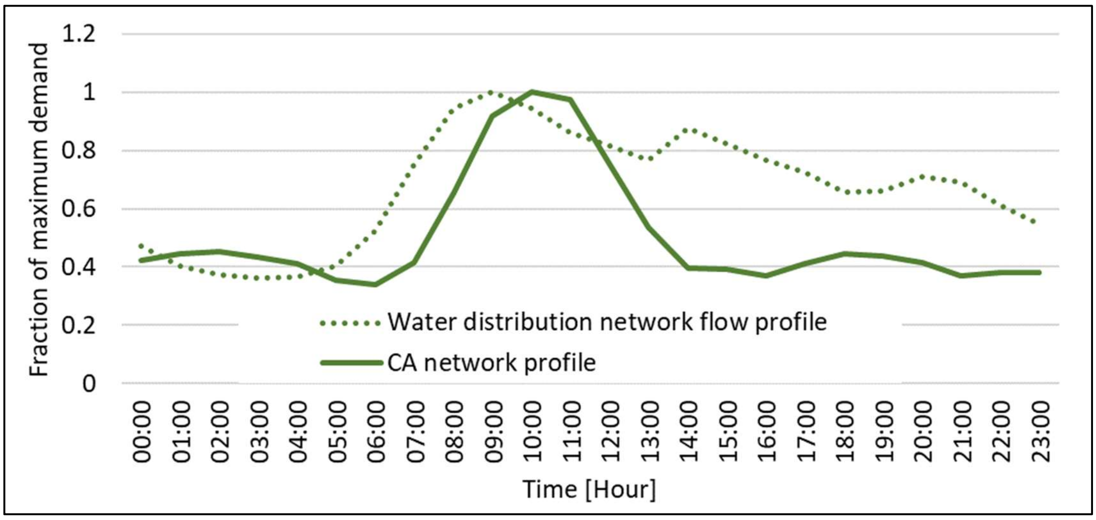


Figure 28: Mass flow profile of a compressed air system and a water distribution system [71], [132]

According to the graph in Figure 28, water distribution networks have a small window, typically between 01:00 and 05:00, in which to obtain the MNF. A typical deep-level mine CA network has a minimum flow which remains relatively constant from 14:00 to 06:00.

The absolute minimum CA flow on a deep-level mine typically occurs during the blasting period. Underground and surface valves are also usually closed during this 3-hour period as there is no need for high-pressure CA during this period as discussed in Section 1.1.3. A false value of the minimum flow may be calculated when using this period. The early morning hour flow (00:00 to 04:00) of CA will thus be used to determine the minimum flow. A graph of the minimum flows for 13 shafts are indicated in Figure 29.

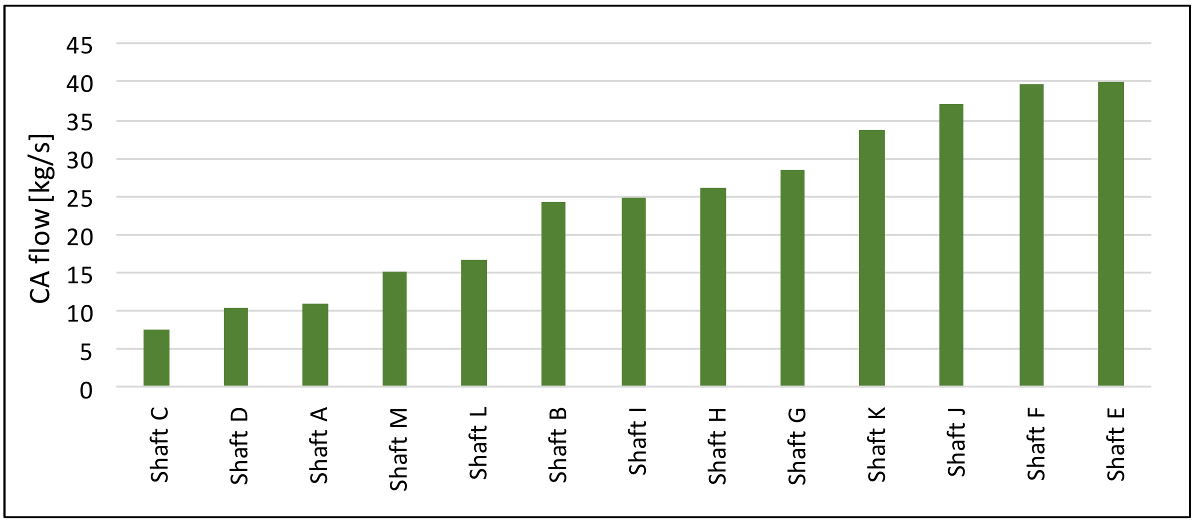


Figure 29: Minimum compressed air flow for various deep-level mining shafts

According to the graph in Figure 29, Shaft L has a higher minimum CA consumption when compared to Shaft M. For an inexperienced auditor, it may seem as if Shaft L has a higher leakage rate when compared to Shaft M. However, Shaft L is operated at a higher pressure.

Normalisation is used when comparing consumers to a benchmark [34]. As an example, two levels which have the same CA consumptions but different production outputs cannot be considered equally efficient according to du Plooy [31]. Shaft data should thus be normalised to incorporate the effect of pressure. A graph illustrating the difference between the normalised shaft consumption and the non-normalised shaft consumption is illustrated in Figure 30.

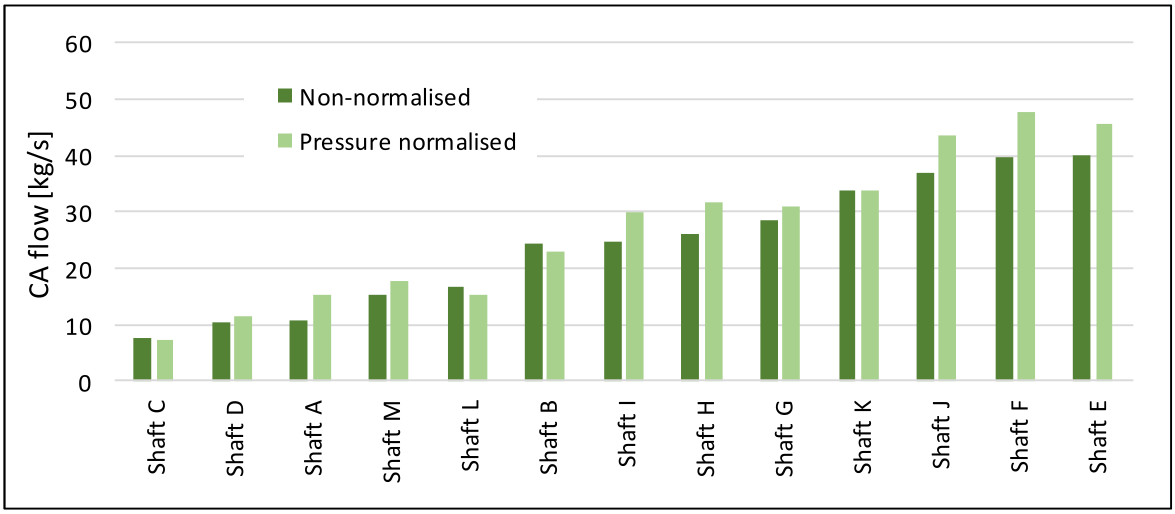


Figure 30: Normalised shaft consumption compared to the non-normalised data[6]

[6] The CA pressure downstream of the surface valve on each shaft was normalised to 550 kPa_g using a simulation of the demand.

According to Equation 1 in Section 1.2.2, a higher CA pressure will result in a higher flowrate at a certain demand. When the downstream pressure of Shaft L and M are set equal, Shaft M will have a higher consumption, indicating that Shaft M has a higher normalised consumption.

A shaft with a high normalised CA consumption does not necessarily give an indication to the difficulty in finding and repairing leaks. According to Oosthuizen, the audit complexities vary from shaft to shaft [72]. Similarly, the complexities also differ from facility to facility in the non-mining industry [28], [88]. It was mentioned in Section 1.1.3, that as more underground piping is inserted, the potential for the number of leaks increases (flange leaks, valve leaks, etc.). The deterioration of the system over time should thus also be incorporated in the calculations [88].

Fewer resources will most likely be required to find and repair one large CA leak when compared to finding and repairing several leaks with a combined CA wastage equal to that of the large leak. This can also explain why the total length of potable water distribution networks are used when calculating wastage benchmarking indicators [136], [137].

Underground CA demand reduction potential is defined in this paper as the leak reduction that can be achieved with a predetermined amount of resources (e.g. auditors and time). It is reasoned that the network length together with the normalised minimum flow of a shaft can be used to indicate the potential for underground demand reduction.

In Section 1.1.3 it was mentioned that a CA column transfers air from the surface to underground via the shaft. From the shaft, the CA is distributed to the working place via the haulage column. At the working place, the CA is distributed to the stopes via a network of plastic or rubber pipes which enters at the cross cut.

The CA distribution network in the active working areas is more dynamic when compared to the haulage network. Columns in these areas are extended, shortened, or moved on a regular basis (typically less than a month) to reach the stoping face. Length measurements taken on one day may not be relevant the following day. The length of the stope network will thus not be incorporated in the total network length.

Deep-level mines often have vast mining areas which have been mined out. The CA columns in these areas are rarely removed as it is not financially viable. These columns will also not be considered in the calculation of the total network size. Columns in these areas are assumed to be isolated from the rest of the network.

Only the length of the shaft and active haulage column will be considered when calculating the total underground CA network length. A means to obtaining the total network length will be discussed in Section 2.2.4. The total CA network length and the corresponding normalised flow for various shafts in Figure 30 are indicated in Figure 31. Data for gold and platinum mining shafts are separated by colour.

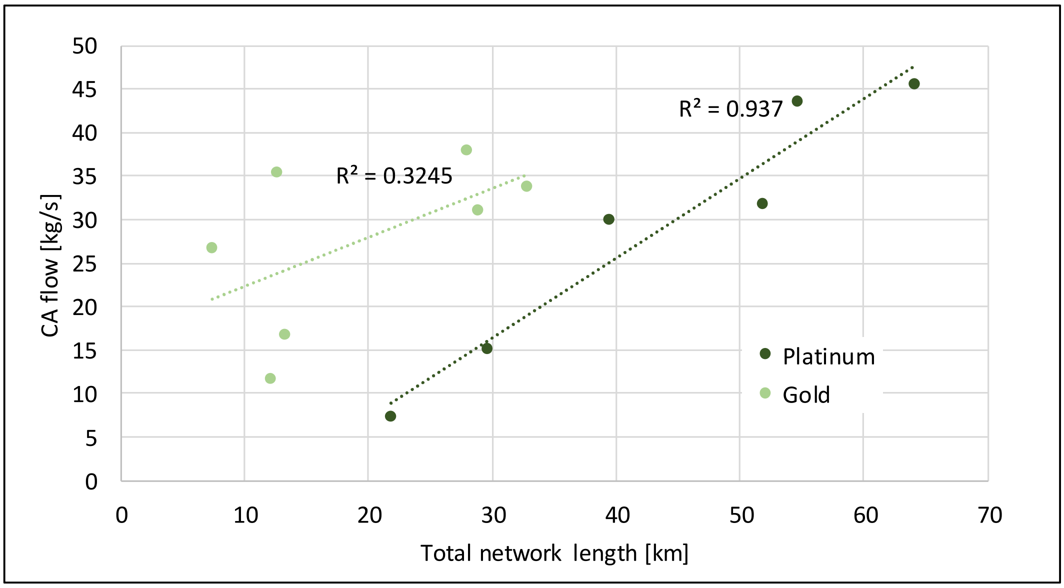


Figure 31: Normalised minimum compressed air flows versus the total network length

The trendline for gold mining shafts has a lower R^2 value compared to the trendline for platinum mining shafts. Gold mines also have a higher demand than platinum mining shafts of the same network size. This thus indicates that these shafts are more inefficient than platinum mines. The inefficiencies of gold mining shafts also vary more than that of platinum mines which can be expected of inefficient shafts according to Cilliers [18] and du Plooy [31]. This thus **verifies** the use of the new parameter as a benchmarking method.

The data in Figure 31 thus indicate that there could be more potential for improvement on gold mines when compared to platinum mines. Gold mines typically have fewer cross cuts and active levels when compared to platinum mines with the same production output. Larger stoping areas are thus allocated to a single cross cut on a typical gold mine when compared to platinum mines, as can be seen in Figure 32.

The stoping area of a cross cut is considered a manageable area to conduct a conventional walk-through audit. A higher CA flow is expected for typical gold mining cross cuts when compared to platinum mining cross cuts. It is thus expected that large leakage areas can more easily be localised in gold mines. This explains why gold mines have a higher benchmarking indicator and further **verifies** the use of this method to determine the demand reduction potential of a shaft.

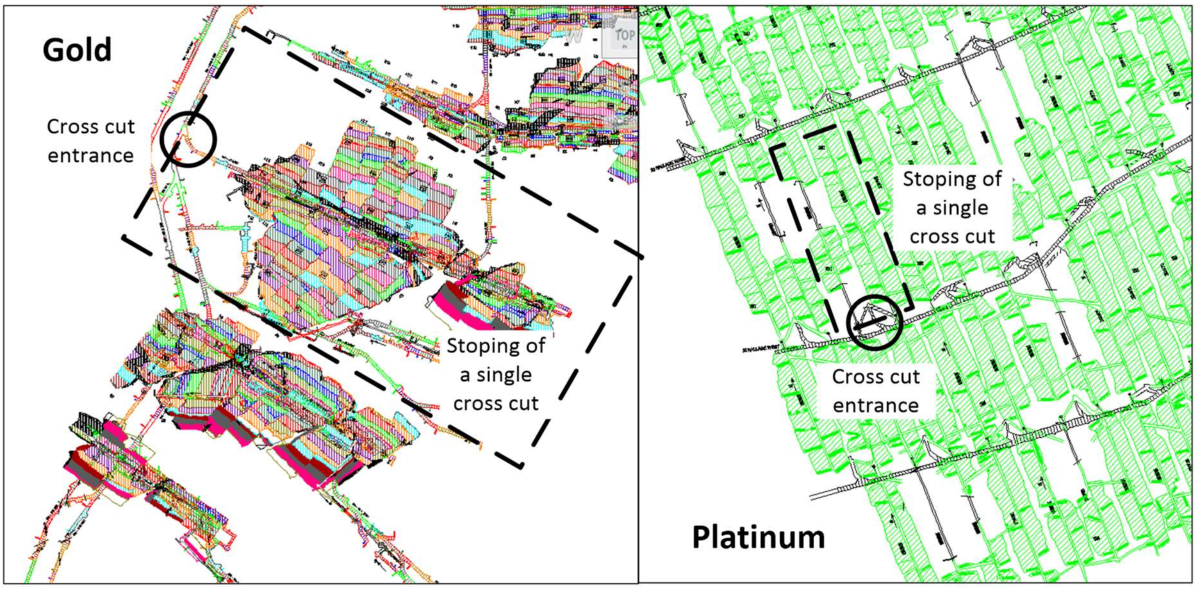


Figure 32: Comparing cross cuts of typical gold and platinum mines

The newly-developed CA demand reduction potential indicator can be calculated with Equation 10.

$$DI = \frac{Q_N}{L} \tag{10}$$

Where:

DI = Demand reduction potential indicator [(kg/s)/km]

Q_N = Normalised shaft CA mass flowrate [kg/s]

L = Underground CA network length [km]

The demand reduction potential indicator aims to give energy managers the ability to identify which shaft has the highest potential for underground leak reduction. Leak repairs on a shaft can be done until the benchmark value (lowest *DI* value) is reached [51].

As indicated in Equation 10, the underground demand reduction indicator, *DI*, is inversely proportional to the total length of the underground CA network, *L*. It is reasoned that the probability of finding sizable leaks which will significantly decrease the CA consumption of a shaft becomes smaller as the size of the network increases.

As discussed in Section 1.1.4, the number of CA leaks should theoretically increase with an increase in the network size. An increase in the network size will also mean that more audit resources will be required to detect CA leaks. The demand reduction indicator value for various gold and platinum mining shafts are indicated in Figure 33.

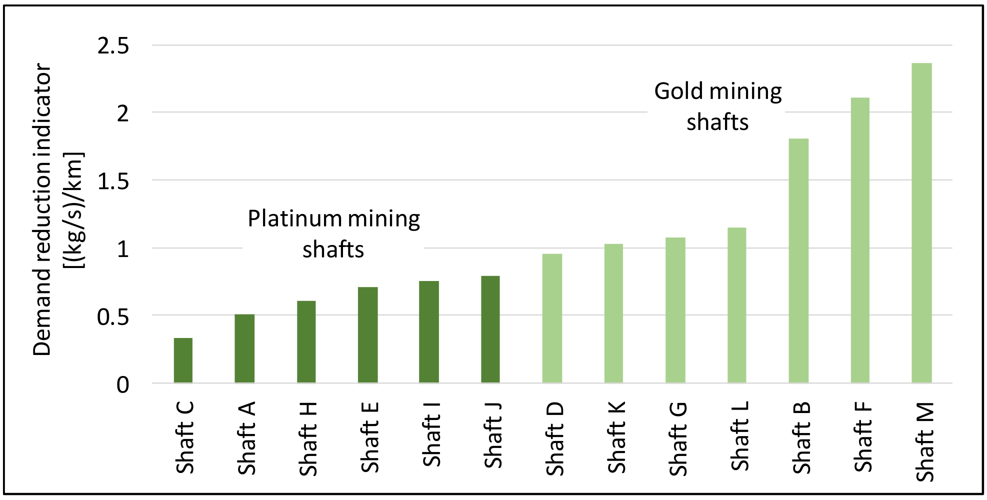


Figure 33: Wastage indicator for various gold and platinum mining shafts

As mentioned in Section 1.2.2, there are existing benchmarking models for deep-level mine CA systems. It was mentioned that these methods focus on the holistic CA savings that can be achieved through demand- and supply-side management. Results from the new demand reduction indicator are compared to an existing benchmarking indicator in Figure 34.

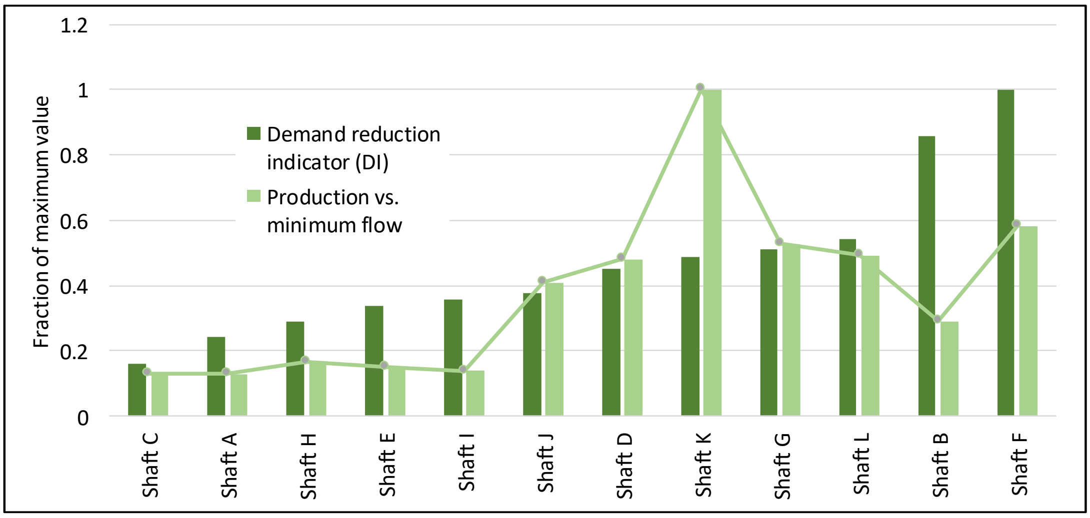


Figure 34: Output comparison of two benchmarking models

From the graph, similar scope for improvement is indicated for the two benchmarking models. There are, however, some drastic differences in the scope identification for various shafts, such as Shaft B and K. These differences may indicate that the potential for CA demand reduction differ from the potential for holistic cost savings on the system. The ability of holistic and the new demand reduction indicator to predict the potential for underground demand reduction will be discussed in Section 3.2.3.

2.2.3 Compressor power reduction limitations

Underground CA demand reduction alone does not necessarily result in compressor electricity cost savings. According to the literature study in Section 1.2.2, an integrated approach, consisting of demand- and supply-side management, should be applied in order to achieve the desired savings.

Before initiating underground demand reduction initiatives, energy managers should first determine if the efforts will be rewarded with electricity cost savings on the compressors [88]. It is possible that the demand reductions achieved can be blown into the atmosphere if the demand is insufficiently reduced.

Compressors can be stopped or throttled to save electrical energy. More electricity cost savings can be achieved by stopping a compressor when compared to throttling. However, stopping a compressor can result in an under-pressurised CA system if the remaining operated compressors are unable to maintain the load [77].

Centrifugal compressors can be throttled by means of guide vane control. However, the throttling abilities of these machines are limited, as mentioned in Section 1.2.2. A graph illustrating the relationship between the CA delivery flow and power consumption of a typical 5 MW rated compressor is illustrated in Figure 35.

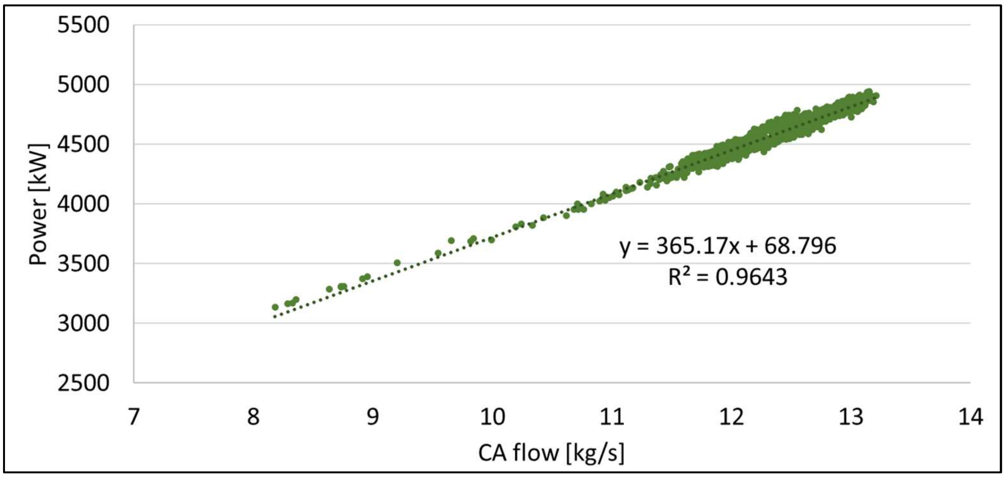


Figure 35: Compressor guide vane throttling at constant pressure

According to the graph in Figure 35 the 5 MW rated compressor can only reduce the CA consumption to a minimum of 8 kg/s. A further reduction in the CA demand will result in the excess supplied CA being blown off into the atmosphere through the blow-off valve. No further power reduction is achieved past this point.

As seen in Figure 35, there is a linear correlation between the CA flow and power consumption. The power consumption is, however, not reduced with the same ratio when compared to the CA flow reduction. This throttling efficiency is known as the part load efficiency and can differ from compressor to compressor.

As mentioned in Section 1.2.5, simulation software can be used as a tool to plan for energy efficiency initiatives. By simulating the characteristics of the shaft compressors and applying good supply-side management practices, the minimum compressor power needed to satisfy the shaft demand can be determined. The minimum power needed to satisfy the demand is determined by changing the compressor operation combinations and the number of active compressors in the simulation.

The flowchart in Figure 80 found in Appendix A was developed to incorporate the compressor simulation and good supply-side management to allow energy managers to create a map of the compressor power consumption and shaft CA demand. A power reduction map of an example shaft is illustrated in Figure 36.

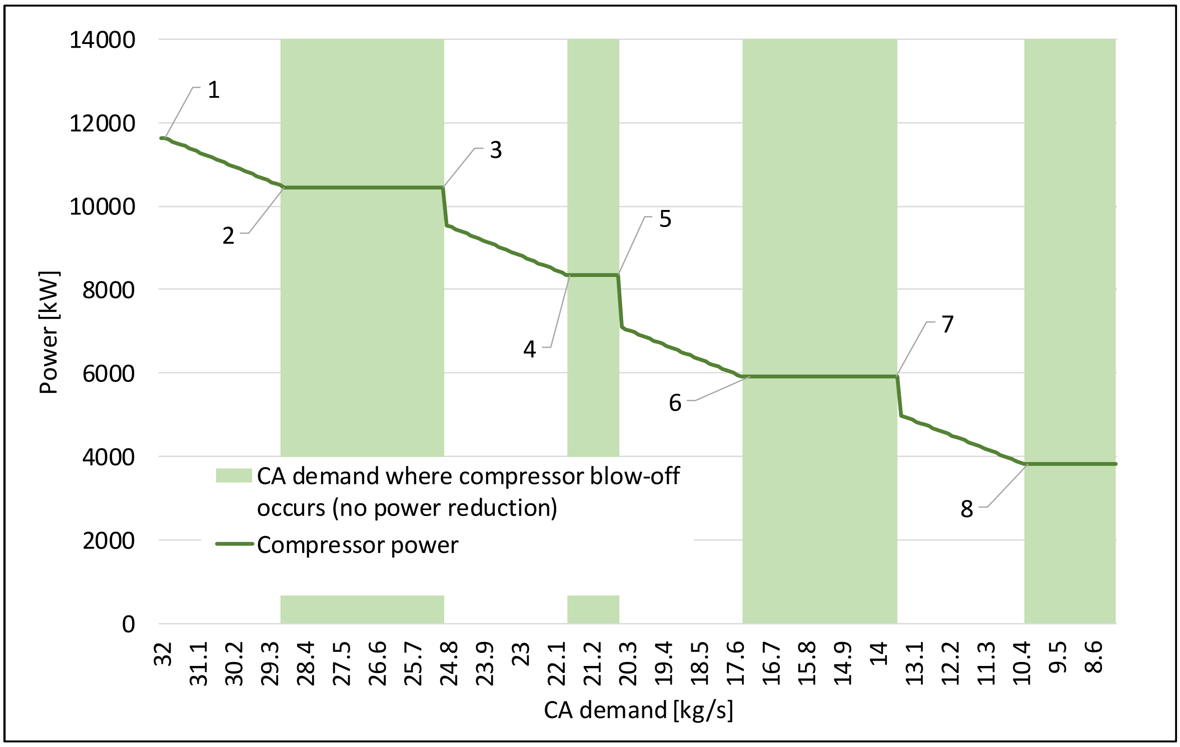


Figure 36: Example shaft compressor power reduction limitations mapping

The CA pressure set point of the example simulation was maintained at 500 kPa_g by applying the control measures in Figure 80. Three compressors were used in this example. Characteristics of the compressors are listed below:

- Compressor 1: Maximum power output = 4600 kW; Guide vanes can reduce the power consumption to 88% of the maximum power output; Efficiency rating = 63.5%.
- Compressor 2: Maximum power output = 4250 kW; Guide vanes are not in a working condition; Efficiency rating = 62 %.
- Compressor 3: Maximum power output = 2000 kW; Guide vanes are not in a working condition; Efficiency rating = 71%

Compressor power consumption transition points can be identified in Figure 36. A discussion of each numbered transition point is given below:

1. All shaft compressors are operated at full load to maintain the set point pressure. The pressure set point will not be reached if the shaft demand exceeds 32 kg/s. Guide vanes on Compressor 1 will decrease the CA supply and power consumption with a decrease in shaft demand.
2. The maximum guide vane throttling capabilities of Compressor 1 are reached. Stopping any of the compressors will result in the set point not being reached. CA blow-off is initiated. Blow-off does not result in further power reduction.
3. Shaft demand is sufficiently low for Compressor 3 to be stopped while still maintaining the pressure set point. Compressor 1 is operated at full load. Stopping Compressor 3 results in a step-change in the total power consumption.
4. Throttling limitations of Compressor 1 have been reached. Further reduction in shaft CA consumption will result in blow-off.
5. Shaft demand is low enough for the set point pressure to be maintained by operating Compressor 1 and Compressor 3 at full load and stopping Compressor 2. A step-change in the total power consumption is observed.
6. Throttling limitations of Compressor 1 have been reached. CA will be blown off with any further reduction in the shaft demand.

7. The shaft CA demand has been reduced sufficiently for Compressor 3 to be stopped.

8. Throttling limitations of Compressor 1 have been reached. CA will be blown off with any further reduction in the shaft demand.

A map of the compressor power consumption and shaft demand, together with the benchmarking models in Section 2.2.2, can assist energy managers on deciding which shaft to prioritise for underground leak management. Decisions can be made based on the amount of resources available to the energy managers.

In Section 2.2.2, it was found that gold mining shafts under investigation have more demand reduction potential when compared to platinum mining shafts. When the compressor configuration of gold and platinum mines are compared, it is found that platinum mines generally have numerous compressors which are shared by multiple shafts in a CA ring. Gold mining shafts, on the other hand, normally have dedicated compressors [73]. Reducing the power consumption of platinum mining shafts may thus require less effort when compared to gold mining shafts.

2.2.4 Acquiring compressed air information

Obtaining underground CA information is generally more difficult than obtaining surface information. There are rarely mining personnel who know the entire CA system underground [30]. Sources where underground information can be obtained will be discussed in this section.

Most of the technical mining personnel should have an idea of the different underground mining sections. It is recommended that a simplified Piping and Instrumentation Diagram (P&ID) of the CA network, such as the one in Figure 37, be created before starting with the underground audits [40], [94]. From this P&ID, auditors should already be able to spot inactive areas where CA wastage can potentially be reduced.

In some instances, there is no flow measurement instrumentation, nor portable flowmeter measurement points available on surface. The shaft CA flow can then be estimated by using the compressor ratings [77]. Obtaining flow measurements with this method is not recommended as it may be far from the actual flow value [82].

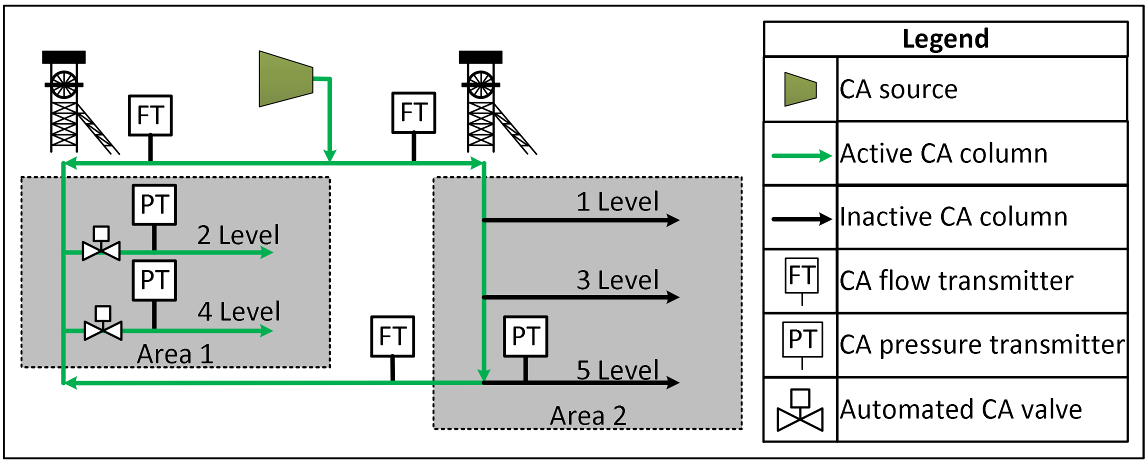


Figure 37: Simplified P&ID of an underground mine compressed air network

Information on the underground instrumentation, also displayed in Figure 37, can be obtained from the shaft instrumentation technicians. If the instrumentation technicians are unable to provide information on the location or if the instrumentation is still functioning properly, a manual instrumentation audit may be necessary.

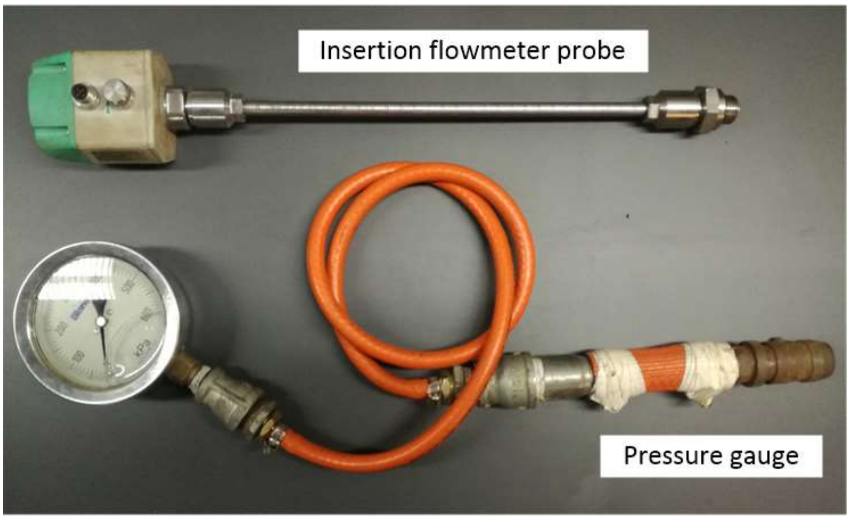


Figure 38: Portable compressed air measurement instrumentation

Portable, calibrated instrumentation, such as insertion flowmeters [61], [82] and pressure gauges, illustrated in Figure 38, can be used to verify instrumentation measurements [37]. These audits will typically only be limited to the station area of the shaft, as CA instrumentation is seldomly found more than 500 m away from the shaft.

Obtaining information on the CA network beyond the station area will require detailed drawings of the underground mining network. The South African Mine Health and Safety Act requires that deep-level mining companies have accurate, up to date, underground drawings [138]. This means that the active haulage lengths, required for the benchmarking model in Section 2.2.2 and the savings quantification method which will be discussed later in Section 2.4.4, is readily available.

Underground drawings can be obtained from the mine surveying offices [40]. The top-view of an underground deep-level mine surveying drawing screenshot is illustrated in Figure 39. Information, such as the total underground CA network length, which was required in Section 2.2.2, can be obtained from these drawings.

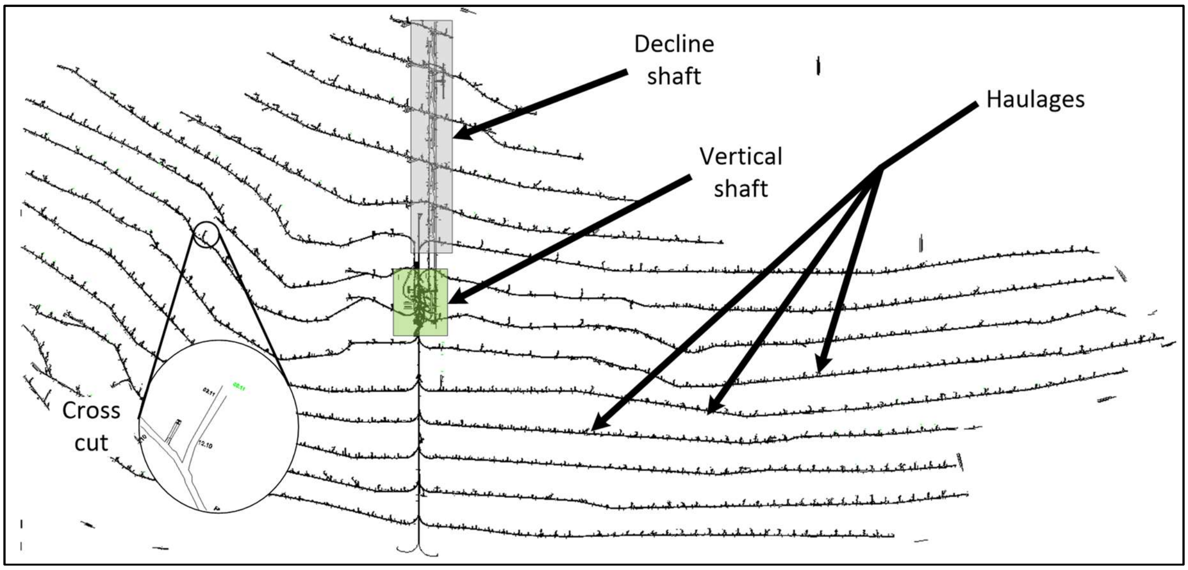


Figure 39: Top-view of an underground surveying drawing

CA auditors should become familiar with the surveying naming convention and terminology to use the drawing when navigating underground. Centre gully numbers, usually spray-painted on the walls next to the loading boxes or cross cuts, can be noted when, for example, a haulage leak is located. Afterwards, the auditor can use the underground drawings obtained from the surveyors to note leak distance from the shaft.

An energy system simulation has been identified as a powerful tool for implementing energy efficiency initiatives in Section 1.2.5. The gathered CA system data can be inserted into simulation software to make more sense of the data and digitally test different scenarios on the system.

Various simulation software packages are available to simulate underground CA networks. In this study, Process Toolbox (PTB) [18] has been chosen as the preferred simulation software for the following reasons:

- Underground surveyor drawings can be imported to PTB. Simulation components can then be placed on the drawing,

- PTB consists of built-in functions to make the construction of complex underground simulations easier, and
- The user can choose to empirically model components if data, such as the pipe roughness, is not available.

A lack of reliable measurement instrumentation will make it difficult to accurately simulate a deep-level mine thermo-hydraulic system. A R^2 value above 0.75 and a root mean squared error below 15% is considered acceptable [99].

2.3 Development of underground leak auditing techniques

2.3.1 Preamble

In the previous section, a new, high-level method to identify potential for electricity reduction through underground leak repair, was developed. Existing underground deep-level mine CA leak auditing methods mainly involve comprehensive audits of entire mining levels at best. These mining levels can span up to 10 km in length.

Objective 2 of this study states that improved deep-level mine CA leak auditing methods must be developed and tested. Development of these methods will be done in this section. The aim of the improved methods is to make deep-level mine audits less resource-intensive and safer for auditors. The new method should also allow auditors to identify and prioritise the larger leaks to significantly reduce the shaft demand.

2.3.2 Supply reduction testing

According to the literature in Section 1.2.2, an integrated savings methodology is the preferred approach to achieving electricity cost savings on a deep-level mine CA system. Supply-side management through compressor and valve control is the first step in decreasing the compressor power consumption on deep-level mines.

CA equipment requires a certain minimum pressure to operate. Compressor and valve control are thus limited to the pressure requirements of the end-users. However, these minimum pressure requirements are often purely subjective. Additional compressors need to be started unnecessarily to satisfy the needs of the underground mining operations.

According to the integrated methodology, illustrated in Figure 17 of Section 1.2.2, supply management through compressor and valve control should be followed by underground leak repair. However, existing leak auditing methods typically focus on reducing the leaks over the entire shaft to correct the problem.

Demand reduction efforts over the entire shaft may, however, only slightly alleviate the pressure problems. According to the pipe physics in Section 1.2.2, the pressure drop over a CA column can be decreased with a decrease in flow. Demand reduction measures on the entire shaft can reduce the pressure drop over the shaft column. However, these columns typically have an Inside Diameter (ID) ranging from 400 to 600 mm to deliver high volumes of CA without significant pressure drops.

The effect of repairing leaks over an entire shaft is illustrated in Figure 40. In this simple example, repairing six leaks over the entire shaft only increased the pressure at the problem area by 15 kPa. Haulage CA columns have smaller IDs (typically 210 mm) when compared to shaft column. A demand reduction on the haulage column with the pressure problem will have a larger effect than the same demand reduction on another part of the shaft.

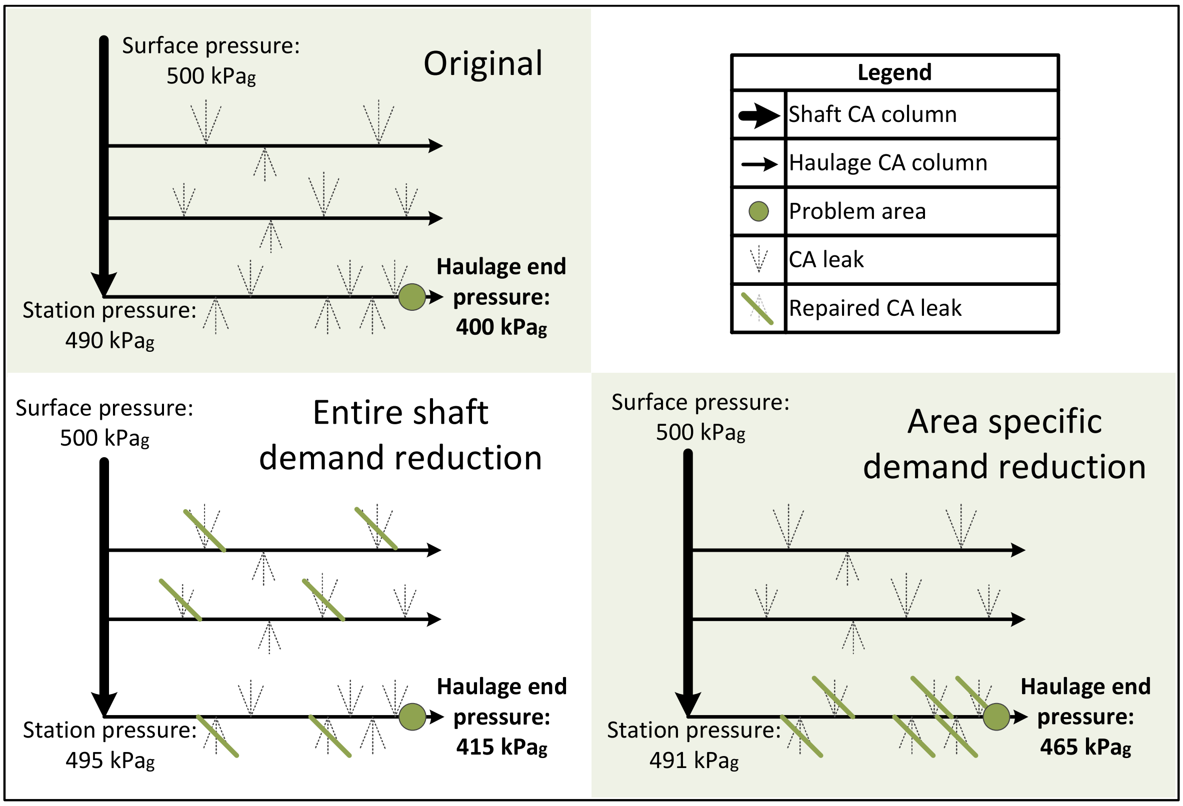


Figure 40: Entire shaft audit versus area-specific audit

A new method to investigate the increased pressure requirements is proposed. The method will involve identifying and investigating the area where the low CA pressure complaints were received. Targeting certain underground regions before a leak detection program is implemented may result in quicker cost savings. A flow diagram describing the new investigation method is displayed in Figure 41.

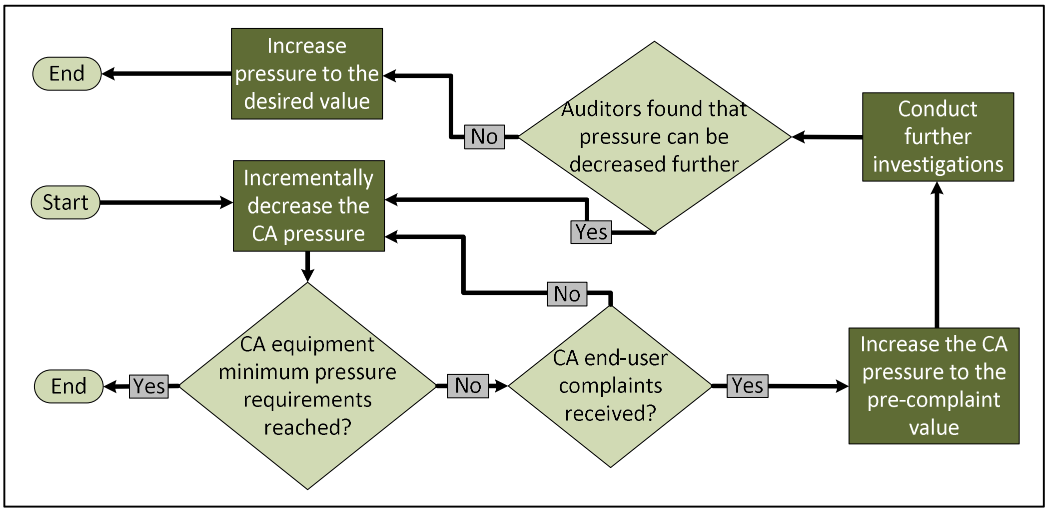


Figure 41: Compressor and valve control procedure

To conduct the compressor and valve control procedure, the CA pressure should be reduced with a specified increment. As mentioned in Section 1.2.2, energy savings initiatives are generally not permitted during the drilling shift. The incremental decrease in pressure should thus preferably only be done during the non-drilling shifts. The increment value is left to the discretion of the control room operator.

If no complaints from production personnel are received, the control room operator must continue to reduce the CA pressure set point until the minimum pressure requirements of the underground equipment are reached. If a CA pressure complaint is received before the minimum pressure requirements are reached, the pressure must be increased to the pressure value before the complaint was received.

Auditors should then launch an investigation to determine the problem area. An "area" in this case can be a specific haulage which lodged a complaint regarding low pressure. The pressure can only be increased after the auditors have finished the investigation and found the pressure to be insufficient. The methods, which will be discussed in Sections 2.3.3 and 2.3.4, can be used to narrow down the leaks in these areas.

2.3.3 Localising compressed air wastage with step-testing

The non-mining industry leak detection methods are more developed than the techniques currently applied to deep-level mine CA systems. An evaluation of different non-mining leak detection methods where conducted in Section 1.2.4. It was determined that step-testing is a suitable method for leak detection on deep-level mine CA systems.

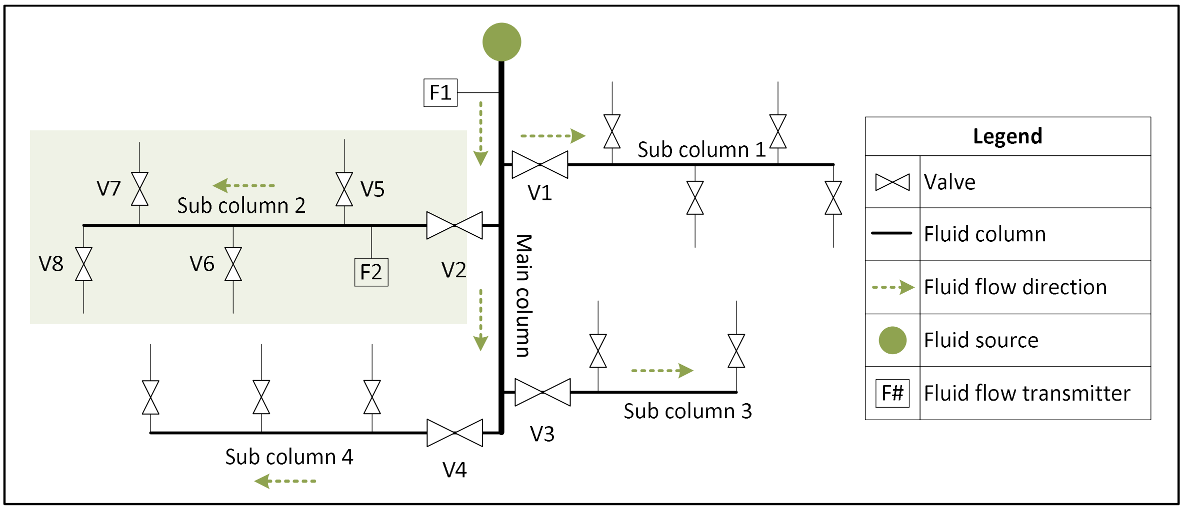


Figure 42: Example diagram used to explain the step-testing method

Step-testing requires minimal resources and infrastructure, such as flowmeters and measurement points, to localise large leaks to manageable areas [33]. Figure 42 illustrates a graphical explanation of the step-testing method.

According to Figure 42, step-testing involves measuring the fluid mass flowrate of the entire system and closing valves V1 to V4 one by one [125]. The mass flowrate of the entire fluid system should show a profile like the one illustrated in Figure 43.

From the profile in Figure 43, when valve V2 was closed, the fluid flow decreased the most when compared to closing the other valves. Step-testing will thus continue on the column of valve V2 where the method will be repeated until a sizable fluid flow has been localised to a manageable area [125].

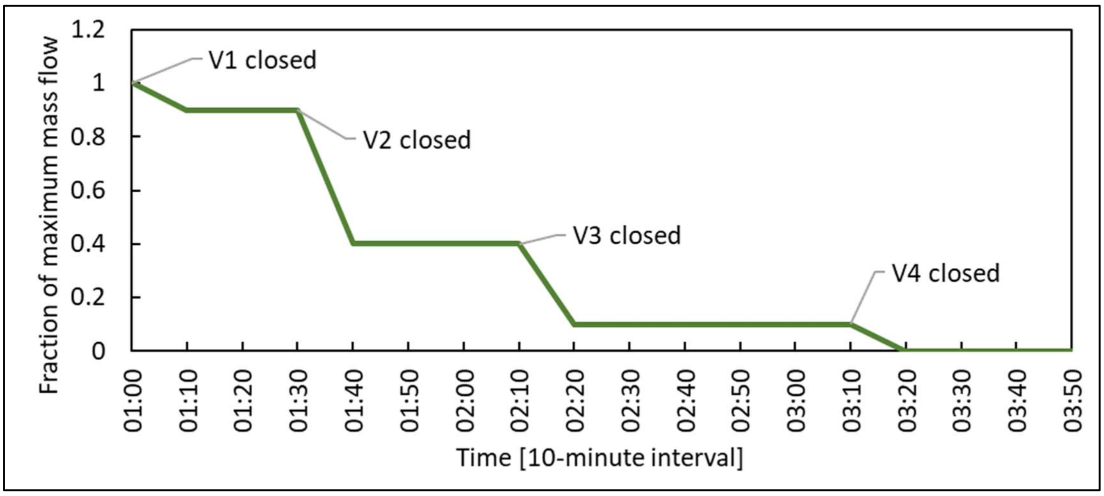


Figure 43: Resulting mass flow profile of the fluid system step-tests (Adapted from [125])

Step-testing allows auditors to localise large leakages without conducting a comprehensive audit of the entire fluid system. This method involves isolating certain areas for a certain amount of time which may come as an inconvenience to the fluid end-users [61], [69]. To minimise this inconvenience, water distribution auditors typically conduct the step-testing at night or early morning when there are minimal water consumers.

Similar to water distribution networks, mining CA systems also have minimum flow periods when the productive use of CA is at a minimum. The water distribution network typically only has a five-hour period in which the step-tests can be done (00:00 to 05:00), as seen in Figure 28 of Section 2.2.2. Deep-level mine CA systems have a longer window in which the step-testing can be done. This window typically ranges from 14:00 to 06:00 on a typical working weekday.

No mining activity is allowed during the blasting shift. However, personnel can enter the shaft station area during the blasting shift. Step-testing can be conducted by isolating the CA of each level one by one. The level isolation valves are usually stationed near the shaft which mining personnel may enter during the blasting shift.

Some shafts have automated CA level valves. Level isolation can thus be done from the control room on surface. Before conducting shaft step-testing, auditors should make sure that all connections feeding from one level to another after the level isolation valve (ring feeds) are closed [125].

After determining the highest CA consuming levels, auditors need to move in to identify the cross cuts with the highest consumption. As mentioned, auditors are not allowed in the haulage or working areas during the blasting shift. Step-testing in the haulages thus need to be done during the afternoon and/or night shift.

As mentioned before in Section 1.1.4, the 16-hour low CA demand period on the deep-level mine does not mean that there are no CA users underground. Critical tasks, such as ore handling with the pneumatic loaders and pneumatic loading boxes, still need to be completed during these periods. Auditors should thus make sure that the mine production process is not affected during step-testing [16].

Stopes are suspected to be the areas with the highest wastage rate on a typical deep-level mining shaft. This area can also be very dangerous, as discussed in Section 1.2.3. Step-testing enables the auditors to determine the CA flow to the stopes without the need to enter the stoping area. This thus makes it a safer auditing method when compared to the conventional auditing method discussed in Section 1.2.2.

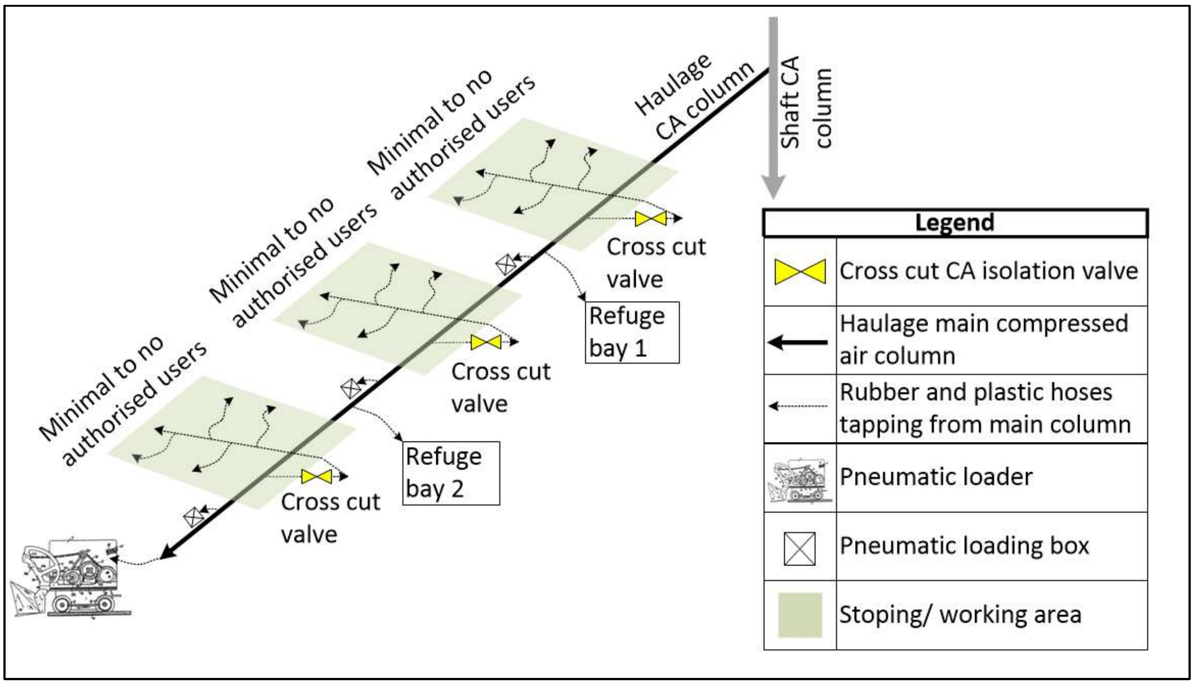


Figure 44: Typical haulage CA piping network

A diagram of a typical haulage CA system is illustrated in Figure 44. This diagram will be used to explain haulage step-testing. According to the diagram in Figure 44, the CA piping for the refuge bays, pneumatic loaders, and loading boxes branch off separately from the piping to the stoping area via the cross cuts. The stope isolation valves (hereafter referred to as cross cut valves) can thus be closed during haulage step-testing without affecting the operation of these units.

When closing the cross cut valve, the location and time at which the valve was closed should be noted [125]. The surveying drawings, which were discussed in Section 2.3.2, can then be used to pinpoint the valve location. Before commencing with the step-testing, the auditors should make sure that all ring feeds between cross cuts should be closed off [125].

The haulage step-testing method will thus be applied by installing a portable CA flowmeter at the start of the haulage, then walking the length of the haulage while closing and opening each cross cut one by one. It is advised to close the valve for a certain period (5-minutes was determined to be enough) and then open it before moving on to the following cross cut valve.

Leaving the cross cut valve closed will result in an overall haulage CA pressure increase. As mentioned in Section 1.2.2, an increase in pressure results in an increased leakage rate. By opening the cross cut valve before closing the next cross cut valve, the leakage rate will be closer to the actual leakage rate when compared to closing all the valves at once.

Conducting step-tests on a CA network branching from a cross cut is very difficult, due to the lack of flow measurement points. The small size of the piping network also makes it less time-consuming to audit using conventional auditing methods. Using a combination of step-testing and conventional auditing methods is thus better than only using step-testing [80], [118]. A sequence for conducting step-testing with a flowmeter is displayed in Figure 45.

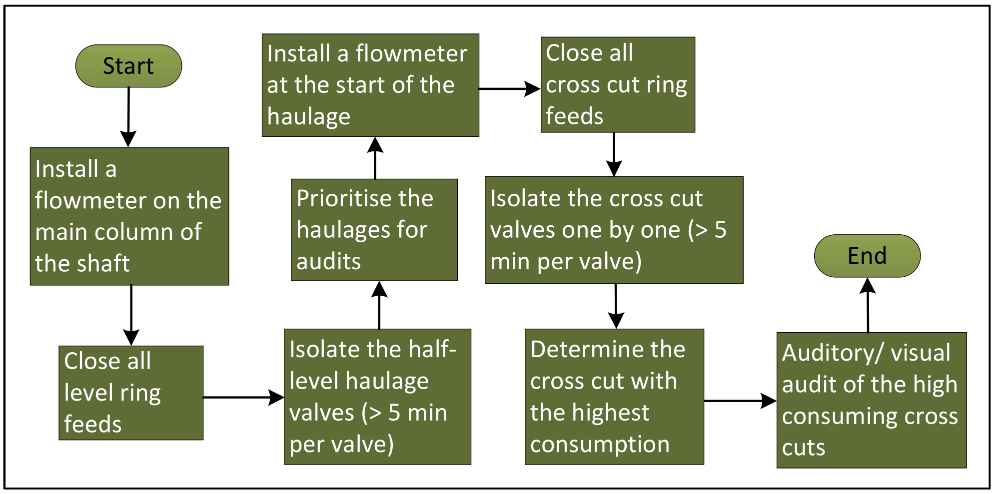


Figure 45: Sequence for conducting haulage step tests with a flowmeter

2.3.4 Step-testing with a pressure logger

The new auditing technique developed in Section 2.3.3 give auditors the ability to identify high Compressed Air (CA) consuming cross cuts. In some instances, insertion flowmeters cannot be used to directly measure the flow of a haulage [31]. Measurement points for portable pressure loggers are easier to come by when compared to measurement points for insertion flowmeters [16].

Pressure loggers have been used to determine the flow to the half level haulage and cross cuts with limited success [16], [39]. A new method has been developed to more accurately calculate the haulage and cross cut CA consumption with a pressure logger. The method involves using a pressure logger with a 1 kPa pressure sensitivity. Previous studies have been limited to low-sensitivity pressure loggers [16], [39].

Auditors may be able to use the step-testing method to determine the CA flow into a level or into a half level haulage if a measurement point is available on the shaft column.

Determining the consumption of cross cuts with a flowmeter installed on the shaft column is not feasible due to the noise in the total shaft consumption.

Process parameters that could not be directly measured could then be calculated by using proxy metering techniques. Proxy metering involves using measured variables and mathematical models to calculate the desired process variable which could not be measured directly [61], [98].

Several studies have determined that the location and the leakage rate of a fluid system can be determined by analysing the pressure drop and fluid flow over the piping system [112], [113], [116], [117]. A diagram depicting the experimental setup of these studies can be seen in Figure 46.

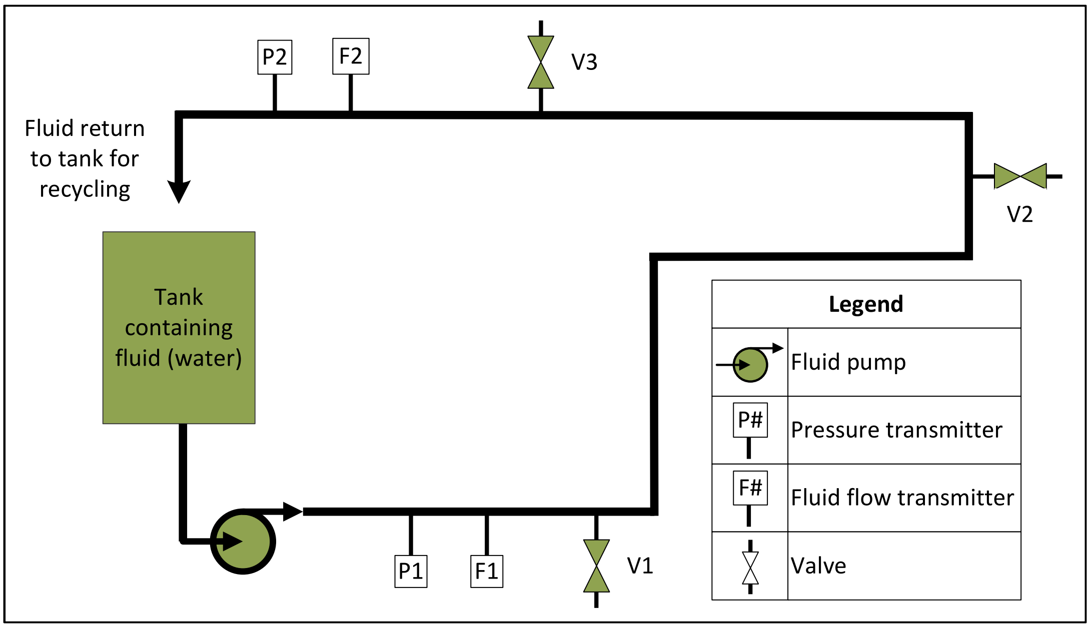


Figure 46: Experimental setup for simulating fluid leaks

The leak localisation method used in Figure 46 involves the installation of a pressure logger and CA flowmeter at the start and end of the piping system. The leaks are then simulated by opening or closing valves V1 to V3. Based on the instrumentation measurements, the leak location and severity can be determined.

The CA flow at the haulage end will typically be zero. It is thus not necessary to install a CA flowmeter at the haulage end as illustrated in Figure 46 [81]. These studies suggest that an equation, such as Equation 11, can be formulated.

$$Q_c = f(Q_H, P_S, P_i, P_f, h, H) \tag{11}$$

Where:

Q_c = Cross cut CA flow [kg/s]

Q_H = Total half level haulage CA flow [kg/s]

P_S = Station pressure at the haulage under investigation [kPa_g]

P_i = Half level haulage end pressure before closing the cross cut valve [kPa_g]

P_f = Half level haulage end pressure after closing the cross cut valve [kPa_g]

h = CA column length from the level station to the cross cut [m]

H = CA column length from the level station to the haulage end [m]

Most mines digitally measure the CA pressure on the level station. By installing one portable pressure logger at the end of the haulage, auditors can determine the pressure drop over the haulage pipeline.

After determining the flow into the half level haulage with the step-testing method developed in Section 2.3.3, step-testing can again be used to determine the effect on the haulage pressure drop when a cross cut valve is closed. Refer to Figure 47 for a graphical explanation of the physical pressure logger step-testing method.

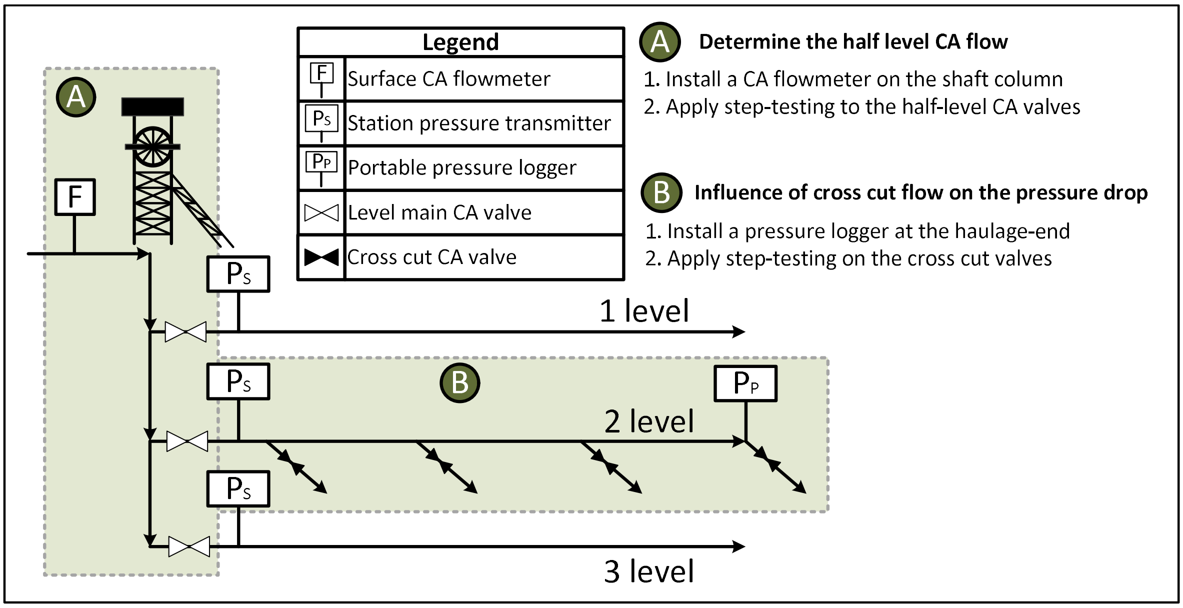


Figure 47: Graphical explanation of the physical pressure logger step-testing

When the pressure drop value for each cross cut has been determined, the CA flowrate into each cross cut needs to be calculated. Thermo-hydraulic simulation software, such as Process Toolbox (PTB), can be used to calculate the flow into each cross cut [117]. PTB enables the user to calculate the CA flowrate into a cross cut by using the equations discussed in Section 1.2.2.

Calculating the flow into each cross cut is a multi-variable problem which is normally solved through trial and error. The pressure drop over the entire haulage is the sum of the pressure drops caused by all leakage points in the specific haulage. As mentioned in Section 2.3.3, closing a cross cut valve affects the flow through the other valves. A method is needed to systematically determine the CA flow value into each cross cut from the pressure drop data that was collected.

Equation 12 has been developed to capture the relationship between the pressure drop, CA flow, and location. Dimensionless variables, such as the fraction or percentage of total haulage CA consumed by a cross cut, have been used to construct Equation 12 [81], [112]. Using these dimensionless variables reduces the number of constants which need to be solved with the data regression tool in Microsoft Excel®.

$$Q_c = Q_H(0.5811 - 0.4826\left(\frac{P_S - P_i}{P_S - P_f}\right) - 0.1356\left(\frac{h}{H}\right)) \quad (12)$$

Where the symbols and units for Equation 12 are the same as that used in Equation 11.

Data from 350 randomly generated simulations were used to determine the constants for Equation 12. The simulations variables and constants represent that of a normal half level haulage CA system. Table 4 lists the variables and constants that were used to construct Equation 12. Some parameters, such as the ID of the pipe and pipe roughness, remains relatively constant [16], [30].

When the polynomial was fitted to the data using the Microsoft Excel® regression tool in the Data Analysis Toolpak, it resulted in a R^2 value of 0.806. This value is sufficient to estimate the flow through each cross cut valve. Minor manual changes can be made to the simulation to achieve the desired cross cut flows.

Table 4: Variables and constants used to construct pressure step-testing equation

Variables	Range/ value
Haulage length	800–3500 m
Half level haulage CA flow	0.17–1.68 kg/s
Maximum flow per leak	0.24 kg/s
Number of leaks simulated	7
Haulage pipe inside diameter	210 mm
Haulage pipe surface roughness	0.09 mm
Level station CA pressure	500 kPa_g
Confidence level	95%

The sequence for obtaining the required pressure logger data and simulating a haulage with the pressure logger data have been developed. This diagram is illustrated in Figure 81 which can be found in Appendix A.

2.3.5 Shaft mass balance

If supply-side limits have been reached, as discussed in the flow diagram (Figure 41) of Section 2.3.2, a mass balance using mass flow loggers can be used to identify larger mining areas of high consumption. A mass balance could identify inactive areas consuming CA which can be sealed off from the rest of the network to obtain significant shaft demand reductions without affecting end-users [40]. A simplified diagram of typical underground CA network areas is illustrated in Figure 48.

Prioritisation of high CA consuming areas has proven to be successful in the identification of wastages higher than 10 kg/s [40]. A request should be submitted to install measurement points if the consumption of the areas cannot be determined with portable measurement equipment. The mass flow to each area in Figure 48 can be calculated with Equations 13 to 15.

$$Q_{A1} = Q_{FT1} + Q_{MP1} - Q_{MP2} \quad (13)$$

$$Q_{A2} = Q_{MP2} \quad (14)$$

$$Q_{A3} = Q_{FT} - Q_{MP} \tag{15}$$

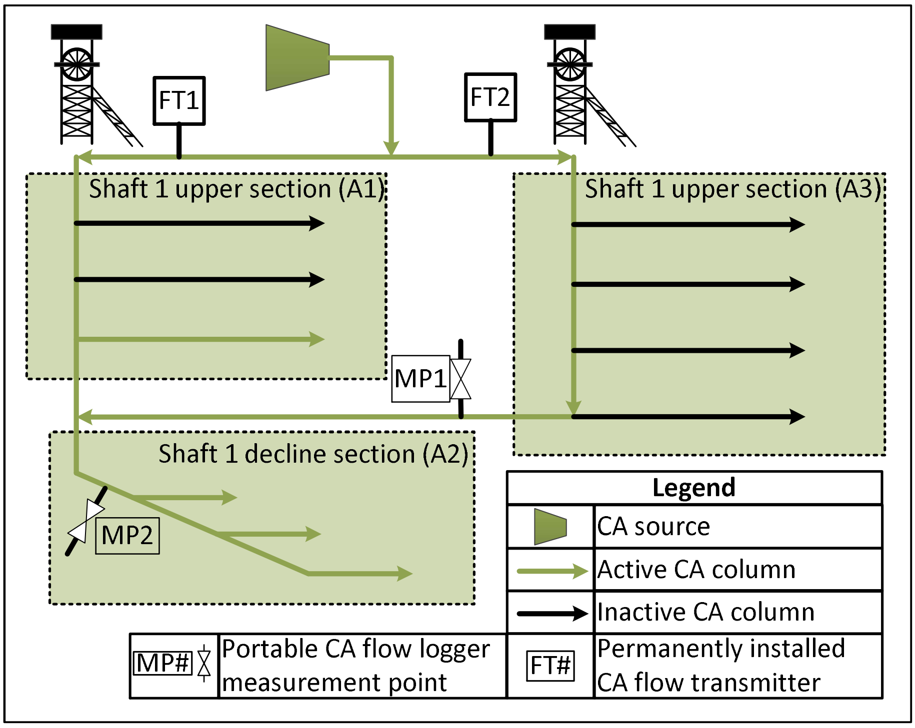


Figure 48: Compressed air areas of a typical deep-level mine

Where:

Q_A = CA consumption of the specified area [kg/s]

Q_{FT} = CA measured at the permanently installed flow transmitter [kg/s]

Q_{MP} = CA measured at the measurement point with a portable flow logger [kg/s]

Underground mine measurement instrumentation data can often not be trusted as mentioned in Section 1.2.3. It is thus recommended to determine the CA flow into a certain area with a portable, calibrated flowmeter. Updated calibration certificates are often available for surface flowmeters as these instruments are sometimes used for shaft billing purposes. These meters can thus also be used to determine the consumption to a specified area.

After a mass balance has been completed on the specified area, the leak location can be narrowed down further by measuring the CA flowrate to each level. High leakage locations can be narrowed down further to manageable areas (cross cuts) by using the step-testing and proxy metering techniques that were developed in Sections 2.3.3 and 2.3.4 respectively.

2.4 Energy management strategy for leak repair

2.4.1 Preamble

Objective 3 of this study states that an integrated methodology needs to be developed to provide a clear procedure for deep-level mine compressor electricity savings through demand reduction. Methods to identify shafts with high demand reduction potential and auditing were discussed in Sections 2.2 and 2.3 respectively. In this section, these developed methods will be integrated into one leak management strategy which can be practically applied to address CA wastage and achieve electricity cost savings.

Mine personnel are usually responsible for repairing the identified leaks. The importance of reporting to relevant mining personnel was discussed in Section 1.2.5. A strategy to use reporting of the identified wastages to gain the attention of relevant mining personnel will be discussed in this section.

Objective 4 of this study states that a savings quantification method (SLA method) should be developed for the accurate quantification of deep-level mine compressor electricity savings. Over- or underestimating the reported savings with electricity cost saving initiatives can have a negative impact on future cost saving initiatives. An improved SLA method will be developed as existing methods are inadequate.

2.4.2 Integrated underground leak management strategy

In Section 1.2.5, it was found that a clear plan can assist with the success of an energy efficiency project. An integrated underground leak management strategy has been developed from the techniques discussed in Sections 2.2 and 2.3. The strategy aims to achieve the maximum possible electricity cost savings through underground leak management.

According to Section 1.2.2, supply-side management should be pursued before moving to leak management. It is, therefore, recommended that the maximum cost savings be achieved through compressor and automated valve control before implementing the new underground leak management strategy. A diagram of the action strategy is displayed in Figure 49.

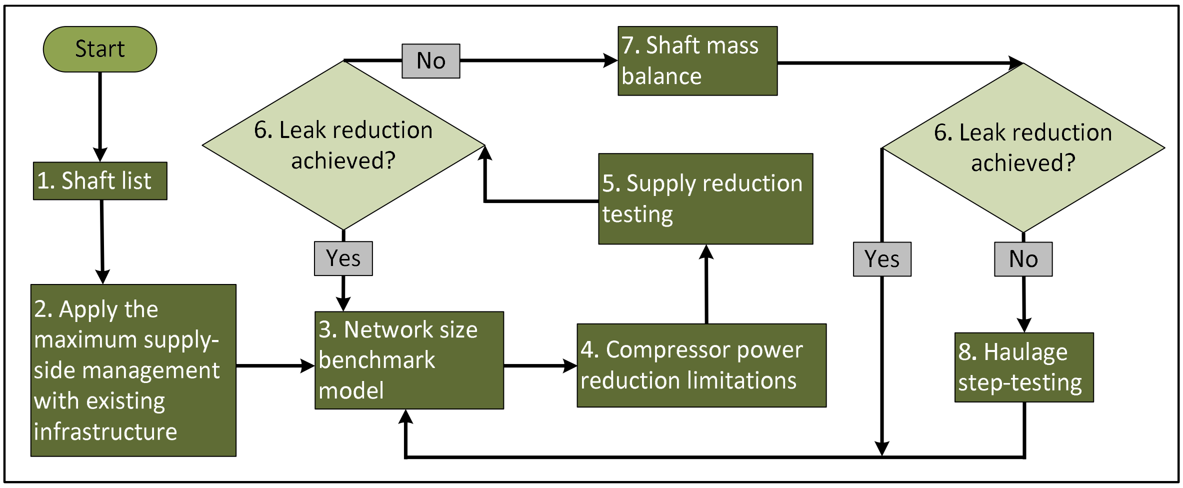


Figure 49: Underground leak management strategy

As seen in Figure 49, the action strategy starts with a list of prospective shafts in Block 1. Maximum supply-side management should be achieved with existing infrastructure, as stated in Block 2, before implementing demand-side management initiatives. After the maximum supply-side management has been achieved, the new benchmarking model developed in Section 2.2.2 is applied to the shaft list (Block 3).

Shafts which, according to the benchmarking model, show potential for demand reduction are evaluated for compressor power reduction limitations in Block 4. Energy managers should prioritise shafts for leak management based on the outcomes of the benchmark model, the compressor power reduction limitations, and the amount of available resources.

After the energy managers have decided which shaft to investigate, Block 5 indicates that the CA supply to the shaft should be reduced according to the strategy detailed in Section 2.3.2. This will allow energy managers to immediately narrow down the areas that inhibit further supply-side management. After the problems in the focus areas have been corrected, the shaft can be re-evaluated for leak management in Blocks 3 and 4.

If all the problems identified in Block 5 have been resolved, energy managers can move on to implement a mass balance on the shaft according to the method discussed in Section 2.3.5. The mass balance should give the energy managers a good idea of the high consuming CA areas and may also reveal inactive levels with pressurised CA columns which can be isolated.

Further investigations can be conducted on high-consuming areas identified with the mass balance. The step-testing audit methods, developed in Sections 2.3.3 and 2.3.4, can then be used to identify high CA consuming cross cuts which can be prioritised for conventional auditing. It is theorised that the method discussed in this section will enable energy managers to effectively reduce underground CA inefficiencies.

2.4.3 Leak repair management

In Section 1.2.3, it was established that ESCos are almost completely reliant on client resources to help with the implementation of electricity cost saving initiatives. It is thus necessary for ESCos to become familiar with the mine management structure to take full advantage of available resources. An organogram of a typical deep-level mining shaft is illustrated in Figure 50.

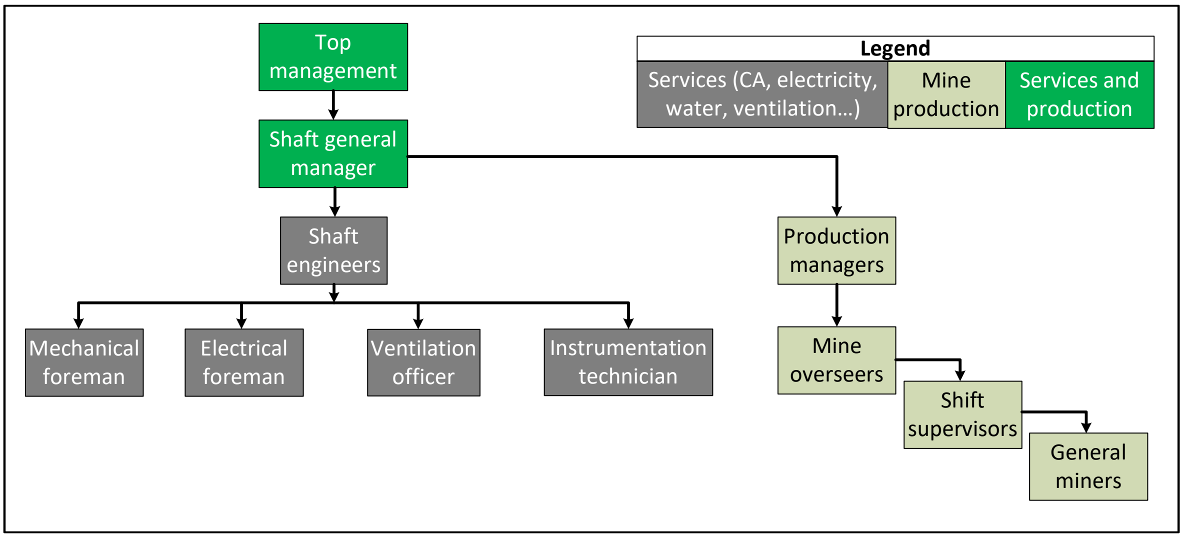


Figure 50: Organogram of a typical mining shaft

The organogram in Figure 50 illustrates that there are mining personnel specifically allocated to mine production and the services which include CA. Mine production personnel consume CA for production purposes, while the engineering department needs to supply the mining personnel with the CA they require.

Engineering personnel are usually responsible for the CA columns stretching from the compressors to the cross cuts. Production personnel are responsible for the CA column from the cross cuts to the stoping area. Leaks are repaired by the technical personnel working under the engineering and production personnel.

As mentioned in Section 1.2.3, energy efficiency on the CA system is a low priority for mining personnel. Leaks thus tend to persist. ESCos are employed as contractors to focus on addressing underground inefficiencies. These companies can identify and prioritise CA leaks, but the repair of these leaks remains the responsibility of mining personnel.

It is recommended that the documented CA leaks first be reported to the technical personnel situated on the lower part of the organogram. These are typically the personnel who are the most affected by the effect of the leaks and can quickly arrange for the leaks to the repaired. If the technical personnel do not cooperate, the documented leaks should be escalated to the next level of management.

When documenting leaks, it is important that mining personnel understand the report and the positive effects leak repair can have. The positive effect of non-energy benefits on production personnel's cooperation was discussed in Section 1.2.5. Top management and engineering personnel may be more interested in the cost savings that can be achieved.

2.4.4 Electricity savings calculation

As discussed in Section 1.2.3, electricity cost savings on deep-level mine CA systems are quantified using Service Level Adjustment (SLA) methods. Existing methods are usually based on production outputs. However, it has been found in Section 1.1.4 that the total CA used for productive purposes can be less than 40% of the total shaft consumption. Most of the CA that can directly be linked to the mine production is consumed during the drilling shift.

In Section 1.1.4 and 2.2.2 it was found that leakages increase with an increase in the size of the underground CA network. It is, therefore, reasoned that the compressor electricity consumption during the non-drilling periods can be related more closely to the size of the underground CA network when compared to production-related SLA methods. Similar to the benchmarking model that was developed in Section 2.2.2, the new SLA method will be based on the total underground CA system length.

As mentioned in Section 1.1.4, CA used during the non-drilling periods for productive purposes is negligible when compared to the wastages. The SLA method will thus only be applicable to the non-drilling period. A separate, production-based SLA method could then be used to adjust the power profile during the drilling shift. The project impact can be calculated with Equations 7 and 8 together with the scaling factor which is calculated in Equation 16.

$$SF = \frac{HL_C}{HL_B} \tag{16}$$

Where:

SF = Scaling factor

HL_C = Current active haulage length [m]

HL_B = Baseline active haulage length [m]

The SLA method described in this section accounts for the increase in shaft consumption occurring due to the CA network expansion, as described in Section 1.1.4. Electricity costs will be calculated based on the leakage rate reduction per length of the underground network.

The baseline consists of a 24-hour compressor power profile constructed with the average pre-implementation data. Unlike the benchmarking model, pressure will not be used to normalise the baseline. This will also allow the quantification of supply-side management electricity cost savings.

The network size baseline adjustment factor can be calculated with Equation 16. It is expected that the new network size SLA method will be a better predictor of what the compressor power profile would have looked like outside the drilling shift if no electricity cost saving initiative was implemented.

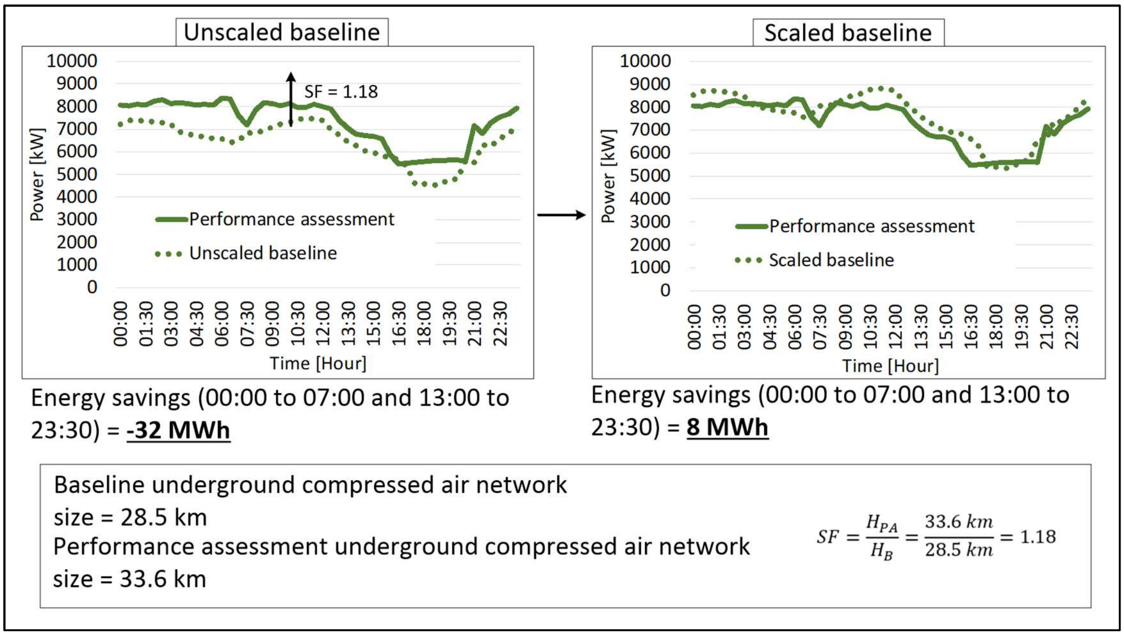


Figure 51: SLA method example

A further explanation on how to calculate the scaled baseline using the CA network size SLA method is illustrated in Figure 51. An expanding gold mine was used as a theoretical example. The ESCo implemented an initiative to increase the time in which peak clipping was implemented on the shaft compressors. An old level was re-opened causing the shaft demand to increase.

As seen in Figure 51, the increase in CA demand causes the Performance Assessment (PA) profile to be higher than that of the unscaled baseline. The daily energy saving outside the drilling shift is thus negative.

According to the new SLA method, the baseline can be adjusted upwards to account for the increased CA network size. Adjusting the baseline will lead to an 8 MWh energy saving outside the drilling shift which is closer to the expected impact from the extended peak clipping initiative.

A PTB compressed air network simulation of Shaft H was used to **verify** the newly-developed SLA method. The simulation meets the simulation accuracy requirements specified in Section 2.2.4. Table 5 contains a list of the Shaft H levels together with the corresponding lengths and mass flows.

Table 5: Level lengths and flows of Shaft H

Level	Length [km]	Mass flow [kg/s]	Level	Length [km]	Mass flow [kg/s]
16-level	5.36	2.08	**27-level**	3.10	2.87
21-level	4.18	2.95	**28-level**	5.18	1.81
22-level	4.28	3.5	**29-level**	4.32	2.91
24-level	6.34	3.25	**30-level**	3.79	2.86
25-level	5.87	3.5	**31-level**	2.84	6.32
26-level	5.35	1.41			

A list of compressors and corresponding specifications are listed in Table 6. The compressor discharge set point was set to a value of 550 kPa_g.

Table 6: Compressor specifications of Shaft H

Compressor number	Max power [kW]	Min power [kW]	Maximum flow [kg/s]	Minimum flow [kg/s]	Efficiency
1	8400	6400	30.1	21.6	0.76
2	5300	5000	19.0	17.4	0.73

Compressor number	Max power [kW]	Min power [kW]	Maximum flow [kg/s]	Minimum flow [kg/s]	Efficiency
3	4300	3400	10.7	8.5	0.61
4	4300	3400	10.7	8.5	0.61
5	2100	1600	5.6	4.3	0.62

A random number of random levels were isolated in the simulation to simulate a decrease in the network size and measure the effect it would have on the total compressor power consumption. A total of 97 scenarios were simulated. Results from the scenarios are presented in Figure 52.

A regression analysis of the simulation results reveals an R^2 of 0.869 which is acceptable for deep-level mine electricity quantification purposes. The simulation thus **verifies** the use of the new SLA method.

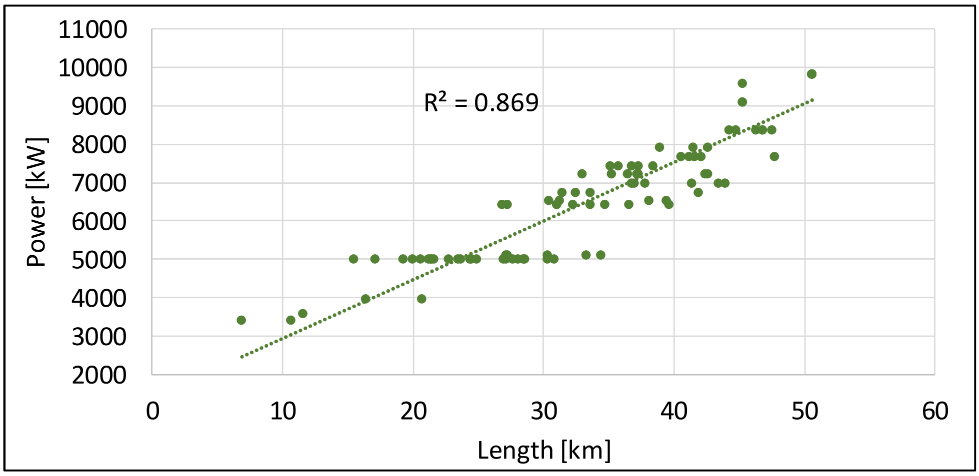


Figure 52: Simulation results for the new SLA method

As seen in Figure 52, a minimum compressor power consumption of 5000 kW can satisfy the CA needs for the simulated shaft if the total haulage length of the shaft ranged from 15 km to 35 km (20 km difference). This thus means that the new SLA method can, in some cases, result in inaccurate cost savings being quantified. Although not clear in the graph, 80% of the 5000 kW simulated scenarios was concentrated within a 6 km range around the mean, thereby explaining why the correlation in the data was still acceptable.

On further investigation it was found that due to the compressor throttling limitations, the minimum compressor power required to satisfy a CA demand ranging from 17 to 11 kg/s, was 4978 kW. Due to the differences in half level efficiencies[7], this meant that a wide of simulated haulage lengths can return a 5000 kW minimum compressor power consumption.

The accuracy of the electricity cost savings quantified by the newly developed SLA model thus increase with an increase in the throttling capabilities of the compressors and an increase in the similar half level efficiencies[7].

2.5 Summary

A need was identified for methodologies to reduce the electricity consumption on deep-level mine compressors through underground demand reduction in Chapter 1. Section 2.2 presented methodologies which could be used to prioritise shafts for CA leak auditing based on the shaft CA and electricity demand reduction potential. After the high potential shafts have been identified, energy managers can use the auditing methods that were developed in Section 2.3 to identify the problem areas for leak localisation.

In Section 2.3.2 a method was developed where supply-side management is used to quickly identify areas which hinder compressor electricity savings. Areas of high demand can be identified with a shaft mass balance discussed in Section 2.3.3. High wastage areas can be narrowed down further using the step-testing and proxy metering techniques that were developed in Sections 2.3.3 and 2.3.4 respectively.

The methods developed in Sections 2.2 and 2.3 were combined into one integrated method which was discussed in Section 2.4.2. According to the integrated method, energy managers first need to determine the potential for electricity reduction, after which underground audits should be conducted. After the leaks have been found and repaired, the shaft should be re-evaluated with the benchmarking model and compressor limitation methodology.

Leaks need to be repaired by mining personnel that are responsible for the area in which the leak is located. A low priority is often given to leak repairs as production is the focus and mining personnel are often not aware of the negative impact leaks have on the CA system. Effective communication of leaks was discussed in Section 2.4.3.

After the leaks have been repaired, the energy savings need to be accurately quantified. A new SLA method was developed in Section 2.4.4 as existing methods lack the ability to accurately quantify the effect of energy efficiency initiatives on CA systems. The method is

[7] Efficiency, in this case, means CA consumption per half level length

based on the total active haulage length that was also used to develop the new benchmarking model.

Chapter 3. Validation and verification through implementation of solutions

3.1 Introduction

In Chapter 1 a need was identified for methods to reduce underground Compressed Air (CA) demand on deep-level mines. Existing electricity cost-saving quantification methods were found to be inadequate. Novel methods to address these shortcomings were developed in Chapter 2.

In this chapter, the methods that were developed in Chapter 2 will be applied to real-world deep-level mining shafts. Results from these case studies will be used to verify and validate the methods developed in this study.

3.2 Application of new benchmarking model

3.2.1 Preamble

In Chapter 1 it was found that existing deep-level mine CA benchmarking models fail to prioritise shafts based on the potential for underground demand reduction potential. These models rather prioritised shafts based on the combined supply and demand management potential.

Objective 1 of this study states that a method should be developed to prioritise shafts for demand reduction. A new benchmarking model together with a compressor power reduction mapping method was created in Sections 2.2.2 and 2.2.3 respectively. In this section, the newly-developed methods will be applied to selected deep-level mining shafts.

3.2.2 Implementing network size benchmarking on selected shafts

The newly-developed benchmarking model, developed in Section 2.2.2, was tested on five case study mines. Information on these shafts are listed in Table 7. To compare the shafts on equal grounds, only the mass balance technique that was discussed in Section 2.3.3 was implemented. Stope demand reduction was thus not carried out on these shafts.

The shaft mass balance on Shaft A will be discussed in Section 3.3.2. Appendix A to Appendix F contains information on the shaft mass balances that were conducted on Shafts B to L respectively. Leak reduction was not achieved on all these shafts due to delayed actions from mining personnel. Information on the identified demand reduction potential is thus indicated instead.

Table 7: Shaft information on benchmarking case studies

Shaft	Mining type	Normalised mass flow [kg/s][8]	Pipe length [km]	Leak reduction indicator [kg/s/km]
Shaft A	PGM	9.82	29.6	0.33
Shaft J	PGM	28.3	54.7	0.52
Shaft L	Gold	15.19	13.2	1.15
Shaft B	Gold	14.91	12.7	1.18
Shaft F	Gold	38.26	27.9	1.37

Results from the case study mass balances and benchmarking indicators are illustrated as a bar chart in Figure 53. Shafts in this bar chart are ranked in ascending order from left to right based on the leak reduction potential indicator. Based on the new benchmarking model, the shaft furthest to the right of the graph will have the highest potential for underground demand reduction, while the shaft furthest to the left will have the lowest potential.

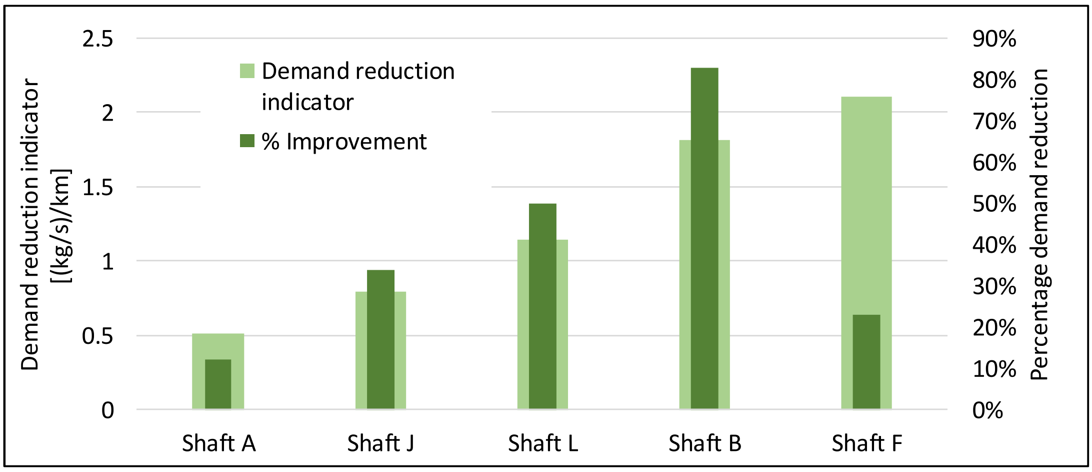


Figure 53: Benchmark priority shafts versus percentage CA reduction achieved/ identified

The actual demand reduction or demand reduction potential that was achieved/ identified for each shaft is indicated with the corresponding demand reduction indicator of the shaft in Figure 53. If the demand reduction potential, indicated as "percentage demand reduction"

[8] CA flow was normalised to an underground pressure of 550 kPa_g

also ascends from left to right, like the leak reduction indicator, it will verify that the benchmarking model can be used to prioritise shafts for demand reduction.

According to the graph in Figure 53, the percentage CA reduction increased with an increase in the leak reduction indicator which provides further **verification** for the use of this prioritisation method. This thus means that using the new benchmarking model is suitable for prioritising shafts for underground demand reduction. However, Shaft F is an outlier.

Shaft F has the highest demand reduction indicator but a mass balance of the shaft revealed sealing off the inactive areas or levels will potentially only result in a leak reduction percentage less than that of Shaft J. Further investigations revealed that Shaft F has high CA consuming levels.

A typical active level has a CA consumption of ± 2 kg/s. The average CA consumption of active levels on Shaft F was 5.1 kg/s, indicating that auditors should rather turn to audits of the active levels to identify high leakage-reduction potential such as that of Shaft B. A detailed audit of the haulages using the audit methods described in Sections 2.3.3 and 2.3.4 could be used to locate the high leakage areas in the active levels.

3.2.3 Comparing the new benchmarking model with existing models

In the previous section, it was determined that the newly-developed benchmarking model was successfully used to prioritise the shafts for demand reduction. In this section, outputs from the new benchmarking model will be compared to the outputs of existing benchmarking models which were discussed in Section 1.2.2.

Additional variables, such as shaft production and depth, are required to apply existing benchmarking models to the case study shafts. These variables are listed in Table 8.

Table 8: Shaft variables required for benchmarking model comparison

Shaft	Monthly compressor energy consumption [MWh]	Monthly production [tonnes][9]	Mine depth [m]	Season
Shaft A	2758	106417	445	Summer
Shaft J	10865	96773	1171	Summer

[9] The monthly production consists of a six-month average

Shaft	Monthly compressor energy consumption [MWh]	Monthly production [tonnes][9]	Mine depth [m]	Season
Shaft L	4351	47617	1649	Winter
Shaft B	3871	71813	1923	Winter
Shaft F	9052	92053	3680	Winter

The information in Table 8 was substituted into Equation 3 of Section 1.2.2 to calculate the compressor energy intensity. Shafts will be prioritised for electricity cost savings based on the calculated intensity in Figure 54. Like the bar graph in Figure 53, the shafts will be ranked from left-to-right in ascending potential for compressor electricity cost savings. The percentage CA reduction that was identified will also be plotted with the corresponding shaft.

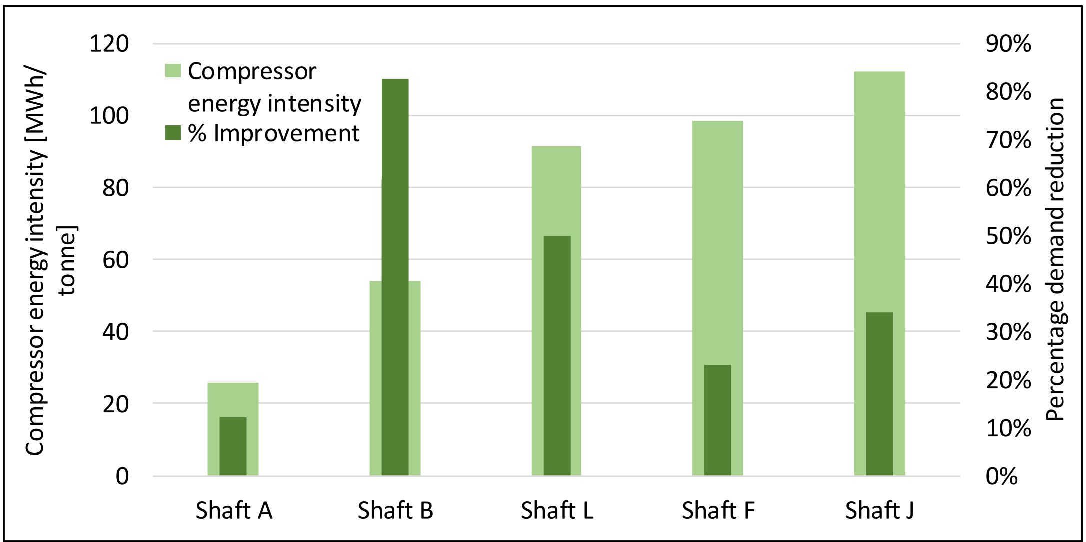


Figure 54: Shaft energy intensity versus percentage CA reduction identified/ achieved

As seen in Figure 54, Shafts B and L were indicated to have the second and third smallest potential for compressor electricity cost savings, respectively. However, CA auditors found that Shafts B and L have the first and second highest demand reduction potential. This thus indicates that using energy intensity is not suitable for determining the demand reduction potential.

The information in Table 8 was substituted into Equations 4 and 5 of Section 1.2.2 to calculate the required compressor energy for the case study shafts. Shafts were prioritised based on the difference between the actual and required compressor energy consumption as a percentage of the actual energy consumption using Equation 17.

$$M = \frac{E_{actual} - E_{required}}{E_{actual}} \times 100 \qquad (17)$$

Where:

M = Multi-variable prioritisation indicator [%]

E_{actual} = Actual monthly compressor electricity consumption [MWh]

$E_{required}$ = Required monthly compressor electricity consumption calculated with Equations 4 or 5 in Section 1.2.2 [MWh]

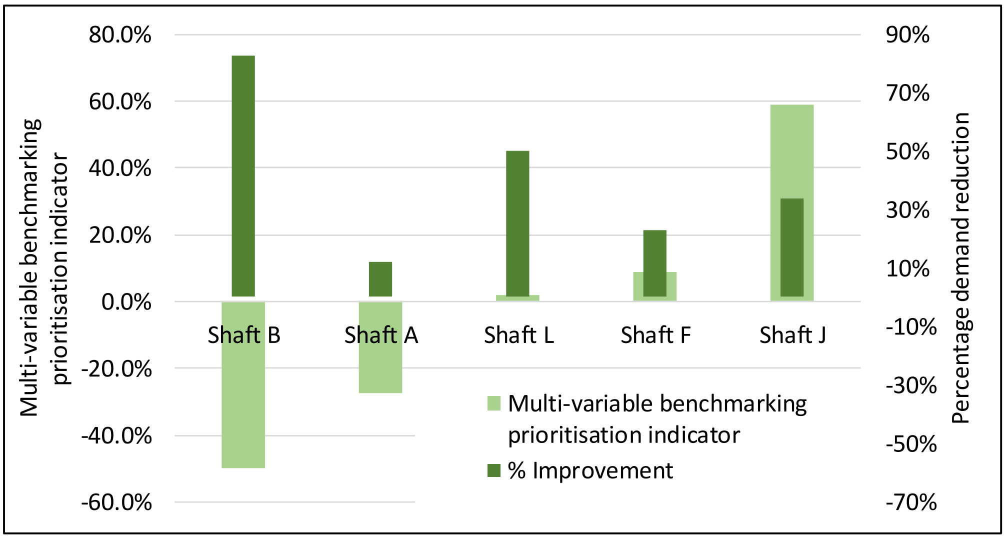
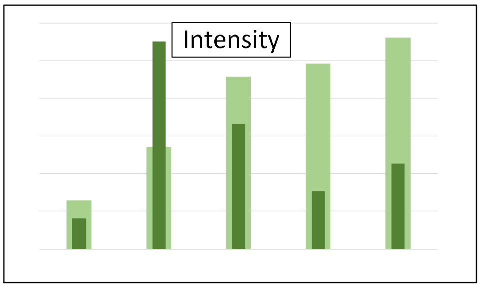


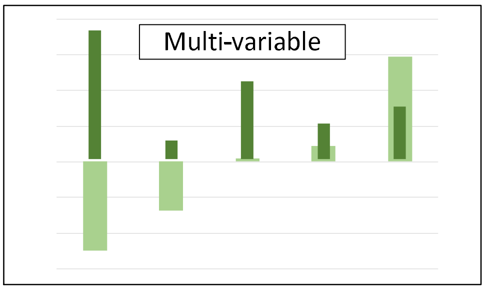
Figure 55: Multi-variable benchmarking versus percentage CA reduction identified/ achieved

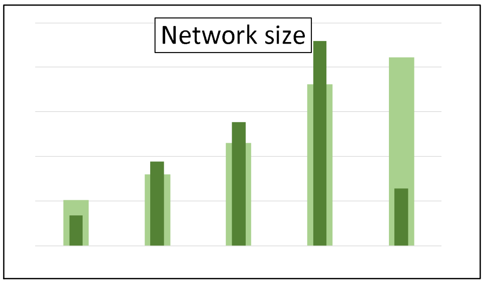
The multi-variable indicator results from substituting the case study information into Equations 4, 5, and 17 were plotted on a bar graph illustrated in Figure 55. The shafts were arranged in ascending compressor electricity cost saving potential.

Similar to the energy intensity prioritisation results in Figure 54, the multi-variable benchmark indicator failed to prioritise the shafts for underground demand reduction, as can be seen in Figure 55. The calculated required energy of two shafts, Shafts B and A, produced negative indicators. This means that shafts are consuming less than the required compressor energy as calculated with the multi-variable benchmark model. An updated model is thus required.

Resulting prioritisation bar charts from the different benchmarking models have all been inserted into Figure 56. The bar charts are labelled “Intensity” for the intensity benchmarking model, “Multi-variable” for the multi-variable benchmarking, and “Network size” for the new benchmarking model that was developed in this study.







	Ideal prioritisation	Intensity	Multi-variable	Network size
Shaft B	1	4	5	2
Shaft L	2	3	3	3
Shaft J	3	1	1	4
Shaft F	4	2	2	1
Shaft A	5	5	4	5

Figure 56: Priorities assigned to shafts for electricity cost saving initiatives

To evaluate the ability of the benchmarking models for prioritising shafts for underground CA demand reduction, the priorities assigned to each shaft will be compared to an ideal prioritisation method. Ideal prioritisation means that the shafts with the highest demand reduction potential will be prioritised for auditing. A table containing the priorities assigned to the case study shafts are also shown in Figure 56.

A scoring method was developed to evaluate the priorities assigned by each benchmarking model. The method involves determining the difference between the ideal prioritisation model and the priority assigned to each shaft with the specified benchmarking model. As an example, priority was given to Shaft B according to the ideal prioritisation model, while the compressor energy intensity model indicated that Shaft B is fourth priority. The difference is three places. Table 9 contains the difference between the ideal and benchmark priorities.

Table 9: Difference between ideal and benchmark priorities

Shaft	Intensity	Multi-variable	Network size
Shaft A	3	4	1
Shaft J	1	1	1
Shaft L	2	2	1
Shaft B	2	2	3
Shaft F	0	1	0
Total	**8**	**10**	**6**

According to the information in Table 9, the network size benchmarking model assigns priorities that are the closest to that of an ideal prioritisation method which thus **validates** the new method. When prioritising shafts for underground demand reduction, it is thus recommended that the network size benchmarking model be used.

A scenario will be used to better conceptualise the improvement in prioritisation of the network size benchmarking model. In this scenario ESCos A and B must each choose two shafts to audit based on the priorities of given by their chosen models. ESCo A decided to use the network size prioritisation model, while ESCo B used the multi-variable model. According to the prioritisation models, ESCo A should audit Shafts B and F, while ESCo B should audit Shafts F and J. Based on the results discussed in this section, ESCo A has to cover an average of 1240 m of haulage pipe to achieve a 1 kg/s leak reduction rate, while ESCo B has to cover 2900 m to achieve the same leak reduction. A 57% improvement in resource utilisation was thus achieved by using the network size prioritisation model.

Other benchmarking models should rather only be used to indicate the combined potential for demand- and supply-side management potential of CA systems.

3.3 Implementation of new audit methodologies

3.3.1 Preamble

According to **Objective 2** of this study, improved auditing methods for deep-level mine CA leak detection must be developed and tested. New audit methodologies were developed in Chapter 2 for conducting audits more efficiently and safely when compared to existing methodologies. In this section, the audit methodologies will be implemented on various deep-level mining shafts.

Objective 3 of this study states that an integrated methodology for shaft prioritisation and auditing must be developed. In Sections 3.3.2 and 3.3.3, the audit methodologies were applied to solve underground pressure complaints on specific levels after supply-side management initiatives resulted in pressure complaints. CA auditors applied the integrated methodology developed in Section 2.4.2 to solve the pressure complaints.

The case study in Section 3.3.4 involved first determining the potential for underground leak management using the newly-developed benchmarking model. Auditors used the mass balance and step-testing methodologies to identify CA wastages underground.

3.3.2 Mass balance implemented on a platinum mining shaft

An ESCo was contracted to reduce the electricity consumption on a CA ring of Mining Company A. This ring consists of three shafts and two compressors houses, as illustrated in Figure 57. Shaft A and E are further sub-divided into sub-shafts A1 to A3 and E1 to E2 respectively. Shaft X was under care and maintenance and consumes an insignificant amount of CA. Compressor House 2 was situated 4 km from Shaft A, resulting in a ± 20 kPa pressure drop.

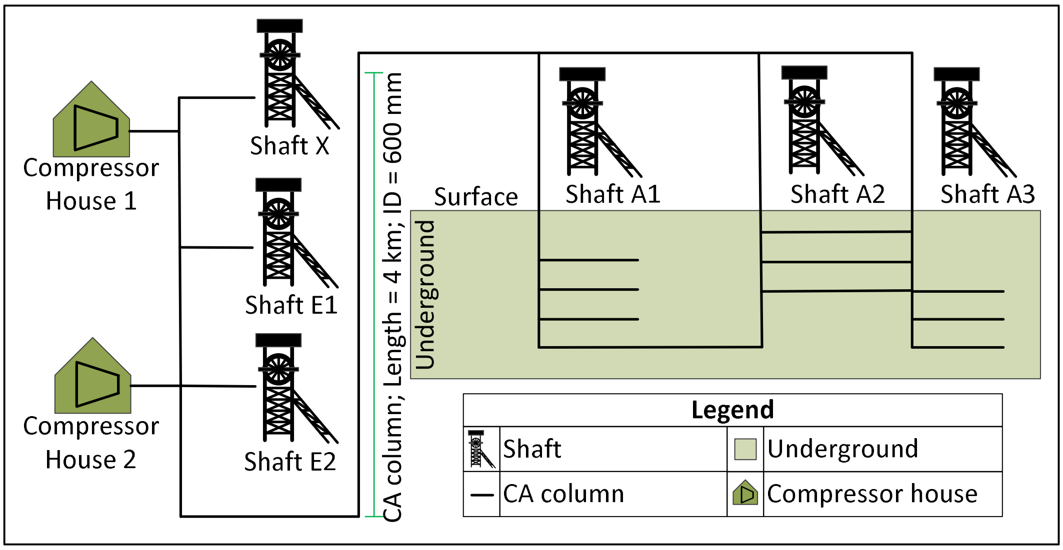


Figure 57: Shaft A and E compressed air ring surface layout

The CA pressure drop from Compressor House 2 to Shaft A resulted in this shaft being the first to complain when supply-side management initiatives were implemented on the compressors. According to the new, integrated methodology developed in Section 2.4.2, further investigation should be conducted by means of the mass balance methodology that was developed in Section 2.3.3.

Complaints on Shaft A were focused to the afternoon shift when the pneumatic loaders were operated. Most of the complaints were received from 9-level UG2 West. Auditors, therefore, decided to start with the mass balance measurements on this half level. A diagram of the CA network to this half level is illustrated in Figure 58.

As seen in Figure 58, 9-level UG2 West receives CA from two sources. The first source of CA is Shaft A2 which was regarded as the main shaft. Shaft A2 supplies CA to all the active levels of this mining complex. The second source of CA was Shaft A1, a sub-shaft which supplied CA to some of the abandoned upper levels. These levels have been abandoned for more than three years.

According to the shaft engineer and relevant production personnel in a pre-implementation interview, the Shaft A1 CA column was not connected to other levels, except 9-level UG2 West. They were also under the impression that the abandoned levels have been isolated from the CA network. This column spans from Shaft A1, through old working areas until it ties in with 9-level UG2 West at Cross cut 41, located 1.8 km from the 9-level station.

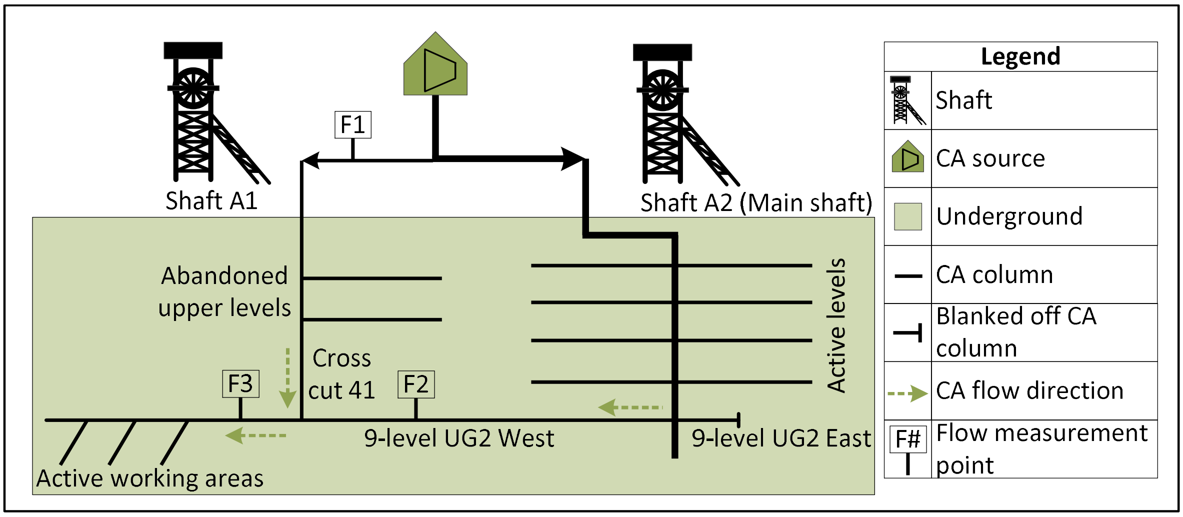


Figure 58: Compressed air network to 9-level UG2 West of the Shaft A1 to A2 mining complex

The initial idea behind the Shaft A1 column was for 9-level UG2 West to have a high pressure, close to the surface pressure, and to supply the lower levels with CA. Pressure loggers were installed over the length of the haulage from 9-level station to Cross cut 41. It was determined that the column pressure decreased from the station to the cross cut. According to Equation 2 in Chapter 1, this haulage was consuming air from the main shaft.

Auditors suspected that the Shaft A1 column could be the source of the problem and thus decided to measure the CA consumption of the abandoned area. As illustrated in Figure 58, a surface measurement point (F_1) and two haulage measurement points (F_2 and F_3) on opposite sides of the incoming Shaft A1, could be used to measure this consumption. The consumption of the abandoned area was calculated with Equation 18.

$$F_A = F_1 - (F_3 - F_2) \quad (18)$$

Where:

F_A = CA consumption rate of the abandoned area [kg/s]

F_1 = CA flowrate of Shaft A1 [kg/s]

F_2 = CA flowrate from 9-level station to Cross cut 41 [kg/s]

F_3 = CA flowrate from Cross cut 41 to the working areas at the end of 9-level UG2 West [kg/s]

A calibrated, portable flowmeter was used to measure the CA consumption of Shaft A1 during the non-drilling shift. A value of 5.06 kg/s was measured at measurement point F_1. A flow of 1.08 kg/s was measured at F_2, while a flow of 2.06 kg/s was measured downstream of the Shaft A1 connection (F_3).

Substituting the measured CA flow measurements into Equation 18 resulted in a flowrate of 4.08 kg/s to the abandoned areas. A shaft inspection of Shaft A1 revealed no major leaks in the shaft column. However, auditors found an un-isolated column to 3-level Merensky West (ID = 210 mm). The column was isolated during the next shaft maintenance period. A graph of the Shaft A consumption before and after the leak repair is illustrated in Figure 59.

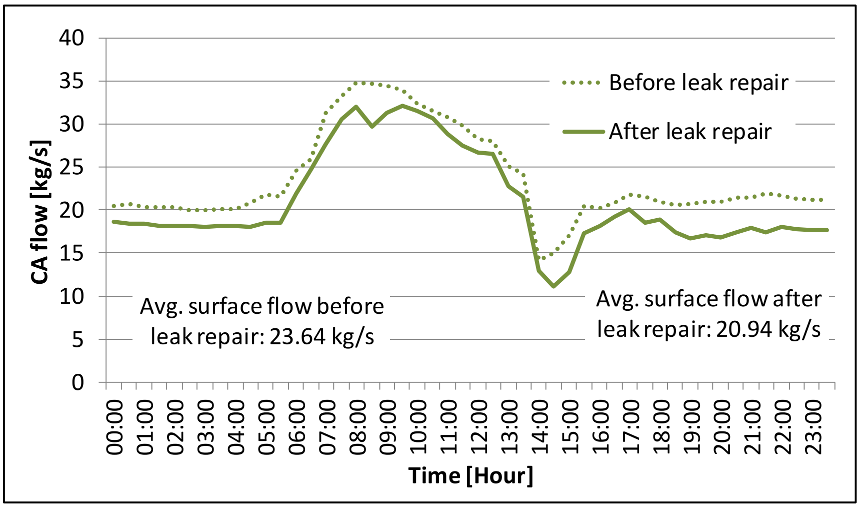


Figure 59: Shaft A compressed air consumption before and after the leak repair[10]

[10] The flow measurements used in this graph consists of the week's data before and a week's data after the leak repair. Only weekday data was included. Due to the before and after measurement periods being two days apart and only being a weeklong each, it was assumed that there were no external conditions, such as an increase or decrease in production, which could significantly affect the compressed air consumption of the shaft. No SLA method was thus necessary.

As can be seen in Figure 59, the total CA consumption of the Shaft A4 to A6 mining complex decreased with an average of 2.70 kg/s over a 24-hour weekday period after 3-level Merensky West was isolated. Further investigations revealed that the pressure set point of the compressors at Compressor House 2 was increased. This resulted in an increased pressure and flow to Shaft A4 to A6. To account for the increase in pressure, the flow was normalised with pressure. The normalised[11] CA decrease was 3.28 kg/s. This was still lower than the expected decrease 4.08 kg/s.

A possible reason for the underperformance can be ascribed to the increase in production activities during the morning shift. This statement is supported when considering the difference between the before and after leak repair graphs during the drilling period and the non-drilling periods. The difference was less during the drilling shift, indicating that the drilling shift consumption increased. This is further supported by the increase in shaft production.

During the investigation, auditors also found a pipe restriction in the CA column of Shaft A1. The column reduced from an inside diameter of 210 mm to 100 mm and returns to a 210 mm column after four meters. This reduction restricts the flow to underground. Two weeks after the leak repair, the sub-shaft column was reconfigured to by-pass the restriction. The CA consumption before and after the reconfiguration can be seen in Figure 60.

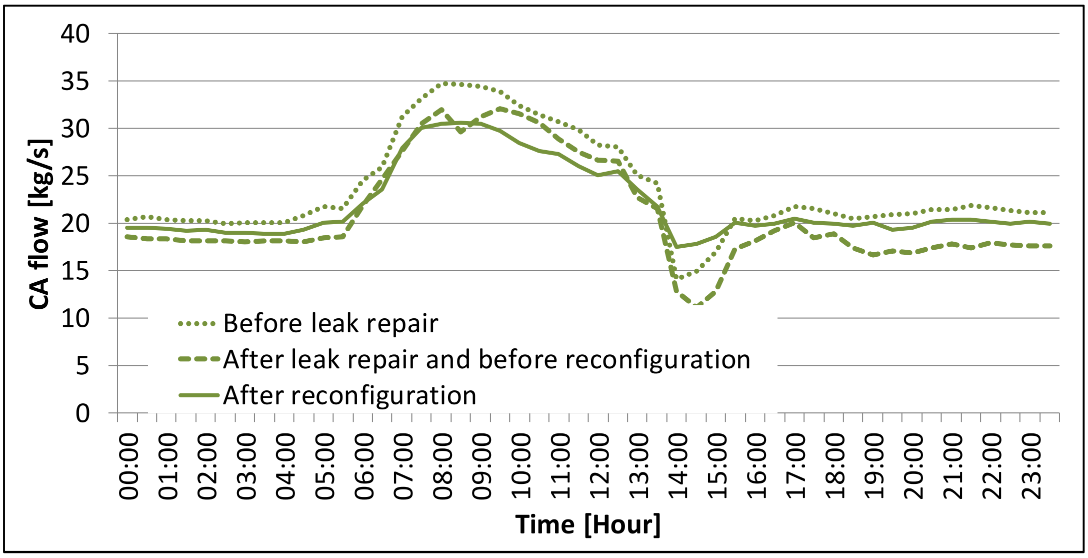


Figure 60: Shaft A compressed air flow after leak repair and pipe reconfiguration

[11] A simulation was used to calculate the shaft complex CA flow after the leak repair if the CA pressure underground did not increase.

According to the graph in Figure 60, the shaft CA consumption increased after the column was reconfigured. The flow reduction since the leak repair was now only 1.24 kg/s. Although the reconfiguration resulted in an increase in CA flow, it also resulted in an increased underground pressure on all levels. Level pressures before and after the leak repair and reconfiguration of the column restriction are presented in Table 10.

As mentioned previously, the pressure set point of the compressors was increased after the leak repair. The increase in the compressor house pressure was subtracted from the pressure increases that were experienced on the levels before and after the leak repair and reconfiguration of the column restriction. Normalised pressure increases of each level is given in the second last and last column of Table 8.

Table 10: Shaft A increase in CA pressure after leak repair and reconfiguration

	Pressure increase [kPa_g]					
	Compressor house header pressure	**6-level station**	**7-level station**	**8-level station**	**9-level station**	**10-level station**
Before leak repair	507.8	419.8	405.8	400.8	395.2	392.3
After leak repair	519.3	433.5	417.8	413.3	410.4	406.0
After reconfiguration	518.9	448.7	427.2	431.0	428.9	422.0
Pressure increase after leak repair and before reconfiguration	**11.5**	**2.2**	**0.5**	**1.0**	**3.7**	**2.2**
Pressure increase after reconfiguration	**11.1**	**17.8**	**10.3**	**19.1**	**22.6**	**18.6**

As seen in Table 10, the CA pressure at the stations of the underground levels were not significantly affected before the removal of the restriction. The pressure only increased with a maximum of 3.7 kPa when subtracting the pressure increase at the compressor house. However, after the reconfiguration the underground pressure increased with an average of 17.7 kPa.

As expected, 9-level received the highest increase in CA pressure, as indicated in Table 10. No complaints were logged in the months following the leak repair and reconfiguration. Energy managers could thus continue with the supply-side management initiatives as indicated in Section 2.4.2.

Previously, a team of four auditors completed a shaft audit of all active haulages of Shaft A. It took the team 12 days to complete the audit (three days per week), amounting to a total of 384-working hours. The audit did not amount to any cost savings. In contrast, two auditors were able to achieve significant savings over an estimated 20-working hours using the methods developed in Sections 2.3.3 and 2.4.2, thus **validating** the use of these methods.

The increase in compressor set point, together with the CA demand fluctuations on the other shafts connected to the ring complicated the electricity cost saving calculations. A simulation of the ring was used to calculate the savings. The CA demand reduction was related to electricity savings based on the efficiency of a 1200 kW rated compressor operated on this ring (332 kW per 1 kg/s CA reduction). This electricity cost saving amounts to an estimated annual electricity cost saving of R2.7-million thus further **validating** the mass balance method described in Section 2.3.3.

3.3.3 Solving pressure complaints with step-testing

Around four months after the leak repair on Shaft A, the compressor control room started to receive new pressure complaints, this time from Shaft E. Similar to Shaft A, the complaints were limited to two haulages. Control room operators needed to start an additional 1200 kW rated compressor to satisfy the pressure needs of these levels.

A mass balance on the whole shaft was done prior to the complaints but no irregularities could be found. Technical personnel from the mine conducted a conventional audit of the haulages and found very few leaks when compared to other haulages. It was also unusual that Shaft E complained although it had a ± 20 kPa higher pressure when compared to Shaft A.

The ESCo decided to apply the step-testing method, developed in Section 2.3.3, to detect wastages and resolve these issues. The first level to complain was 11-level Merensky West. It took two auditors five hours to complete the audit during a cleaning shift. A pressure logger (only capable of measuring in 10 kPa increments) and a portable CA flowmeter were installed. A layout of 11-level Merensky West can be seen in Figure 61.

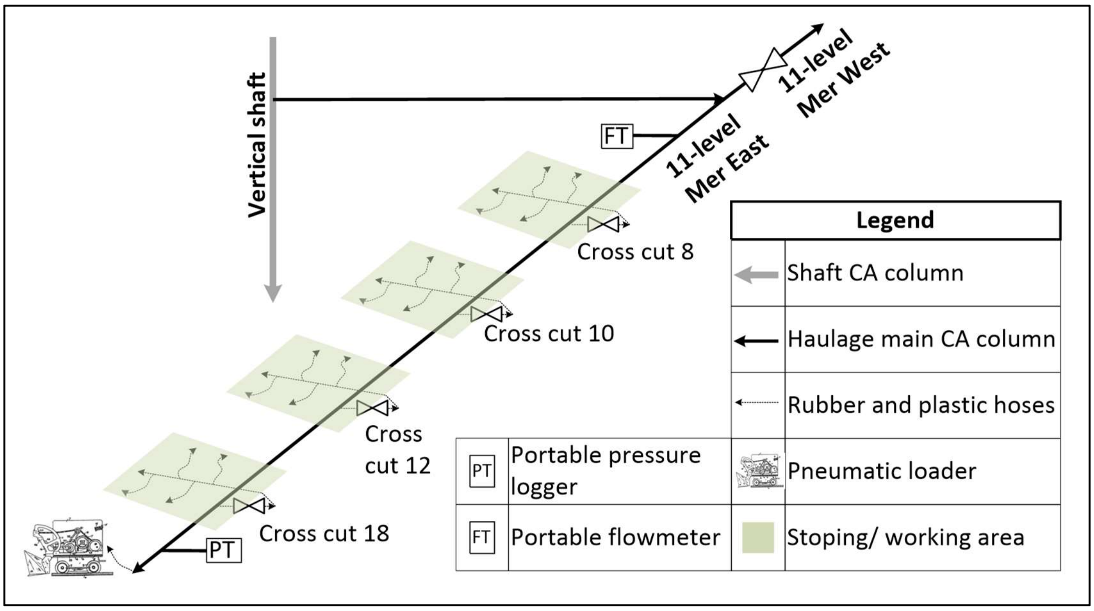


Figure 61: Step-testing on Shaft E, 11-level Merensky West

There were four cross cuts that could be closed in this haulage, as indicated in Figure 61. Auditors had to install a portable flowmeter and pressure logger at the start and the end of the haulage respectively. After both measurement instruments were installed, the auditors closed each cross cut one by one. The audit results are presented in Figure 62.

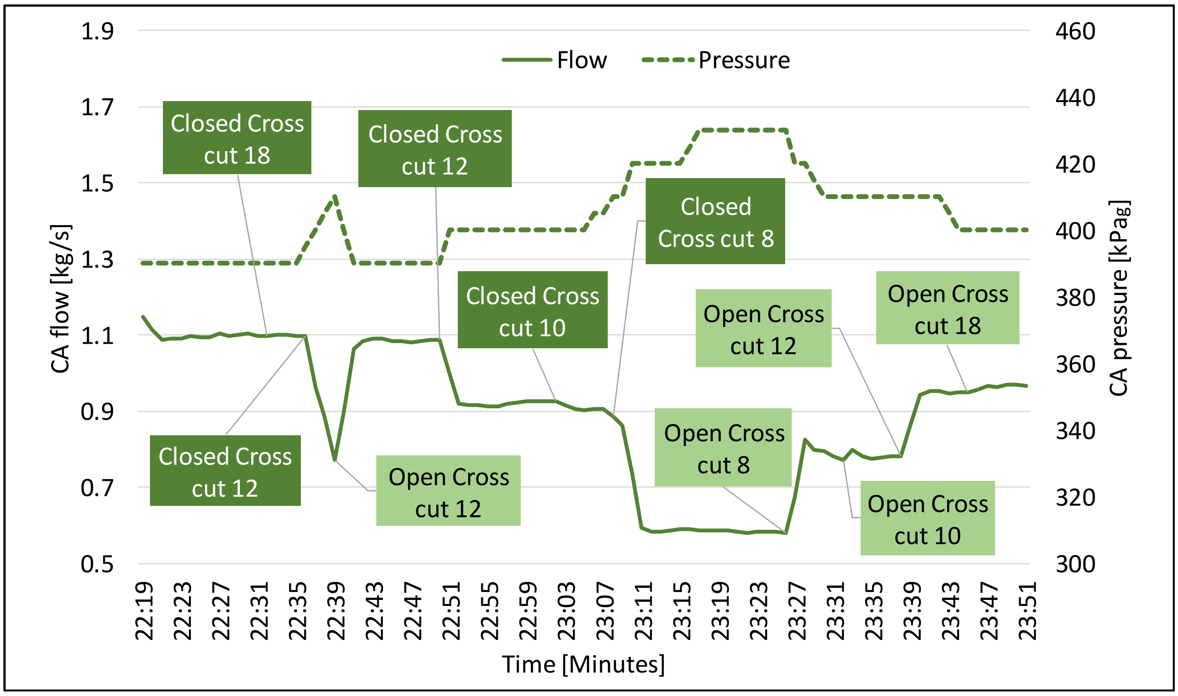


Figure 62: Step-testing results on 11-level Merensky West of Shaft E

According to the results illustrated in Figure 62, 11-level Merensky West had a total CA flow of around 1.1 kg/s which is high for a half level haulage. This resulted in a low pressure at the haulage end where the loader was operated. As illustrated in Figure 62, one of the cross cuts, Cross cut 12, had to be re-opened as personnel were pumping water out of the raise with a large pneumatic pump. This was a non-routine task.

After closing the cross cut valves, the total haulage CA consumption dropped by 40%, while the end pressure increased from 400 kPa_g to 430 kPa_g. The audit results were presented to the shift supervisor and the shaft engineer. The shift supervisor was satisfied with the increase in pressure. No complaints were received after the audit as they now knew how to manage their own pressure instead of relying on an additional compressor to be started.

A second CA pressure complaint was received three months after the first complaint on Shaft E. This time, 24-level UG2 West, located on the decline section, complained. The level on which the previous complaint was lodged is located on the upper section of the shaft which received CA through a different column. These complaints are thus not related to a certain section of the mine but rather to individual haulages. A step-testing audit was conducted on 24-level UG2 West. A flowmeter was installed at the start of the haulage. Results of the audit are illustrated in Figure 63.

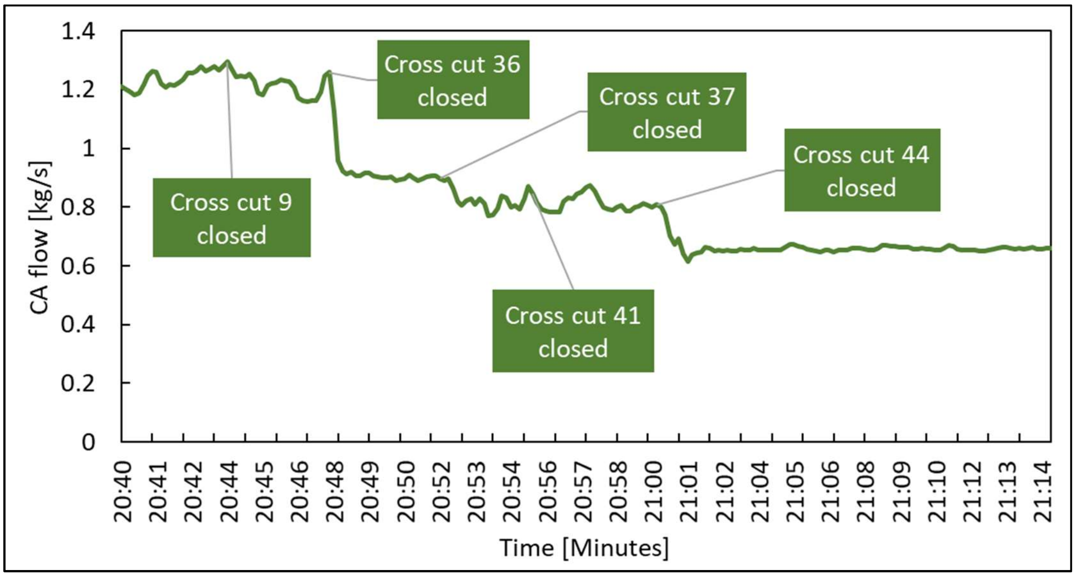


Figure 63: Step-testing results of 24-level UG2 West on Shaft E

A 28% reduction in the total haulage CA flow was observed when Cross cut 36 was closed. The auditors concluded the audit by conducting a conventional comprehensive audit of the stope CA network branching from Cross cut 36. Two fully-opened 1-inch rubber hoses were found blowing CA onto a stoping face. Photos of these hoses are illustrated in Figure 64. This serves as a **verification** for the flowmeter step-testing method and the integrated methodology which were developed in Sections 2.3.3 and 2.4.2 respectively.

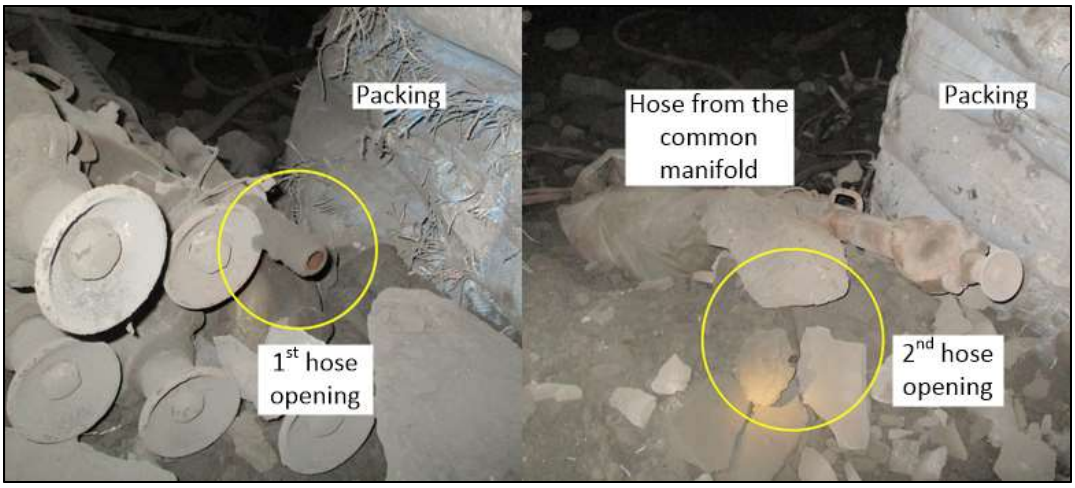


Figure 64: Photos of the open CA hoses 24-level UG2 West of Shaft E

In both cases, the reduced complaints resulted in an annual electrical cost avoidance of approximately R1.4-million as an additional VK10 compressor did not need to be started during the Eskom evening peak period.

Follow-up audits were conducted on 11-level Merensky West and 24-level UG2 West about six months after the first audit. Although no complaints were received, the CA consumption on these haulages increased. The compressed air flow on 11-level Merensky West increased from 1.19 kg/s to 1.24 kg/s while the flow of 24-level increased from 0.98 kg/s to 1.28 kg/s. Possible explanations for the increase in flow include the restructuring of mine managers and shift supervisors and the increase in the haulage length as both haulages were in development.

A minimum flow reduction of 40% was achieved by closing the existing cross cut valves on the investigated haulages. Extrapolating this flow reduction over 25 deep-level mines used in the study of Vermeulen [21] and assuming the percentage power reduction is equal to the percentage flow reduction will result in an annual electricity cost saving of R620-million during the non-drilling shift (14:00 to 07:00).

To maintain a 40% CA flow reduction, it is assumed that it will take auditors 384-working hours, as mentioned in Section 3.3.2, to audit a typical shaft each month at a rate of R300[12] per working hour. Maintaining the savings will thus come at an annual cost of R34.6-million. Installation of automated stope isolation valves may remove the dependence on labour to manually close stope isolation valves to achieve the desired savings [51].

[12] According to payscale.com, the median hourly rate of a South African instrumentation technician, who is assumed to be skilled to do such audits, is R300.

3.3.4 Complete shaft audit

A deep-level platinum mining shaft, Shaft H, near the Rustenburg area was chosen for the full-scale CA audit. The shaft was one of many shafts in the area belonging to Mining Group A. A pressure higher than 480 kPag was required for the shaft conveying system to remain in operation. Benchmarking indicators of the shafts on Mining Group A are indicated in Figure 65.

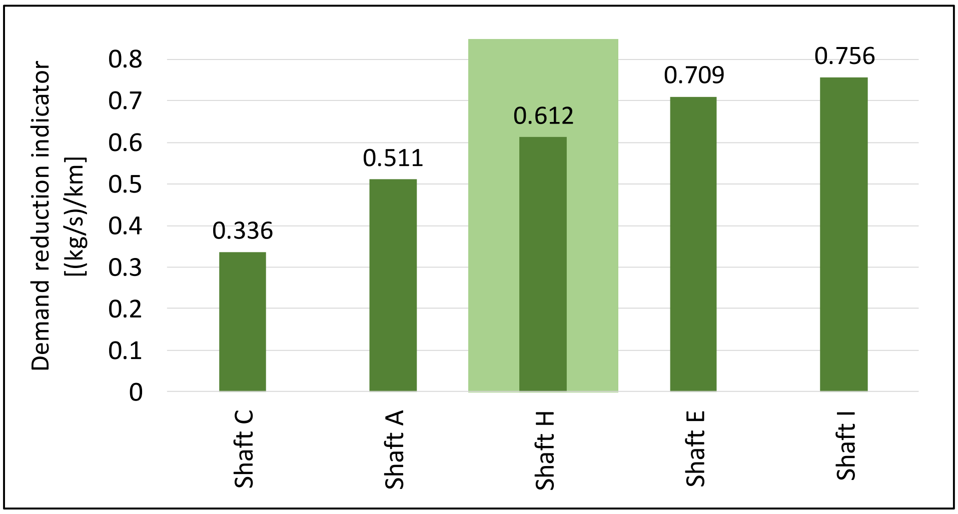


Figure 65: Benchmarking the shafts of Mining Group A – Focus on Shaft H

As seen on the graph in Figure 65, Shaft H was not the least efficient shaft of Mining Group A. However, the CA network size benchmarking indicator indicates that Shaft H was about 80% less efficient than the most efficient shaft. There could thus still be significant scope for demand reduction on this shaft. A graph mapping the compressor limitations is illustrated in Figure 66.

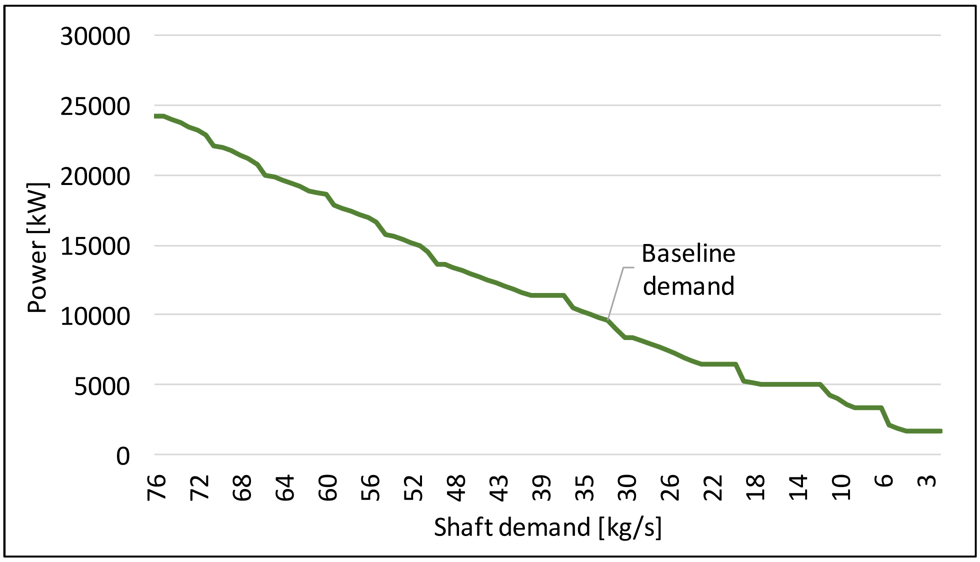


Figure 66: Shaft H compressor limitations mapping

According to the graph in Figure 66, demand reduction will result in compressor power savings, as both the VK100 and the VK25 in operation in the baseline period can reduce the power consumption through guide vane control. Reducing the CA demand with 2 kg/s will lead to the VK25 compressor being stopped resulting in a step-change in the power consumption. Further investigation was thus needed on Shaft H. A simplified CA network drawing of Shaft H is displayed in Figure 67.

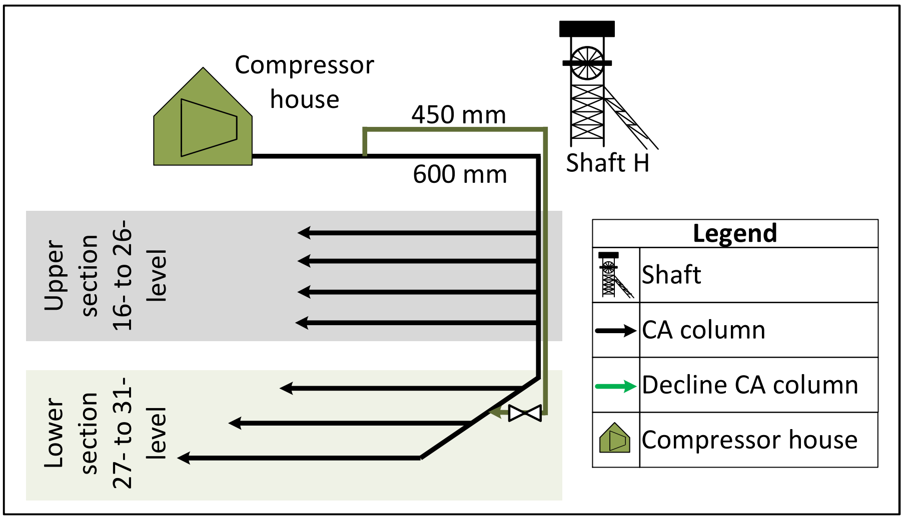


Figure 67: Simplified compressed air network layout of Shaft H

According to the layout in Figure 67, there are two distinguishable underground sections. The upper section consists of 16- to 26-level, while the lower or decline section consists of 27- to 31-level. CA was transferred underground via a 600 mm column, referred to as the main column, and 450 mm column, referred to as the decline column. The 600 mm column provides CA to the upper section. The 450 mm column connects with the main column after 28-level at the lower section.

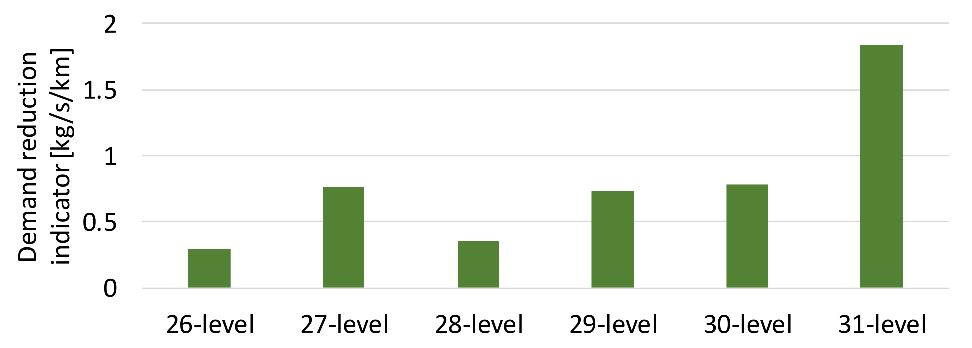
An instrumentation audit of the shaft revealed that the installed underground CA flowmeters were not accurate. The surface flowmeter, which measures the consumption of the entire shaft, was calibrated as it was used for billing purposes. A combination of portable flowmeters and the existing surface flowmeter were used to complete the mass balance of the two sections. The manual valve connecting the upper and lower sections needed to be closed while the measurements were taken.

Table 11: Shaft H mass balance results

Section	CA night shift mass flowrate [kg/s]	Section length [m]	Demand reduction indicator [kg/s/km]
Upper	14.11	51 215	0.276
Lower	14.86	21 561	0.689

According to the results illustrated in Table 11, the CA mass flow was split nearly equally between the upper and the lower section. However, the upper section has a larger CA network when compared the lower section. The length indicator thus indicated that the lower section contains more than double the scope for underground demand reduction when compared to the upper section.

Further investigations were conducted on the lower sections. As mentioned previously, the existing underground CA flowmeters were not accurate. Auditors thus decided to determine the mass flowrate by means of level step-testing. The step-testing results can be viewed in Figure 68.



Level	CA flow [kg/s]	DI [kg/s/km]	Level	CA flow [kg/s]	DI [kg/s/km]
26-level	1.28	0.29	**29-level**	2.85	0.73
27-level	2.44	0.76	**30-level**	2.74	0.78
28-level	1.68	0.36	**31-level**	5.15	1.84

Figure 68: Shaft H lower level benchmarking results

According to the benchmarking results in Figure 68, 31-level has the highest demand reduction indicator (DI). The indicator on 31-level was more than two times higher when compared to 30-level which has the second highest demand reduction indicator. Further investigations were thus conducted on 31-level.

Application of step-testing was unsuccessful on the east haulage of 31-level. Most of the cross cuts CA columns on this haulage were interconnected. Closing one cross cut valve would just result in air reaching the stoping area of that cross cut through the CA column of another cross cut.

Auditors managed to conduct step-tests on the west haulage using the proxy metering method that was discussed in Section 2.3.4. The ratio of flow distribution to the east and the west haulage was estimated with the pressure readings at the end of the haulage. Additional audit information can be found in Appendix G.

Previous audits revealed that high-consuming cross cuts can be attributed to the use of open-ended CA columns that are used to ventilate the raise areas. These columns are referred to as blowers. It has been determined that one blower has a consumption of 0.16 kg/s. Results of the step-testing together with the locations of the identified blowers are displayed in Figure 69.

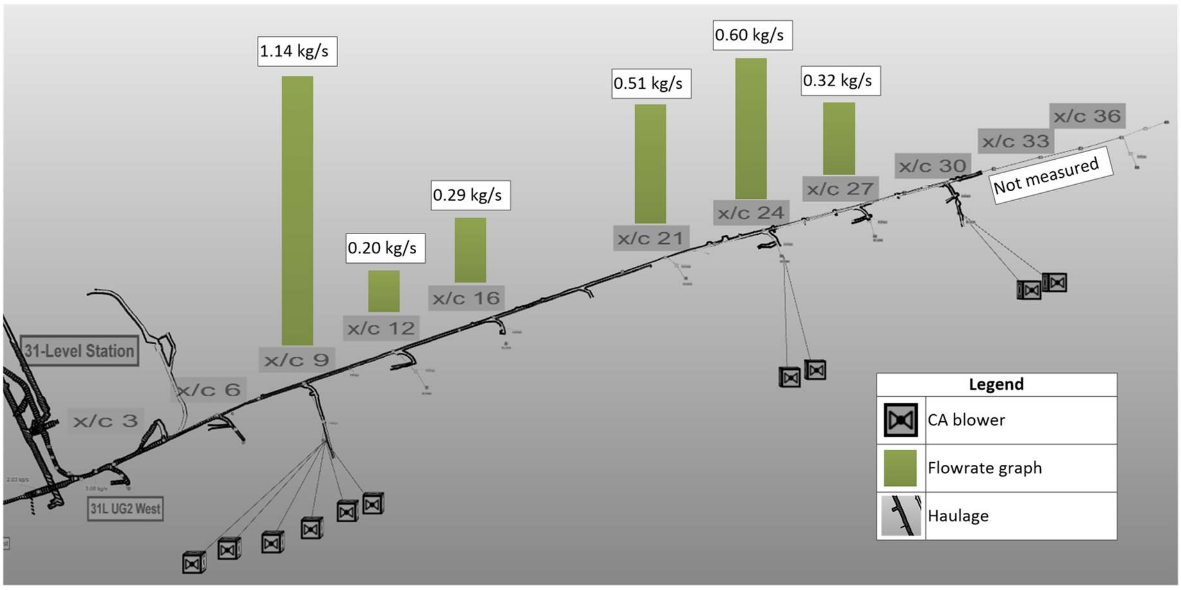


Figure 69: Step-testing results on 31-level UG2 West of Shaft H

As seen in Figure 69, the high consumption cross cuts correspond to the areas with high concentration of blowers. Most notably was the high CA flowrate of Cross cut 9 which corresponds with the results from mine auditors. This thus provides **verification** for pressure logger step-testing method that was developed in Section 2.3.4.

According to the mining standards of Mining Group A, CA may only be used to ventilate when a ventilation column is not installed. Many of the blowers were found to be installed in parallel with ventilation columns, as seen in Figure 70. This was done as the ventilation columns did not supply enough air to cool the working area. These columns were usually in a poor condition.

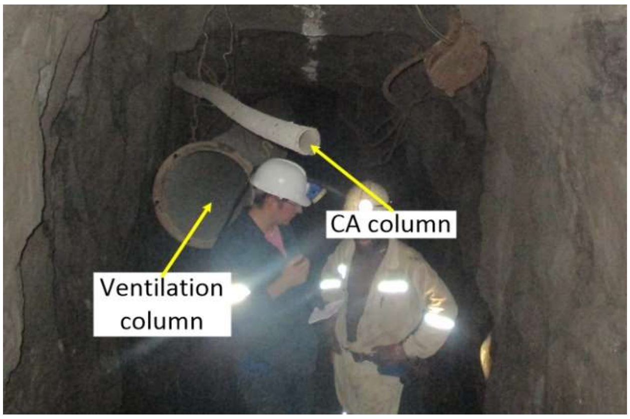


Figure 70: CA column installed in parallel with a ventilation column

Instead of repairing the ventilation columns, mining personnel will rather install a blower in parallel with a ventilation column to cool the working place. Installing a blower requires less effort than repairing the ventilation column. However, blowers require more energy to supply the same volume of breathable air.

After requests from the shaft top management, a comprehensive audit was conducted by the ventilation department to find the working areas where unauthorised blowers are being used.

The comprehensive shaft audit was conducted by four personnel from the ventilation department and extended over a period of three months (1920 working hours). A total number of 41 unauthorised blowers were found over the entire shaft. Figure 71 illustrates the distribution of the blowers on Shaft H.

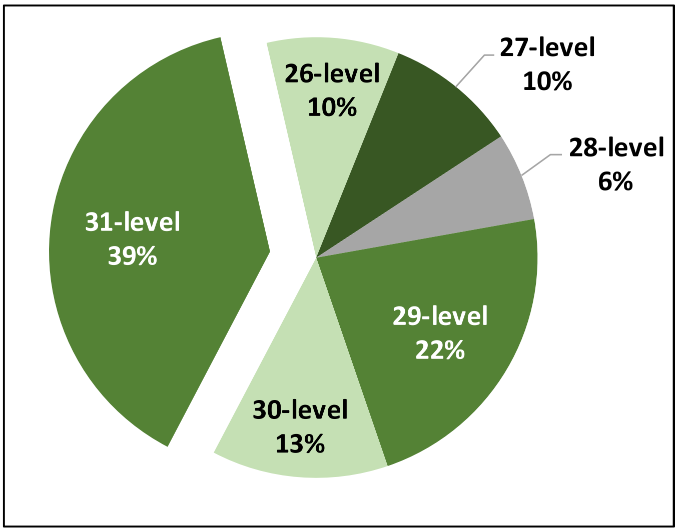


Figure 71: Unauthorised blower distribution on Shaft H

As expected, 31-level contained most of the blowers when compared to the other levels in the lower section. Two auditors took roughly three working days (48 working hours) to prioritise 31-level. It is assumed that another three days were required to visually inspect the entire CA network of 31-level. It will thus take ± 8 hours per blower identified.

It is assumed that 50% of the ventilation department's time can be allocated to the identification of the blowers in the three-month period. According to this data, approximately 23 hours were needed per blower identified. A 65% improvement in the blower identification rate was thus achieved. This thus provides further **validation** of the step-testing and integrated methodologies developed in Sections 2.3.3 and 2.4.2 respectively.

Frequent audits by the ESCo to find and address the CA blowers would not have been sustainable. As discussed in Section 1.2.5, improved results are expected when mining personnel take responsibility for the energy efficiency on the shaft. The ESCo requested that various mining departments assist with the audits.

Personnel from the ventilation, safety, evaluation, rock engineering, and surveying departments conduct daily, department-specific audits on the underground working places and report on the findings to the production personnel. The ESCo requested that these personnel incorporate unauthorised CA usage into their audit checklists. Blower reports from these personnel allowed the blowers to be addressed on a more regular interval.

A simulation of the entire CA system revealed that a demand reduction of 2.98 kg/s was achievable if all unauthorised blowers are removed underground. Reports received after the project implementation revealed that unauthorised blowers were still present on the shaft. An analysis of the data revealed that the demand only decreased with 0.68 kg/s.

3.4 Savings quantification with network size scaling

3.4.1 Preamble

According to **Objective 4** of this study, an improved savings quantification method needs to be developed and tested. Electricity saving quantification methods, also referred to as Service Level Adjustment (SLA) methods, were reviewed in Section 1.2.3. These methods lack the ability to accurately quantify electricity savings on deep-level mine CA systems. A new SLA method was developed in Section 2.4.4 to address this need. This new method involves using the baseline and actual CA network length to calculate a baseline adjustment factor. In this section, the new method will be tested to real-world scenarios.

3.4.2 Quantification of savings after an expansion in operations

Sweeping is a common occurrence on platinum and gold mines. The sweeping process involves recovering the remaining blasted ore from working places that have been mined out. CA was mainly required to open the loading boxes when sweeping. The entire column of a level being sweeped thus needs to be pressurised.

Prior to the unauthorised blower removal initiative that was discussed in Section 3.3.4, three mining levels were reopened for sweeping on Shaft H. Reopening these levels resulted in an increased CA consumption thus increasing the compressor power consumption. The unscaled compressor power baseline together with the PA power profile is illustrated in Figure 72.

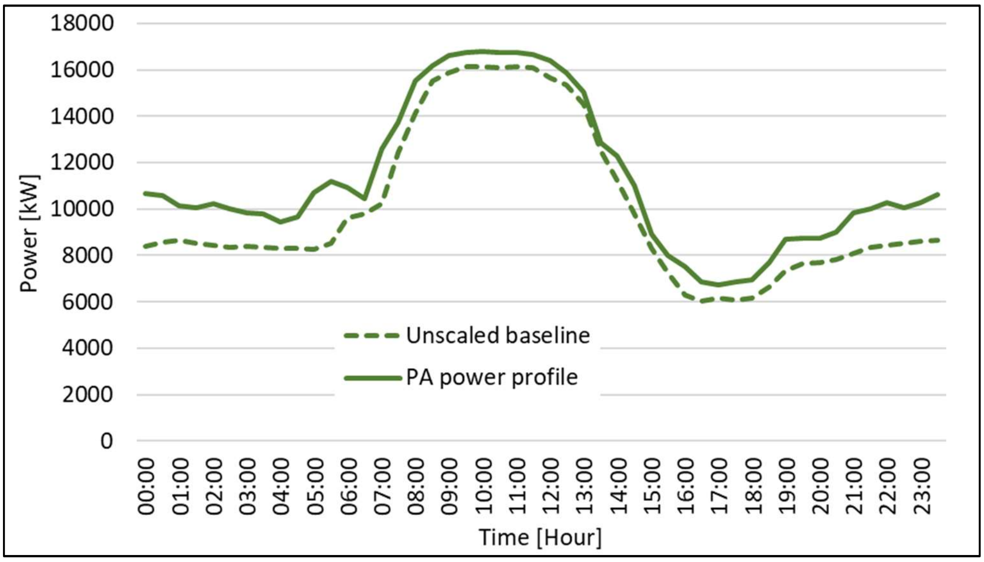


Figure 72: Shaft H increased compressor power profile

An additional compressor had to be started during the non-drilling periods to supply the shaft with enough pressure. More compressors could not be started to maintain the pressure set point during the drilling shift due to electrical constraints. This explains why the increase in compressor power consumption was higher during the non-drilling shift in Figure 72.

The ESCo did not implement any new compressor electricity cost saving initiatives on Shaft H before and after the old levels were reopened for sweeping. An ideal SLA method should thus indicate that the ESCo had no impact on the power profile of the compressors.

A scaling factor was calculated using each of the existing SLA methods and the newly-developed CA network size SLA method. The resulting scaling factors and the parameters used to calculate the scaling factors are given in Table 12.

Table 12: Shaft H scaling factor calculation

SLA method	Baseline parameters	Performance assessment parameters	Scaling factor
No scaling	Not applicable	Not applicable	1.00
Production scaling	Avg. daily production = 4518 tonnes	Avg. daily production = 4335 tonnes	0.96
Peak matching	Avg. peak power = 14 952 kW	Avg. peak power = 15 819 kW	1.06
Network size scaling	Baseline pipe length = 60.6 km	PA pipe length = 72.8 km	1.20

Labour issues resulted in lower-than-normal production figures during the PA period. Sweeping is generally known to have a lower production when compared to the normal production levels. The production gained through sweeping could thus not compensate for the decrease in normal production, resulting in a scaling factor lower than one, as seen in Table 12.

An increase in the overall power profile of Shaft H is observed in Figure 72. The average compressor power consumption from 07:00 to 13:00 increased with 867 kW. Calculating a scaling factor with the peak matching SLA method will thus result in a scaling factor higher than one.

The reopened mining levels of Shaft H consisted of the old levels in the upper section. These levels are generally known to be longer than the lower levels. An additional 12 km was added to the total CA network length. The scaling factor calculated with the network size method will thus scale the baseline upwards. Figure 73 illustrates the energy savings calculated with the different SLA methods. Also illustrated in Figure 73 is the “actual energy savings impact of the implemented initiative.” As mentioned earlier, no energy saving initiative was being implemented on this shaft. This means that the actual impact is zero.

According to the results in Figure 73, applying no baseline scaling results in negative energy cost savings. This also motivates the use of SLA methods to account for changes in the mining operations. As mentioned previously, the shaft production did not increase after the old levels were reopened. The production scaling method thus also failed to accurately project the actual energy cost savings.

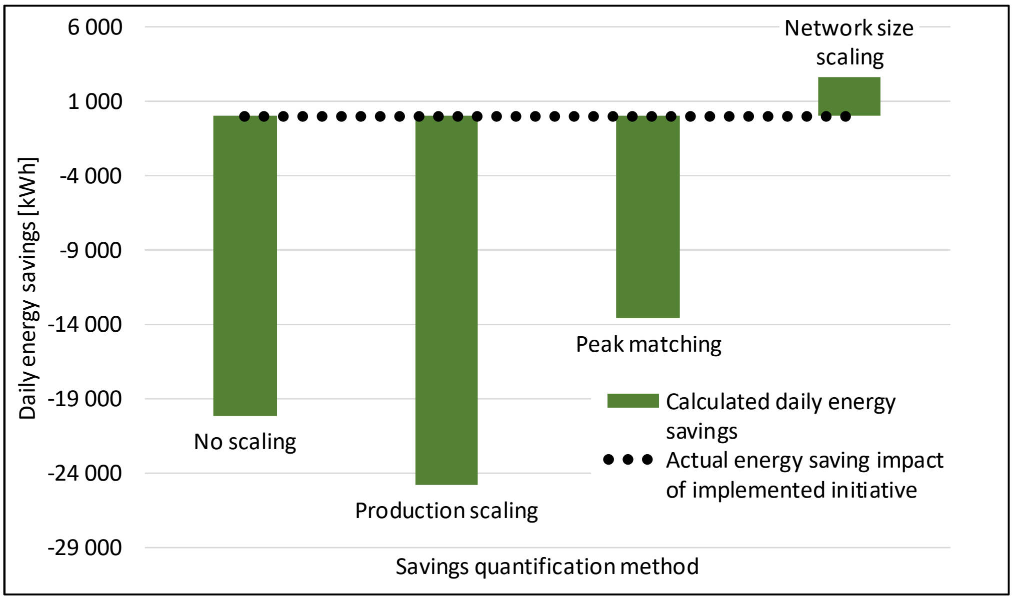


Figure 73: Shaft H energy savings calculated with different SLA methods

The peak matching SLA method scaled the baseline upwards, but the compressor electrical restrictions during the drilling shift meant that energy cost savings were underestimated during the non-drilling shifts. Positive energy cost savings were calculated with the new CA network size SLA method. The error of the energy saving calculated with this method was, however, much lower than that of the existing baseline SLA methods as seen in Figure 73.

3.4.3 Leak repair savings quantification

The investigations on Shaft A, which were discussed in Section 3.3.2, involved the detection and isolation of CA wastage to an inactive level of a deep-level mining shaft. The wastage isolation resulted in a decreased CA consumption and an increase in the overall downstream pressure.

As mentioned in Section 3.3.2, Shaft A does not have dedicated compressors. Instead, the shaft receives CA from a ring which is shared by other shafts. A simulation of the shaft was thus constructed to calculate the actual impact of isolating the wastage.

To isolate the impact of the CA wastage isolation from the initiatives implemented on the other shafts, the CA consumption of the shaft was related to compressor electricity consumption. It is assumed that a 1200 kW compressor operated at 900 kW delivers CA at 2.35 kg/s. A daily energy saving of 6335 kWh from 17:30 to 06:30 was expected (Actual impact.) The resulting scaling factor for different SLA methods are given in Table 13.

Table 13: Shaft A scaling factor calculation

SLA method	Baseline parameter	Performance assessment parameter	Scaling factor
No scaling	Not applicable	Not applicable	1.00
Production scaling	Avg. daily production = 3161 tonnes	Avg. daily production = 3612 tonnes	1.14
Peak matching	Avg. baseline peak power = 5082 kW	Avg. PA peak power = 4410 kW	0.87
Network size scaling	Baseline pipe length = 29.6 km	PA pipe length = 29.6 km	1.00

During the same period of the wastage isolation, drilling crews were moved to more productive areas of the shaft and improved pneumatic drilling bits were introduced. These changes resulted in an increased production. According to the production SLA method, the baseline should be scaled with a factor of 1.143.

The wastage isolation resulted in an all-day CA consumption reduction. Reduced consumption during the drilling shift means that the scaling factor calculated with the peak matching SLA method will scale the baseline downward. Calculating the impact of the initiative with the peak matching method will thus result in a lower cost saving when compared to the no scaling method.

The CA network size did not show any significant changes during the implementation period. A scaling factor of one is thus calculated with the new network size SLA method, meaning that that baseline will not be scaled. Non-drilling shift energy savings for Shaft A calculated with different SLA methods are illustrated in Figure 74.

As seen in Figure 74, the no scaling and CA network size scaling SLA methods have the smallest error. A saving of 6654 kWh was calculated with both SLA methods, due to the unchanged network size. The production SLA method reveals an energy saving of 13 271 kWh which is 110% higher than the expected energy saving. Energy savings calculated with these two SLA methods are thus inaccurate.

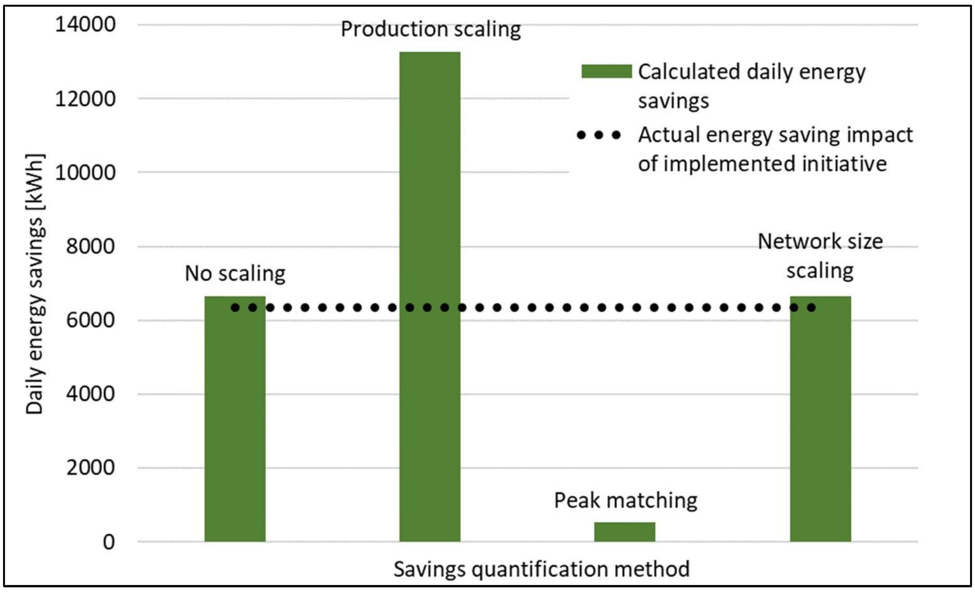


Figure 74: Shaft A energy savings calculated with different SLA methods

3.4.4 Savings quantification of compressor efficiency improvement

The following case study was implemented on the CA system of Shaft B which is a gold mining shaft. Two compressor houses supply the shaft with CA. One of the compressor houses contains two 4800 kW rated compressors. One of these compressors are operated as a baseload compressor in normal operation.

Four 910 kW rated trimming compressors are situated in the second compressor house. Technical problems resulted in these compressors being stopped and the second 4800 kW compressor being started. The new operation improved the CA system energy efficiency. The baseline and actual power profiles are illustrated in Figure 75.

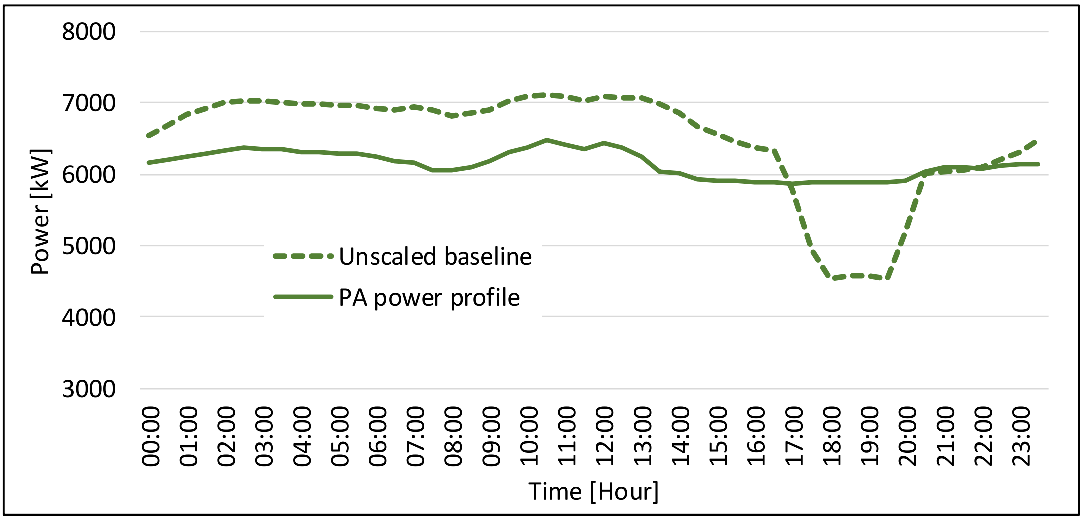


Figure 75: Shaft B baseline and PA power profile

As seen in Figure 75, peak clipping in the blasting shift was cancelled. Mining personnel did not allow a 4800 kW machine to be stopped during the blasting shift due to start-up concerns and the inability of one 4800 kW compressor to maintain the pressure set point during this period. CA information required for the calculation of the baseline scaling factors are given in Table 14.

Table 14: Shaft B scaling factor calculation

SLA method	Baseline parameter	Performance assessment parameter	Scaling factor
No scaling	Not applicable	Not applicable	1.00
Production scaling	Avg. daily production = 2901 tonnes	Avg. daily production = 2501 tonnes	0.86
Peak matching	Avg. baseline peak power = 6995 kW	Avg. PA peak power = 6268 kW	0.90
Network size scaling	Baseline pipe length = 12.7 km	PA pipe length = 12.7 km	1.00

The baseline scaling factors calculated in Table 14 were used to quantify the energy saving impact of the new compressor operation. Figure 76 illustrates the energy savings quantified with different SLA methods. An energy saving of -1376 kWh is expected when the drilling shift is excluded due to the blasting shift peak clipping being cancelled. When the entire day is considered, the expected savings (actual impact) increases to 3292 kWh.

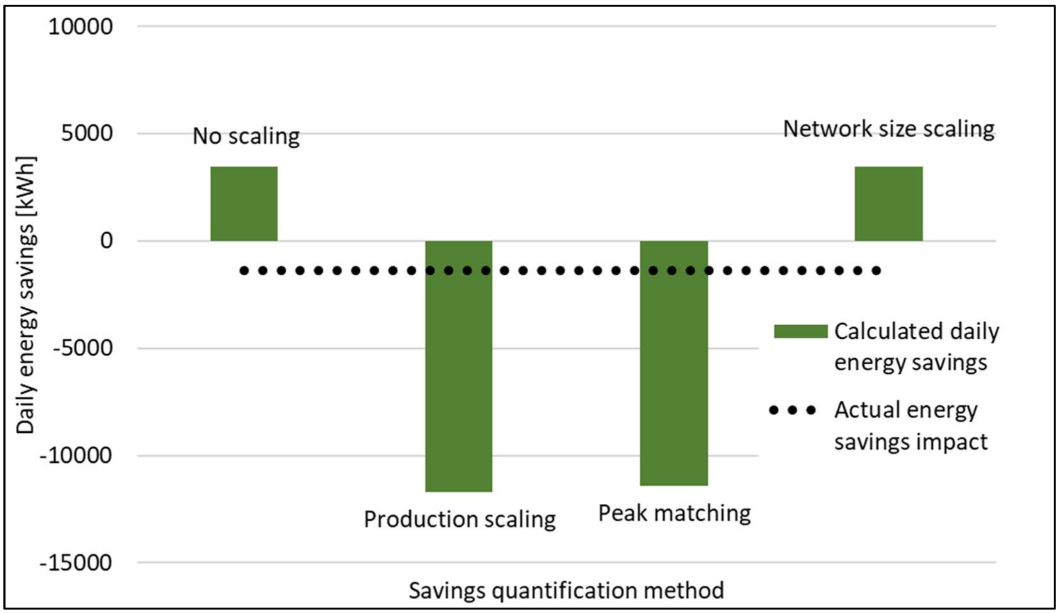


Figure 76: Shaft B energy savings calculated with different SLA methods

As seen in Figure 76, the production and peak matching SLA methods produced negative energy savings and have the highest errors. The no scaling and CA network size scaling methods had smaller errors when compared to the production and peak matching methods but predicted positive cost savings.

3.4.5 Savings quantification on a mine with reduced production

An overall decrease in production activities was experienced during the drilling shift on the CA ring of Shafts C and I. Production crews were being transferred to another mining shaft which resulted in a reduced CA and compressor energy consumption during the drilling shift. A compressor power profile of the ring is illustrated in Figure 77.

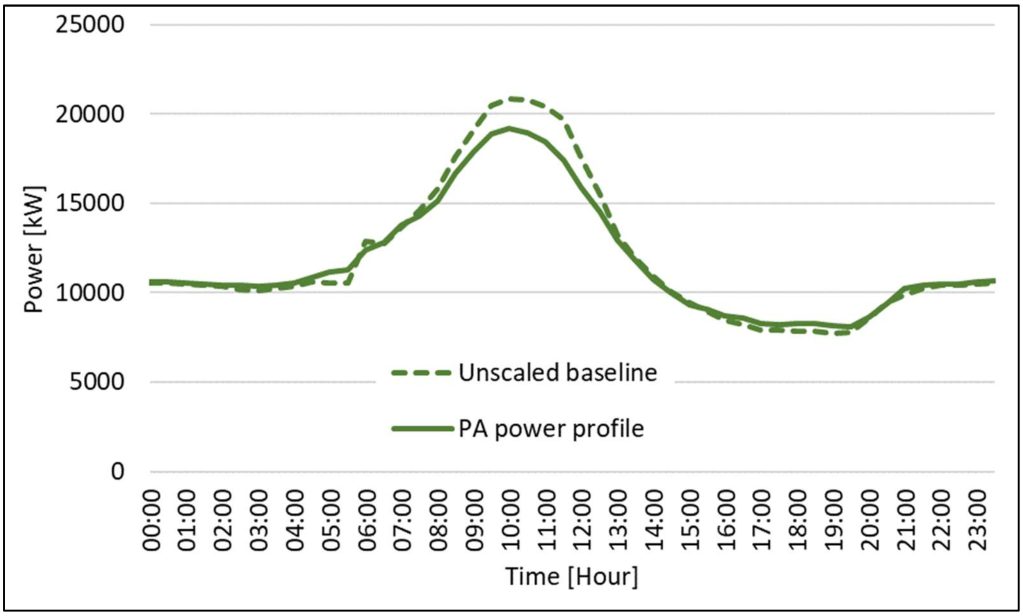


Figure 77: Shaft C and I compressed air network power profiles

As seen in Figure 77, the power profile during the PA period significantly decreased during the drilling shift. The power profile during the non-drilling shifts, however, almost remained the same as in the baseline period.

Further investigations revealed that the levels on which the moved production crews worked during the baseline period was being sweeped and equipment reclamation was taking place. The columns of these levels thus needed to remain pressurised to supply CA to the refuge bays and other equipment.

Like Shaft H, no new compressor energy saving initiatives had been implemented on the shafts of this CA ring. Energy saving quantification methods should thus ideally indicate a zero-energy saving impact. Table 15 lists the parameters needed for the scaling factor calculation and the resulting scaling factors.

Table 15: Shaft C and I complex scaling factor calculation

SLA method	Baseline parameter	Performance assessment parameter	Scaling factor
No scaling	Not applicable	Not applicable	1.00
Production scaling	Average monthly production = 182 237 tonnes	Average monthly production = 113 603 tonnes	0.62
Peak matching	Avg. baseline peak power = 14 952 kW	Avg. PA peak power = 15 819 kW	0.93
Network size scaling	Baseline pipe length = 105.32 km	PA pipe length = 105.32 km	1.00

The average production drastically decreased in the two-month PA period compared to a two-month average daily production during the measured baseline period. Production scaling thus resulted in a low scaling factor, as seen in Table 15. The peak matching SLA method also indicates that the baseline should be scaled down.

The no scaling and CA network size scaling models both have the same scaling factors. This is due to the size of the haulage CA piping length that did not decrease with the production, as discussed above. Energy savings calculated with the SLA methods are presented in Figure 78.

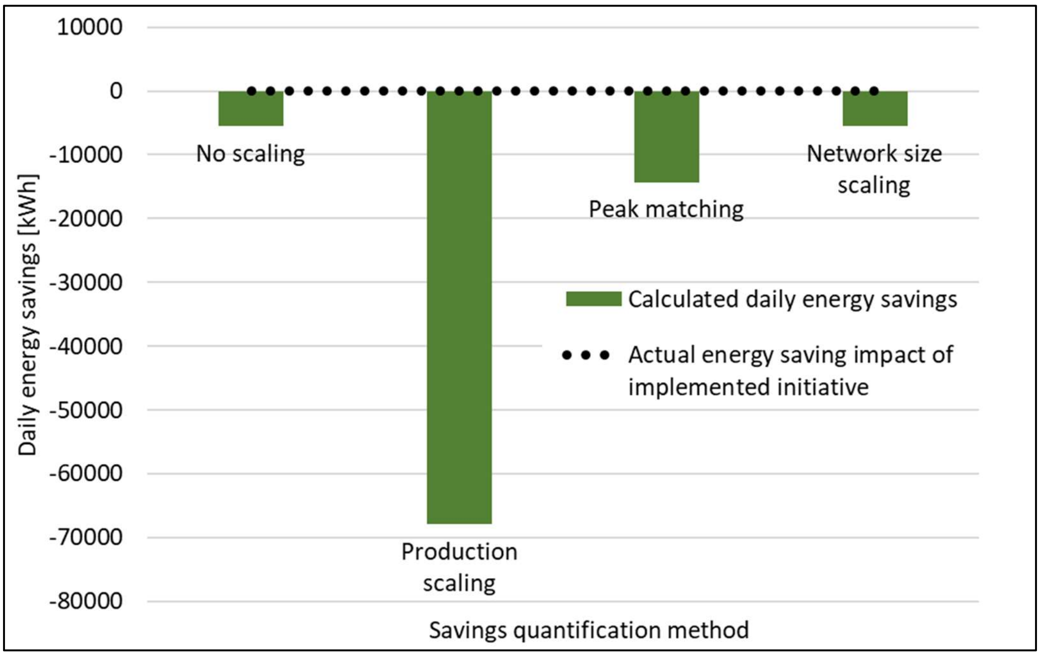


Figure 78: Shaft C and I complex energy savings calculated with different SLA methods

Once again, the production SLA method failed to accurately quantify the impact of the energy savings on the shaft, as can be seen in the graph of Figure 78. A smaller energy saving error was calculated with the peak matching method when compared to the production SLA method.

As explained in Section 1.1.4, more air is consumed for production related activities in the drilling shift when compared to the non-drilling shifts. Only 10% of the air used during the drilling shift can be linked to the shaft production [29]. This may explain why the peak power consumption did not decrease proportional to the production decrease of the shaft.

Energy savings calculated with the no scaling and CA network size methods had the smallest errors when compared to the other scaling methods. The same energy saving was again calculated with both these methods due to the unchanged CA network size from the baseline period to the PA period.

3.4.6 Summary of savings quantification methods

In this section, four SLA methods were compared using different case studies. A comparison of the error between the expected and calculated energy saving during the non-drilling shifts for each SLA method is presented in Figure 79.

In Section 1.2.3 it was mentioned that ESCos typically switch to the no scaling method when other SLA methods inadequately quantify the effect of the energy savings initiatives. However, in the case study implemented on Shaft H, the no scaling method failed to accurately quantify the impact of the energy saving project.

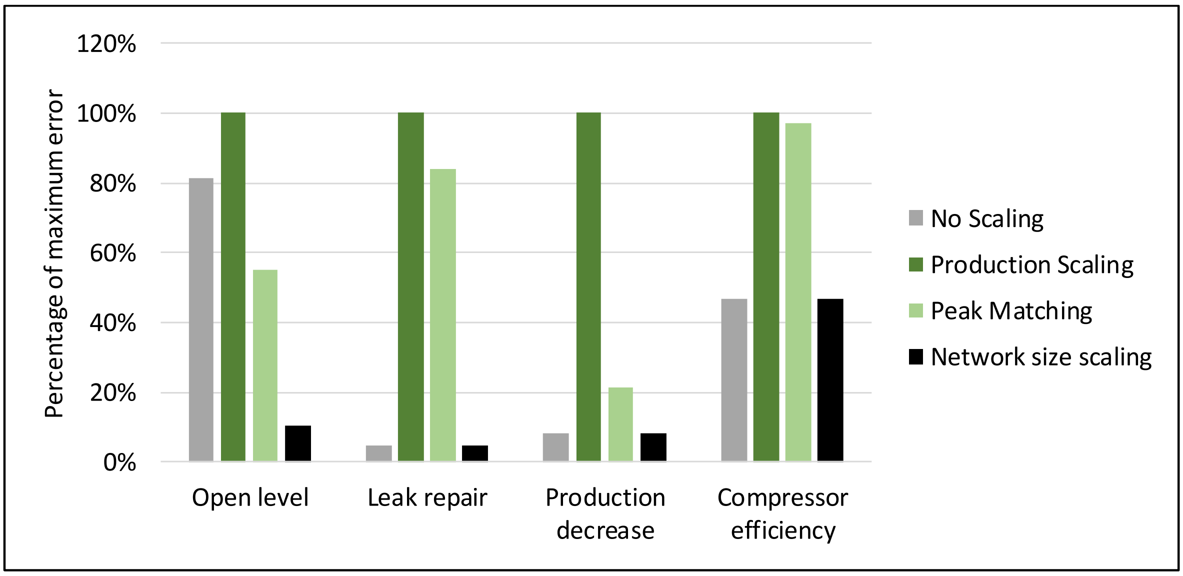


Figure 79: Error comparison of various SLA methods

As seen in Figure 79, production-based SLA methods, which include production scaling and peak matching, performed the worst in nearly all the case studies. This confirms the literature study in Sections 1.1.4 and 1.2.3 which stated that there is a poor correlation between CA consumption and production.

According to the information in Figure 79, the actual impact of CA energy savings initiatives could be calculated more accurately by considering the length of the active haulage network. The new SLA method resulted in an 18 to 83% improvement in the savings prediction thus providing **validation** for the use of the new SLA method developed in Section 2.4.4.

3.5 Summary

In Chapter 1, a need was identified for improved wastage identification and savings quantification methods on deep-level mine CA systems. Several methods were developed in Chapter 2 to address these needs. The developed methods were verified with tests on actual deep-level mine CA systems in Chapter 3 which validated the use of these methods.

A novel benchmarking model was developed to prioritise shafts for underground demand reduction based on the active underground CA network length and normalised minimum flow. The new model was found to have improved prioritisation capabilities when compared to existing benchmarking models.

Once a shaft is prioritised, it previously required a manual audit of the entire shaft to identify the wastages. New audit methodologies were developed which consists of a shaft mass balance methodology to firstly identify underground mining areas of high CA consumption. Secondly, wastages can further be narrowed down with the use of the new step-testing and proxy metering methodologies.

The integrated methodology, which incorporates the new audit methodologies, was applied to four deep-level mine CA case studies. In the first case study, the mass balance methodology was used to narrow down a 4.08 kg/s leak in an abandoned area. Repairing the leak resulted in an average overall underground pressure increase of 17.7 kPa and a flow reduction of 1.24 kg/s.

Supply-side management on Shaft E resulted in CA pressure complaints on two separate half levels. Auditors followed the integrated methodology and conducted step-tests on both half levels. The audit findings were reported to the relevant mining personnel. No complaints were lodged afterwards as the mining personnel addressed the identified issues. An estimated cost avoidance of R1.4-million was achieved.

The final case study was conducted on Shaft H. After a mass balance of the shaft, 31-level was prioritised for further audits. 39% of the unauthorised CA blowers on the entire shaft were found on this level. It is estimated that the new audit methodology resulted in a 65% increase in the wastage identification rate when compared to conventional audit methods.

Existing SLA methods to quantify the cost savings were found to be inadequate. A new method was developed for improved savings quantification. The new method was tested on five case studies and delivered an 18 to 83% improvement in savings prediction when compared to existing SLA methods.

Chapter 4. Conclusion and recommendations

4.1 Conclusion

Deep-level gold and platinum mining contribute significantly to the South African economy. However, high operational expenses and low mineral prices have been plaguing this industry. Mines have little to no influence on the mineral prices but can increase profits by reducing operational expenses.

Electricity contributes to 11% of the operational expenses on a typical mine. Industrial centrifugal compressors are significant consumers of electricity. Up to 50% of the electricity consumption on mines can be attributed to the generation of Compressed Air (CA). Recent studies revealed that there is still significant scope to reduce the electricity consumption of deep-level mine CA systems.

Most studies on deep-level mine compressor electricity reduction focus on supply-side management. This includes compressor and automated valve control to match the supply of CA with the demand. However, these practices are limited to the pressure requirements of the underground end-users. Electricity savings can be achieved through demand-side management without negatively affecting end-users.

Underground CA demand reduction have received little attention in literature. Deep-level mines are known to have large underground CA networks stretching tens of kilometres in total length. Managing the demand of such large systems is labour-intensive and often do not deliver the desired results. A need was identified for methods to identify underground wastages with limited resources and accurately quantify the savings achieved.

Benchmarking has been used on deep-level mines to identify scope and prioritise shafts for CA system electricity savings. However, existing methods focus on the combined scope for demand- and supply-side reduction. A novel benchmarking model was developed to compare the demand of various shafts.

The benchmarking model incorporates new parameters previously not considered by other deep-level mine CA benchmarking studies. These parameters include the total active underground CA network length and the normalised minimum flow to calculate a shaft demand reduction indicator. Five case study shafts were used to validate the model results.

A 25 to 40% improvement in prioritising shafts for underground demand reduction was achieved when the new model was compared to existing models.

Underground audits need to be conducted after a shaft has been prioritised with the new benchmarking model. Existing CA audit methods used on deep-level mines and other industries which also utilise CA, were found to be labour-intensive and deliver disappointing results. An audit method, called step-testing, and other proxy metering techniques, typically used to localise leaks in the potable water industry, was adopted to be used on deep-level mine CA systems.

The benchmarking model together with the audit methods were combined into one integrated methodology which aims to achieve maximum compressor electricity savings with the available resources. Existing integrated methodologies focused on reducing the compressor power consumption through supply-side management and did not specify how the underground CA audits should be approached.

The integrated methodology was implemented on a deep-level mining CA ring which consists of Shafts A and E. According to the methodology, a mass balance of Shaft A was required. A large leak was found with the mass balance method which resulted in a 17.7 kPa overall shaft pressure increase and a flow reduction of 1.24 kg/s amounting to an electricity cost reduction of R2.7-million per annum. Additionally, an estimated audit time reduction of 95% was achieved when compared to the conventional audit that was previously conducted on the entire shaft.

The integrated methodology together with the new step-testing method was applied on two levels of Shaft E after low pressure complaints were received. Auditors presented the step-testing results to the relevant mine personnel who applied the recommendations. An increase in pressure and up to 40% decrease in CA flow was achieved on these levels. No complaints were received after the recommendations were implemented. Supply-side management initiatives could thus continue. An annual electricity cost saving of R620-million is estimated if the demand on 25 deep-level mining shafts can be reduced by 40% outside the drilling period.

Supply-side management initiatives on Shaft H were limited by the pressure requirements of the conveyance system. Shaft H was notorious for the unauthorised use of CA for ventilation (unauthorised blowers). Mass balances and step-tests from the integrated methodology developed in this study led auditors to a high consuming level which held 39%

of the documented unauthorised blowers on the shaft. An estimated 65% increase in the blower identification rate was achieved when compared to conventional audit methods.

It is important for savings achieved through efficiency initiatives to be quantified accurately. Current savings quantification methods (SLA methods) primarily use production as a parameter to predict the initiative impact. A poor correlation between compressor energy consumption and production meant that the output from these methods was questionable. A novel SLA method was developed to address this need.

The new SLA method was applied to four case study shafts. In each case study, a particular event resulted in changes to the compressor electricity consumption of the shaft. Savings quantified by existing methods were compared to that of the new method. Application of the new method resulted in an 18 to 83% improvement in savings prediction.

Objectives of this study are listed in Section 1.3. These objectives required methods to be developed to address the shortcomings that were identified in Chapter 1. The developed methods should then be verified and implemented to prove the validity. A summary containing the sections where the objectives were developed, verified, implemented, and validated is listed in Table 16.

Table 16: Summary of sections where objectives were reached

Obj.	NCN[13]	Development	Verification	Implementation	Validation
1	1	Section 2.2.2	Sections 2.2.2 and 3.2.2	Sections 3.2.2 and 3.3.4	Sections 3.2.2 and 3.3.4
2	2; 3	Sections 2.3.3 and 2.3.4	Sections 3.3.3 and 3.3.4	Sections 3.3.3 and 3.3.4	Sections 3.3.3 and 3.3.4
3	4	Section 2.4.2	Section 3.3.2	Sections 3.3.2 3.3.3 and 3.3.4	Section 3.3.2, 3.3.3 and 3.3.4
4	5	Section 2.4.4	Sections 2.4.4 and 3.4.2	Section 3.4	Section 3.4.6

[13] NCN – Novel Contribution Number

4.2 Recommendations for future work

There is significant scope for improving the efficiency on deep-level mine CA systems. The author identified various shortcomings in literature and in practice. Some of the shortcomings were addressed in this study, but other still warrant further investigation. This section contains a list of the author's recommendation for further work.

Recommendation 1:

Methods were developed in Section 2.3.3 and 2.3.4 to identify high CA wastage areas and determine what the effect would be if the leaks were repaired. Some leaks, such as that found in haulage piping networks, could not be quantified with these methods.

Leaks in the haulage piping network are usually quantified by substituting the hole diameter and line pressure into Equation 1. Leak rates can be accurately determined using this method [80]. However, in Section 1.2.2 it was determined that the effect of leak repair is often overestimated.

Determining the effect of leak repair with the help of simulation software is time-consuming. Numerous studies have determined that proxy metering techniques can be used to determine the location and size of a leak in a pipeline. It is recommended that an empirical equation be created to easily calculate the real impact of repairing a leak based on the leak size and location.

Recommendation 2:

In this study, the CA electricity cost savings potential of a shaft was determined by using a newly-developed benchmarking model and considering the shaft compressor limitations in Sections 2.2.2 and 2.2.3 respectively. It is, however, possible that a shaft could have a high demand reduction potential according to the new benchmarking model, but significant electricity cost savings can only be achieved once the air is significantly reduced to stop a compressor.

The author recommended that the energy managers consider the leak management potential, the compressor limitations, and the available resources before prioritising a shaft for leak auditing. It is recommended that further studies should be done to determine the relationship between the leak reduction potential, compressor limitation, and available resources.

Recommendation 3:

The benchmarking model developed in Section 2.2.2 used the CA flowrate in the low consuming periods together with the total length of the underground network to calculate a demand reduction indicator. This indicator is then used to prioritise shafts based on the underground demand reduction potential.

Water distribution network networks usually include the number of nodes into their benchmarking calculation [125], [132]. It is recommended that the benchmarking model developed in this study be improved by also incorporating the number of nodes (number of cross cuts or levels.)

Recommendation 4:

CA is used for various purposes in the non-mining industry [34]. Similar to South Africa, for example, New Zealand also has industries with large compressed air systems [63]. There can thus be significant scope to reduce the compressor electricity consumption in other industries. It is recommended that the methods developed in this study also be applied to non-deep-level mining industries.

Recommendation 5:

As mentioned in Recommendation 4, CA is used for various purposes in other industries. A glass bottle manufacturing plant may use the CA for bottle shaping purposes [68], while it is used to operate a baghouse in the cement industry [66]. It is thus difficult to evaluate the CA usage of different industries with each other [68], [85], [88].

The new benchmarking model, developed in Section 2.2.2, does not take the facility production into account. Only the size of the network and the CA consumption during the low demand periods are considered. It is recommended that further studies be done on using the benchmarking model developed in this study to prioritise facilities of various industries for CA demand reduction.

Recommendation 6:

In parallel to the CA system, deep-level mines in South Africa also usually have an underground service water reticulation system. Service water from surface is gravity-fed underground where it is then distributed to the various levels and stopes.

After the service water is used, it is pumped to surface. Reducing service water leakages can lead to electricity cost savings on the service water pumps [13]. It is recommended that the methods developed in this study also be implemented on mine service water reticulation networks.

Recommendation 7:

Similar to other industries [27], [108], energy efficiency awareness among deep-level mining personnel, especially among the general miners, is lacking. Further study is required on integrating energy efficiency awareness into vocational training programs.

Recommendation 8:

Step-testing in the deep-level mining industry had limited success mainly as a result of leaking cross cut valves and haulage CA column leaks. Pressure spot checks on regular intervals over the haulage CA column could reveal high-consuming segments with higher accuracy when compared to step-testing.

Recommendation 9:

The new SLA developed in this study should be used with caution. Limitations of this SLA method was brought to light in Section 2.2.4. Although the validation results in Section 3.4 seems promising, more case studies need to be conducted before the new SLA method is recognised as an official M&V method for measuring the cost savings on CA systems.

Recommendation 10:

Apart from the limitations mentioned in Recommendation 9, the SLA method is only capable of quantifying the electricity cost savings during the non-drilling shift, which also excludes the blasting shift when the CA to levels are closed. More studies thus needs to be done to create an SLA method which can accurately quantify the electricity cost savings achieved over a full 24-hour mining cycle.

Recommendation 11:

The audits that were conducted in Section 3.2 were limited to the mass balance method discussed in Section 2.3.5. Improved results may be achieved by conducting the step-testing method developed in Section 2.3.3.

Recommendation 12:

In Section 1.2.5, it was found that automation of leak detection can reduce the reliance on labour-intensive auditing methods to identify leaks. The auditing methods developed in this study still heavily rely on labour to identify underground CA leaks. There is a need for more studies to be done on the automation of energy audits, such as CA leak detection in underground mines.

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Appendix A Sequence for compressor electricity reduction mapping

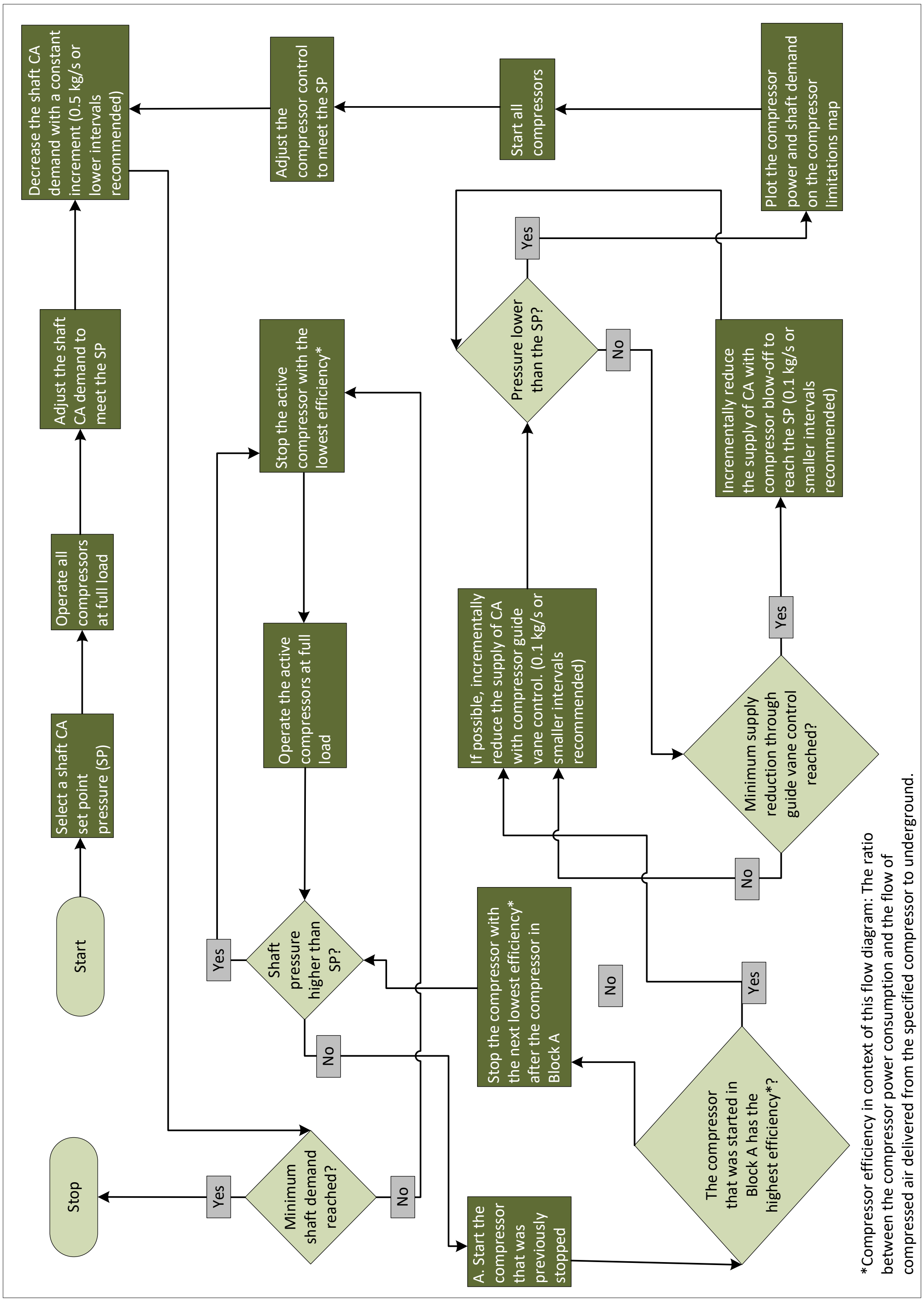

Figure 80: Sequence for compressor electricity reduction mapping

Appendix B Sequence for simulating a haulage with pressure logger data

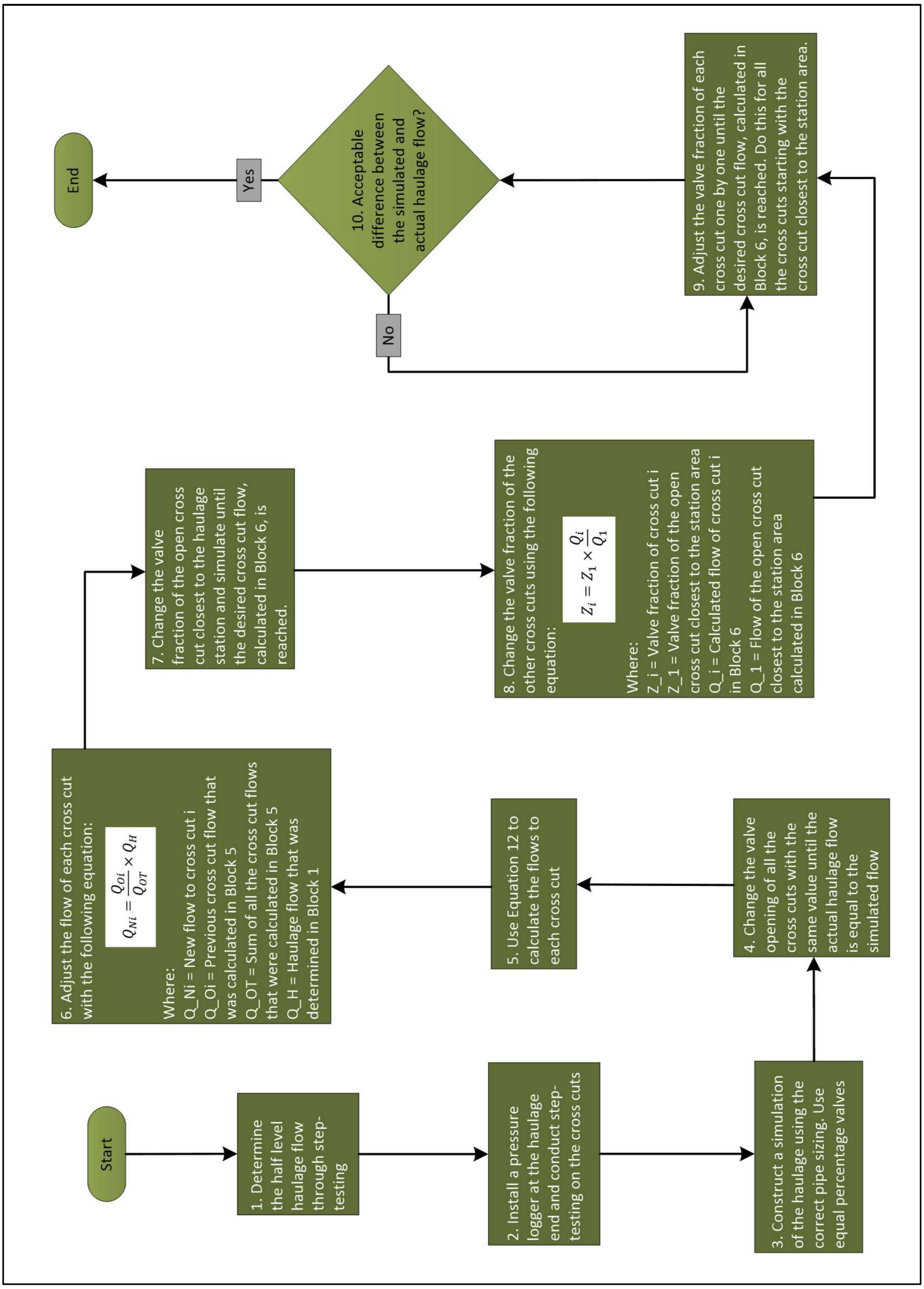

Figure 81: Sequence for simulating a haulage with pressure logger data

Appendix C Mass balance on Shaft B

A mass balance was implemented on a gold mining shaft, Shaft B, in the Gauteng province. According to Figure 82, Shaft B has the third highest potential for demand reduction of the 13 shafts evaluated with the benchmarking model in Section 2.2.2.

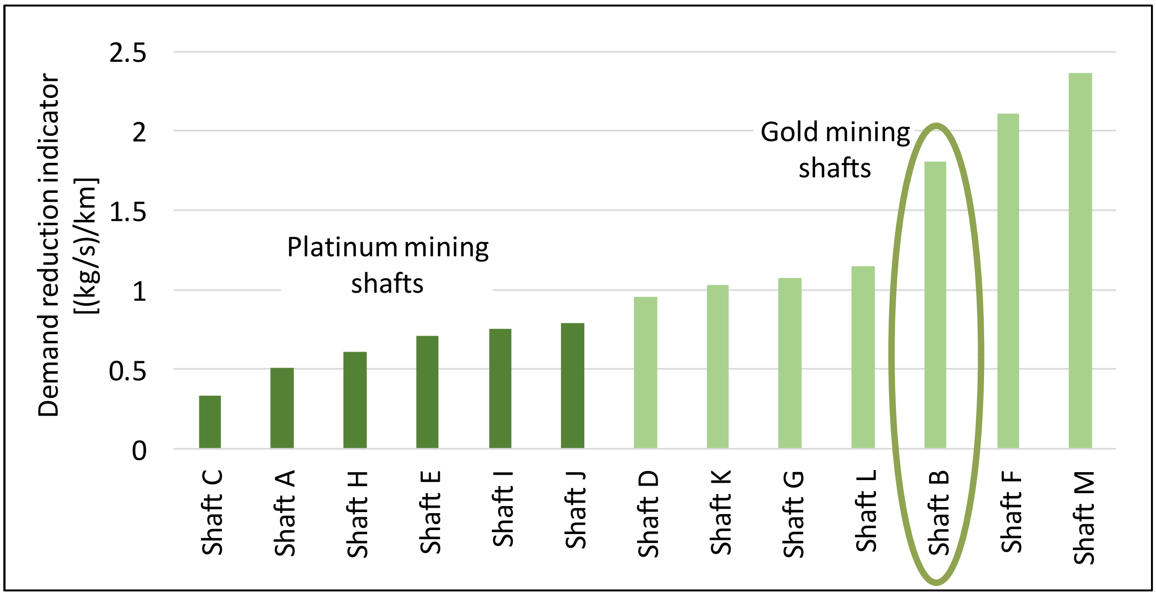

Figure 82: Shaft B prioritised on the benchmarking graph

A lack of operational instrumentation on the shaft required that CA auditors determine the flow to each active level with the use of a calibrated, portable flowmeter. The low demand flow to three of the four active levels could be determined. These flow values, together with the calculated shaft flow value, is given in Table 17.

Table 17: Mass balance results of Shaft B

Flow measurement location	Range/ value
Calculated shaft flow	14.91 kg/s
192-level	0.70 kg/s
197-level	1.06 kg/s
202-level	0.82 kg/s

Operational surface measurement instrumentation on Shaft B is limited to the power meters installed on the compressors. The shaft flow in Table 17 needed to be calculated with the rated compressor power in a period during the low CA demand time when the compressors where operated at full load.

According to the CA auditors, 207-level, which is also an active level, could not be measured as there was a lack measurement points for the portable flowmeter. This level is, however, a new level that is being developed. The authorised CA consumption of 207-level is regarded to be negligible when compared to the other active levels.

A large portion of the generated CA (82.7%) was determined to be wasted underground. The wastages in this case are regarded as easily fixable, as the high wastage rate on Shaft B can be addressed by isolating the inactive levels from the shaft CA column. At the time of publication, the inactive levels are yet to be isolated.

Appendix D Mass balance on Shaft F

A mass balance was implemented on mining Shaft F, located in the Gauteng province. According to the benchmarking indicator that was developed in Section 2.2.2, this mining shaft has the second highest demand reduction potential when compared to 13 other mining shafts. The benchmarking prioritisation graph, with Shaft F highlighted, is illustrated in Figure 83.

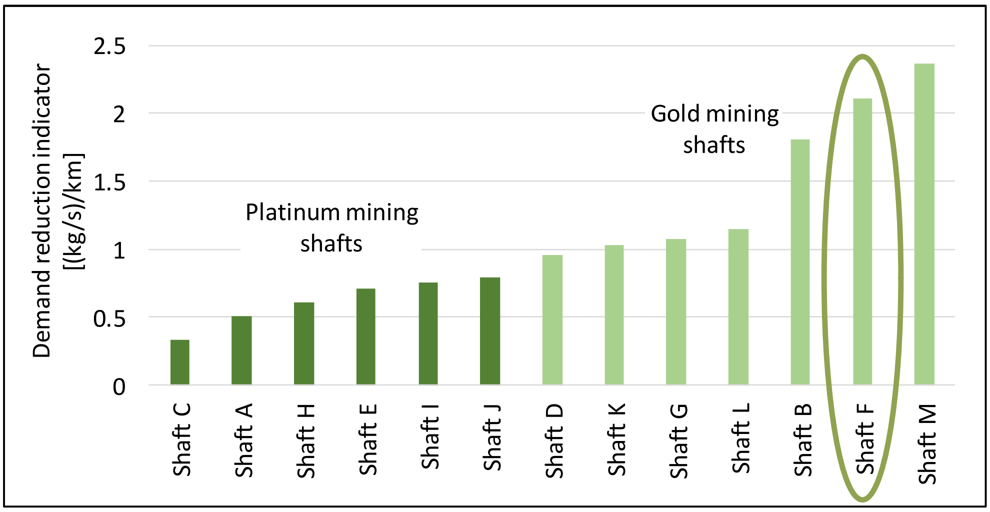

Figure 83: Shaft F prioritised on the benchmarking graph

A simplified drawing of the shaft is illustrated in Figure 84. Also illustrated in the drawing is the CA mass flows that were measured during the low demand period. Only 25.22 kg/s of the 34.58 kg/s CA reaches the active levels. The deficit of the CA flow is lost through the inactive levels. A reduction in CA can easily be obtained by isolating these levels from the CA network.

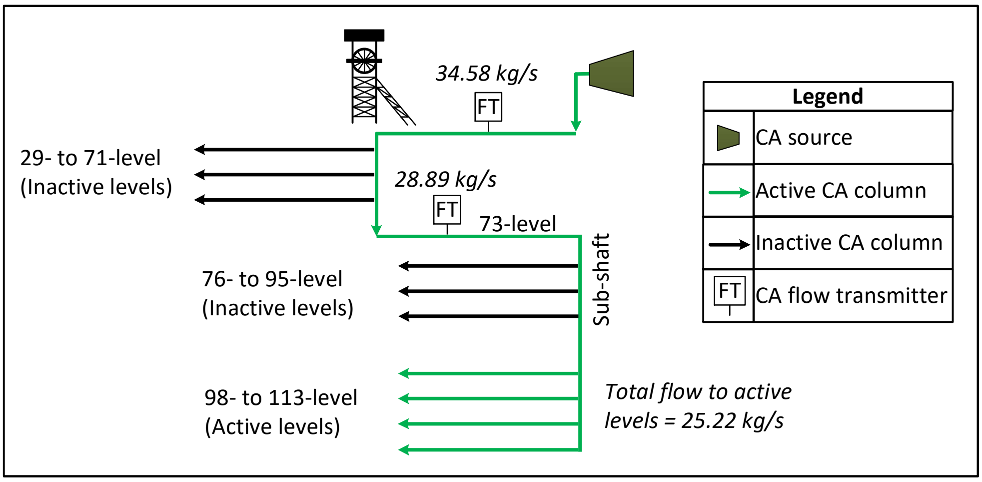

Figure 84: Simplified CA reticulation drawing of Shaft F

Appendix E Mass balance on Shaft J

Shaft J is a platinum mining shaft in the Limpopo region. According to the benchmarking graph in Figure 85, this shaft has the highest demand reduction potential indicator of all evaluated platinum shafts.

Five compressors, each with an installed capacity larger than 4 MW, supplies the shaft with CA. Normal compressor operation involves operating three compressors in the non-drilling shift and four compressors in the drilling shift.

None of these compressors have working guide vanes. If the shaft demand is not sufficiently reduced, excess CA will be vented through the blow-off valve resulting in no electricity savings.

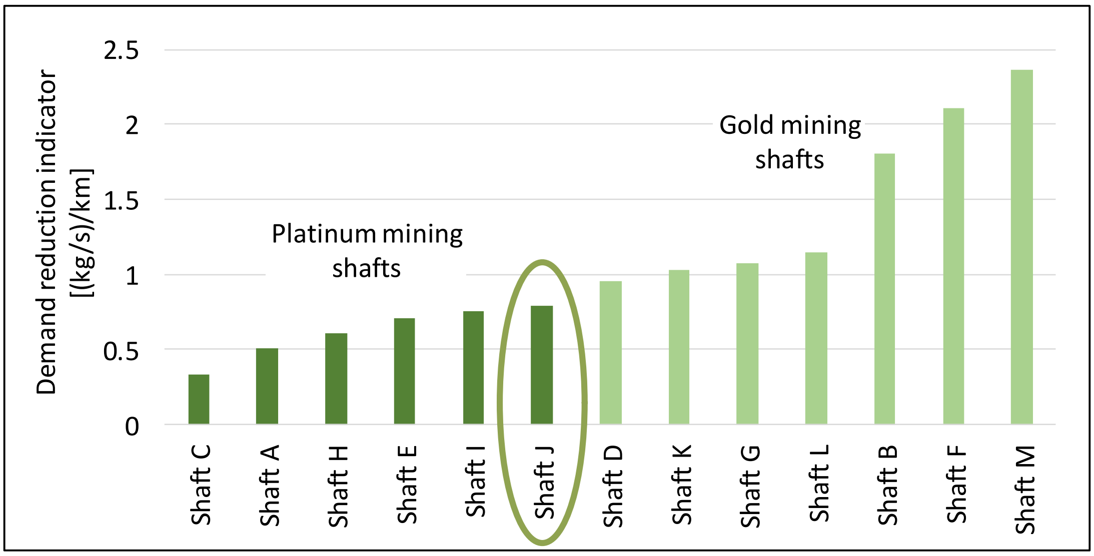

Figure 85: Shaft J prioritised on the benchmarking graph

Personnel from Shaft J conducted a CA audit of the shaft levels to determine which of the inactive levels have not been sealed. No measurement instrumentation was used. An inactive level with an open CA column was found. Closing this column resulted in a drastic reduction of the shaft demand.

A map of the compressor power reduction capabilities during the non-drilling shift is shown in Figure 86. As seen in the figure, a demand reduction of 3.7 kg/s was required to stop a compressor and obtain electricity cost savings whilst maintaining the pressure above the set point. Closing the inactive level resulted in a decreased demand of 9.6 kg/s.

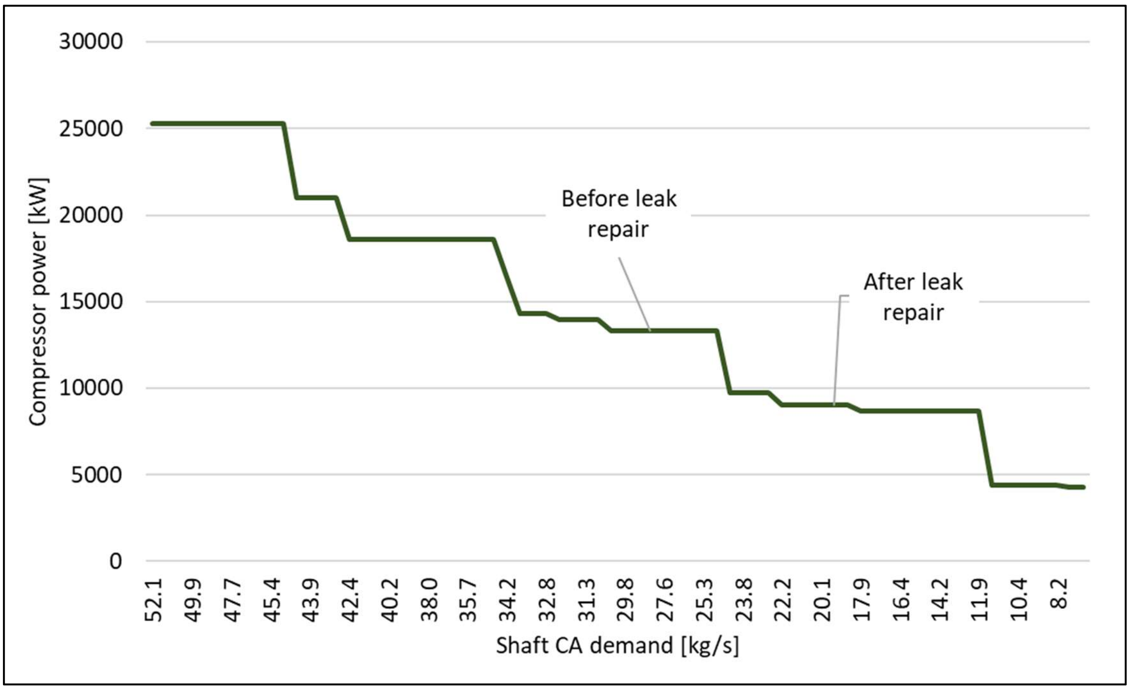

Figure 86: Compressor power reduction map of Shaft J

Appendix F Mass balance on Shaft L

A mass balance was implemented on a gold mining shaft, Shaft L, located in the Gauteng province. As seen in Figure 87, Shaft L shows the 4th highest potential for demand reduction of the 13 shafts evaluated for demand reduction potential in Section 2.2.2.

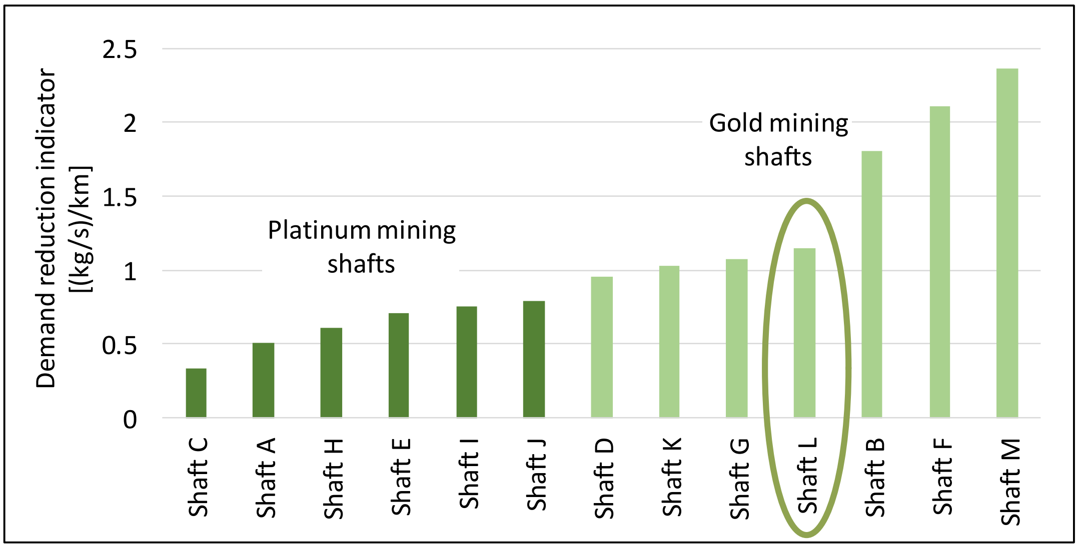

Figure 87: Shaft L prioritised on the benchmarking graph

Shaft L has four levels which are in active production. A mass balance of the shaft areas revealed that only about 50% of the shaft CA consumption reaches the active levels. The rest of the CA was determined to be consumed by the upper, inactive levels, specifically 26- and 29-level.

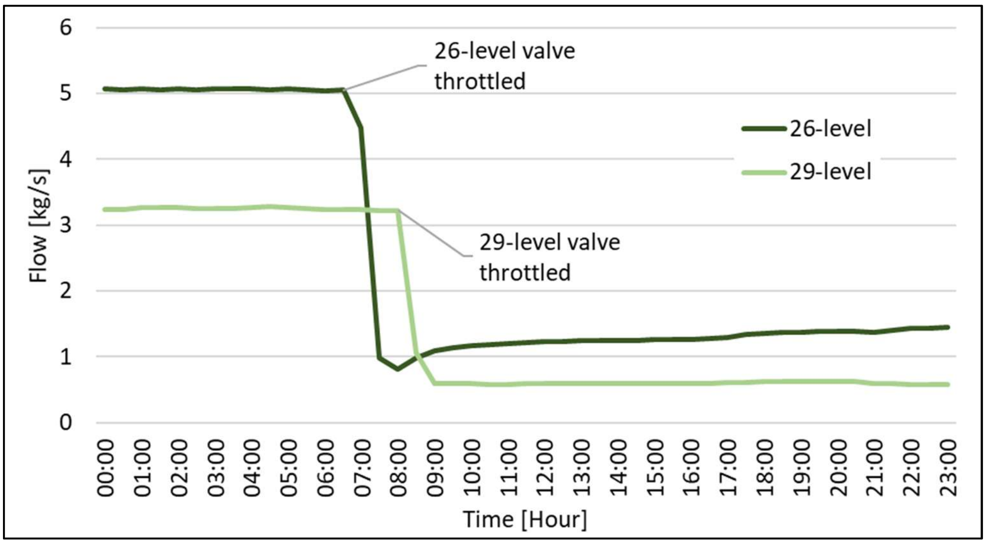

Figure 88: CA flow reduction on 26- and 29-level of Shaft L

These two inactive levels contained refuge bays which, by law, needed to be pressurised. Auditors thus requested that the CA to these levels be throttled to only supply the necessary pressure to the refuge bays. The flow reduction as a result of throttling these levels is illustrated in Figure 88.

The combined compressor power decreased with a daily average of 330 kW as can be seen in Figure 89. This is not as much as expected, seeing that almost 50% of the CA demand was reduced. According to the information in Section 2.2.3, this could be due to the limited ability of the compressors to reduce the power consumption. The author was unable to determine the partial load fraction of the compressors due to a lack of operational measurement instrumentation.

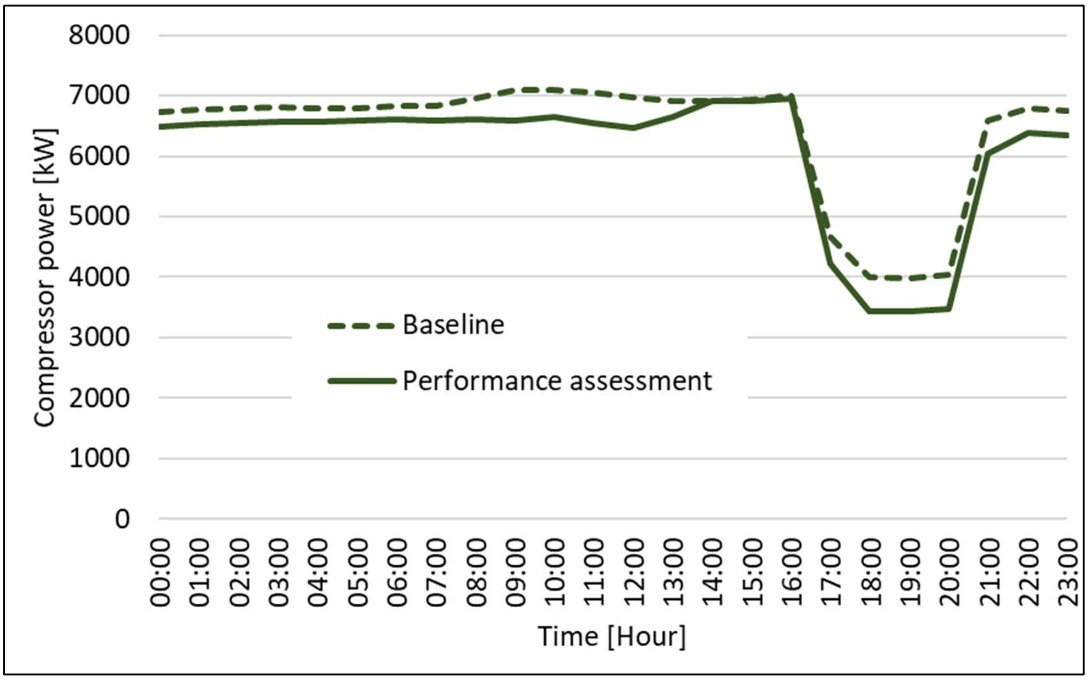

Figure 89: Compressor power demand reduction on Shaft L

Appendix G Shaft H 31-level UG2 West simulation details

It is estimated that the total CA consumption of 31-level was 3.06 kg/s. The haulage column had an inside diameter of 210 mm from the east-west split. From the entrance of the station to the split the column has a diameter of 280 mm. The level pressure transmitter is located at the level station.

A CA pressure logger, capable of reading 1 kPa pressure increments, was installed at Cross cut 36 which is regarded as the haulage end. Step-testing was then conducted by closing and opening the cross cut valves one by one. A graph illustrating the step-testing results followed by information on each cross cut is given in Figure 90 and Table 18 respectively.

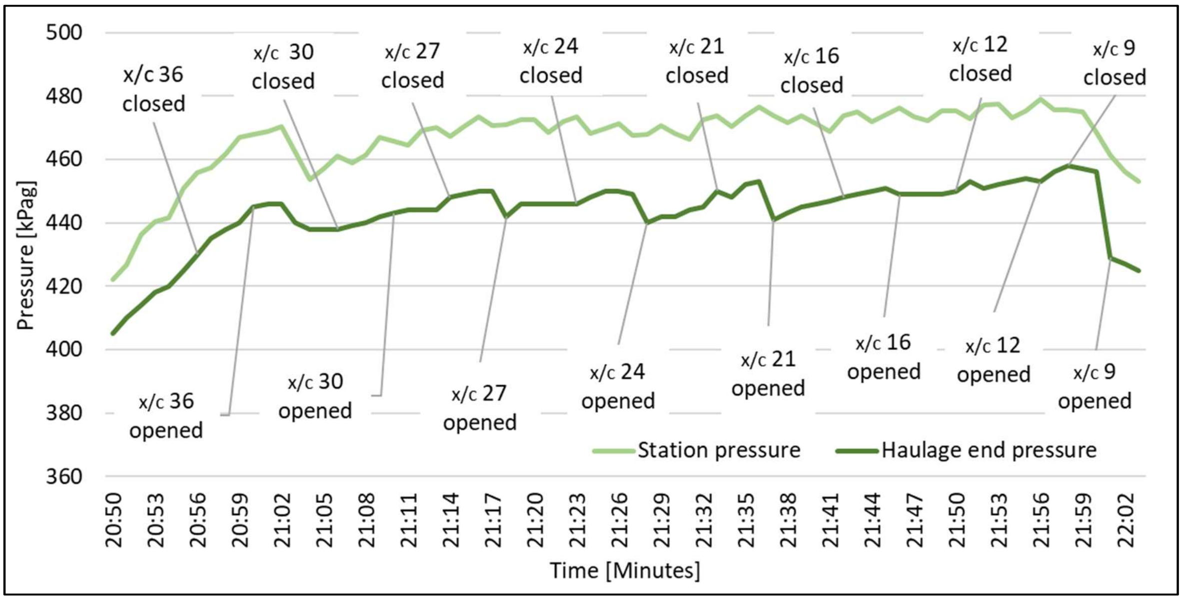

Figure 90: Shaft H 11-level UG2 west step-testing results

Table 18: Shaft H 31-level west cross cut information

Cross cut	Distance from station [m]	Pressure drop when closed [kPa][14]	Calculated flow [kg/s]
9	324	10	1.1
12	447	0	0
16	572	2	0.3

[14] This value was calculated from a normalised pressure. The normalised pressure was calculated by subtracting

Cross cut	Distance from station [m]	Pressure drop when closed [kPa][14]	Calculated flow [kg/s]
21	797	5	0.5
24	921	6	0.6
27	1051	4	0.3
30	1159	0	0
36	1374	0	0