

## **EXISTING ENERGY SAVING MEASURES**

---

Shortcomings of existing energy efficiency initiatives on mine compressed air systems

---

## **2 EXISTING ENERGY SAVING MEASURES**

### **2.1 Introduction**

Chapter 1 gave insight into the compressed air systems used on South African deep-level gold and platinum mines. It was shown that various initiatives have been implemented to reduce electricity consumption of industrial compressed air systems. The compressed air systems used in deep-level gold and platinum mines are typically much larger and extend over longer distances than the systems used in most industrial processes.

Chapter 2 will focus on existing energy saving projects completed at deep-level gold and platinum mines. However, real mine names cannot be used due to confidentiality agreements with the mining companies. The mines will therefore be referred to as Mine 1, Mine 2, Mine 3 and so forth.

### **2.2 Compressor control systems**

A centrifugal compressor's supply flow rate can be controlled by restricting the airflow rate into the compressor. The airflow can be restricted by controlling inlet valve openings or changing vane angles on the inlet side of the compressor. A decrease in the supply flow rate would decrease the compressor's power consumption. However, any centrifugal compressor has a minimum operating flow rate that must be maintained to prevent compressor surge. Compressor surge can result in damage to the compressor and must therefore be avoided [11], [34], [35], [36], [37].

Control systems such as blow-off and/or unloading systems are used to avoid compressor surge. The control equipment will change the inlet and/or blow-off valve positions to keep the delivery pressure of the compressor within a safe operating range [11], [34], [35], [36]. A photo indicating some peripherals of the inlet control valve system on a Brown Boveri Sulzer 51 000 m<sup>3</sup>/h centrifugal compressor is shown in Figure 12. This compressor is powered by a 4 800 kW electrical motor.

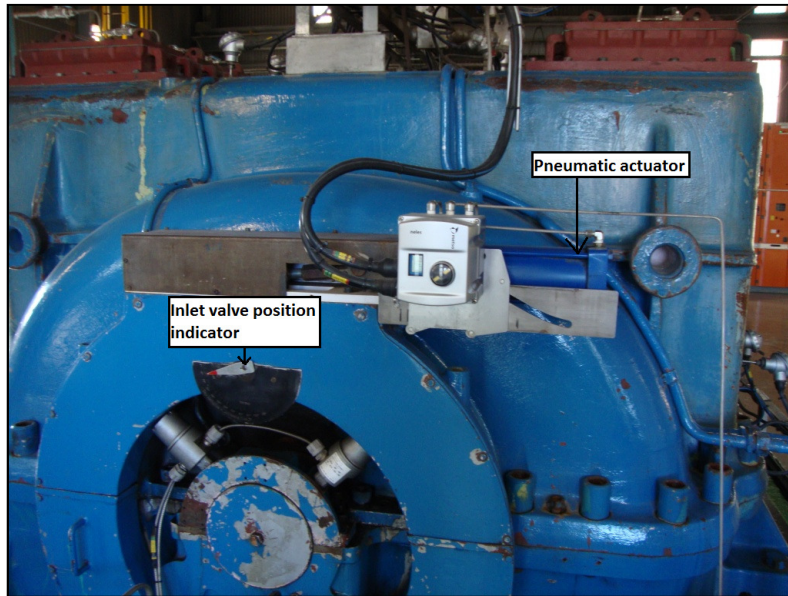


Figure 12 – Photo of a centrifugal compressor inlet valve control systems<sup>12</sup>

A blow-off valve can also be used to prevent surge in a centrifugal compressor. An open blow-off valve will result in an increase in flow that could prevent surge. An example of a blow-off valve on a 51 000 m<sup>3</sup>/h, 4 800 kW Ingersoll Rand Centac centrifugal compressor is shown in Figure 13.



Figure 13 – Photo showing a blow-off valve on a centrifugal compressor<sup>13</sup>

---

<sup>12</sup> Photo taken at a South African mine

<sup>13</sup> Photo taken at a South African mine

Information regarding specific surge control techniques is widely available [11], [34], [35], [36]. Specific surge control techniques will not be investigated in detail since it falls outside the scope of this study. Only changes to the energy consumption of compressed air systems as a result of the control systems will be investigated.

Compressed air systems with an irregular compressed air demand, or systems where the demand is lower than the minimum supply capacity of the compressors in operation, could result in frequent stopping and starting of compressors. Most mine personnel do not allow frequent stopping and starting of compressors.

An example of unnecessary compressor operation occurred at Mine 1. Compressor operators at Mine 1 used to operate a fixed number of compressors during non-drilling periods. An energy saving project comprised a revised compressor control strategy that involved two of the three shafts at Mine 1. An average saving of 4.77 MW was realised during the Eskom evening peak period [9], [38], [39].

The saving was increased to 15.18 MW after the incorporation of the compressed air system at the third shaft. This resulted in a further saving of 3.8 MW that extended over a 24-hour period. The largest contribution towards the average saving achieved over a 24-hour period was the use of more efficient compressors located at the third shaft. An alternative to frequent stopping and starting is to load and unload the compressor according to the air demand [9], [22], [27], [39], [40].

An unload condition of a compressor typically entails a small inlet valve opening and an open blow-off valve. All of the compressed air generated by the compressor is then released into the atmosphere. Compressor power consumption during an unloaded condition depends on the specific characteristics of the machine. The power consumption during unloaded conditions of typical mine compressors vary between 20% and 60% of the machines rated power [13], [22].

An alternative approach to stopping and starting of compressors is to control the rotational speed of a compressor by using a VSD. However, results from the use of VSDs on mine compressed air systems were not available. Results were, however, obtained for VSDs installed on the compressors used in gas processing systems. But, it was evident from the publications regarding the installation of VSDs on compressors that more research and development is still required [41].

Budget costs received from possible VSD suppliers were also analysed to determine the possible use of VSDs to reduce compressor power consumption for mining applications. The budget costs for the supply of a VSD for a typical mining compressor is R6.2 million. This cost does not include any installation costs such as cabling, labour, additional civil work changes to the switchgear and so forth. It is expected that the additional costs could result in a total cost of more than double the cost of supplying the VSD. This assumption is made based on practical experience with VSD installations on pumping systems at mining sites.

It would thus be more economical to improve on the existing compressor control systems or to implement measures to reduce the demand for compressed air. A sufficient reduction in the demand for compressed air could result in the shutdown of a compressor. The energy saving as a result of a compressor that is stopped would be more than the saving achieved for a compressor running at a reduced load.

Other possible focus areas to reduce compressor power consumption were identified by analysing the different parameters that determine compressor power consumption. An equation that can be used for these purposes was analysed in Chapter 1. Equation 1 can be rewritten by using Equation 2 and Equation 3 as follows:

Equation 4:

$$P_{electrical} = \frac{A \cdot C_{discharge} \cdot n \cdot p_{line} \cdot T_{inlet}}{T_{line} \cdot \eta_{comp} \cdot (n-1)} \cdot \left[ \left( \frac{p_2}{p_1} \right)^{(n-1)/n} - 1 \right] \cdot \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}} \cdot \sqrt{kR * 1000 \left( \frac{2}{k+1} \right) T_{line}}$$

$$\eta_{motor}$$

Where:

$P_{electrical}$	= Electrical power (kW)
$A$	= Minimum cross-sectional area
$C_{discharge}$	= Discharge coefficient
$n$	= Polytropic compression exponent
$p_{line}$	= Line pressure (kPa)
$T_{inlet}$	= Inlet temperature (Kelvin)
$T_{line}$	= Line temperature (Kelvin)
$\eta_{comp}$	= Compressor efficiency
$p_2$	= Compressor discharge pressure (kPa)
$p_1$	= Compressor inlet pressure (kPa)
$k$	= Specific heat ratio
$R$	= Gas constant (0.287 kJ/kg.K)
$\eta_{motor}$	= Motor efficiency

Compressor control systems can be used to effectively control some of the parameters in Equation 4 to reduce compressor power consumption. A compressor control system cannot change some fixed parameters such as: the demand on the system, inlet pressure, inlet temperature, polytropic compression exponent, specific heat ratio, gas constant and the electrical motor efficiency.

The control system could, however, be used to ensure that the compressor is operated at the most efficient point. Set points on the control system will determine the delivery pressure of the machine and also the positions of the inlet and blow-off valves. Improper operation of the compressor controller could therefore result in unnecessary power consumption.

It is evident from Equation 4 that the system pressure has a large impact on the power consumption of a compressed air system. The discharge pressure of the compressor will determine the amount of energy per unit mass of air delivered. A high discharge pressure will require more energy to deliver a unit mass of air than a lower discharge pressure.

The line pressure influences the mass flow rate through leaks in the system. A high pressure will therefore result in a higher mass flow rate as a result of system leaks than a lower line pressure. The line pressure of a system is linked to the delivery set point of the compressor control system. It is therefore obvious that the delivery pressure set point of the compressor control system must be as low as possible to prevent unnecessary power consumption.

The relationship between compressor power consumption and system pressure will be investigated graphically by using a base pressure of 700 kPa for the compressor discharge pressure as well as for the line pressure in Equation 4. The following values were used as inputs to Equation 4 to illustrate the effect of reduced pressure on compressor power consumption:

## Existing energy saving measures

Gas constant:	0.287 kJ/kg.K
Specific heat ratio:	1.4
The polytropic compression exponent:	1.4
Intake temperature:	298K
Line temperature:	303K
Intake pressure:	89 kPa
Discharge / System pressure range:	300–700 kPa
Compressor efficiency:	80%
Motor efficiency:	90%
Hole diameter:	33 mm

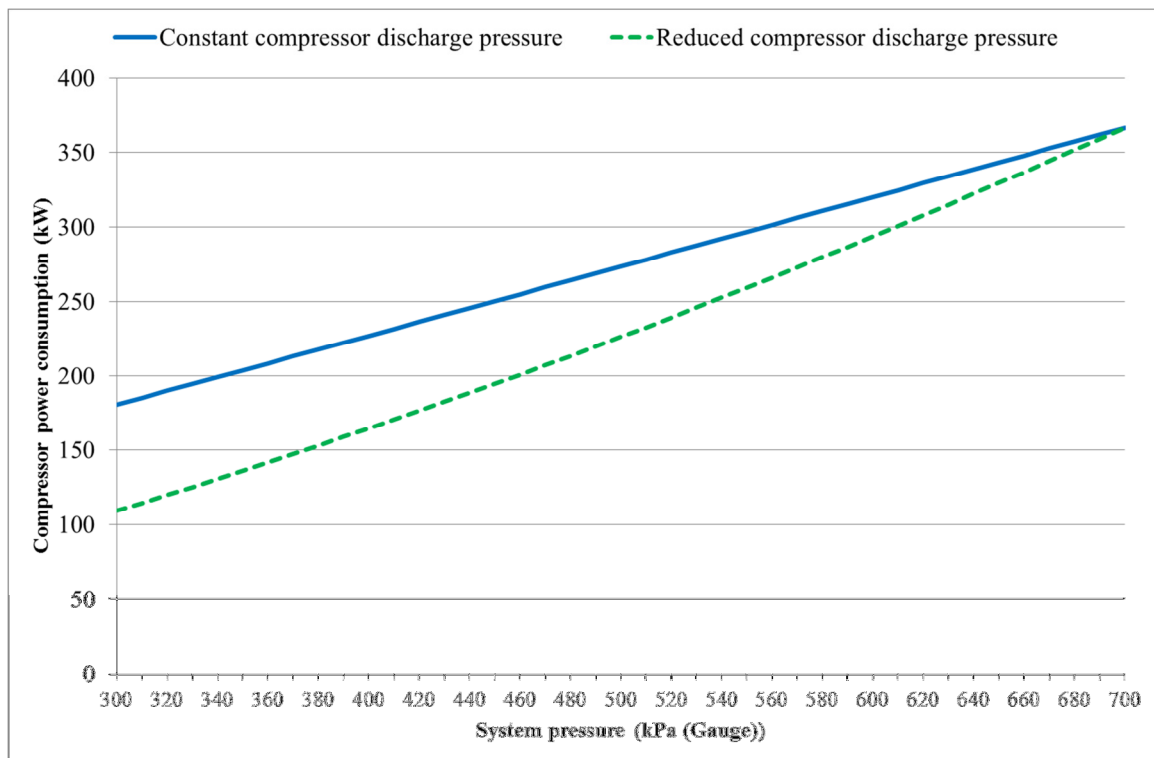


Figure 14 – Relationship between system pressure and compressor power consumption

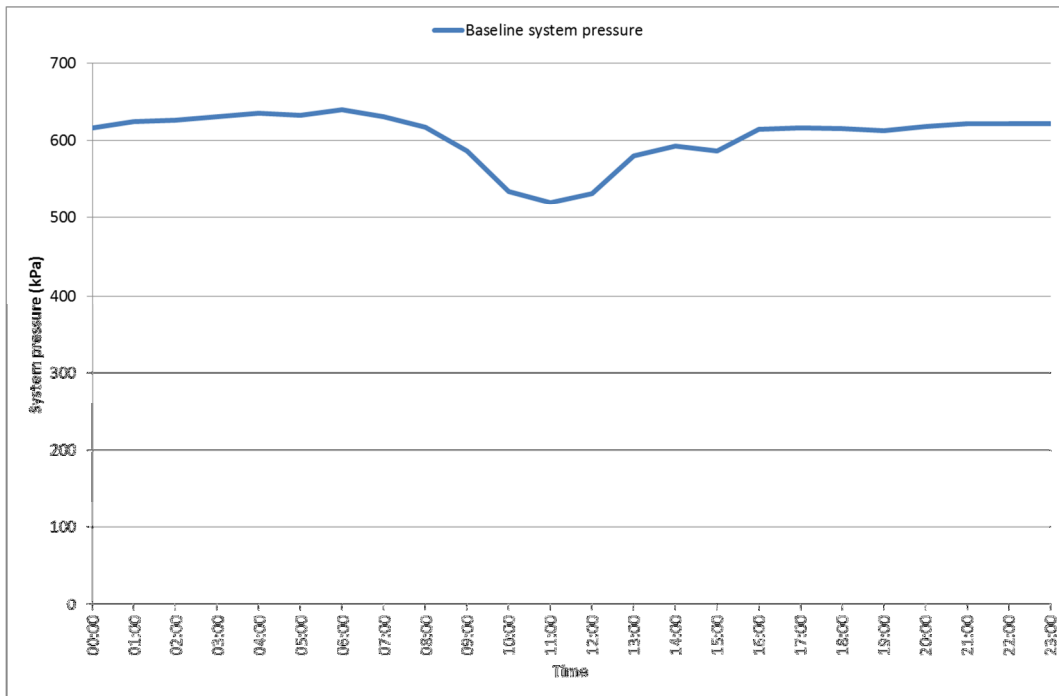
Both lines in Figure 14 indicate the compressor power consumption for a fixed leak size at different pressures. The power calculation for the “constant compressor discharge pressure” line assumes that the compressor discharge pressure remains at 700 kPa throughout the pressure range. The reduced system pressures are therefore obtained through control valves. The “reduced compressor discharge pressure” line indicates the compressor power consumption due to a reduction in compressor discharge pressure.

Observation of Figure 14 indicates a significant difference between compressor power consumption for the constant discharge pressure scenario and for the reduced discharge pressure scenario. Analyses of the results show that a factor ranging from 1.6 to 1.8 can be used to estimate the compressor power savings due to a reduction in compressor discharge pressure.

A frequently used guideline (often used to calculate energy savings as a result of a decrease in system pressure) states that a 14 kPa reduction in system pressure will result in a 1% reduction in power consumption [42], [43]. This guideline is equivalent to a reduction factor of 2 that is higher than the theoretical value that range between 1.6 and 1.8. It is likely that the general guideline estimates higher savings due to the added effect of a reduction in line friction due to the reduced mass flow rate.

The approximation method derived from Equation 4 implies that an absolute pressure reduction of 10% should result in a theoretical saving of between 16% and 18%. This approximation method will be referred to as the as “the saving approximation method for a change in system pressure”. The saving approximation method for a change in system pressure will only apply if the pressures remain between 300 kPa and 700 kPa. This approximation method would provide more conservative savings than the frequently used guideline. This approximation method will be tested against results achieved for projects implemented on mine compressed air systems.

The approximation method was tested by analysing the results of a project that was implemented at a deep-level mine. This deep-level mine will be referred to as Mine 2. The compressors at Mine 2 were already controlled by an automated control system prior to the implementation of the project. The initial control parameters at Mine 2 resulted in frequent stopping and starting of compressors during low demand periods. The system pressure prior to the implementation of the project is shown in Figure 15 [9], [27], [39], [44].



*Figure 15 – Baseline system pressure at Mine 2*

It is evident from Figure 15 that the system pressure is at its lowest during the peak drilling period. This is in contrast to the compressed air requirements of the mine where the highest pressures are required during this time. The average weekday compressor power consumption prior to the implementation of the project can be seen in Figure 16. It is clear from the graph that the compressed air supply is increased during the peak drilling time to counter the increased demand.

An energy saving project that involved upgrades to the compressor control system was implemented to counter the frequent stopping and starting of the compressors. The parameters of the control system were also fine-tuned to control the system pressure to values that follow the pressure requirements of the different shift cycles.

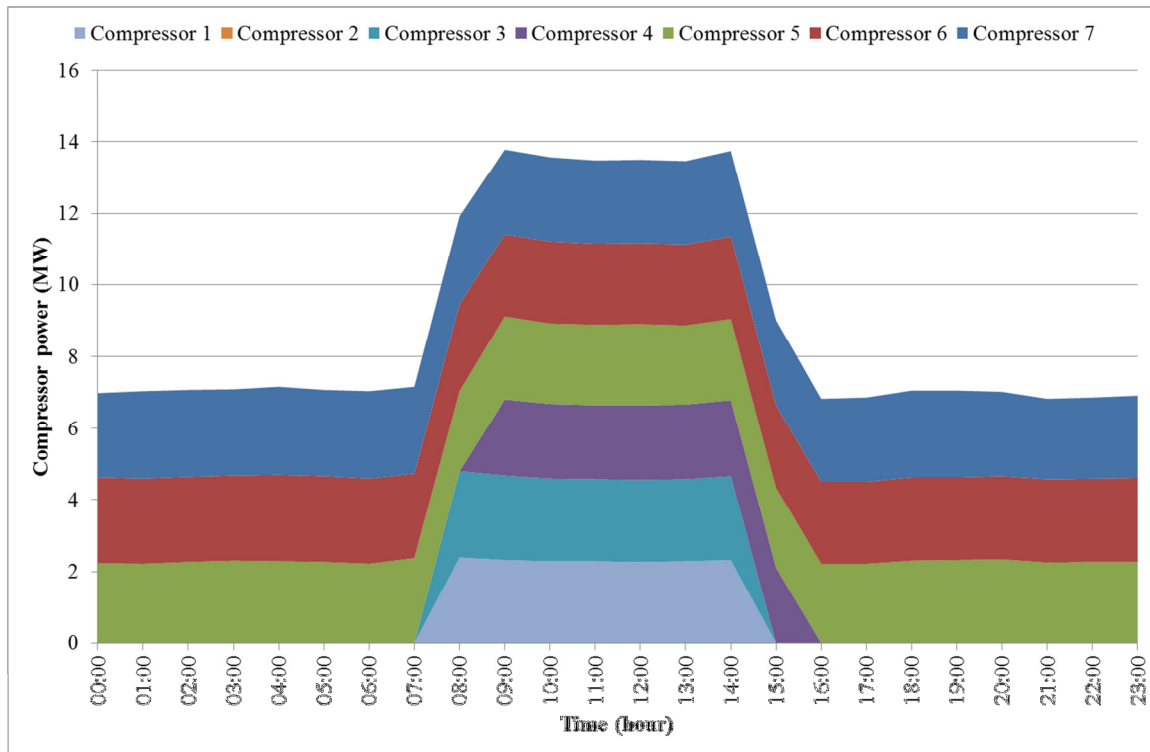


Figure 16 – Mine 2 baseline compressor power consumption [22]

The combination of the improved compressor control system and the reduced system pressure resulted in an average daily power saving of 1.07 MW during the first three months after project completion. A follow-up study revealed that three compressors were always operated as baseload compressors. The operating parameters of one of the three machines were, however, alternating between the loaded and off-loaded position during the blasting period. A second machine was alternating between minimum and maximum inlet guide vane positions during the first part of the cleaning shift [27].

The original saving of 1.07 MW was achieved by operating the compressors in off-loaded conditions and at reduced guide vane positions. Compressor running in the off-loaded state, however, still consumes electricity without supplying any compressed air. The control parameters were fine-tuned further to maximise the cost savings for the client. This improvement increased the average daily energy efficiency to 2.4 MW [22], [46].

The resultant power consumption profile is shown in Figure 17 [46]. Analysis of Figure 17 indicates that the minimum number of compressors was reduced from three to two during non-peak production periods. A comparison between the baseline system pressure and the post-implementation system pressure is shown in Figure 18 [46]. It is evident from the figure that the system pressure was particularly reduced during the non-drilling periods.

The average post-implementation system pressure was reduced by 18% compared to the baseline system pressure. Compressor power consumption was reduced by approximately 29% after the implementation of the project. The ratio between the system pressure reduction and the compressor power reduction is therefore 1.6. This ratio corresponds to the saving approximation method for a change in system pressure that estimates a fractional reduction in power consumption of between 1.6 and 1.8 times the fractional change in pressure.

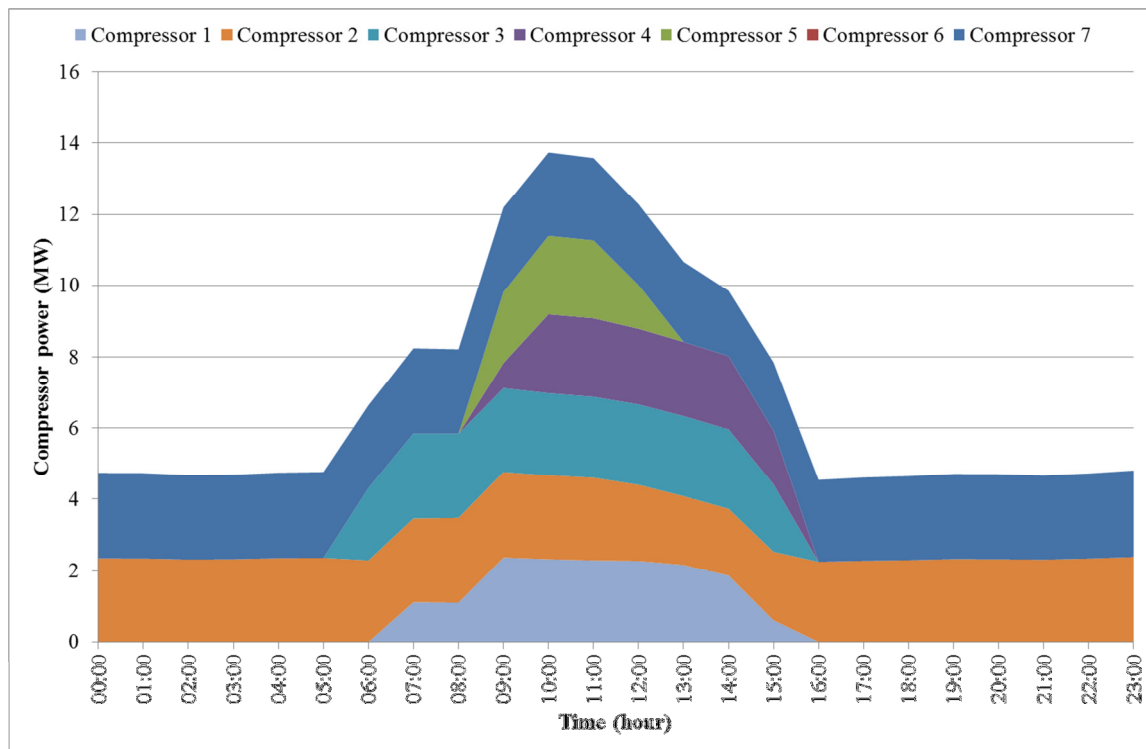


Figure 17 – Mine 2 compressor power consumption after implementation of revised control system [46]

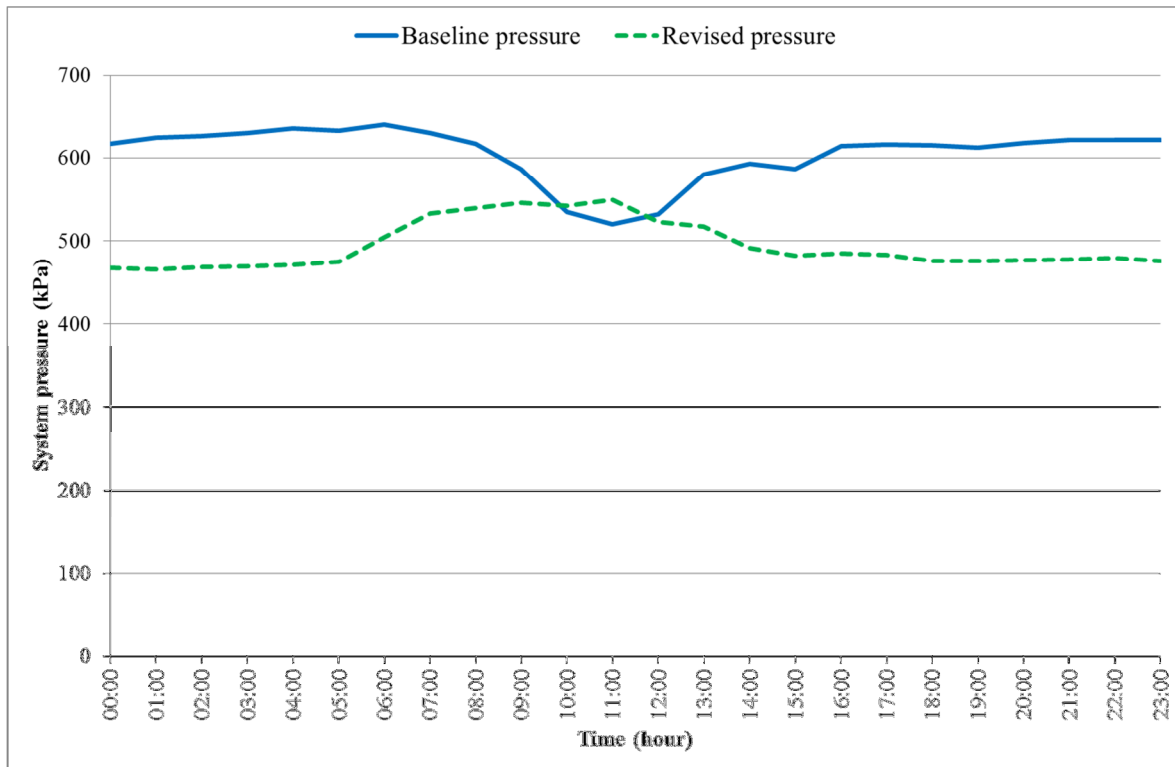


Figure 18 – System pressure comparison for Mine 2 [46]

The impact of improved compressor control and the validity of the saving approximation method for a change in system pressure were investigated by analysing the results from a project implemented at Mine 10. Initial tests conducted at Mine 10 showed that it is possible to reduce compressor power consumption by 10.8 MW during the Eskom evening peak period [38], [39]. An average saving of 10.8 MW is equivalent to a 30% reduction in compressor power consumption.

The tests involved the operation of the minimum number of compressors to sustain an average system pressure of 400 kPa throughout the Eskom evening peak period [38], [39]. This was compared to typical average pressures of approximately 500 kPa during other times. The system pressure was therefore reduced by 20% during the tests. The ratio between the percentage pressure reduction and the percentage power reduction is thus 1.5. This is close to the saving approximation method for a change in system pressure that estimates a fractional reduction in power consumption of between 1.6 and 1.8 times the fractional change in pressure.

The results from a project implemented at Mine 11 were also investigated to determine the validity of the saving approximation method for a change in system pressure. The aim of the project was to reduce compressor power consumption between 18:00 and 20:00. The results from the project were analysed by different authors. The savings claimed by the different authors vary between 1.9 MW and 2.2 MW [13], [14], [22], [46], [45], [47].

The reason for the difference in savings claimed is because different data sets were used to calculate the savings. Data for the period from March 2010 to April 2010 was studied further for the purposes of this study to get a better understanding of the impact of a reduction in system pressure. The dataset used shows that an average saving of 2.1 MW was achieved between 18:00 and 20:00.

Analysis of the post-implementation power consumption profile revealed a 24-hour energy efficiency component even though the project was aimed at a reduction between 18:00 and 20:00 only. Data between 23:00 and 16:00 was used to quantify the daily energy efficiency savings. Data between 16:00 and 23:00 was excluded from the calculation because it was difficult to quantify between the different saving components during this period.

The data revealed that an average saving of 0.58 MW was achieved between 23:00 and 16:00. Additional information regarding the techniques used to reduce the compressor power consumption during this period was not published since the project was only aimed at a reduction between 18:00 and 20:00.

The techniques employed to reduce the compressor power consumption between 18:00 and 20:00 included a reduction in system pressure as well as the installation of two underground control valves. It is assumed that the resultant saving of 1.52 MW (after the effect of the 24-hour energy efficiency component was removed) was achieved through a reduction in pressure together with the installation of two control valves.

The underground control valves were installed after it was discovered that compressed air was used for ventilation on these levels. The control valves were configured to isolate the compressed air supply to the levels between 18:00 and 20:00. A leak management study revealed that the isolation of the compressed air supply to two of the levels resulted in an additional saving of 0.69 MW [14], [47].

It is assumed that the resultant electricity saving of 0.83 MW during the evening peak is due to the system pressure reduction. A saving of 0.83 MW is equal to a reduction of 21% from the baseline. The system pressure was reduced by approximately 15% during the control period. This is a ratio of 1.4 between the power saved and the pressure reduction. This value is lower than the saving approximation method for a change in system pressure that estimates a ratio of between 1.6 and 1.8.

The inconsistency of the datasets makes it difficult to assess the impact of the pressure reduction with a great accuracy. The ratio of 1.4 is therefore considered to be close enough to the theoretical values that range between 1.6 and 1.8 [45], [14], [47]. Analyses of the results achieved for different projects show that the frequently used guideline (that estimates an energy saving of 1% for a 14 kPa pressure decrease) could possibly overestimate savings.

The new saving approximation method for a change in system pressure provides a more conservative estimation of the savings. This method states that a factor ranging from 1.6 to 1.8 can be used to estimate the compressor power savings due to reduced compressor discharge pressure. This implies that an absolute pressure reduction of 10% should result in an average saving of between 16% and 18%. This saving approximation method for a change in system pressure is only applicable if the pressures remain between 300 kPa and 700 kPa.

### **2.3 Surface air distribution control**

Many of the precious metal processing plants at mining operations make use of the same compressed air system that supplies compressed air for mining purposes. The pressure requirements for most deep-level gold and platinum mines vary according to the shift periods [43]. However, most precious metal processing plants require a constant compressed air pressure.

The system pressure of a typical compressed air installation is determined by the equipment with the highest pressure requirement. The pressure requirement for most processing plants is higher than that of the shafts - especially during non-drilling periods. The system pressure will therefore be determined by the pressure requirements of the processing plants [13], [48].

The compressed air consumed by processing plants is normally much lower than the consumption by the production shafts [13], [48]. The entire compressed air system must therefore be pressurised according to the pressure required by the processing plants [13], [48]. This is despite the relatively low flow demand. Tests and simulations conducted on the compressed air system at Mine 1 showed that the installation of a dedicated plant compressor could realise an average daily energy saving of 20.2 MWh [49].

The installation of surface air distribution control valves can also be used to separate high pressure users from low pressure users [50]. The relationship between the system pressure and the airflow rate will be investigated to determine a method to estimate energy savings due to surface air distribution control. The potential energy savings impact of pressure control valves can then be used to determine the viability of such projects.

In the previous section Equation 4 was used to determine the effect on the power consumption due to a reduction in system pressure. Equation 4 is shown again for reference purposes:

$$P_{electrical} = \frac{A \cdot C_{discharge} \cdot n \cdot p_{line} \cdot T_{inlet}}{T_{line} \cdot \eta_{comp} \cdot (n-1)} \cdot \left[ \left( \frac{p_2}{p_1} \right)^{(n-1)/n} - 1 \right] \cdot \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}} \cdot \sqrt{kR * 1000 \left( \frac{2}{k+1} \right) T_{line}}$$

$\eta_{motor}$

Assume that all of the variables except for the line pressure remain fixed in the equation. Equation 4 can then be simplified as follows:

Equation 5:

$$P_{electrical} = F_{power\_line\_pressure} \cdot P_{line}$$

Where:

$P_{electrical}$  = Electrical power (kW)

$F_{power\_line\_pressure}$  = Power to line pressure ratio (kW/kPa)

$P_{line}$  = Line pressure (kPa)

It is evident that the pressure of the system is directly related to the power consumption of the compressor. A system that is operated at unnecessary high pressures would therefore result in excessive power consumption due to the mass flow losses through leaks. A reduction in system pressure would reduce the mass flow rate through all the leaks and equipment in operation in the system and could result in a decrease in power consumption. Savings can thus be expected if the pressure is reduced wherever possible.

It is evident from Equation 5 that an absolute pressure reduction of X% would result in a theoretical compressor power reduction of X% if the compressor discharge pressure remains unchanged. The saving approximation method for surface air distribution control initiatives is derived directly from this relationship. Surface air distribution control typically entails a reduction in pressure for certain sections of the system. The compressed air demand, of the section to be operated at a reduced pressure, will be reduced by the same fraction as the fractional change in pressure.

This reduction in compressed air demand will result in a reduction in compressor power consumption provided that the compressor control system has the ability to reduce the compressed air supply. The saving approximation method for surface air distribution control estimates that an X% reduction in absolute pressure will result in an  $(X \times Y)\%$  reduction in compressor power consumption; where Y is the percentage contribution to the total system demand by the part of the system that will be controlled to the new pressure.

Results from projects where control valves were installed on the surface distribution networks of mine compressed air systems will be investigated to determine if this saving approximation method is accurate. It is expected that the actual savings obtained from projects that employ pressure control techniques will differ from the theoretical savings due to external factors.

A project aimed at reducing compressor power consumption during the Eskom evening peak was implemented at Mine 3. The project entailed centralised compressor control and monitoring, as well as installing control valves at some shafts. The project resulted in an average reduction of 6.56 MW between 18:00 and 20:00 on weekdays. These savings were achieved through an improvement of the control schedules of the compressors [40].

A follow-up project at Mine 3, aimed at a 24-hour energy efficiency saving, made use of surface control valves to split the compressed air system into a high-pressure section and a low-pressure section. The project also involved underground pressure control at selected mining levels. The average ring pressure prior to the installation of surface control valves was 562 kPa.

The average control pressure on the high-pressure side of the ring after the installation of the surface control valves was 539 kPa compared to 462 kPa on the low-pressure side of the ring. The low-pressure side accounted for approximately 34% of the total ring remand. The absolute pressure on the high-pressure side of the ring decreased by 4%, while the pressure on the low-pressure side decreased by 15%. The saving approximation method for surface air distribution control estimates that the percentage reduction in pressure will result in a similar reduction in flow.

As a result, a flow reduction of 4% is expected for the high-pressure side compared to a reduction of 15% for the low-pressure side. This equates to a reduction of 1.7 MW. Actual compressor power consumption was reduced by an average of 1.8 MW over a 24-hour period [50].

So, there is a difference of 0.1 MW between the estimated saving and the saving achieved. Underground control valves were also installed at one of the main production shafts during the same period as the surface control valves [51]. However, many of these control valves were disabled by mine employees shortly after installation. The contribution to the savings from the control valves is therefore assumed to be negligible.

An underground connection between two of the main production shafts were also established to reduce line losses. Consequently it is assumed that the additional saving of 0.1 MW could be attributed to the reduction in losses. The results from the project implemented at Mine 3 verify that the saving approximation method for surface air distribution control provides an accurate estimation of the savings.

The saving approximation method for surface air distribution control will also be tested by using the results obtained from a project implemented at Mine 4. Compressed air at Mine 4 is used at two shafts, namely 1 # and 3#, and a gold plant. Compressed air is supplied by eleven compressors with a total installed capacity of 38.65 MW. The pressure requirements of the shafts vary according to the different shift periods. As an example, compressed air must be supplied at a higher pressure during the drilling periods than during the blasting periods. However, the pressure requirements at the gold plant necessitate a constant compressor delivery pressure of 420 kPa [13].

Surface control valves were installed to reduce the compressed air demand at the shafts during the Eskom evening peak (18:00 to 20:00). It was possible to use the control valves to reduce the shaft pressures during this period because it coincides with the blasting period. The pressure requirement during the blasting period is 380 kPa compared to the constant 420 kPa required by the plant. An evening peak saving of 8.26 MW was claimed for the surface valve control project [13], [48].

The baseline profile and the achieved profile for the project are shown in Figure 19. It is clear from Figure 19 that compressor power consumption was not only reduced during the Eskom evening peak period. This was unexpected since the control valves at 1# were only operated for two hours per day [13]. The control valves on the air lines that supply 3# were also not operational and did therefore not contribute to any savings [13]. It is therefore highly unlikely that the control valves contributed to savings over a complete 24-hour period.

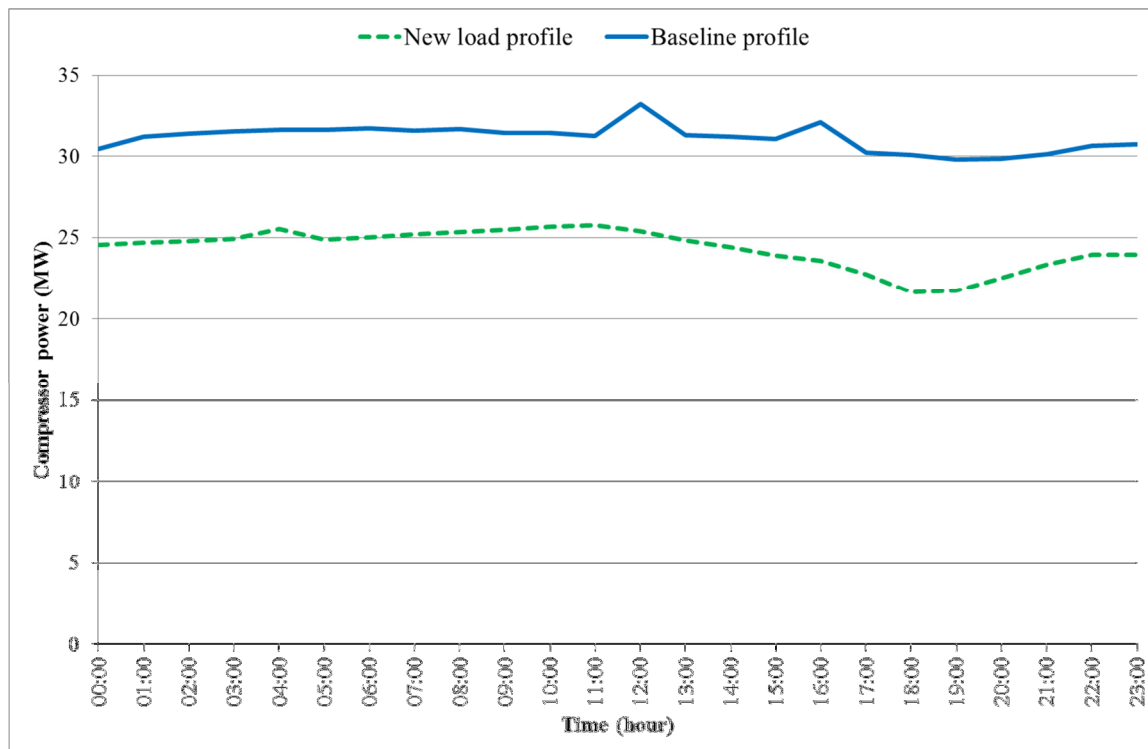


Figure 19 – Compressor power consumption comparison between baseline and new load profile for Mine 4 [13]

Baseline scaling techniques are sometimes employed to ensure that the correct baseline is used to measure the savings [52]. Peak power baseline scaling is sometimes used to normalise a baseline to account for changes in the usage of the system that did not form part of the energy saving project.

This method can be used to negate the effect of the 24-hour energy efficiency component by assuming that the effect of the control valves is zero during the peak production periods. This assumption can be made because the peak production periods do not coincide with the

Eskom evening peak period. The result of the baseline that was scaled according to the maximum power consumption of a typical weekday is shown in Figure 20. The new load profile compared to the peak scaled baseline reduced the evening peak saving from 8.26 MW to 1.6 MW.

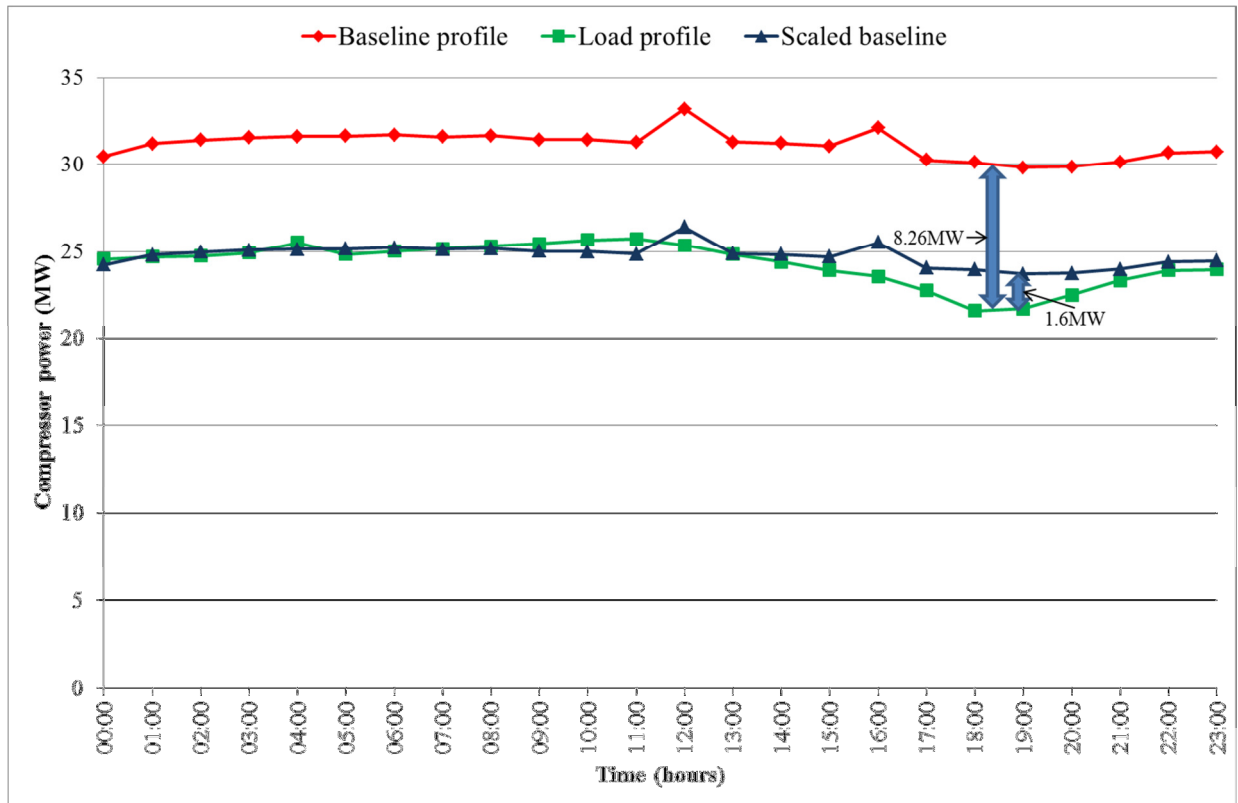


Figure 20 – Compressor power consumption showing scaled baseline for Mine 4

The saving approximation method for surface air distribution control will be tested against the scaled saving of 1.6 MW. The implementation of control valves resulted in a surface pressure reduction of 7.7% during the Eskom evening peak. The saving approximation method for surface air distribution control therefore suggests a compressor power reduction of 7.7% for the portion of air throttled by the control valves. This corresponds to a saving of 1.8 MW if measured against the scaled baseline. Thus the difference between the approximated value and the scaled peak-clip saving of 1.6 MW is 13%.

The saving estimation of 1.8 MW does not account for the demand of 3# or the plant. It can therefore be expected that the savings calculated with the saving approximation method would be higher than the actual savings achieved. The results from the peak-clip portion of the savings at Mine 4 verified that the saving estimation method provided a satisfactory estimation of the savings to be achieved due to surface air distribution control.

The saving estimation method for surface air distribution control was also tested against the results achieved from a project implemented at Mine 5. Compressed air at the mine is consumed at two shafts, namely 4# and 7#, and a gold plant. Compressed air is supplied by four compressors situated at 7# and one compressor at 4#. The compressed air systems at the two shafts are connected by means of an underground pipe network.

A project aimed at reducing compressor power consumption during the Eskom evening peak period comprised the installation of two surface control valves, compressor inlet valve controllers, as well as a centralised control system. Both of the control valves were installed on the compressed air supply that feeds 7# [13], [48].

The compressor delivery set points were automatically controlled by the centralised control system after project completion. One of the two valves was closed completely during the Eskom evening peak and the other one was partially closed to reduce compressed air consumption. The project managed to reduce the demand during the Eskom evening peak by between 3.7 MW and 4.32 MW [13], [48], [53].

A comparison between the baseline compressor power consumption and the power consumption after project implementation is shown in Figure 21. The figure indicates a 24-hour energy efficiency of 5.5 MW even though the aim of the project was to reduce compressor power consumption during the Eskom evening peak only [13], [48], [53].

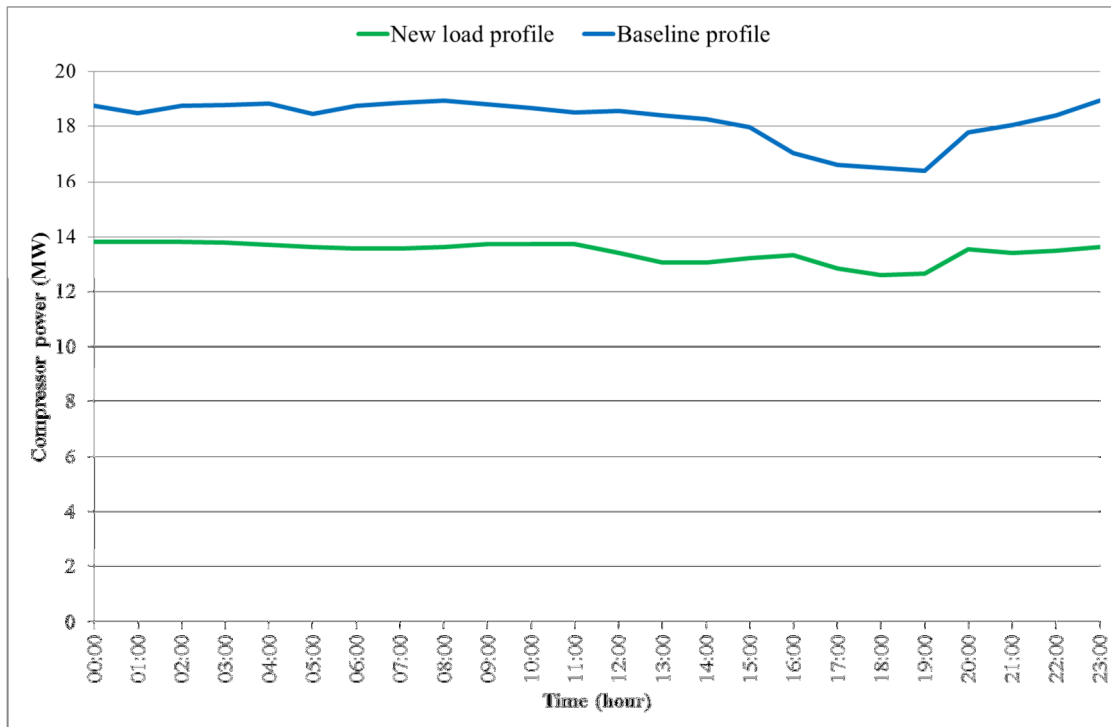


Figure 21 – Compressor power consumption comparison between baseline and new load profile for Mine 5 [13]

The impact of the surface control valves was analysed by comparing the system pressure profiles on Level 23 and Level 37 with the compressor power consumption profiles. This comparison is shown in Figure 22. The graph indicates that the control valves resulted in a system pressure reduction during the control period.

The power consumption and pressure before and after the control period were used as no-control reference points to calculate the effect of the control valves. These no-control reference points, together with the reference points used for the control period, are indicated on the graph.

The average system pressure during the control period was on average 3.1% lower than the system pressure when the surface valves were not controlled. The saving approximation method for surface air distribution control implies a 3.1% reduction in power consumption during the control period. A 3% reduction in power consumption is equal to 510 kW.

A comparison between compressor power consumption during the control period and power consumption during the no-control period indicates an actual power reduction of 714 kW during the control period. The estimated power consumption is therefore 28% lower than the actual power consumption. The difference between the estimated power reduction and the actual power reduction due to the valve control is small considering that a saving of 714 kW represents only 19% of the 3.79 MW that was claimed.

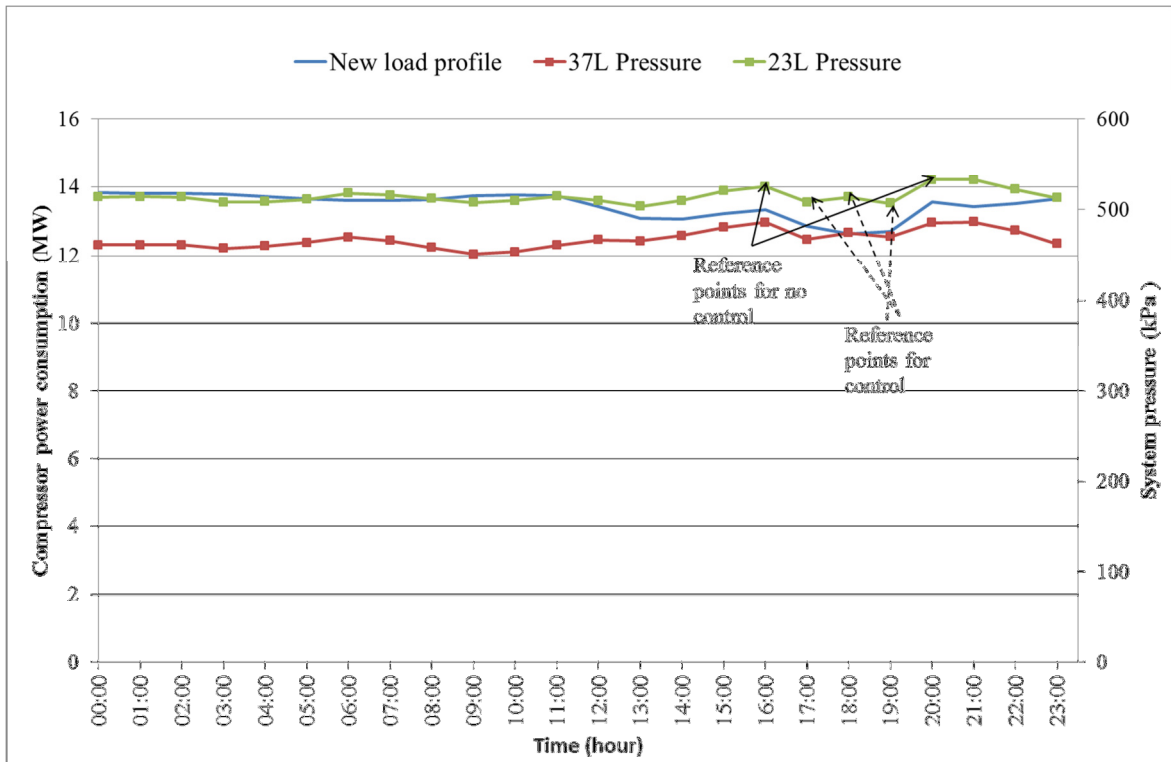


Figure 22 – Comparison between underground system pressure and compressor power consumption for mines

The majority of the savings were therefore not realised by the surface valve control. Results during the commissioning of the system suggest that 26% of the evening peak-clip saving was achieved through improved compressor set-point control [53]. Insufficient information is available to provide a proper explanation of how the resultant 55% reduction was achieved. Mention was made that energy savings projects have a knock-on effect where people are made aware of the costs of energy and they will thus become more energy conscious. It is said that leaks were also fixed and open-ended blow pipes were sealed off [13].

The lack of information regarding the contributions of the savings by the project in the published data is an indication that compressed air systems is often incorrectly analysed. Energy saving projects on mine compressed air systems are then sometimes done without a proper understanding of the system. As a result the need for a simplified integrated approach is required.

The results obtained from a project implemented at Mine 6 will also be used to verify the saving approximation method for surface air distribution control. Mine 6 is unique in the sense that no production takes place at the main production shaft during the Eskom evening peak hours. The only compressed air requirements during this time are for refuge bays, loading box cylinders on some mining levels at the main production shaft, and the gold plant [13], [45].

The refuge bays require a surface pressure of approximately 120 kPa compared to a requirement of approximately 500 kPa for the gold plant. It would therefore be possible to lower the shaft pressure to only 120 kPa during the Eskom evening peak period if alternative power supplies are installed on the loading box cylinders [13], [45].

The loading boxes were converted to use hydraulic cylinders instead of pneumatic cylinders. This allowed a compressed air pressure of only 120 kPa for the shaft. A control valve was installed to reduce the shaft pressure during the Eskom evening peak while still maintaining the required plant pressure. This project resulted in an average evening peak saving of 3.05 MW [13], [45].

The average system pressure at the main production shaft was 450 kPa compared to 510 kPa at the plant and the other shafts prior to the installation of the control valves. A pressure reduction from 450 kPa to 120 kPa for the main production shaft is equivalent to an absolute pressure reduction of 61% if the atmospheric pressure is taken as 87 kPa.

A reduction in compressor airflow consumption of 61% for the main production shaft is therefore expected. Data analysis revealed that the baseline flow consumption was reduced by 78% at the main production shaft during the two-hour control period.

The difference between the expected flow reduction and the actual reduction is most likely due to the large reduction in line losses at the reduced flow rates. The flow demand from the loading boxes was also removed as a result of the hydraulic conversion. The saving approximation method for surface air distribution control will therefore provide a conservative estimate.

This project resulted in an average evening peak saving of 3.05 MW. The main production shaft accounted for approximately 60% of the flow demand during the Eskom evening peak period prior to the installation of the control valves. A 78% reduction in the demand from the main shaft is therefore expected to reduce the total demand of the system by approximately 46%. A 46% reduction in flow should thus reduce compressor power consumption by approximately 46%. A saving of 3.05 MW equates to a reduction of only 29% which is much lower than the expected reduction of 46%.

The reason for the unexpected low savings was due to a restriction in the control of the compressors. It was not possible to stop a compressor to match the reduced supply when the flow was reduced due to mechanical problems with the compressors. Compressors were operated in an unloaded condition to reduce power consumption during the control periods [13], [45].

It would be possible to increase the saving to 6.65 MW if the mechanical problems of the compressors are fixed. This is equivalent to a 62% reduction; that is much higher than the expected reduction of 46%. Analysis of the system pressures at the other shafts and the gold plant revealed that the system pressure was on average 10 kPa lower during the performance assessment of the project.

It is expected that a system pressure reduction from 510 kPa to 500 kPa would result in a compressor power reduction of approximately 3% according to saving approximation method for surface air distribution control. The saving approximation methods for system pressure reduction and for surface distribution control would therefore estimate a reduction of 49%. A 49% reduction is equal to a saving of 5.2 MW.

So the saving approximation methods provided a conservative saving with an error of 28%. The underestimation of the savings is probably due to the added benefits of reduced line losses. An error of 28% may be high, but it provides a good estimation before detailed analysis and engineering effort is used to analyse a system. It was therefore verified that the saving approximation method for surface air distribution control provides a conservative estimation for compressor power savings.

It was also verified that it is possible to reduce compressed air consumption by means of surface control systems. Analysis of the savings claimed by some of the projects indicated that actual impacts of the projects are often misinterpreted. It was also revealed that revised compressor control strategies were required to realise electricity savings. The revised compressor control strategies resulted in electricity savings even when surface control was not activated. It is therefore clear that efficient operation of the compressors has a larger impact on the savings achieved than the control valves. The control valves were however required to maximise the savings.

### **2.4 Underground distribution control**

It was shown in the previous section that surface air distribution control can be used to reduce mine compressor power consumption. A saving approximation method for surface air distribution control was also developed to estimate the savings as a result of control valves. The drawback of surface control valves is that the control pressure must be set according to the requirements of the equipment with the highest pressure requirement. Some loading boxes require a constant compressed air pressure throughout all mining shifts. Many loading boxes are designed to operate at pressures of at least 450 kPa.

The pressure requirements of these loading boxes will thus determine the control set point of the surface control valves. The underground compressed air distribution network will therefore be pressurised according to the pressure requirements of these loading boxes. Most pneumatic applications situated further from the shaft area do not require high pressures at all times. Underground control valves can therefore be used to reduce the pressure for selected time periods on individual levels.

It is therefore expected that underground level control valves can be used to reduce compressed air consumption. The same principles will apply to underground pressure control that would apply to surface distribution control. The only additional aspect to consider is the contribution of the control demand to total flow demand. The results from projects that involved the installation of multiple underground control valves will be investigated to verify that the saving approximation method for surface air distribution control can also be applied for underground distribution control.

The added benefit as a result of the improvement in control flexibility will also be investigated. This will be done by analysing the results achieved on several mine compressed air systems where underground valves were installed.

Underground control valves were installed on eleven underground mining levels at Mine 7. An Eskom evening peak saving of 3.4 MW was claimed for the project. Detailed analysis of the electricity consumption profile after project completion indicated energy efficiency savings throughout a 24-hour period even though the control valves are only operated during the Eskom evening peak periods [54], [55].

The claimed saving of 3.4 MW was therefore not only as a result of the underground control valves. Thus it is likely that other factors such as improved compressor control and a reduction in demand due to leak repair contributed significantly to the savings. So, the added benefit as a result of the control valves could not be determined for Mine 7.

It is obvious from the analysis of the literature that the results were not correctly interpreted. It is most likely due to a misunderstanding of the real impact of energy savings initiatives on compressed air systems. The lack of information made it impossible to verify the saving approximation method at Mine 7 [54], [55].

The energy savings claimed for a project implemented at Mine 8 that involved underground control valves was also investigated to determine the impact of underground control valves. An average saving of 4.7 MW was achieved between 15:00 and 20:00 [54], [55]. It is claimed that the savings were achieved by means of the underground control valves.

Published information provides only details for the set-up of one control level. The control system was configured to reduce the flow on that specific level by 10%. An assumption that all of the levels were controlled to reduce flow by 10% implies a reduction of 10% in compressor power consumption. A saving of 4.7 MW is, however, equivalent to a reduction of 27% from the baseline [54], [55].

A follow-up project conducted on the same compressed air system resulted in an average saving of 5.4 MW over a 24-hour period. The saving between 18:00 and 20:00 was increased to 7.29 MW with the follow-up projects. This is a reduction of 43% from the original baseline. The published data suggests that the increased savings were achieved through automatic compressor delivery control. The published information from the follow-up project mentions that the valves on some of the underground levels were closed completely between 18:00 and 20:00 [27], [44].

Complete closure of high demand levels would result in a 100% reduction in flow. It is highly likely that the closure of one or more levels will result in a significant reduction in total demand. The distribution of the flow demands for the different underground levels was, however, not published. The accuracy of the saving approximation method for underground distribution control could therefore not be verified against the data available for the project implemented at Mine 8.

The multiple underground control valves provided the opportunity to reduce the demand at some levels completely. A project that involved the installation of underground control valves at the two main production shafts at Mine 9 resulted in an Eskom evening peak reduction of 5.75 MW. The results published claims that the control valves contributed significantly to savings achieved [54], [55].

Additional data was available to analyse the results of the project in more detail. This was done to determine the real impact of the control valves and also to determine the accuracy of the saving approximation method for underground distribution control. A data analysis for two months' data during the performance assessment of the project was used.

It was not possible to use all of the data points used by the Measurement and Verification (M&V) team for the data analysis. The reason for this is that the corresponding flow and pressure data at all the relevant measurement points used in this analysis was not available for all the data points that were used to calculate the power consumption.

The average weekday compressed airflow consumed by 1# and 2# is shown in Figure 23. It is observed from the graph that the compressed airflow to 1# was reduced during the control period between 17:00 and 20:00. It is, however, also evident from the figure that the flow consumption at 2# did not show the same visible reduction. Compressed air consumption at 1# was reduced by approximately 10% during the control period. This is five times more than the average decrease of 2% obtained at 2#.

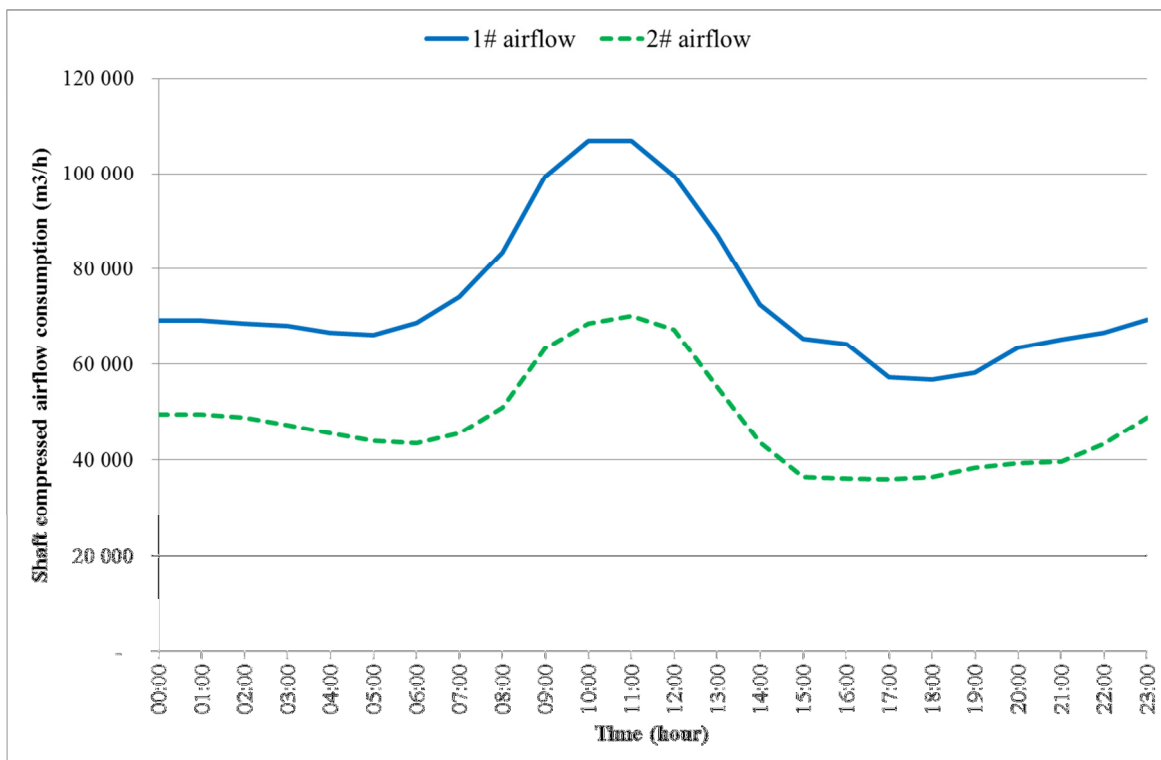


Figure 23 – 1# and 2# flow consumption at Mine 9

The changes to the underground system pressures at both shafts were investigated to determine the impact of the control valves. It was found that six of the nine levels at 1# reduced the level pressures by between 5.4% and 10.5%. Five of the ten control valves installed at 2# resulted in pressure reductions that ranged between 1.4% and 3.3%.

Data analysis revealed that control valves on some levels were closed completely during the control periods without a significant pressure reduction downstream of the valve. One can assume that the compressed air demands at these levels are too low to result in a significant pressure drop over a three-hour control period.

However, the control valves on some levels did not respond to the control set points supplied to the valves. The non-response was due to communication problems that were experienced. The average underground pressures were 555 kPa at 1# and 545 kPa at 2#. Mine management allowed a minimum pressure of only 520 kPa during the control period. The average allowable absolute pressure reduction at 1# was therefore 5% and that at 2# was 4%.

The airflow at 1# decreased by approximately 10% with a pressure reduction of only 5%. This does not correlate with the saving approximation method for underground distribution control. Further data analysis revealed that the compressed air demand on the rest of the ring increased during the control periods. Discussions with mine employees revealed that some of the levels at both 1# and 2# have underground compressed air connections with other shafts. These shafts have separate compressed air supply points. Control valves were not installed at these shafts.

Compressed air was therefore delivered via another supply point to some of the control levels. Consequently, the actual demand was not reduced by 10%. Compressed air was merely redirected to follow another path.

A flow reduction of only 2% was achieved at 2# even though the allowable pressure reduction was 4%. It was expected that the reduced savings were attributed to the malfunctioning of many of the valves at 2#. However, data analysis revealed that the average pressure of one of the underground levels at 2# was below 500 kPa throughout the day. A further pressure reduction was therefore not possible for this level.

Discussions with mine personnel revealed that this level has a ring feed connection to other shafts on the ring that do not have control valves installed. So, the expected 4% energy reduction was not realised due to the high demand from the ring feeds to other shafts that resulted in low pressures; combined with the fact that only half of the levels had fully functional control valves.

It is obvious from the results that the saving approximation method for underground distribution control can only be applied if the demand distribution between the different levels and shafts are known. Other influences such as ring feeds must also be considered.

The impact of the control valves on the power consumption of the compressors was also investigated. A comparison between the baseline power consumption and the new load profile for the same period used for the flow and pressure analysis is shown in Figure 24.

It is evident from the figure that compressor power was not just reduced during the valve control period. An additional reduction in compressor power consumption is observed during the control period. Data analysis shows an additional saving of only 1% during the control period. This is much less than the average reduction of 10% in flow consumption for 1# and 2% for 2#.

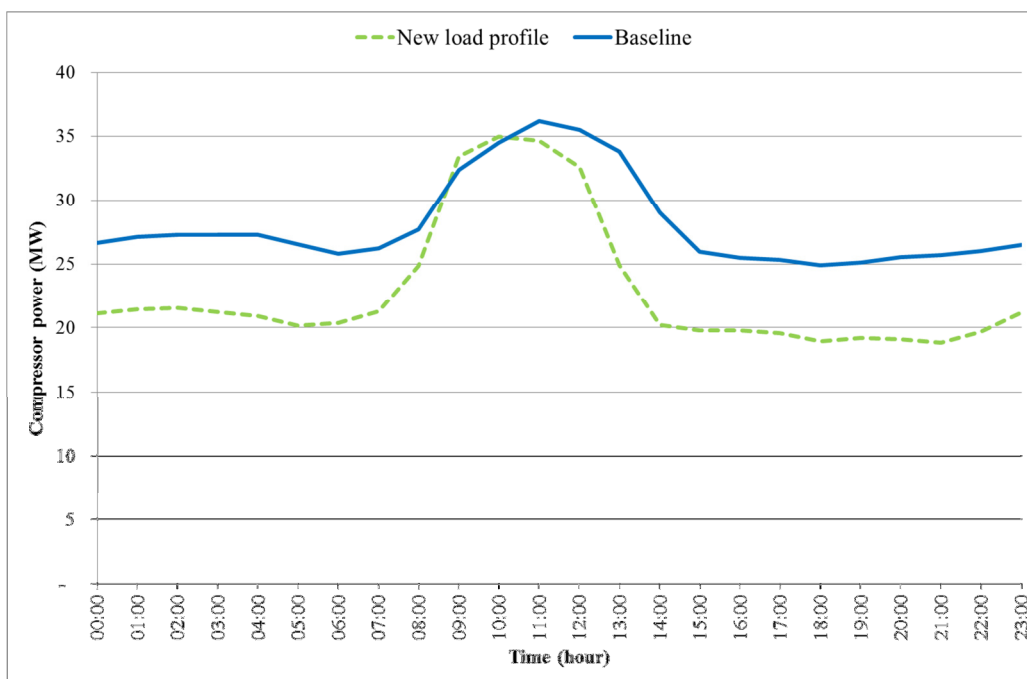
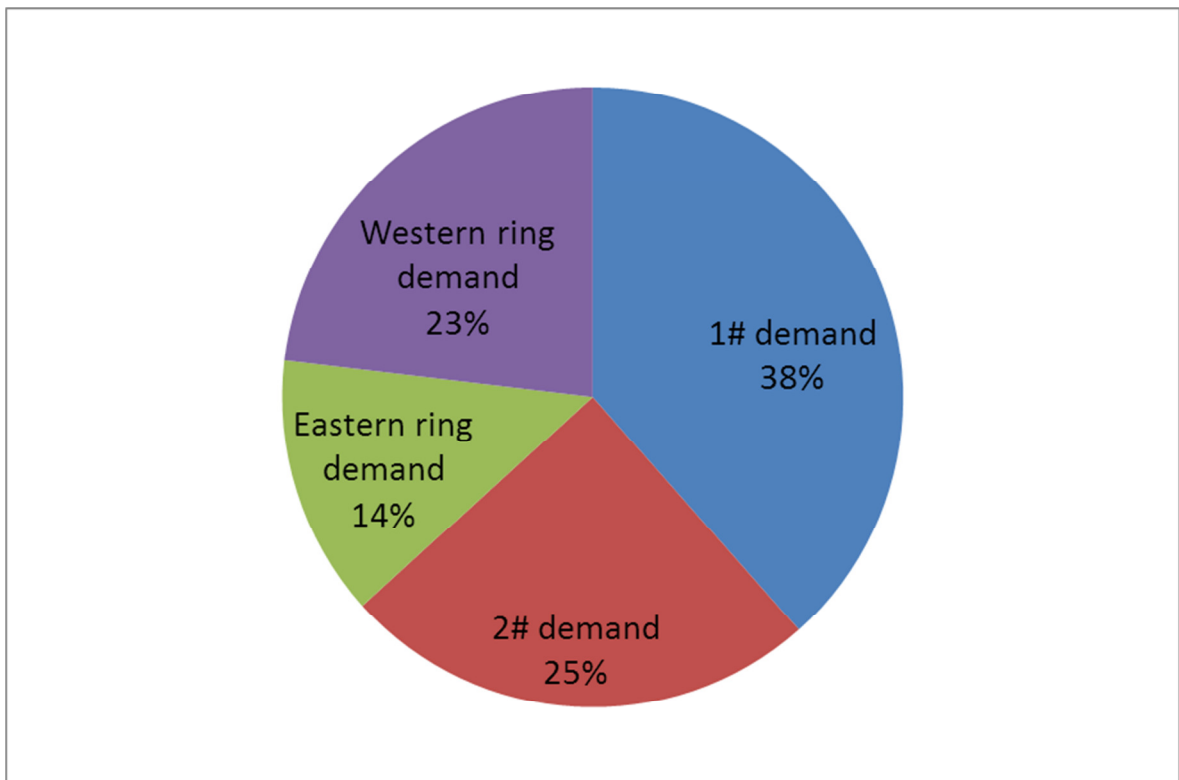


Figure 24 – Comparison between power consumption before and after installing control valves at Mine 9

Analysis of the data revealed that the installation of multiple underground control valves did not realise significant savings. Underground control valves are better suited for applications where time and pressure schedules vary significantly between different levels such as the compressed air system at Mine 8.

The small impact on total power consumption is due to the fact that control valves were not installed on the other shafts located on the same compressed air network. The other shafts on the ring were grouped into either the Eastern ring or the Western ring. The compressed air distribution between the two shafts and the two rings are shown in Figure 25. It is clear from the graph that the installation of control valves on the other shafts is required to realise the full benefit of control valves.



*Figure 25 – Mine 9 average daily compressed air distribution*

It is evident that the control valves did not contribute significantly to the 5.75 MW saving. The data analysis revealed that the majority of the savings were achieved through improved compressor control.

The results from projects that involved the installation of multiple underground control valves verified that the saving approximation method for surface air distribution control can also be applied for underground distribution control. The saving approximation method for both surface and underground control will now be referred to as the saving approximation method for air distribution control.

## **2.5 Replacing pneumatic applications**

Another approach to reduce compressor power consumption is to consider the replacement of pneumatic applications. In 1996 AngloGold Ashanti started with feasibility studies to determine if it would be possible to replace pneumatic rock drills with electrically powered rock drills. Tau Tona mine was identified as a case study since they already experienced drilling problems due to low compressed air pressures at the working areas [56].

Initial studies suggested that it would be up to 38% cheaper to operate electric drills compared to traditional pneumatic drills. AngloGold Ashanti approached Hilti to develop an electric rock drill suitable for underground mining. It took Hilti four years to produce the first electric prototype. This prototype presented several problems such as drill steel failures, and poor penetration rates making it inadequate for underground mining conditions [56].

Hilti improved the electric rock drills over a period of six years to make them more suitable for underground mining. Mine management decided to roll out the improved electric drills to long-term panels during February 2006. A total of sixty-one panels were equipped with the improved electric drills by the end of 2007. Consequently it took a total of eleven years from the decision to investigate the use of electric drills until the use thereof [56].

The true impact on the electrical power reduction due to the use of electric drills is not reported in available literature. Information available in other literature does however still mention compressed air consumption at the Tau Tona mine after the implementation of the electric drills [9], [40].

Cost comparisons in 2003 showed that the Hilti electric drills were on average 5.5 times more costly to operate than a traditional pneumatic drill [56]. A different feasibility study found that electric rock drills would be between 2.2 and 2.6 times more expensive to operate than pneumatic rock drills. This excludes the capital costs required for the electrical upgrades and equipment [57].

The abovementioned feasibility studies focused on the replacement of pneumatic rock drills with electric drills in existing operations. A study aimed at determining the feasibility of equipping newly developed sections of Anglo Platinum mines with electric rock drills instead of pneumatic rock drills was conducted [25].

The estimated capital costs of equipping a new section with compressors, piping and so forth, is R44 million compared to a capital layout of R21 million for an electric drilling system [25]. Yearly operating costs for pneumatic rock drills would amount to R8.6 million per annum, compared to R30.1 million for the electric drilling system [25].

So, during the first year it would cost R52.6 million to operate the pneumatic system compared to R51.1 million for the electric system. The combined capital and operating costs for an electric drilling system would thus be R1.5 million less than the pneumatic system during the first year of operation. The operating cost of the electric drilling system from the second year onwards would be R21.5 million more per year.

Therefore, it is not cost effective to replace pneumatic rock drills with electric rock drills by using available technologies. Electric rock drilling is a new technology compared to pneumatic rock drills. Further advances in the electric drills are required to reduce the operating costs of electric drills. Drastically reduced operating costs would improve the financial viability of these drills.

Another alternative to pneumatic rock drills is hydropowered rock drills. The use of hydraulic rock drills for mining in South Africa is not a new concept. Studies regarding the use of these rock drills in South Africa were done as far back as 1975 [58].

Most comparisons between pneumatic rock drills and other rock drills (such as electric or hydraulic drills) assume that all mine compressors are installed and operated for the rock drills only. One such an example is a comparative study where it was stated that pneumatic rock drills would consume nine times more electricity than hydropower drills [59].

Most deep-level mining operations make use of other pneumatic equipment. The equipment includes loading boxes, loaders and refuge bays. So, compressed air is required even when rock drills are not in operation. The replacement of pneumatic drills with electric or hydropower drills would then not result in the complete removal of compressor air at these mines.

The results obtained from a case study at Mine 6 were discussed in Section 2.3. An Eskom evening peak saving of 3.05 MW was obtained by means of a surface control valve that was used to reduce the shaft pressure. It was possible to reduce the pressure to 120 kPa because no drilling takes place at this mine during the Eskom evening peak period. Mine management specified a minimum control pressure of 120 kPa to ensure air supply at the refuge bays [45].

However, the loading boxes that form part of the ore-handling system were still operated during this period and required a supply pressure of approximately 450 kPa. The loading boxes would malfunction at a pressure of 120 kPa. The loading boxes at Mine 6 were converted to a hydraulic system. This ensured that the loading boxes could still be operated while the system pressure was reduced to 120 kPa [45].

The savings obtained at Mine 6 were limited to the Eskom evening peak period because no production takes place between 18:00 and 20:00. Compressed air at higher pressures is however still required during the production shifts to operate a wide range of equipment such as rock drills and loaders [45].

Loaders also known as rock shovels, are used at many mines. These loaders are often in operation during the cleaning shifts to clear blasted rock. The entire compressed air system must then be pressurised to ensure sufficient operation of the loaders. Alternatives to these loaders have been developed [12].

A comparison between theoretical calculations and data retrieved from an actual deep-level mine compressed air system revealed that a typical mine compressor will consume 86 kW to deliver compressed air at flow rate of 1 m<sup>3</sup>/h at a pressure of 500 kPa [33]. A flow reduction of 1 m<sup>3</sup>/h at the point of use would therefore result in reduced compressor power consumption of at least 86 kW.

A distance of between two kilometres and six kilometres from the point of supply to the point of use is a common occurrence in mine compressed air systems. It can therefore be expected that a reduction of 1 m<sup>3</sup>/h would result in a reduction of more than 86 kW due to the losses in the compressed air system.

A typical pneumatic loader consumes compressed air at a rate of approximately 1 600 m<sup>3</sup>/h. This relates to an electricity demand of approximately 138 kW on a typical deep-level mine compressed air system. This is comparable to a 15 kW electric motor used to power a newly developed hydraulic counterpart. The hydraulic loader is estimated to cost approximately 40% more than a pneumatic loader [12].

The additional capital cost of the hydraulic loader could be recovered within two years if all other maintenance and infrastructure costs are assumed to be equivalent to the pneumatic loader. Available literature regarding the effectiveness of the hydraulic loader is limited [12]. The introduction of the electric drill to deep-level mining operations proved to be very difficult.

It also took more than eleven years for the development of the electric drill before the drill performance came close to the performance of pneumatic drills. Electric drills also cost more to operate than pneumatic drills even though they use less electricity. Consequently the development of a proven hydraulic loader is expected to take a long time. Possible increased maintenance costs for the hydraulic loader is not available [12].

## 2.6 Fixing leaks

Between 10% and 30% of the compressed air generated on industrial compressed air systems is lost due to leaks in the system [11]. Compressed air leakages that contribute to as much as 65% have been identified in industrial compressed air systems [20]. The complexity of mine compressed air systems combined with the harsh conditions in which they operate, result in a high likelihood of leaks.

As an example, a single leak that was repaired at an old South African mine resulted in a 1 MW decrease in compressor power consumption [63]. The average compressor power consumption for this system used to be approximately 7.5MW prior to the leak repair [63]. The repair of the single leak therefore resulted in a 13% decrease in power consumption. Compressed air leaks at mining operations can mainly be attributed to improper use, poor maintenance, accidental damage and vandalism.

Some mine compressed air systems consume as much as 1 029 MWh of electricity on a typical working weekday [22]. Using a leak factor of 30% implies that compressed air leaks can account for as much as 309 MWh of electricity consumption per day in one mine compressed air system. Leak management and repair could therefore realise substantial electricity cost savings. The costs and availability of replacement parts and labour together with the production losses due to system downtime can make it uneconomical and unpractical to fix leaks.

Two extremes of leaks can be considered by comparing the compressor power consumption of a single 10 mm leak with the compressor power consumption of a 200 mm open ended pipe. The theoretical power consumption due to a 10 mm leak with rough edges is 19 kW (refer to appendix A for the calculation). A single 10mm leak would account for 456kWh electricity consumption per day. This is only 0.05% of the average daily electricity consumption of a compressed air system that consumes 1 029 MWh per weekday. The effect of one 10 mm leak is thus negligible in such a large mine compressed air system.

The theoretical compressor power consumption due to a single 200 mm open ended compressed air pipe is 11.5 MW (refer to appendix A for the calculation). Such a leak would account for 277MWh electricity consumption per day. A single 200mm open ended pipe would therefore contribute to 27% of the total power consumption of a system that consumes 1 029 MWh per day.

A leak factor of 30% on a compressed air system with a daily electricity consumption of 1 029 MWh implies that a multitude of air leaks with varying sizes are spread throughout the system. A compressed air leak management programme that prioritises leak repairs according to their size and ease of repair is required to make it financially feasible to do repair leaks.

Visits to underground mining levels revealed that workers in the hot working areas often use open-ended compressed air pipes for ventilation and cooling. This cooling technique is often employed when other ventilation and cooling systems are inadequate. It is possible that the costs associated with the installation of alternative cooling equipment is much more than the electricity cost associated with the open-ended blowing from compressed air pipes. It has been shown that timer-based control valves can be used to reduce compressed air wastage when workers are not present [14], [47].

## 2.7 Conclusion

The findings indicated that most of the energy saving measures on compressed air systems focuses only on specific techniques. None of the projects used an integrated approach to consider the entire compressed air system. A summary of the focus areas for the projects investigated is shown in Table 2. The green blocks indicate that a specific measure was implemented at the mine.

## Existing energy saving measures

*Table 2 – Summary of energy saving measures implemented at South African mines*

Name	Energy efficiency measures						
	Efficient compressor selection	Compressor control	Surface distribution control	Underground distribution control	Replace pneumatic equipment	Reduced system pressure	Leak management
Mine 1					Limited		
Mine 2							
Mine 3				Limited			
Mine 4							
Mine 5							
Mine 6					Limited		
Mine 7							
Mine 8							
Mine 9				Limited			
Mine 10							
Mine 11						Limited	Limited

The aim of this study is to obtain a strategy that integrates all aspects of a compressed air system. A new integrated approach will be discussed in the next chapter.