

Integrating various energy saving initiatives on compressed air systems of typical South African gold mines

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Abstract

Electrical energy is commonly used in households and in industry – demand continues to rise due to economic and population growth. This requires that energy suppliers must increase their supply capacity. The result is that end-user energy costs continue to increase, therefore a growing need exists to reduce electrical energy demand in South Africa and internationally.

Households account for the majority of electrical energy customers, but they only consume a fraction of the total energy supplied. The industrial sector and mines combined consume approximately 42% of the total electrical energy produced. Approximately 10% of this energy goes into compressed air production.

This study focuses on methods of reducing the requirement of compressed air in industry so that the demand for electrical energy can be reduced. Many studies have focused on specific methods of reducing energy usage associated with compressed air production. These methods are categorised into methods of reducing compressed air requirements and methods of increasing compressed air supply efficiency.

This study aims to combine these efforts into a single optimised solution. Although this study includes industry in general, the central focus is on the South African mining industry. Two different mining sites are considered and analysed as case studies. Methods of reducing energy required to produce compressed air were applied to each case study. Case Study 1 only allowed limited control of the compressed air system. In Case Study 2 integrated control was realised. Energy usage of compressors was reduced by 18.9% and 42.9% respectively.

Results show that system savings can be doubled by combining different methods of reducing energy usage of compressed air. This, however, requires continuous monitoring and control of the air network at each section supplied with compressed air.

The study is limited to achieving savings by changing the air system. Additional savings can be achieved by training personnel, altering schedules of production activities and implementing a system designed to locate air leaks.

Keywords: Compressed air, air network optimisation, demand-side management (DSM), energy savings, mine compressed air.

Samevatting

Elektriese energie word algemeen in huishoudings, asook in die industriële sektore gebruik. Energieverbruikers neem daagliks toe. Dit veroorsaak dat energieverkaffers hul kapasiteit moet vergroot. Die gevolg hiervan is dat energiekostes aanhou om toe te neem en energieverbruikers hul verbruik moet verminder om sodoende kostes te verlaag.

Huishoudelike verbruikers beslaan die grootste deel van energieverbruikers, maar gebruik slegs 'n fraksie van die totale gegenereerde energie. Gekombineerd gebruik die industriële sektor en myne ongeveer 42% van die totale gegenereerde energie. Ongeveer 10% van hierdie energie word gebruik om druklug te verskaf.

Hierdie studie fokus op metodes om die verbruik van druklug in die industrie te verminder om sodoende die verbruik van elektriese energie te verminder. 'n Aantal studies het reeds fokus geplaas op die metodes om energieverbruik, wat spesifiek verband hou met die vervaardiging van druklug, te verminder. Hierdie metodes kan gekategoriseer word as: metodes wat die verbruik van druklug verminder; of metodes wat die produksie van druklug meer effektief maak.

Die studie beoog om hierdie metodes te kombineer om sodoende 'n geoptimaliseerde oplossing te bied. Alhoewel hierdie studie industrie in die algemeen insluit, fokus dit op die Suid-Afrikaanse mynindustrie. Twee myne word gebruik as gevallestudies. Metodes om die energieverbruik geassosieer met die verskaffing van druklug te verminder word toegepas op elke gevallestudie. Gevallestudie 1 het slegs toegelaat dat beperkte beheer op die druklugstelsel toegepas kon word. In Gevallestudie 2 was totale geïntegreerde beheer toegepas. Energieverbruik van kompressors was onderskeidelik verminder met 18.9% en 42.9%.

Resultate wys dat die besparing verdubbel kan word deur die energieverbruik van druklugstelsels te verminder deur verskillende metodes toe te pas. Dit vereis egter dat elke gedeelte van die druklugstelsel deurlopend gemonitor, en beheer kan word.

Die studie word ingeperk deurdat besparings slegs verkry kan word deur die aanpassing van die druklugstelsel. Verdere besparings kan verkry word deur personeel op te lei, produksie aktiwiteits skedules te verander, en 'n sisteem in plek te sit wat luglekke uitwys.

Sleutel woorde: Druklug, lugnetwerk optimisering, DSM, energiebesparings, druklug op myne.

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List of Units

Symbol	Unit	Description
#	N/A	Denotes a mining shaft, i.e. 3# refers to the Number 3 shaft
\$	Dollar	American currency
A	Ampere	Electric current
c	Cents	South African currency
G	Giga	Denotes 1×10^9
h	Hour	Measure of time. 1h = 60s
J	Joule	Measure of energy
K	Kelvin	Measure of absolute temperature
k	Kilo	Denotes 1×10^3
kg	Kilogram	Measure of weight
M	Mega	Denotes 1×10^6
m	Metre	Metric unit for distance
mm	Millimetre	Measure of distance (1×10^{-3} m)
N	Newton	Measure of force
Pa	Pascal	Measurement for pressure
s	Second	Measure of time
V	Volt	Electric potential difference
W	Watt	Power

List of Symbols

Symbol	Description	Unit
\dot{V}	Volume flow rate	m^3/s
\dot{m}	Mass flow	kg/s
D	Diameter	m
d	Diameter	m
e	Pipe roughness	m
f	Friction factor	none
g	Gravitational acceleration	Taken as $9.81 \text{ m}/\text{s}^2$
h	Head or Height	m
I	Electric current	A
k	Specific heat ratio	none
L	Length	m
M	Mach number	none
n	Polytropic exponent	none
P	Power or Pressure	W or Pa
R	Gas constant	$\text{kJ}/\text{kg}\cdot\text{K}$
Re	Reynolds number	none
S	Stroke length	m
T	Temperature or Time period	K or h or s
t	Time	h or s
v	Velocity	m/s
V	Volume or Electric potential difference	m^3 or V
W	Power	W
μ	Viscosity	Ns/m^2
π	Pi	none
ρ	Density	kg/m^3
σ	Angle	Degrees or Radians
η	Efficiency	none

List of Abbreviations

Symbol	Breakdown
CALDS	Compressed Air Leakage Documentation System
CV	Control Valve
DME	Department of Minerals and Energy
DSM	Demand-side Management
EE	Energy Efficiency
IGVC	Inlet Guide Vane Control
LG	Local Generation
M&V	Maintenance and Verification
MV	Manual Valve
PA	Performance Assessment
PG	Pressure Gage
PLC	Programmable Logic Controller
POU	Point of Use
PT	Pressure Transmitter
SCADA	Supervisory Control and Data Acquisition
VSD	Variable Speed Drive
WBS	Work Breakdown Structure

General Terminology

Term	Description
Normalised	<p>In this study <i>normalised</i> conditions refer to standard atmospheric conditions:</p> <ul style="list-style-type: none">• Absolute air pressure: 101.3 kPa• Air temperature: 20 °C (293.15 K) <p>Unless otherwise specified flow rate refers to normalised flow rate.</p>
Compressed Air Pressure	<p>This refers to the gage pressure to which air is compressed. Gage pressure is taken as the difference between the absolute pressure of compressed air and normalised air pressure.</p>
Local Generation	<p>Refers to a type of air network layout. Refer to Figure 1.7.</p>
Point of Use	<p>Refers to a type of air network layout. Refer to Figure 1.7.</p>
Inlet Guide Vane Control	<p>A control philosophy and system where the inlet guide vanes of compressors are opened/closed to reduce airflow through the compressor to enable the compressor to vary the compressed air supply.</p>
Tramming	<p>Transportation of ore by locomotive.</p>
Set Point	<p>A control loop will adjust outputs which affect a certain process variable. The outputs will be adjusted such that the process variable is changed to the set point.</p>

1 Introduction

1.1 Background

South Africa generated 42% of the African continent’s electrical energy in 2007 – rendering it the main producer of electrical energy in Africa [1,2,3]. The country’s electrical energy demand has increased significantly from 2001 to 2007 [4,2,3] as indicated in Figure 1.1.

Figure 1.2 shows that Eskom, the main producer of electrical energy in South Africa [3], has experienced a reduction in reserve electrical energy margins from 25% in 2000 to 6% in 2007 [2,5,3].

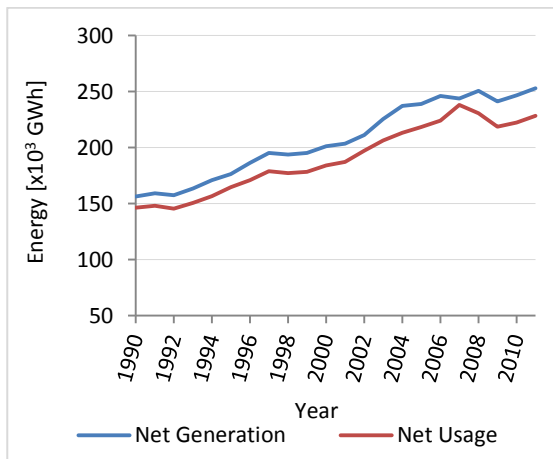


Figure 1.1 – Electrical energy supply and demand of South Africa.

Data courtesy of [2,4].

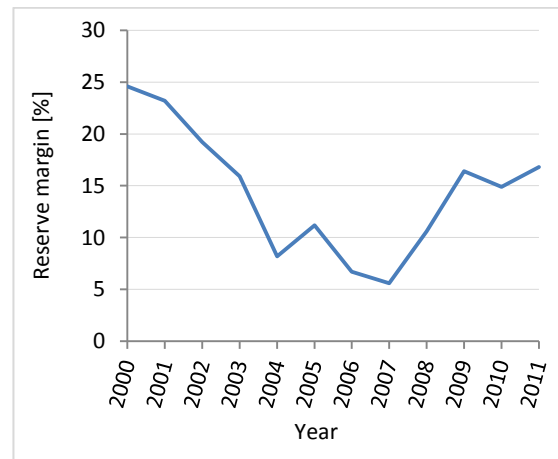


Figure 1.2 – Eskom electrical energy reserve supply.

Data courtesy of [5,4].

During 2007 electrical energy demand could not always be met. As a result Eskom and the Department of Minerals and Energy (DME) released a policy document titled, “National response to South Africa’s electricity shortage” to address this problem [2]. Plans included a R150 billion investment into the generation, transmission and distribution of electrical energy [6] which included the recommissioning of three coal-fired power stations as well as the construction of new plants [2,6]. An additional electrical power supply capacity of 22 GW is expected by 2017 [6].

Due to the huge capital investment required for the additional infrastructure to increase Eskom’s supply capacity, South Africa has experienced major electricity price increases. Figure 1.3 shows the trend of the average price of electricity in South Africa from 2007 to 2011. Further periodical increases are expected [2,1,3]. These price increases place industrial end-users under increasing pressure to reduce electrical energy consumption despite increases in

production output [1]. With the ongoing increase in electrical energy prices the cost saving (per unit reduction in electrical energy consumption) also increases [7].

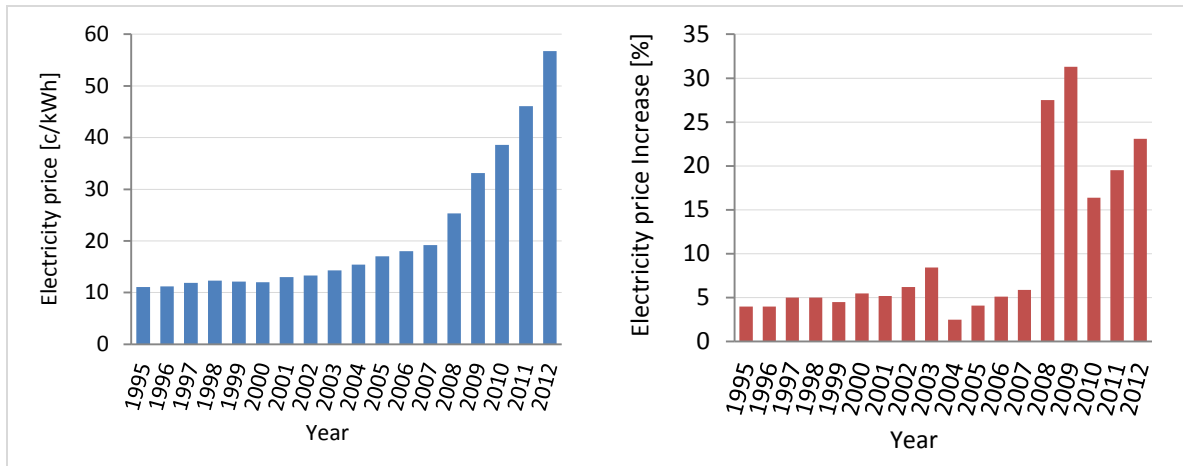


Figure 1.3 – Eskom average electricity price history.
Data courtesy of [8,9,10,11]

In addition to increasing energy supply to meet demands, Eskom and the DME also promote energy saving initiatives, such as demand-side management (DSM). Typical initiatives, such as energy efficiency (EE) improvements, where energy efficient equipment and processes are used to reduce overall electrical energy consumption, [12] are being implemented. EE initiatives are regarded as one of the most cost-effective ways to reduce electrical energy usage [1].

Other DSM initiatives, where the demand for electrical energy is reduced by switching off electrical equipment during certain time intervals [12], has also been found to be effective [4,7]. DSM strategies have been successfully implemented using various different methods [12,4,1].

1.2 Energy usage in industry and the mining environment

Figure 1.4 shows that 14.5% of the electrical energy produced by Eskom in 2010 was consumed by the South African mining industry and 26.6% by the industrial sector [4]. Similar trends have been observed since 1995 [13,3]. Furthermore, it has been seen that the energy cost related to the production of compressed air contributes approximately 10% to the total electrical energy costs [7,14]. This is regarded as a significant amount and has been found to be an international trend [7,15]. Only 25% of these costs are due to initial investment and maintenance while the remaining 75% is attributed to electrical energy costs [7].

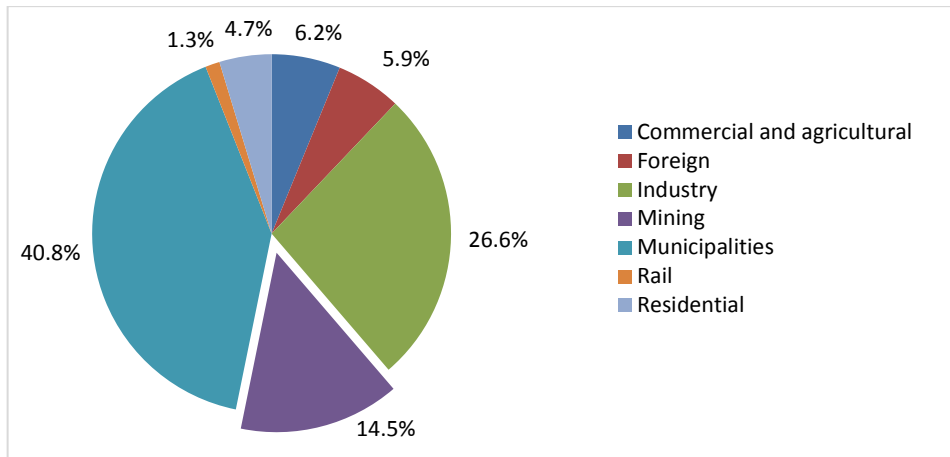


Figure 1.4 – Eskom electricity sales for year ended 31 March 2011.
Courtesy of [4].

1.3 Compressed air usage in industry

Figure 1.5 shows a typical compressed air network. Compressed air networks are relatively easy to install and can easily be expanded. This is one of the reasons why compressed air is widely used in industry for a vast range of production activities, including mining [2,7].

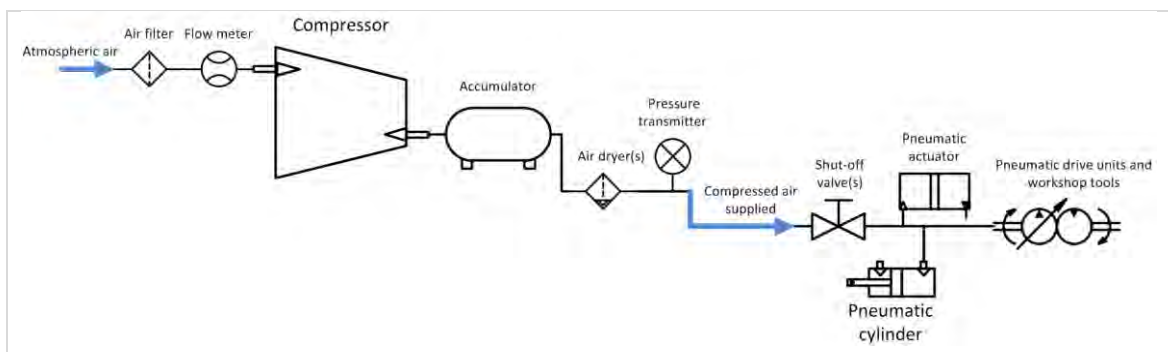


Figure 1.5 – Typical compressed air network.

Compressed air is regarded as the fourth-most widely used utility and, as indicated in Figure 1.6, the most expensive to produce [16,7]. Despite the high cost involved in producing compressed air, many industrial facilities do not analyse these costs. By analysing these costs small changes can be identified that, once implemented, could reduce the amount of electrical energy required to produce a unit of compressed air [7]. Methods for reducing electrical energy required to produce compressed air will be discussed in the following section.

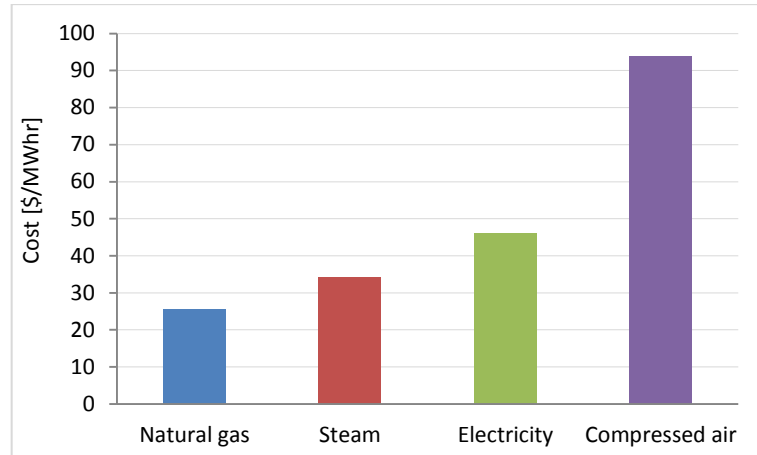


Figure 1.6 – Cost of energy delivery methods.
Courtesy of [16].

1.4 Present methods of reducing energy required to produce compressed air

Studies have shown that the electrical energy demand of compressors can, and have been reduced by implementing energy saving initiatives under one of two main categories. In the first category compressed air demand is reduced; in the second supply efficiency is increased. Studies have shown that improvements to compressed air systems could result in electrical energy savings of 25 – 50% [17].

1.4.1 Reducing compressed air demand

In this study compressed air consumption is divided into three categories:

1. Authorised equipment use.
2. Unauthorised equipment use.
3. Air leaks.

The first category refers to compressed air usage as a result of authorised use of equipment during production activities. The second category refers to compressed air usage due to unauthorised use of equipment. The final contributor to compressed air usage is air leaks. This air consumption is not related to any production activity or equipment use and is regarded as a complete waste of compressed air.

1.4.1.1 Reducing compressed air demand of authorised equipment use

The compressed airflow requirement will be considerably reduced by replacing pneumatic equipment with alternative nonpneumatic equipment. This presents the opportunity to completely shut down air supply to not only a certain section, but possibly an entire factory or plant. Before this study commenced pneumatic rock drills were replaced by hydro-powered rock drills at the same site considered in Case Study 1. According to personnel this reduced the compressed air requirement of the shaft section by 80 – 90%.

Most manufacturing processes – making use of compressed air – have one critical component requiring a certain minimum pressure which is greater than other components operating of the same compressed air network. This pressure will determine the minimum air pressure that has to be supplied by compressors to the entire air network. Studies show that by reducing the critical end-user pressure requirements, compressed air usage of end-users and air leaks are lowered [18,19,7]. The overall pressure requirement of compressed air can also be reduced by replacing pneumatic equipment.

1.4.1.2 Reducing unauthorised equipment use

In some industrial plants certain production activities are limited by a specific time schedule during which they should be conducted. The study [20] shows that by forcing personnel to keep to this time schedule, energy costs associated with compressed air generation can be reduced. This was done by implementing the use of valves set on timers to restrict compressed air supply during certain time intervals. This method of reducing compressed air demand during specific time periods is especially effective in countries such as South Africa where electrical energy cost is dependent on the time at which the energy was consumed [20,21].

1.4.1.3 Reducing compressed air demand of air leaks

Unwanted air leaks result in compressed air being wasted and can also result in significant air pressure losses downstream of the leak [17,22]. This affects production and results in an increase of compressor energy and maintenance requirements. Research shows that by performing regular inspections and maintenance on piping networks air loss through leaks are minimised and compressed air demand is kept to a minimum [23]. Two case studies showed a reduction in power consumption of 14% and 20% respectively after major air leaks have been repaired [20,23].

1.4.2 Increasing the efficiency of compressed air supply

Two of the major factors that contribute to the cost of producing compressed air are the type of compressor control and compressor sizing [7]. Inefficient and oversized compressors were found to have the highest annual operating cost per unit compressed air produced [24,7,25]. For this reason EE projects have been implemented on compressed air networks in order to reduce costs.

Improvements include coordinating and synchronising supply with demand by correctly sizing compressors and switching off compressors when demand is reduced. Other methods include: reducing average air inlet temperature to the compressor; using high-efficiency motors; and using an aftercooler [7,26].

1.4.2.1 Optimising the air network

Three common layouts for compressed air networks are shown in Figure 1.7. A plant air layout is not considered optimal for large air networks due to its typical low efficiency of 60%, and its infrastructure complexity that increases with larger networks [16]. The low efficiency is due to the large pressure losses associated with the long distance over which the compressed air must travel to reach the end-user. For small networks with pipe lengths of less than 100 m, friction losses are less important than for the large piping networks of more than one kilometre in length.

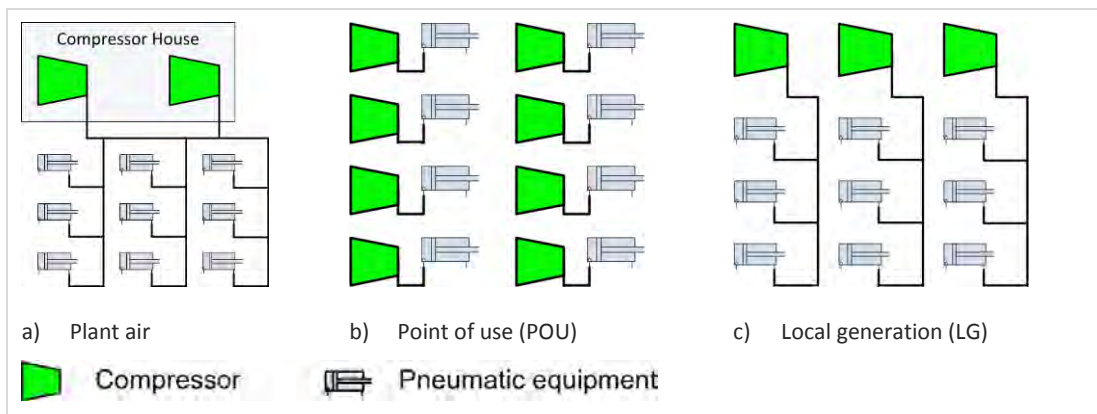


Figure 1.7 – Common compressed air network layouts.

Courtesy of [16].

As indicated in Figure 1.8, research shows that maximum energy usage could be reduced by as much as 45% by selecting the correct compressed air network layout for a specific plant.

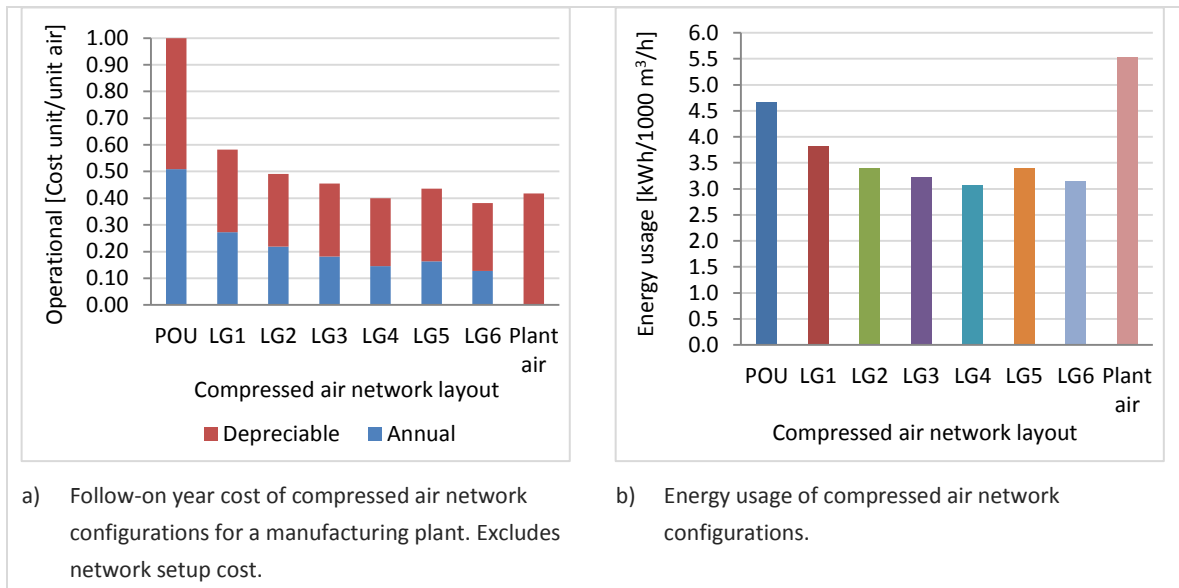


Figure 1.8 – Energy usage and cost of compressed air network configurations for a manufacturing plant.

Courtesy of [16].

Components, such as air dryers and filters, are commonly used in air networks to ensure that clean compressed air is supplied [27]. This increases the pressure loss between the supply source and the end-user. Studies have shown that by ensuring these components are clean, properly maintained and installed at the correct location, pressure losses can be minimised [26,27].

1.4.2.2 Optimising air compression

Air compressors can be optimised by implementing specially designed control systems, such as Ingersoll Rands’ Air System Controller [28], which includes performance management. Optimised maximum cut-off pressure control of compressors has also proved to increase efficiency [25].

It has also been found that by implementing inlet guide vane control (IGVC), which allows compressor output to be varied, the energy requirement of compressors has been reduced [29].

The compressed air process can also be made more efficient by reducing compressor inlet air temperatures and using intercoolers between compression stages. For every 3 °C reduction in inlet air temperature an estimated electrical energy saving of 1% can be realised [7].

1.4.2.3 Optimising electrical motors driving compressors

Studies show that by using high-efficiency electrical motors to drive compressors a saving of 2 – 8% can be realised [7,15]. Many compressed air systems are designed to operate at full-load conditions, although system demand does not always require these conditions [7].

By making use of a variable speed drive (VSD) the speed of an electric motor can be regulated to match actual load conditions [7,30,31] which will reduce energy consumption of the relevant motor. The benefit of using a VSD to regulate the motor speed increases with an increase in the motor's rating, however costs also increase. For large motors (more than one megawatt) this cost renders the use of VSDs unfeasible.

1.5 Objectives and problem statement

With the ongoing increase in electrical energy prices it becomes essential for end-users to reduce their energy demand. This not only applies to domestic households, but is vital for the survival of industrial, manufacturing and mining institutions.

The objective of this study is to investigate and combine methods for reducing electrical energy usage by improving on, and optimising the use of compressed air. The study will focus on the mining industry where large compressed air networks, consisting of several kilometres of piping, are installed. The aim is to provide a solution where existing methods are combined into a single integrated cost-saving solution.

1.6 Overview of this document

In Chapter 1 an overview of energy usage in industrial sectors is shown. Studies have shown that 14.5% of overall electrical energy produced is consumed by the mining sector. Furthermore, 10% of this energy is consumed by air compressors. Several methods of reducing compressed air usage in general have also been reviewed.

The study will continue in Chapter 2 by investigating compressed air usage in the mining environment and estimating related electrical energy costs. Methods for reducing compressed air usage in the mining environment will be further investigated and proposed in Section 2.4. Electrical energy savings obtained by the proposed methods are then approximated in Section 2.5.

In Chapter 3 and Chapter 4 a selection of proposed compressed air saving methods is applied to two case studies. The study is concluded in Chapter 5 by briefly reviewing the proposed solutions, results, applications in industrial sectors, limits of this study and presenting recommendations for future studies.

2 Developing an integrated solution

2.1 Introduction

In order to develop an integrated solution, parameters affecting the electrical power requirement of a compressed air system must first be identified and their effect on the system determined. The parameters include: the system compressed air demand; and the efficiency at which compressed air is delivered. These parameters are in turn determined by additional secondary parameters which will be analysed further in this chapter.

After quantifying the effects of these secondary parameters, methods to reduce electrical power requirements of a typical mine compressed air network are proposed. These methods are analysed further to estimate and quantify their respective effects on the electrical power requirement of an air network. Some of the proposed methods have been implemented in case studies which are discussed in Chapter 3 and Chapter 4.

2.2 Calculating compressed air usage

Compressed air is used by a wide variety of equipment during the production process of a mine. Typical mining activities conducted in the case studies are listed in Table 2.1.

Table 2.1 – Typical mining activities conducted in the case studies.

Activity	Description	Equipment	Air Requirement	
			Pressure	Flow
Agitation	Agitation of water dams and agitated tank leaching	Agitation tanks – open-ended pipes	Medium (200 – 300 kPa)	High
Drilling	Drilling for development and obtaining ore	Mining drills	High (>350 kPa)	High
General Maintenance	Workshop air	Small air nozzles	Medium (250 kPa)	Low
Hoisting	Hoisting ore from shaft bottom to surface	Actuators	High (>350 kPa)	Low
Loading	Loading ore into loading boxes	Actuators	High (>350 kPa)	Low
Refuge Bays	Positive pressure required in refuge bays	Open-end pipe	Low (150 – 200 kPa)	High
Sweeping (Cleaning)	Cleaning of mining and development areas	Brooms and air/water nozzles	Medium (250 kPa)	High
Tramming	Transferring ore by locomotive to loading boxes	Actuators	High (>350 kPa)	Low

2.2.1 Pneumatic equipment

Pneumatic equipment used on the mines mainly includes cylinders, valve actuators, loaders and rock drills. Figure 2.1 illustrates a typical pneumatic cylinder setup and operations where these cylinders are used.

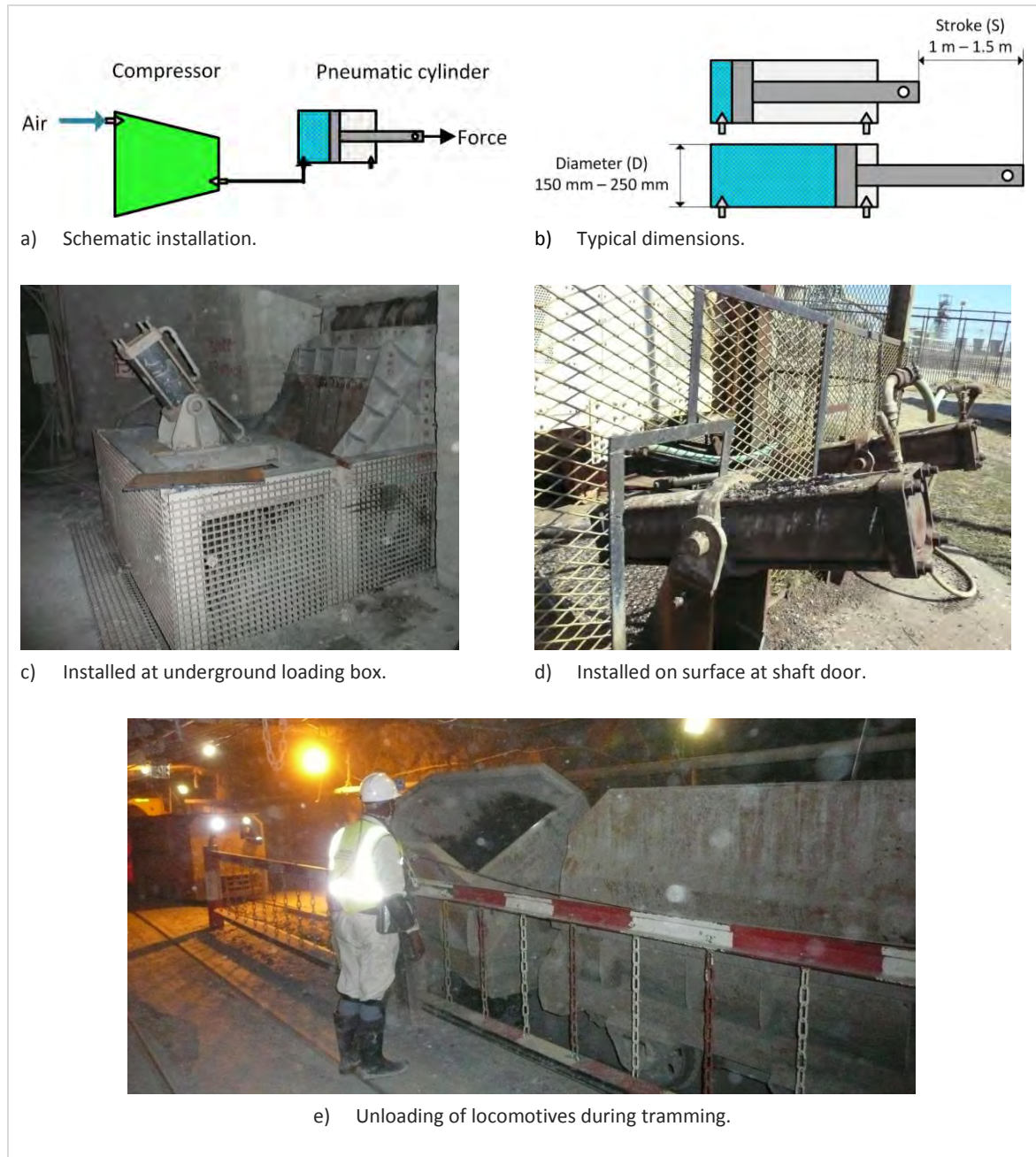


Figure 2.1 – Typical pneumatic cylinder operations in the mining environment.

Pneumatic cylinders are used to operate loading boxes during loading and tramping operations. Each of these cylinders requires a medium- to high air pressure of 350 – 600 kPa at a low compressed airflow rate of 2 – 50 m³/h, depending on the size and the operation time.

Valve actuators, which are also considered a type of pneumatic actuator and are shown in Figure 2.2, are utilised to open and close control valves.

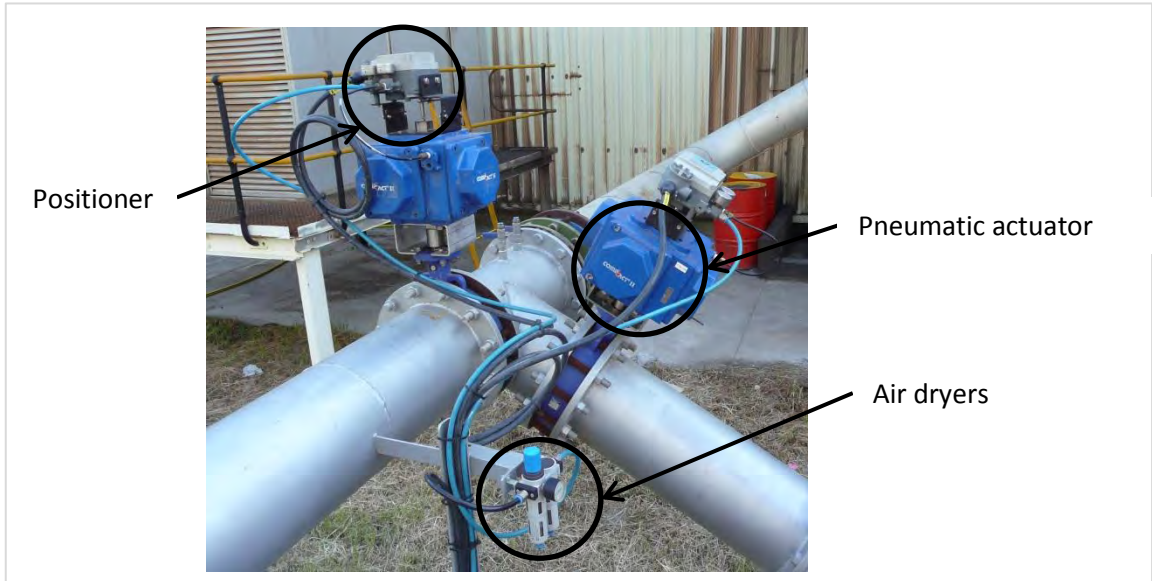


Figure 2.2 – Typical pneumatic valve actuator setup.

Figure 2.3 shows the ideal theoretical compressed air consumption required for various pneumatic cylinder sizes. Calculations are based on a stroke of one meter and a five-second stroke duration. Detailed calculations are shown in Appendix A.1.1.

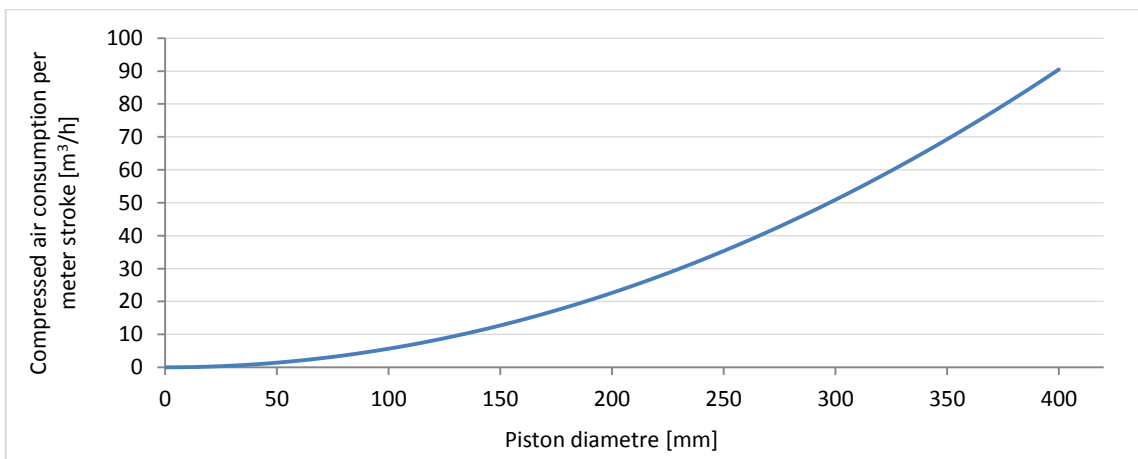


Figure 2.3 – Air consumption of a pneumatic cylinder.

Typical industrial centrifugal compressors installed on South African mines produce compressed air at 500 – 600 kPa, at a normalised flow rate of 10 000 – 60 000 m³/h while consuming 1 – 6 MW. This data was obtained directly from the mines during the case studies.

The air requirements for pneumatic cylinder operation are relatively small when compared to the actual airflow and pressure supplied by industrial compressors. This means that the energy requirement to operate the pneumatic cylinders is also much less than the energy consumed

by the compressors. Although pneumatic cylinders consume a relatively small amount of energy, the energy requirement costs of pneumatic cylinders are determined by the resources required to produce this minimum pressure at the installed location of the pneumatic cylinders.

Thus, the total cost of pneumatic cylinders must include energy consumed to provide compressed air to the cylinder(s). As shown in Figure 2.7 to Figure 2.9 large compressed air networks, consisting of several kilometres of piping, experience large pressure losses from the supply source to the end-user. These pressure losses are due to pipe wall friction and air leaks and result in greater costs to provide the correct air pressure to the end-user.

Typical loaders, shown in Figure 2.4, used during loading operations require compressed air of 450 – 860 kPa at an airflow of 420 – 1080 m³/h or 0.74 – 3.31 kg/s. Each loading cycle takes about 6 – 7 seconds [32]. In the case studies considered the loaders were able to operate effectively at a minimum pressure of 450 kPa. As with pneumatic cylinders, the cost related to produce adequate compressed air for loaders must include costs due to air network losses from the point of supply to the end-user.



Figure 2.4 – Pneumatic loaders used underground.

A typical rock drill (shown in Figure 2.5) requires compressed air at 350 – 600 kPa at a flow rate of 160 – 400 m³/h or 0.23 – 0.89 kg/s [33,34]. Mining personnel reported that compressed air at a pressure of 400 kPa proved to be sufficient for drilling purposes.



Figure 2.5 – Typical hand-held rock drill.

During cleaning shifts air is used for sweeping and loading operations. Sweeping operations require 50 mm open-ended hoses while pneumatic cylinders are utilised for loading operations. Figure 2.6 shows the expected airflow rate through a 50 mm open-ended nozzle as a function of initial compressed air pressure.

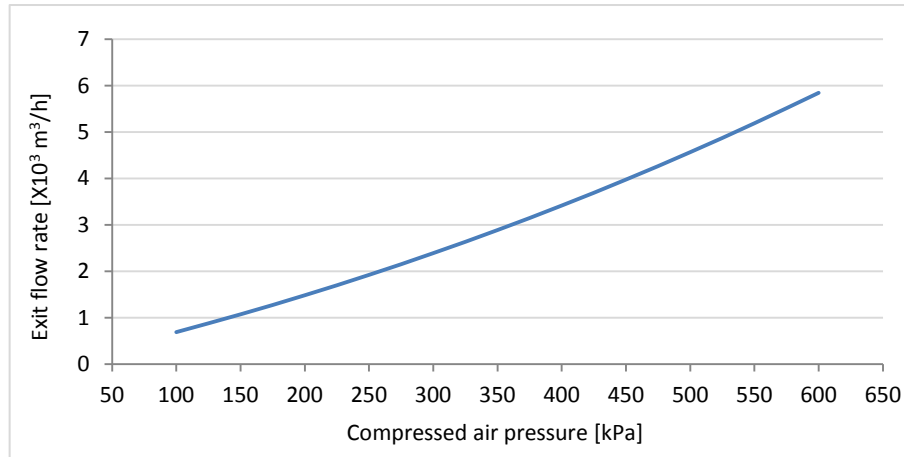


Figure 2.6 – Flow through a diameter 50 mm nozzle.

2.2.2 Compressed air distribution system

Mine compressed air networks usually comprise an extensive and intricate pipe network consisting of several kilometres of piping – both on surface and underground. On typical mines each underground mining level is supplied with compressed air. Pipe diameters used on compressed air networks varies from 50 mm (typically for instrumentation air lines), to 500 mm (typically for shaft supply manifolds).

Figure 2.7 to Figure 2.9 show the pressure losses due to pipe wall friction per 100 m of piping as a function of airflow rate. These graphs are based on the Darcy-Weisbach pipe-friction equation and the Colebrook-White friction-factor equation [35]. Refer to Appendix A.1.3 for detailed calculations of pressure losses. As indicated in these figures, pressure losses due to pipe wall friction are strongly dependent on the combination of pipe diameter and volumetric airflow rate.

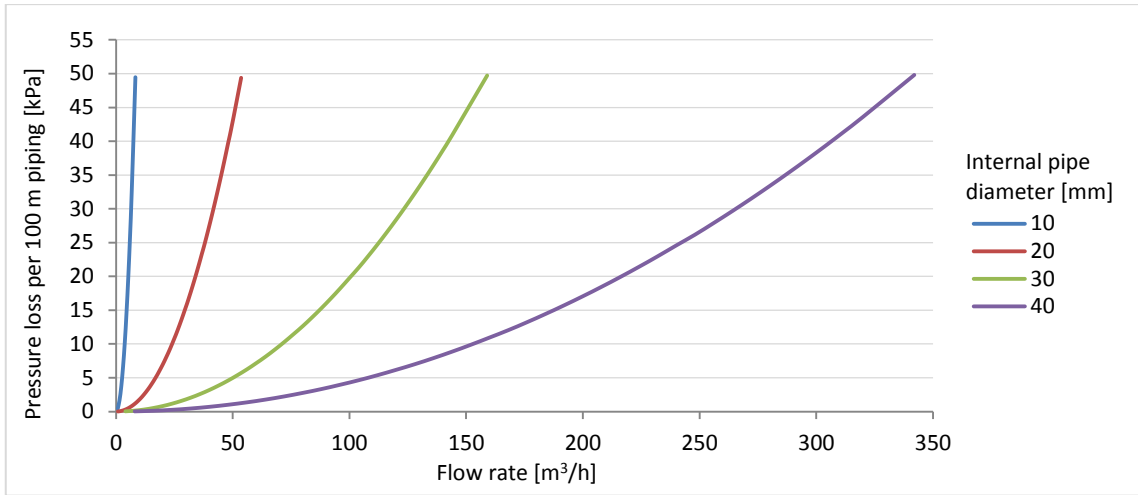


Figure 2.7 – Calculated pressure loss due to pipe friction for air at 600 kPa absolute pressure through pipes with internal diameter 10 – 40 mm.

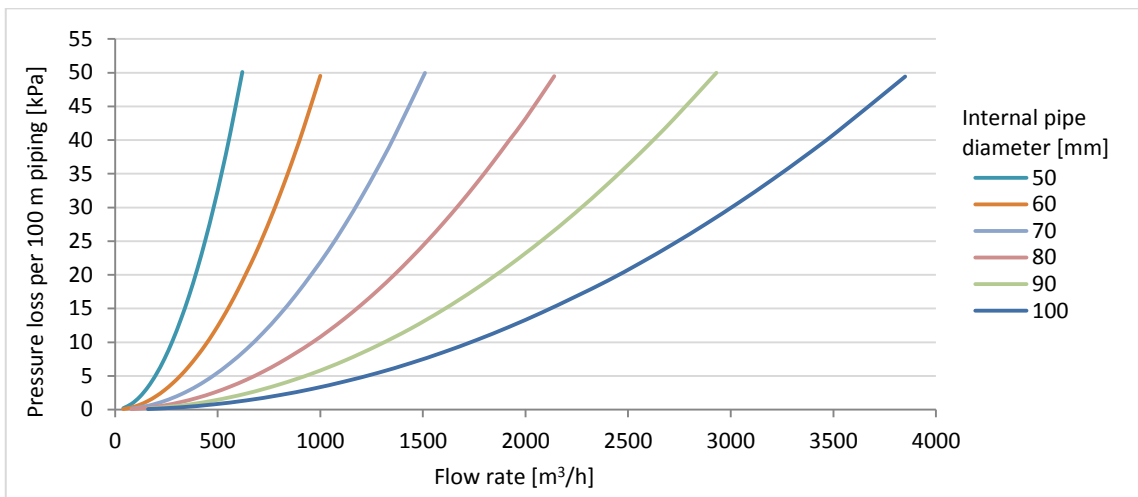


Figure 2.8 – Calculated pressure loss due to pipe friction for air at 600 kPa absolute pressure through pipes with internal diameter 50 – 100 mm.

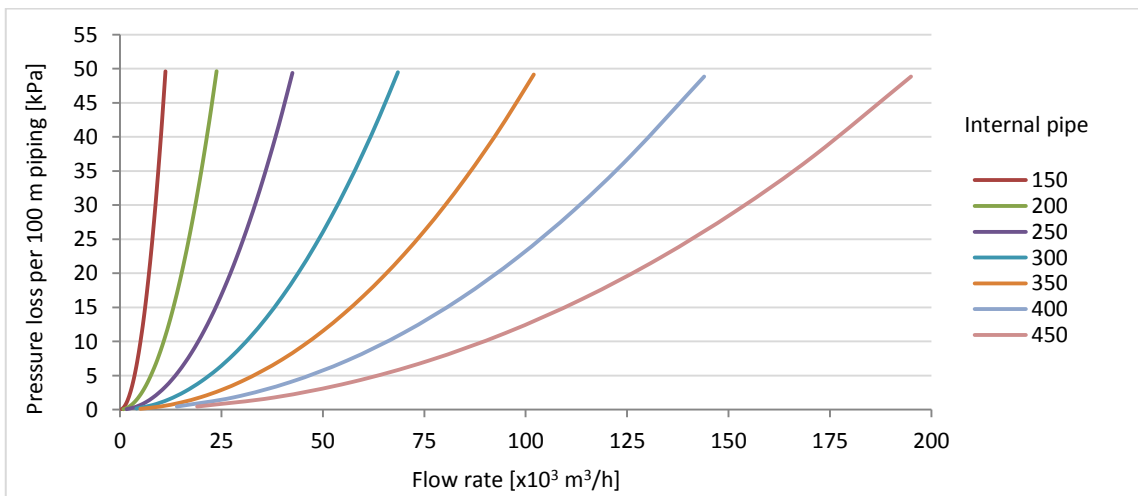


Figure 2.9 – Calculated pressure drop due to pipe friction for air at 600 kPa absolute pressure through pipes with internal diameter 150 – 450 mm.

Figure 2.10 shows that for a given mass flow, pressure loss decreases with an increase in supply pressure. This is due to the fact that to sustain a given mass flow, the volumetric flow rate at compressor outlet is decreased as the delivery pressure (density) is increased. This shows that friction losses are more affected by an increase in fluid velocity than an increase in fluid density which then results in the pressure loss increasing with an increase in flow velocity.

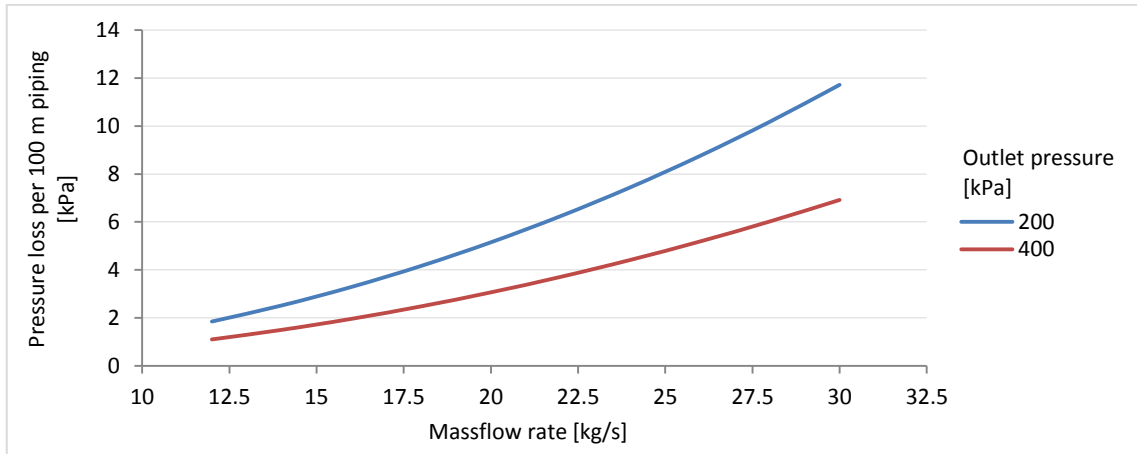


Figure 2.10 – Calculated pressure loss due to pipe friction for airflow through a 500 mm internal diameter pipe.

It must be noted that although the outlet velocity of air decreases with an increase in outlet pressure for a given mass-flow rate, it is impractical to increase the delivery pressure without increasing the delivery flow velocity for large air networks. This is due to the large volumetric capacity of a large air network which is not easily pressurised to a higher pressure. Furthermore, air usage of equipment and loss through air leaks also increase with a higher supply pressure.

Additional friction losses are also caused by the pipe entrance and exit profiles. Sudden contractions or expansions, fittings (bends, elbows, T-sections, etc.), and ‘control objects’ (such as restrictions, valves and nozzles) are also responsible for pressure losses. These friction losses are commonly referred to as ‘minor losses’ [36] although it might become significant when short pipe distribution lengths are encountered. Since piping networks of several kilometres are used in the case studies these minor losses will be neglected

Figure 2.11 shows the pressure loss of air (compressed to 500 kPa) for every 100 m of piping used as a function of pipe roughness where the internal pipe diameter is 450 mm. Maximum airflow through pipes of this size is not expected to exceed 8 000 – 10 000 m³/h according to data obtained from the case studies.

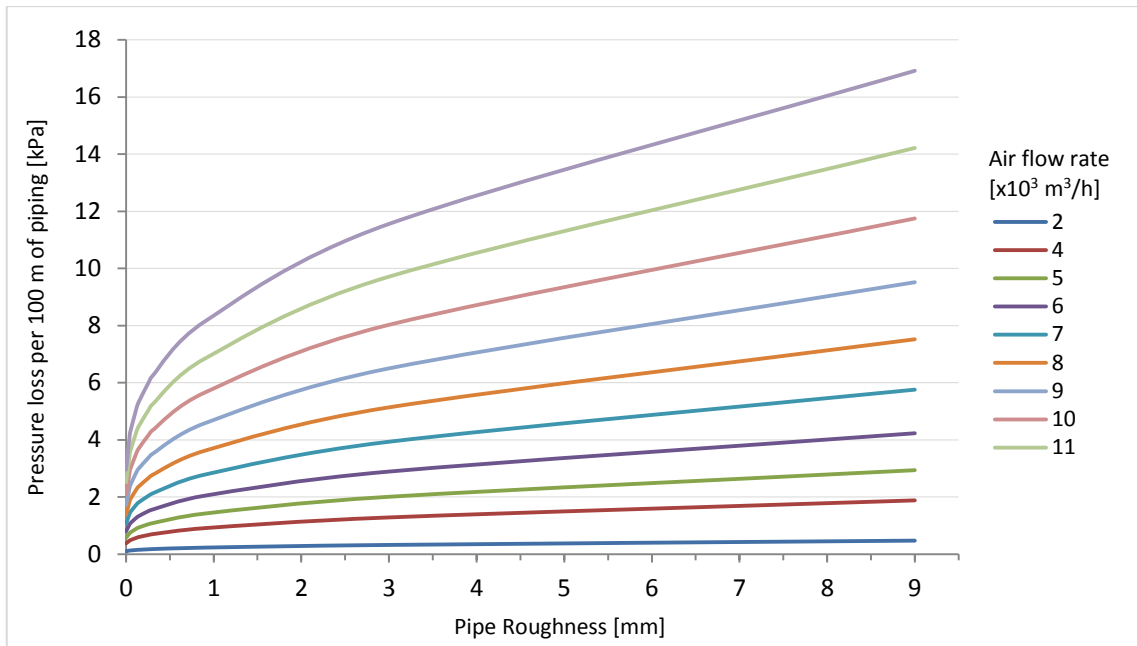


Figure 2.11 – Pressure loss due to friction as a function of pipe roughness for air compressed to 500 kPa.

Pipe roughness increases with usage due to corrosion and encrustations which result in an increase of friction losses over time [35]. The increase in pipe roughness will be disregarded in calculations for this study since, as shown in Figure 2.12, friction loss is not a strong function of pipe roughness for a pipe roughness below 0.3 mm (as found in the case studies).

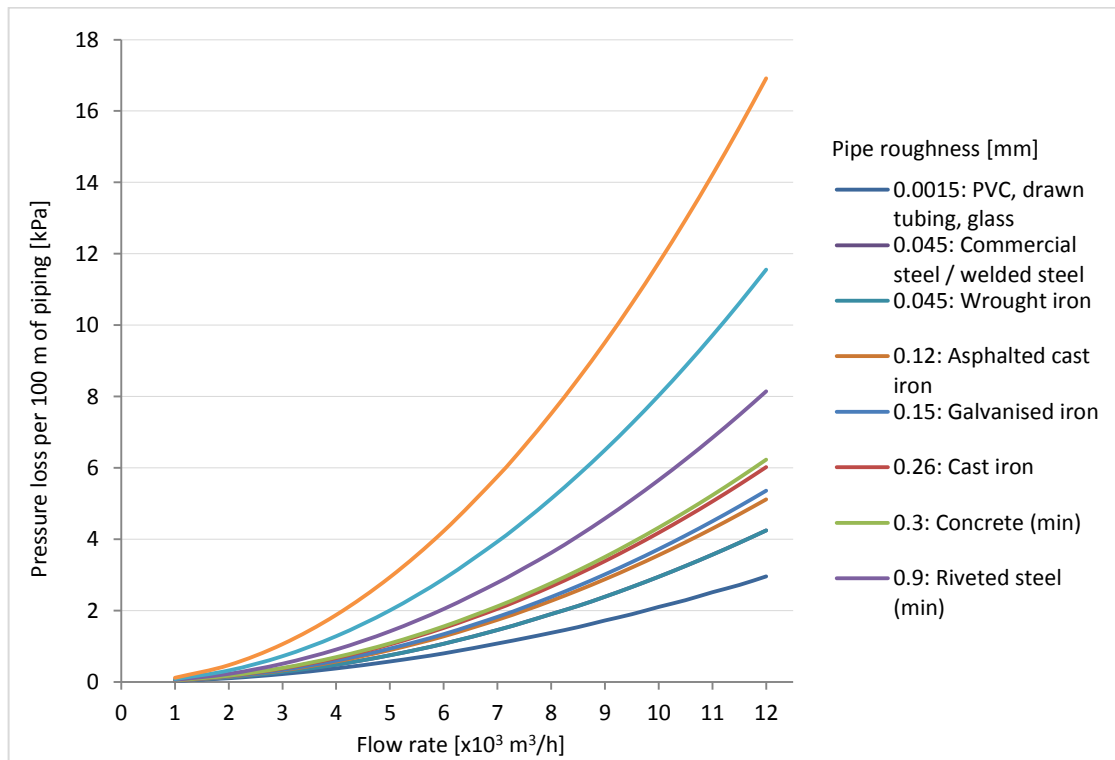


Figure 2.12 – Pressure loss due to friction as a function of pipe flow rate for air compressed at 600kPa absolute pressure.

Due to the harsh underground mining environment pipe networks are often damaged and left unrepaired and/or unmaintained unless the damage is considered to be critical [7]. Examples of damaged pipe can be seen in Figure 2.13 where leaks were left unrepaired, or only partially repaired, and piping unmaintained for long periods extending over several months and even years. As a result air leaks occur on a large scale.



Figure 2.13 – Typical unmaintained piping sections.

Holes in the pipes may be as small as 1 mm^2 , or as large as the diameter of a 250 mm open-ended pipe. Air lost due to air leaks is shown in Figure 2.14 and Figure 2.15. Appendix A.1.4 provides detailed calculations with regard to flow loss through holes of various sizes in the compressed air pipe line.

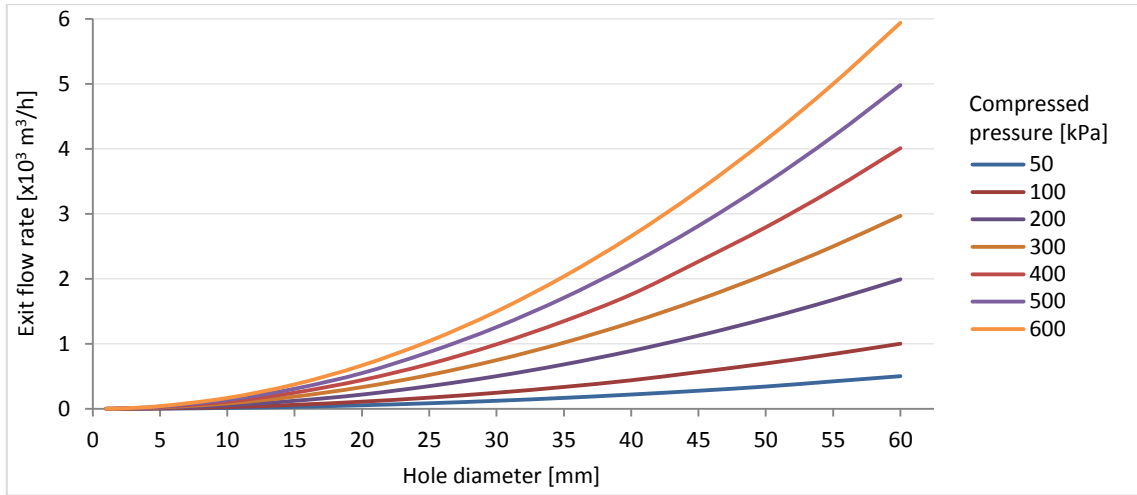


Figure 2.14 – Air losses as a function of hole diameter smaller than 60 mm.

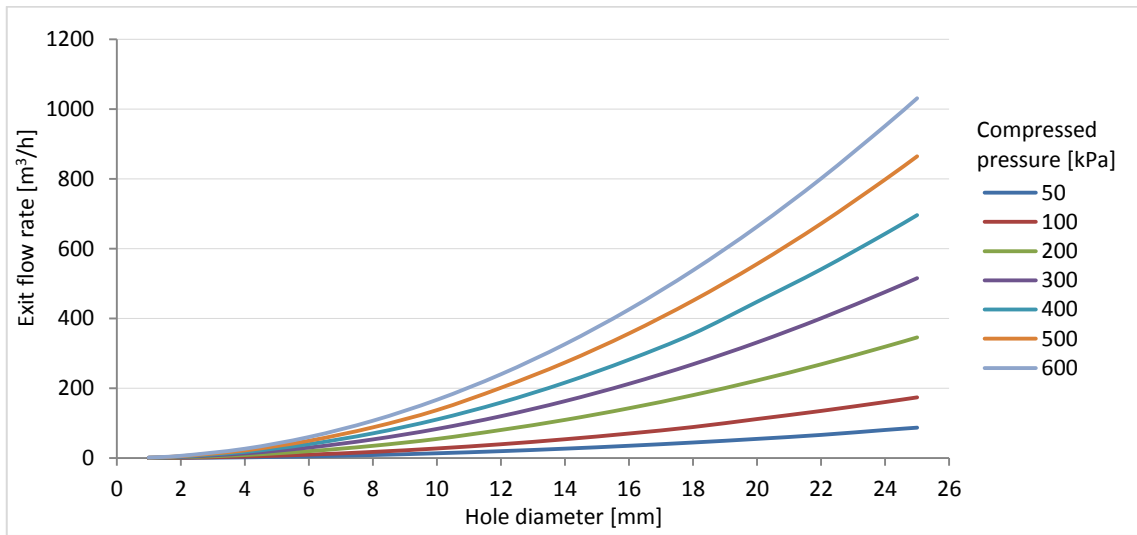


Figure 2.15 – Air losses as a function of hole diameter smaller than 25 mm.

2.3 Electrical power required to produce compressed air

2.3.1 Electrical power consumed by compressors

Approximate electrical power consumed to compress air from standard atmospheric conditions (101.3 kPa, 20°C) is shown in Figure 2.16 and Figure 2.17. Figure 2.16 shows the electrical power requirement as a function of delivery pressure. As expected the power required to produce compressed air increases with delivery pressure and flow rate.

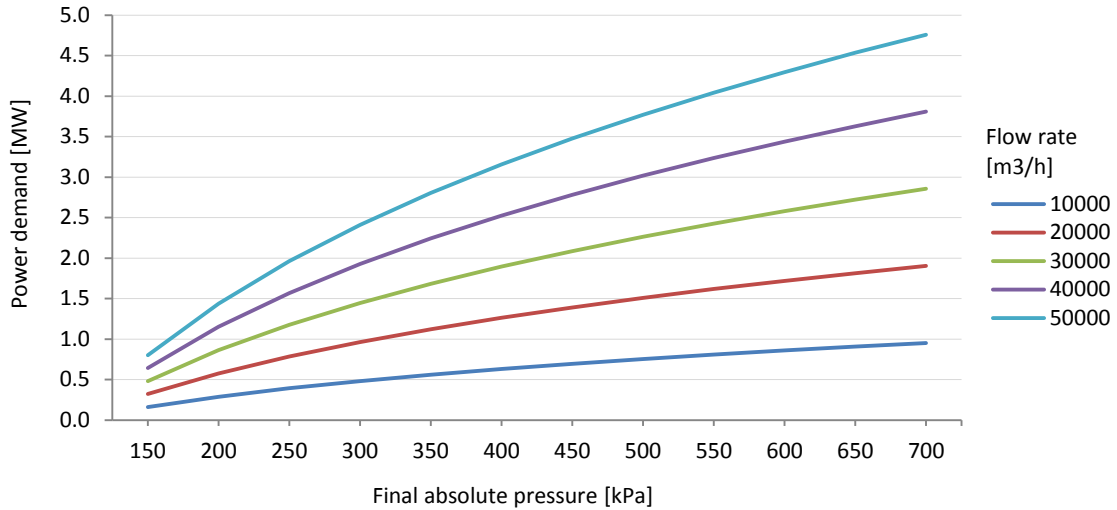


Figure 2.16 – Estimated electrical power required to compress air from atmospheric conditions.

Figure 2.17 shows the expected electrical power requirement for a mass airflow of 3.345 kg/s (10 000 m³/h) along with data obtained from the case studies. As shown, the estimated calculations correspond well with actual values. Refer to Appendix A.1.5 for detailed calculations with regard to estimated power required to produce compressed air.

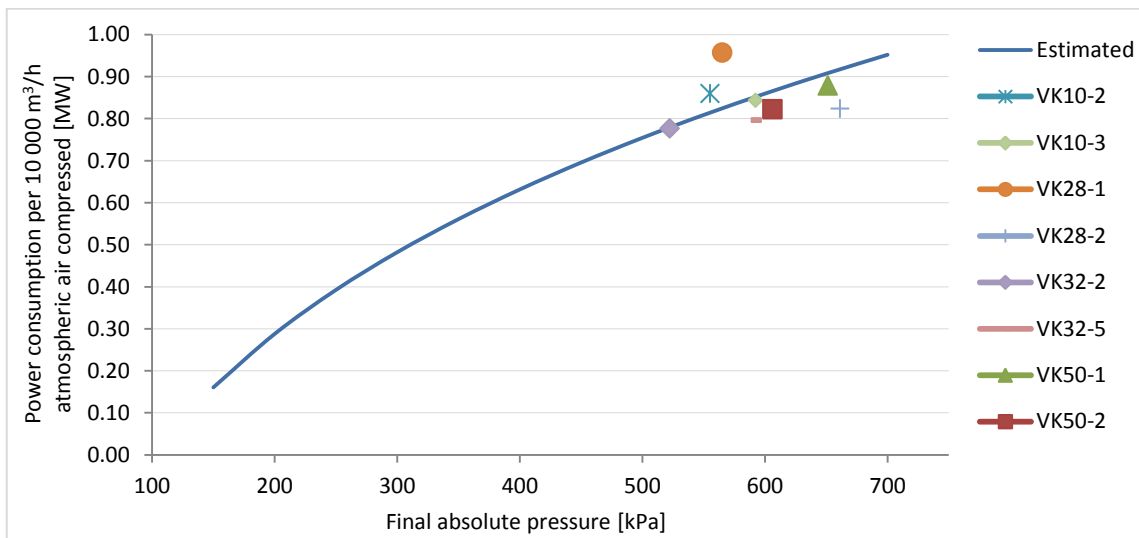


Figure 2.17 – Estimated power required to produce compressed air at 3.34 kg/s compared to actual data.

The calculations assume a compressor efficiency of 80% and an electrical motor efficiency of 90%. This results in an overall compressor efficiency of 72%. The power required to produce compressed air can be reduced by increasing either of these efficiencies by applying the methods discussed in Section 2.4.2.

2.3.2 Electrical power required to supply compressed air for general mining activities and network losses

Table 2.2 shows the estimated electrical power required to supply compressed air for typical mining activities.

Table 2.2 – Estimated power required to supply compressed air for general mining activities and network losses.

Description	Air Usage		Calculated Per		Power Requirement [kW]	Typical Quantity		Total Power Requirement [kW]
	Pressure [kPa]	Flow [m ³ /h]	Unit	QTY		Unit	QTY	
Air leaks	500	180	Per dia 10mm hole/leak	1	13.58	Leaks per mining level	4	54.32
Agitation	300	1500	Per agitator tank	1	72.33	Agitator tank per mining level	1	72.33
Refuge bays	250	300	Refuge bay	1	11.78	Refuge bays per work area	1	11.78
Workshops	500	500	Workshop	1	37.72	Workshops per mining level	2	75.44
Sweeping & cleaning	250	2000	Dia 50mm air hose	1	78.51	Hoses per mining level	2	157.02
Drilling	450	200	Drill	1	13.91	Drills per mining level	15	208.68
Tramming	500	12	150mm Cylinder	1	0.91	Cylinders per mining level	4	3.62
Loading	450	500	Loader	1	34.78	Loaders per mining level	2	69.56
Hoisting	500	12	150mm Cylinder	1	0.91	Cylinders per mining shaft	4	3.62

2.4 Optimising a mine compressed air network

The power required to produce compressed air is mainly dependent on air demand and supply efficiency. Compressed air demand is determined by parameters such as the minimum end-user pressure, mass-flow rate and minimum air network pressure. Supply efficiency is determined by compressor specifications, network length, layout type and piping used.

Methods of reducing energy required for compressed air will be discussed in two categories, namely:

1. Reducing compressed air demand.
2. Increasing compressed air supply efficiency.

2.4.1 Reducing compressed air demand

2.4.1.1 Reducing compressed air demand of authorised equipment use

In the mining industry it is compulsory for refuge bays to be supplied with a positive pressure. However, by replacing pneumatic equipment with nonpneumatic alternatives air usage could be discontinued on certain sections. The extent to which air usage can be reduced depends on the mine layout and site conditions. Typical examples of nonpneumatic methods for production are shown in Table 2.3.

Table 2.3 – Possible replacements for pneumatic equipment.

Pneumatic equipment	Replacements
Cylinders	Hydropower/hydraulic cylinders
Valve actuators	Electrical actuated actuators
Rock drills	Hydro-powered rock drills
Workshop tools	Electrical powered tools

Alternatively, pneumatic equipment should be selected in such a manner that the required air pressure is reduced while still maintaining efficient production operations. As indicated in Figure 2.16 and Figure 2.19, less electrical energy is required when using a lower air pressure. This will result in cost savings for the mine.

Figure 2.16 shows that the compressor power requirement is strongly dependent on the mass-flow rate and pressure at which compressed air is delivered. If the mass flow of air is kept constant and the supply pressure is reduced, the speed of air in the pipeline increases for a given pipe diameter (see Equation A.2). This will result in an increase in pipe-friction losses, especially for large air networks as found on typical South African mines. Thus, a reduction in the pressure required by pneumatic equipment does not necessarily result in the same

reduction in compressor air supply pressure. The optimised pressure set points of compressors must be calculated for each site.

Reducing delivery pressure will also result in reduced losses through air leaks as indicated by Figure 2.14 and Figure 2.15.

2.4.1.2 Reducing unauthorised equipment use

Studies show that, especially in the mining industry, compressed air is commonly used for unauthorised activities. Such activities include cooling of bearings, cooling of rock faces where mining commence, and providing additional air for ventilation. In South African mines open-ended air hoses of 50 mm in diameter are typically used for additional unauthorised ventilation underground [20]. As shown in Figure 2.14 and Figure 2.15, this unauthorised use of compressed air could increase the demand for compressed air significantly.

Unauthorised use of compressed air can be reduced by restricting compressed air supply to the demand of production activities. This includes installation of a control valve on the air line supplying each section. On mines these valves should be installed on each underground level where compressed air is supplied.

Furthermore, it is possible to schedule production activities with similar compressed air requirements together. By doing this compressed air supply quantities can be varied and availability of compressed air for unauthorised use reduced.

2.4.1.3 Reducing air leaks

Due to the large air networks installed on mines, maintenance of these networks is often neglected. This results in air leaks which increases with time. Leaks are typically found on fittings, taps, damaged piping and equipment. Typical leaks vary from 1 mm to 250 mm diameter of an open-ended pipe. As shown in Figure 2.14 and Figure 2.15, the flow rate of air through a single air leak can be significant.

By reducing air leaks the total airflow through the network will be reduced and pressures more easily managed and maintained. This will have the obvious benefit of reduced compressor power consumption. Pressure losses due to pipe friction will also be reduced since these losses are a function of the flow rate through the network.

To further minimise losses due to air leaks all unused pipes should be blanked off as close to the compressor supply point as possible. This will reduce the possibility of leaks through an abandoned, unused and unmaintained pipe. A system should also be in place where leaks are noted and dedicated personnel employed to repair the leaks.

2.4.2 Increasing compressed air supply efficiency

2.4.2.1 Optimising the air network

Typically, mines make use of a 'plant air' or 'local generation' compressed air network layout extending from 1 km to as long as 70 km. For these large networks maintenance requirements increase and the effect of unmaintained piping escalates to all operations [16].

Where site conditions allow for modifications to the air network, it might be beneficial to alter the network layout from one type to another. Whether this will prove to be more efficient is dependent on a detailed site investigation and analysis of the air network.

Figure 2.7 to Figure 2.10 clearly show that pressure losses, due to pipe friction, are strongly dependent on the pipe diameter and airspeed inside the pipe. Pressure losses through the supply network are accommodated by increasing the pressure supplied by compressors. It is important that a mine air network is designed to accommodate the required flow rate while keeping pressure losses to a minimum. This can be done by increasing the diameter of pipes as shown in Figure 2.7 to Figure 2.10.

Where end-user requirements differ, and compressed air cannot be varied, air must be supplied at the maximum end-user pressure demand. This increases compressed air usage and losses through air leaks. By altering the air network layout, to separate the network into separate high- and low-pressure systems, reduced energy consumption can be expected.

2.4.2.2 Optimising air compression

Compressor efficiency can be increased by controlling inlet guide vanes optimally, reducing compressor air inlet temperature and ensuring filters and coolers are regularly monitored and maintained [7].

Additional, and regular maintenance, has been found to improve efficiency of the compression process which includes supply of clean, dry compressed air [19]. This maintenance includes:

1. Regular inspection and cleaning of filters and air dryers [26,37].
2. Proper maintenance of the compressor cooling system and lubricants [7]. This includes pumps, fans and lubricant fluids.
3. Proper and regular maintenance of coolers and heat exchangers.

2.4.2.3 Optimising electrical motors driving compressors

Compressed air demand usually varies significantly between production activities. By implementing VSDs on the electrical motors that drive compressors, electrical energy consumption will be reduced as compressed air demand is reduced [7]. Electrical motors can also be replaced with high-efficiency motors.

2.5 Calculating the energy savings of these initiatives

Energy required to compress air is directly proportional to the overall compression ratio and the mass-flow rate. Thus, by reducing either the final pressure of compressed air, or the mass-flow rate of compressed air, the work required to produce compressed air will be reduced. The expected electrical power saving realised by these initiatives can be determined by using Figure 2.18 and Figure 2.19.

Figure 2.18 shows the estimated reduction in electrical power required to produce compressed air for a reduction of 1 000 m³/h in inlet airflow rate. For example, if air is being compressed from atmospheric conditions to 350 kPa and the airflow rate at the compressor inlet is reduced by 1 000 m³/h, then the compressor’s power consumption will be reduced by an estimated 70 kW.

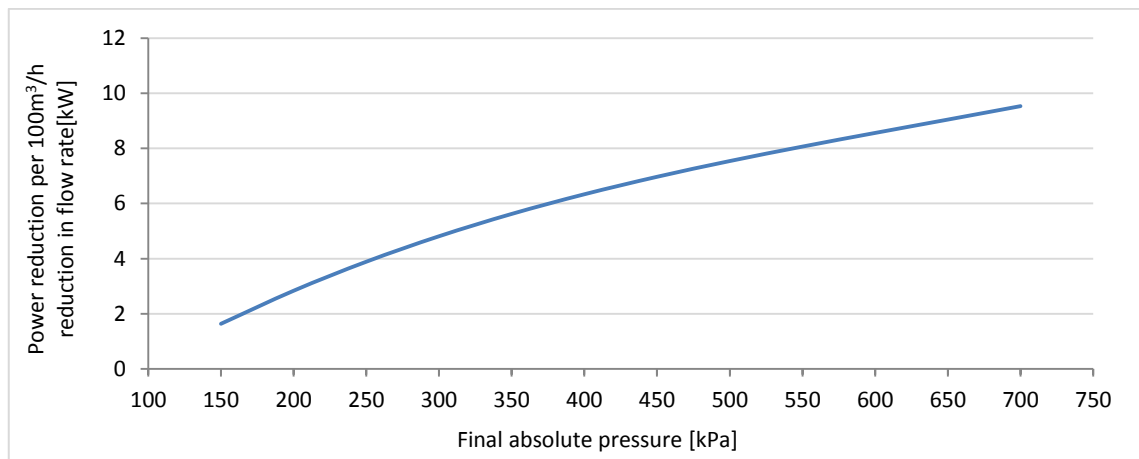


Figure 2.18 – Electrical power saved per 1000 m³/h normalised airflow reduced.

Figure 2.19 shows the estimated reduction in electrical power consumption as a function of reduction in delivery pressure per 10 000 m³/h air compressed. For example, if compressed air is supplied at a flow rate of 10 000 m³/h, and the supply pressure is reduced by 50 kPa from 600 kPa to 550 kPa, the reduction in electrical power requirement is approximately 50 kW.

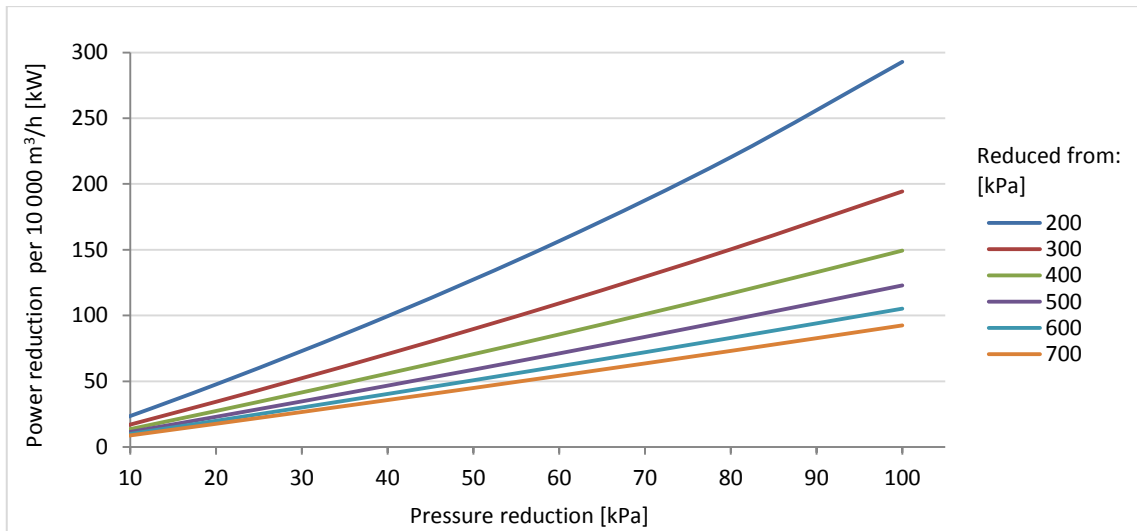


Figure 2.19 – Electrical power saved by reducing final supply pressure.

These graphs can be used to determine estimated energy savings where the flow rate of air and/or delivery pressure of compressors are varied. Other graphs presented in Section 2.2 can be used to determine to what extent changes to the air network will affect the compressed air requirement. In conjunction with Figure 2.18 and Figure 2.19 energy saving can be approximated.

2.6 Conclusion

Electrical energy required to produce compressed air is governed by compressor efficiency, mass-flow air produced and compressor-pressure ratio. The mass flow and delivery pressure required is determined by the end-user and affected by the physical condition of the air network. Proposed methods for optimising compressed air networks to reduce power requirements are: 1) reducing compressed air demand; and 2) increasing compressed air supply efficiency. Mechanisms for applying these methods on typical South African mines are summarised in Table 2.4.

Table 2.4 – Methods for reducing energy requirement to produce compressed air.

Description	Effectiveness	Cost
Methods for reducing compressed air demand		
1. Reducing compressed air demand of authorised equipment use		
1.1. Replacing pneumatic equipment with alternative nonpneumatic equipment	High	High
1.2. Reducing pressure requirement of pneumatic equipment	High	Medium – High

Methods of reducing energy requirement to produce compressed air (continued).

Description	Effectiveness	Cost
Methods of reducing compressed air demand (continued)		
2. Reducing unauthorised equipment use		
2.1. Optimising operation time and schedule of pneumatic equipment	High	Low
2.2. Restricting compressed air supply during certain time intervals	High	Low
3. Reducing air leaks		
3.1. Regular maintenance and inspection of piping network	High	Low – Medium
3.2. Blanking off unused sections	High	Low
Methods of increasing compressed air supply efficiency		
4. Optimising the air network		
4.1. Correct sizing of piping system	High	Medium – High (depending on network size)
4.2. Separation of air networks	Medium – High	Low – Medium
4.3. Maintaining network components	Medium	Low – Medium
5. Optimising air compression		
5.1. Implement an optimised control system incorporating IGVC	High	High
5.2. Reducing compressor inlet air temperature	Medium	Medium
5.3. Installing after- and intercoolers	High	Medium – High
6. Optimising electrical motors driving compressors		
6.1. Using high-efficiency electrical motors	Medium – High	Medium
6.2. Implement VSDs	Medium – High	Medium – High

Due to the complex relationship between the electrical power requirement of compressed air and the compressed air network parameters (such as, supply pressure, airflow rate, pipe wall friction and related component flow losses) each network must be evaluated in detail before it can be optimised.

General graphs presented in this chapter can be used to approximate savings that will result from air network optimisation. Certain methods of optimisation have been applied in case studies which will be discussed in Chapter 3.

3 Case Study 1: Limited application of energy savings initiatives

3.1 General introduction to case studies

Two case studies are considered. The first case study explores the potential when, due to a limited budget, only limited energy savings opportunities can be implemented. Each case study is completed in four different phases. During the first phase (First-off Investigation), the site layout and production schedule is noted and investigated. The performance baselines, against which impact of optimisation methods are measured, are defined during this period.

The next phase (Proposal) is where a project, which is expected to reduce compressed air usage, is proposed from details obtained during the First-off Investigation. Optimisation methods discussed in Chapter 2 are proposed to reduce the electrical energy requirement of compressed air networks. During this phase actual onsite data is recorded or, if available and reliable, historical data is used to determine whether the proposed solution will be viable.

If the proposed saving initiatives are approved the third phase (Implementation) is executed where proposed developments and installations are executed.

Finally, tested and optimised systems are presented to the relevant clients. Hereafter the initiatives are maintained and revised for possible further optimisation to ensure sustainable savings. Table 3.1 shows the planned sequence of these four phases.

Table 3.1 – Procedure followed for implementation of energy saving initiatives (case studies).

WBS	Phase	Procedure description
1.	First-off Investigation	Collect log sheets, obtain site layout information, production schedules, equipment usage log sheets and possibly install power meter loggers.
2.	Proposal	Propose a project to reduce energy requirement using the data obtained in Phase 1.
2.1.	First-off Proposal	Formulate a first-off proposal from information obtained during investigation. This will form the basis for future proposals.
2.2.	Investigation Verification	Verify information obtained during site investigation and consult mining personnel to identify obstacles with regards to first-off proposal.

Procedure followed for implementation of energy saving initiatives (case studies) (continued).

WBS	Phase	Procedure description
2.3.	Proposal Finalisation	Revise first-off proposal from information obtained during investigation verification.
2.3.1.	Theoretical Analysis	Analyse the proposed solution and determine theoretical (estimated) savings.
2.3.2.	Optimisation	Optimise proposal with client and formulate final solution.
2.3.3.	Costing And Feasibility Study	Estimate project cost, determine feasibility and present the business plan.
3.	Implementation	Implement finalised project and solution.
3.1.	Hardware Installation	Install required hardware.
3.2.	Commissioning	Commission installed hardware.
3.3.	Testing	Test control philosophy and implement.
3.4.	Initial Optimisation	Optimising of control parameters.
3.5.	Training	Train site personnel to operate installed systems.
3.6.	Integrated Optimisation	Optimise control parameters with site personnel. Site personnel should continue with optimisation during the operational lifetime of the mine.
4.	Maintenance and Continuous Optimisation	Maintain project and savings.

3.2 Introduction to the case study

Figure 3.1 shows the surface layout before optimisation methods were applied. The layout includes one mining shaft and one gold processing plant.

Temporary power loggers were installed to record compressor power consumption during a three-month period from 10 July 2009 to 30 September 2009. This period is referred to as the baseline period during which the average weekday power usage – referred to as the power baseline – was defined. Performance of energy saving initiatives was measured against the baseline. The baseline was verified by a measurement and verification (M&V) team.

Compressed air savings were achieved by first implementing underground mining section air volume flow supply control. Further savings were achieved by partitioning the air supply manifold into two separate sections and controlling the compressor’s delivery pressure. After optimising the air supply, it may be possible to stop one or more compressors resulting in further electrical and financial savings.

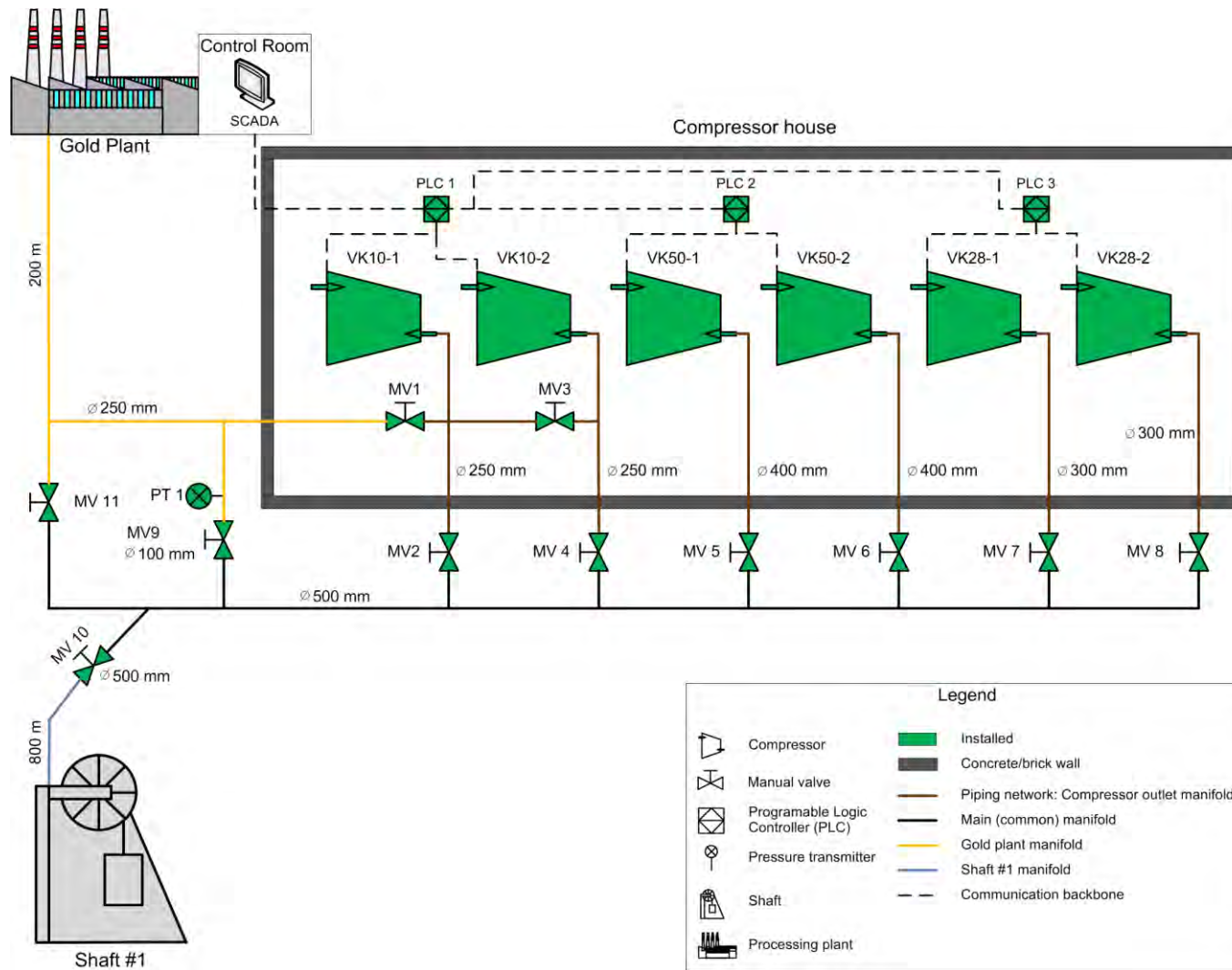


Figure 3.1 – Case Study 1: Schematic surface layout.

3.3 First-off Investigation – Overview of compressed air network

3.3.1 Instrumentation and data logging

Due to budget restrictions, instrumentation and data logging capabilities were limited at this site. Temporary power loggers had to be installed to measure the power baseline of compressors. Power calculations done from the readings obtained from ammeters and voltmeters verified the power meter readings.

Although pressure and flow estimates were shown on the SCADA, no system was available to log these values. For this reason pressure and flow baselines are not available. Since this study focuses on the electrical energy usage of compressors detailed flow and pressure readings are not essential, but would be useful.

3.3.2 Surface layout

The initial surface layout is shown in Figure 3.1 to Figure 3.3 . As indicated on Figure 3.1 there were a total of six compressors. These compressors included:

- Two VK10 compressors with an installed capacity of 1.05 MW each
- Two VK28 compressors with an installed capacity of 2.6 MW each
- Two VK50 compressors with an installed capacity of 5.1 MW each

The total installed capacity was 17.5 MW. Compressor ratings are given in Table 3.2. Note that these ratings were specified at standard atmospheric conditions (atmospheric air pressure of 101.3 kPa and temperature of 20°C). A typical compressor installation is shown in Figure 3.2.

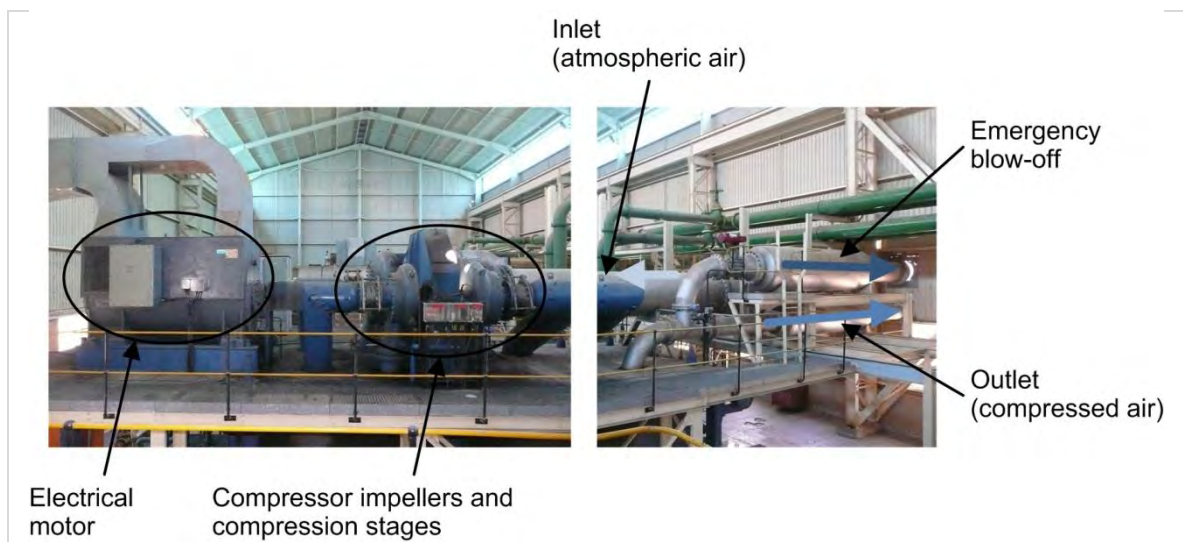


Figure 3.2 – Case Study 1: Typical compressor installation.

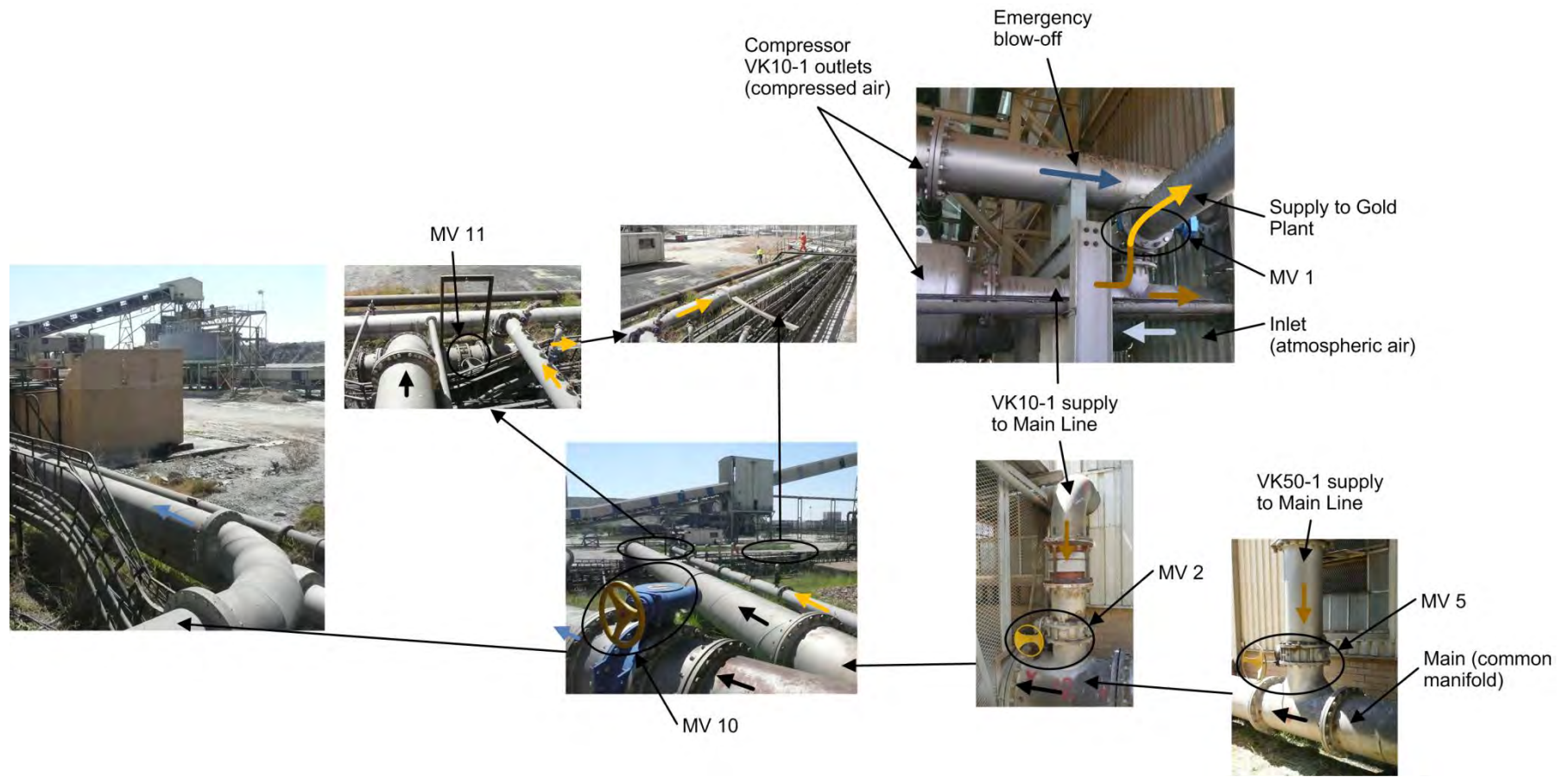


Figure 3.3 – Case Study 1: Valves installed on surface before implementation of optimisation methods.

Note:

MV – Manual Valve

CV – Control Valve

Table 3.2 – Case Study 1: Ratings of installed compressors.

Compressor	Quantity	Installed capacity [MW]	Rated inlet flow rate [m ³ /h]	Totals	
				Installed capacity	Flow rate
VK10	2	1.05	10 000	2.1	20 000
VK28	2	2.6	28 000	5.2	56 000
VK50	2	5.1	50 000	11	100 000
Total	6			17.5	176 000

Compressed air was supplied via an intricate piping system, referred to as the air network, from the compressor house located opposite the gold plant. The network allowed air to be supplied from the compressors to end-users and consisted of several kilometres of piping.

Compressors supplied air into a common manifold, referred to as the main manifold, which was then separated into two manifolds. Each of the two manifolds supplied air to a different section on the surface. The manifolds were interconnected through shut-off valves. All valves were fully opened so that compressed air was naturally shared between the manifolds.

Volumetric flow meters were installed on each compressor’s inlet manifold and pressure transmitters were installed at each compressor’s discharge manifold. All compressor instrumentation and pressure transmitters were connected to relevant programmable logic controllers (PLCs) located in the compressor house. The PLCs allowed compressors to be stopped and started from the SCADA located in the gold plant control room. Compressor IGVC was also incorporated in the PLCs. All instrumentation was monitored from the SCADA.

3.3.3 Underground layout

Figure 3.4 shows the overall underground layout before project implementation. As indicated there were eight working levels spaced approximately 50 m vertically apart. The majority of mining activities were executed from Level #19 (approximately 1.9 km below surface) to Level #23 (approximately 2.2 km below surface).

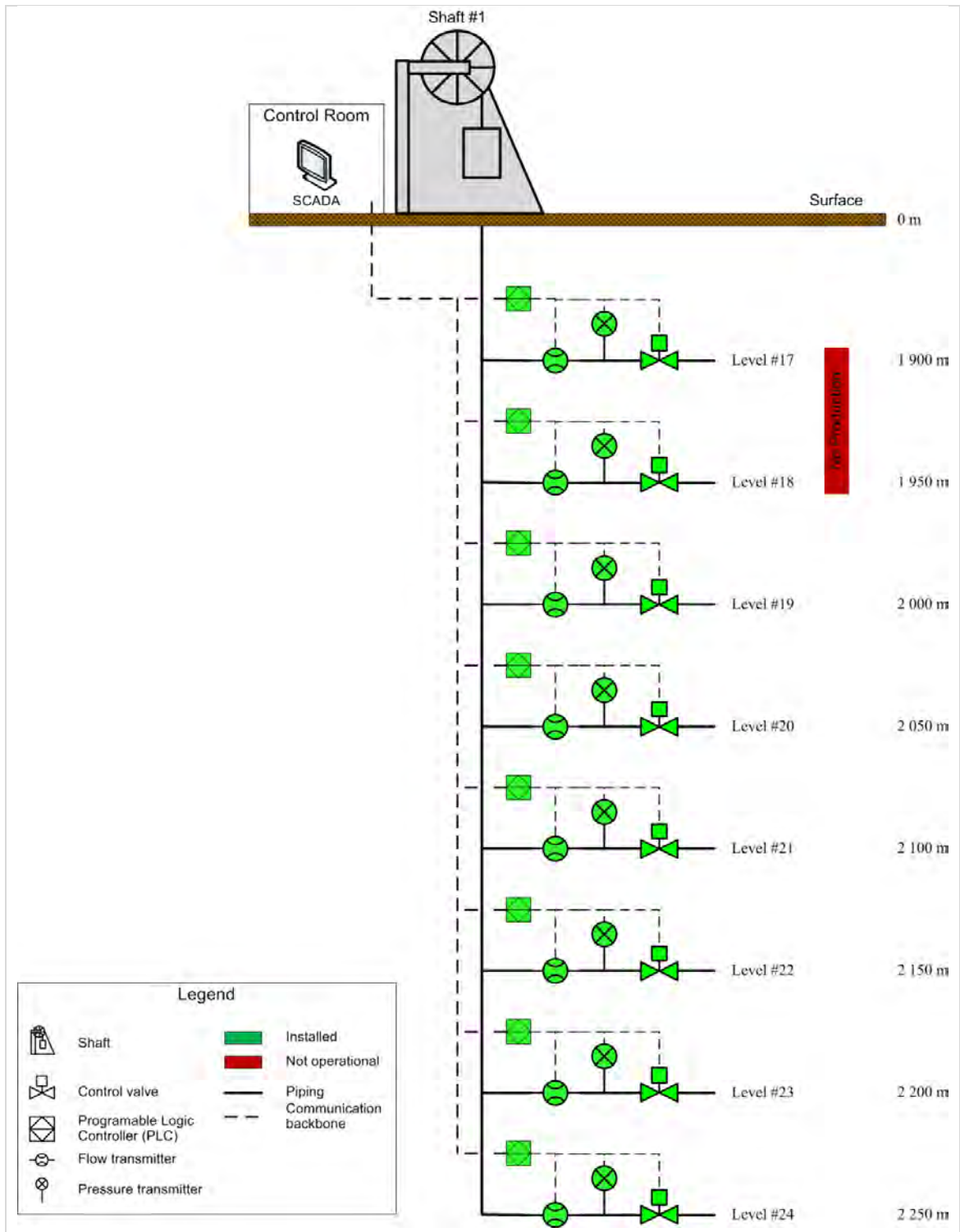


Figure 3.4 – Case Study 1: Underground layout before implementation of optimisation methods.

Figure 3.5 shows the general layout of each underground level. A control valve was installed on each of the eight mining levels – approximately 50 m downstream of the shaft entrance at the respective levels. A pressure transmitter and a flow transmitter were also installed upstream of the valve. Data obtained from these transmitters was also shown on the SCADA in the control room, but was not recorded.

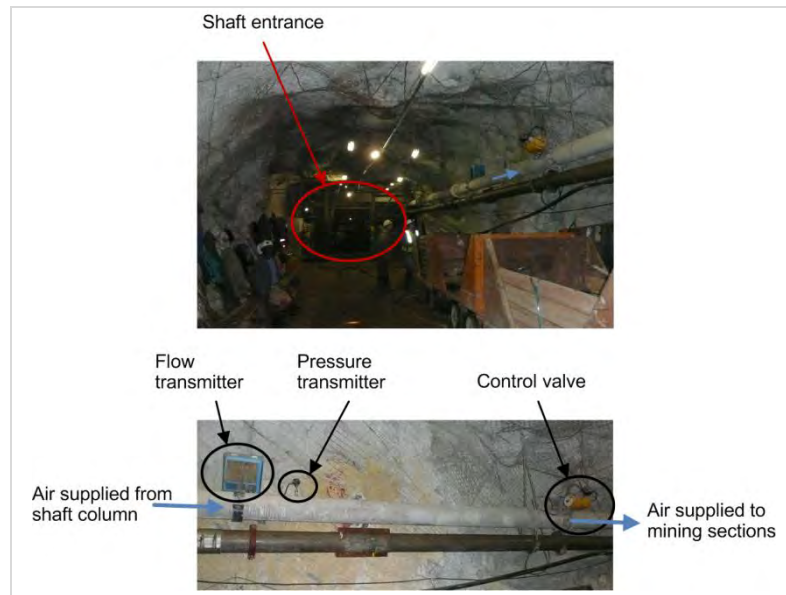


Figure 3.5 – Case Study 1: Typical underground control valve setup.

3.3.4 Compressed air requirement and electrical energy demand

The typical daily schedule for mining activities and respective compressed air requirement – as obtained from mining personnel and equipment data sheets – is shown in Table 3.3.

Table 3.3 – Case Study 1: Typical daily mining activity schedule.

Time	Activity	Compressed air requirement	
		Pressure [kPa]	Airflow
09:00 – 15:00	Sweeping, drilling and cleaning, hoisting.	440	High
15:00 – 21:00	No mining activity. Ventilation, refuge bays, agitation, tramming, hoisting.	250	Low
21:00 – 04:00	Zalsgieter loaders, tramming, hoisting.	400 – 450	High. Requires 4 m ³ per operational cycle (load, collect and unload)
04:00 – 09:00	No mining activity. Ventilation, refuge bays, tramming, hoisting.	250	Low

3.3.4.1 Compressed air requirement of Shaft #1

On Shaft #1 an average total of 116 pneumatic rock drills were operated simultaneously during drilling shifts (typically 09:00 – 15:00). These drills required 350 – 400 kPa air pressure to operate efficiently and consumed compressed air at 160 – 210 m³/h. Thus, the total estimated compressed air volume flow of rock drills varied from 18 560 m³/h to 24 360 m³/h.

16 loaders were used during loading shifts (typically 20:00 – 04:00). These loaders required air at 450 – 500 kPa with each loader consuming compressed air at approximately 420 – 500 m³/h. The total compressed air requirement of loaders ranged from 6 720 m³/h to 8 000 m³/h. A total of 45 pneumatic cylinders were operated for approximately six hours per day (24-hour cycle). These cylinders were used to operate loading boxes on each level. Each cylinder had a piston diameter of 200 mm and stroke of 1.2 m. Each cylinder required compressed air at 400 – 420 kPa and consumed air at approximately 27.1 m³/h. The total average compressed air requirement of pneumatic cylinders was calculated as 305 m³/h.

Other pneumatic cylinders were also used, but may be neglected due to the fact that they were not operated frequently and required only small quantities of air. Compressed air requirements for agitation, as well as unrepaired leaks and open ends, were assumed to be negligible in these calculations. These air losses were not easily quantified due to relevant site data being unavailable.

Figure 3.6 shows the minimum and maximum pressure requirements of Shaft #1. Despite pressure losses due to pipe wall friction and air leaks an average pressure increase of 66 kPa was measured between the compressor outlet pressure on surface, and the pressure measured by pressure transmitters installed on underground levels. This pressure increase is due to the depth of underground mining levels which reached down to Level #23, approximately 2.2 km below surface.

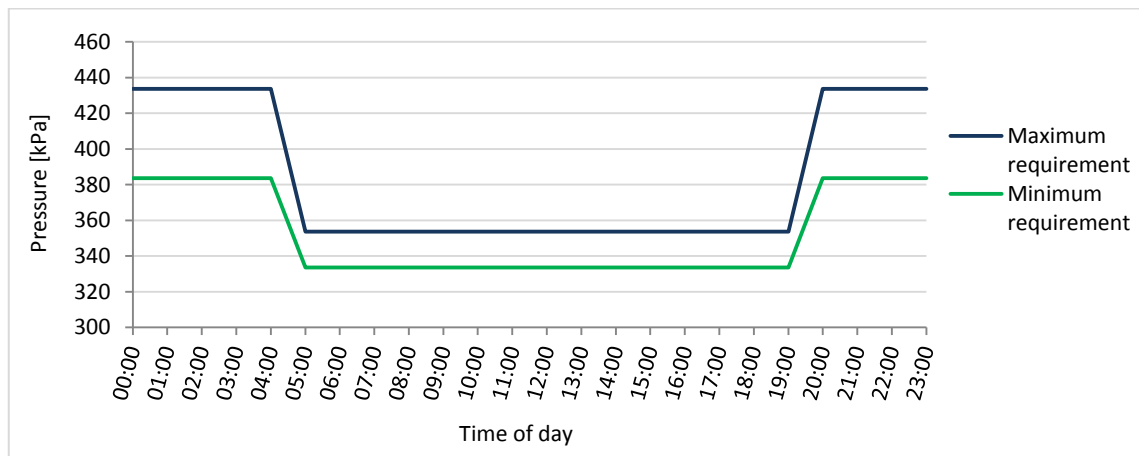


Figure 3.6 – Case Study 1: Shaft #1 compressed air pressure requirement on surface.

Figure 3.7 indicates the estimated flow requirement on Shaft #1. Note that the minimum flow requirement did not take the flow required for agitation, refuge bays and air leaks into account.

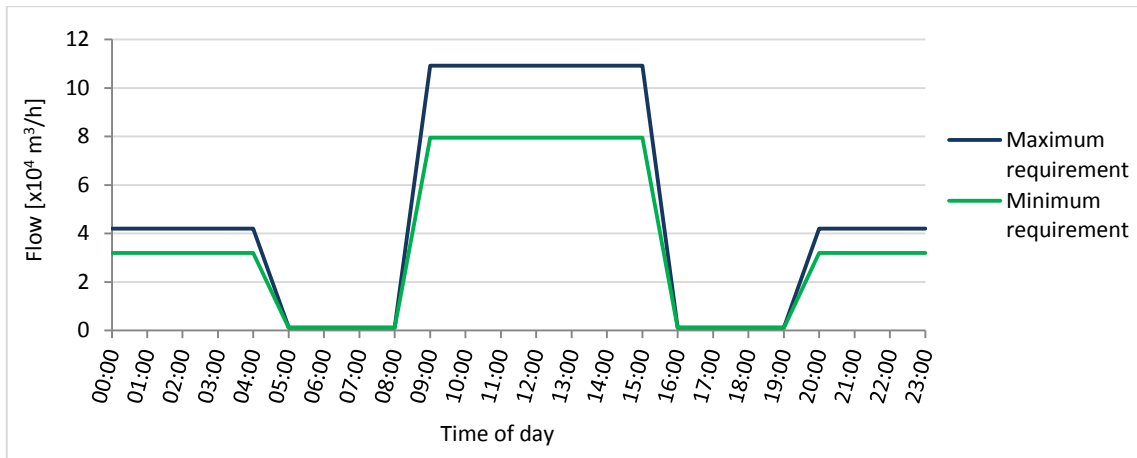


Figure 3.7 – Case Study 1: Shaft #1 normalised compressed airflow requirements.

3.3.4.2 Compressed air requirement of the gold processing plant

The gold plant situated opposite the compressor house operated 24 hours each day and required compressed air at 450 – 500 kPa with a flow demand ranging from 6 000 m³/h to 9 000 m³/h. The air was mainly used to operate pneumatic actuators and for agitation and oxidation.

The minimum and maximum pressure requirements of the gold plant were 450 kPa and 500 kPa respectively. This was 30 kPa more than the requirement at the gold plant due to an average pressure loss of 30 kPa measured between the compressor delivery pressure on surface and the pressure measured by pressure transmitters installed at the gold plant. This loss was higher than expected due to large air dryers that were installed at the gold plant through which air had to travel before it was supplied to the plant.

3.3.4.3 Total compressed air requirement

The minimum and maximum pressure required from compressor outlets for Case Study 1 were 480 kPa and 530 kPa respectively. Since compressed air was supplied from a common manifold this demand was determined by the maximum requirement between Shaft #1 and the gold plant.

Figure 3.8 shows the total estimated compressed airflow requirement of Case Study 1. This requirement did not take any additional air leaks into account. As stated earlier, the air requirement of agitation underground and refuge bays had been neglected.

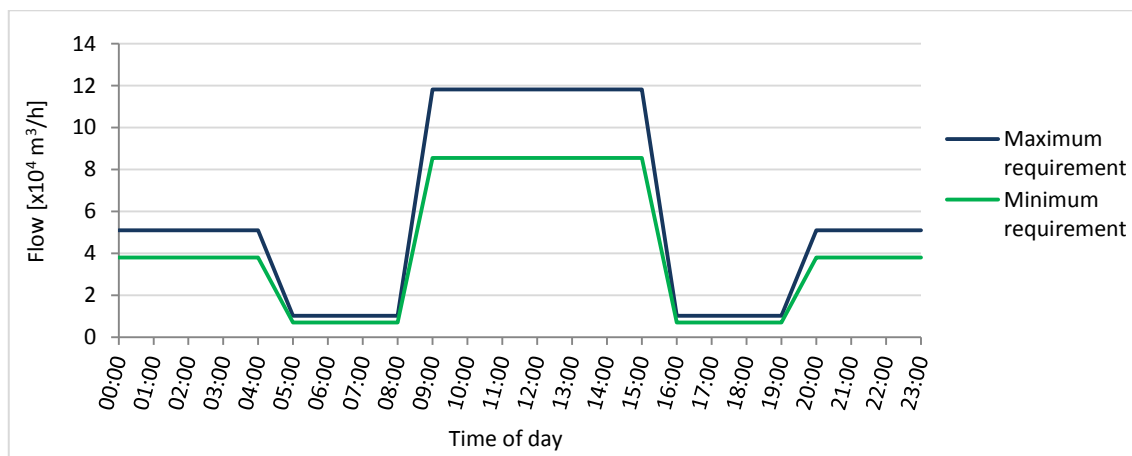


Figure 3.8 – Case Study 1: Total compressed airflow requirement.

3.3.4.4 Electrical energy required to meet compressed air demand

The estimated power required to produce compressed air according to the pressure and flow demand is shown in Figure 3.9. This was calculated assuming an overall compressor efficiency of 72%.

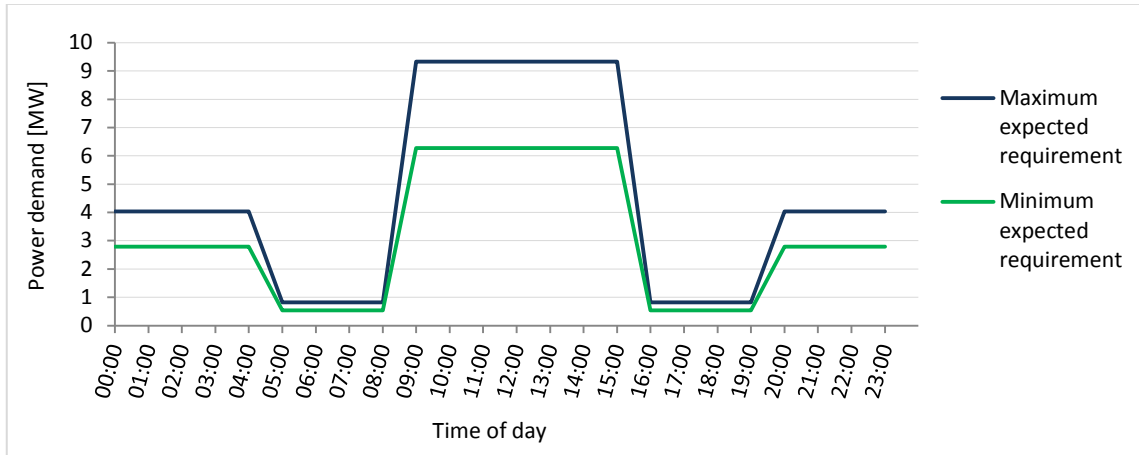


Figure 3.9 – Case Study 1: Minimum and maximum power requirement.

3.3.4.5 Defining baselines

To calculate the power baseline, the compressor power consumption was measured at two-minute intervals during the baseline period. Average power readings were computed for one-hour intervals over a 24-hour time period, from midnight to midnight. This was referred to as the power profile. The average power usage during this 24-hourly profile was referred to as the average daily power usage. Daily electrical energy usage can be calculated by multiplying the average daily power usage by the time period, in this case 24 hours.

The average 24-hour power usage profile for weekdays during the baseline period, was referred to as the baseline profile and formed the basis against which the performance of the optimisation methods was measured. An M&V team was assigned to verify and approve the baseline.

Due to the fact that the pressure and flow data could not be logged from the SCADA these baselines were not defined. Thus, the performance of saving initiatives was only measured against the power baseline.

3.3.4.6 Comparing compressed air supply with required demands

Figure 3.10 shows the power baseline which indicates that actual power consumption exceeded maximum expected demand on a permanent basis. It was safe to assume that the maximum compressed air pressure and the flow supplied also exceeded the maximum demands. This showed that the compressed air network could be significantly optimised.

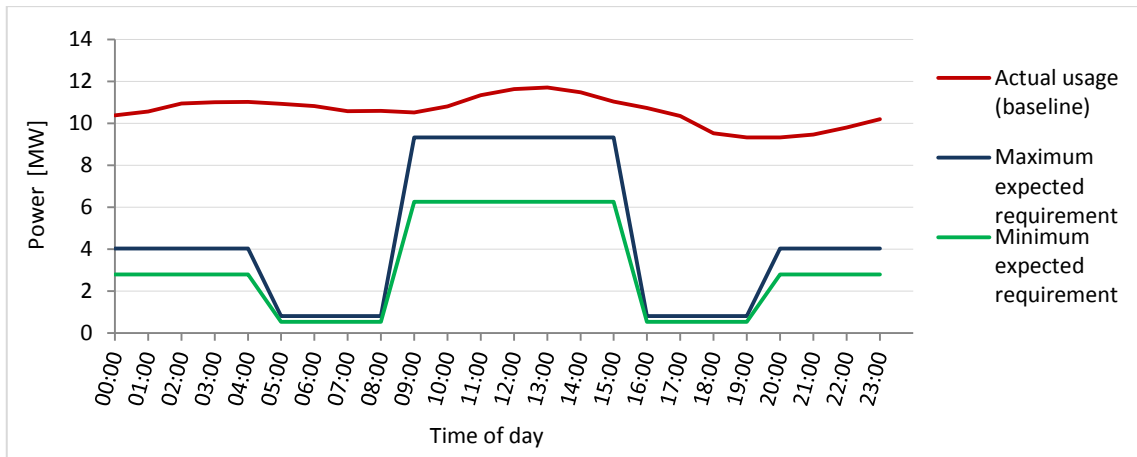


Figure 3.10 – Case Study 1: Power consumption during July 2009 – end September 2009.

3.4 Proposal – Demand optimisation and equipment selection

3.4.1 Considering methods of optimisation

The methods which were considered for reducing the compressed air demand and increasing the compressed air supply efficiency are summarised in Table 3.4.

Table 3.4 – Case Study 1: Considering methods for reducing power requirements of the compressed air network.

Description	Solution
Methods for reducing compressed air demand	
1. Reducing compressed air demand of authorised equipment use.	
1.1. Replacing pneumatic equipment with alternative nonpneumatic equipment.	Consider replacing pneumatic cylinders and rock drills on Shaft #1 with hydro-powered equipment. This was not feasible due to the complicated shaft layout.
1.2. Reducing pressure requirement of pneumatic equipment.	Consider replacing pneumatic cylinders on Shaft #1 with cylinders having a larger diameter piston. This was not feasible due to the high cost of replacing pneumatic cylinders.
2. Reducing unauthorised equipment use.	
2.1. Optimising operation time and schedule of pneumatic equipment.	Optimise compressor set points for the mining shaft and gold plant separately.
2.2. Restricting compressed air supply during certain time intervals.	Already implemented by installation of underground control valves which control compressed airflow supplied to each mining section.

Case Study 1: Considering methods of reducing power requirements of the compressed air network (continued).

Description	Solution
Methods of reducing compressed air demand	
3. Reducing air leaks.	
3.1. Regular maintenance and inspection of piping network.	Implement a Compressed Air Leakage Documentation System (CALDS).
3.2. Blanking off of unused sections.	Already implemented on levels where mining activities are no longer conducted.
Methods of increasing compressed air supply efficiency	
4. Optimising the air network.	
4.1. Correct sizing of piping system.	No problems found.
4.2. Separation of air networks.	Separate network to allow delivery pressure to Shaft #1 to be reduced during low demand periods.
4.3. Maintaining network components.	Already in place.
5. Optimising air compression.	
5.1. Implement an optimised control system incorporating IGVC.	Already implemented.
5.2. Reducing compressor inlet air temperature.	Not considered practical on this site.
5.3. Installing after- and intercoolers.	Intercoolers are installed between compressor stages.
6. Optimising electrical motors driving compressors.	
6.1. Using high-efficiency electrical motors.	Motors are 90% efficient and will not be replaced.
6.2. Implement VSDs.	Not feasible due to extremely high cost related to VSDs.
Legend	<div style="display: flex; align-items: center; gap: 10px;"> <div style="width: 20px; height: 15px; background-color: #e08080; border: 1px solid black;"></div> Methods not feasible or practical. </div> <div style="display: flex; align-items: center; gap: 10px; margin-top: 5px;"> <div style="width: 20px; height: 15px; background-color: #4a86e8; border: 1px solid black;"></div> Additional methods implemented. </div>

3.4.2 Applying optimisation methods

3.4.2.1 Method 2 – Reducing unauthorised equipment use

Compressed air optimisation methods which resulted in a reduction of compressed air consumption of authorised and unauthorised equipment use (such as the restriction of underground mining section airflow supply) have been implemented before this study commenced.

This was done by means of control valves, as shown in Figure 3.5, that were installed on the air network of each underground mining level. These valves were installed to regulate the flow supplied to each individual mining level. Each valve regulated the flow – measured from a flow meter installed upstream of the control valve whenever a predetermined value was exceeded. The results of the flow control implemented by the control valves can be seen in the power baseline which tends to decrease during low demand periods.

Proposed as part of this study was that each underground control valve had to be controlled according to the pressure, instead of the flow supplied downstream of the control valve. This, however, could not be implemented due to the budget restriction placed on this case study.

3.4.2.2 Method 3 – Reducing air leaks

Investigations revealed a large amount of air leaks present on the air network. Air leaks were found on surface near the compressor house, at the ventilation fans, at a ventilation shaft, on mining levels, in the gold plant and continued to exist. It was found that personnel were not aware of these air leaks, nor did they realise the detrimental effects that these leaks had on energy consumption.

A CALDS was proposed which would aid personnel in locating and documenting the air leaks. The proposed system was developed to provide a platform where documented air leaks, along with the estimated air loss and cost, were reported to management. This would increase awareness of the negative effects the air leaks imposed on the system, and encourage personnel to repair leaks that were found.

3.4.2.3 Method 4 – Optimising the air network

Site investigations showed that the compressed air pressure requirement could be separated into two categories, namely:

1. Low pressure, high flow (referring to the compressed air requirement of Shaft #1).
2. High pressure, low flow (referring to the compressed air requirement of the gold plant).

Due to the difference in pressure requirement it would be most beneficial having two supply manifolds, each supplying the relevant section with compressed air at the correct high- or low pressure. This would allow the pressure supplied to Shaft #1 to be reduced to below the minimum requirement of the gold plant during certain time periods.

Since the gold plant required a much lower maximum flow rate than Shaft #1, the majority of compressors should be available to supply Shaft #1. The proposed compressed air network layout for creating two separate supply manifolds is shown in Figure 3.12. Proposed changes included closing certain manual valves and the installation of one PLC, two control valves and two pressure transmitters. Figure 3.11 shows two of the installed control valves.



Figure 3.11 – Case Study 1: Proposed installations.

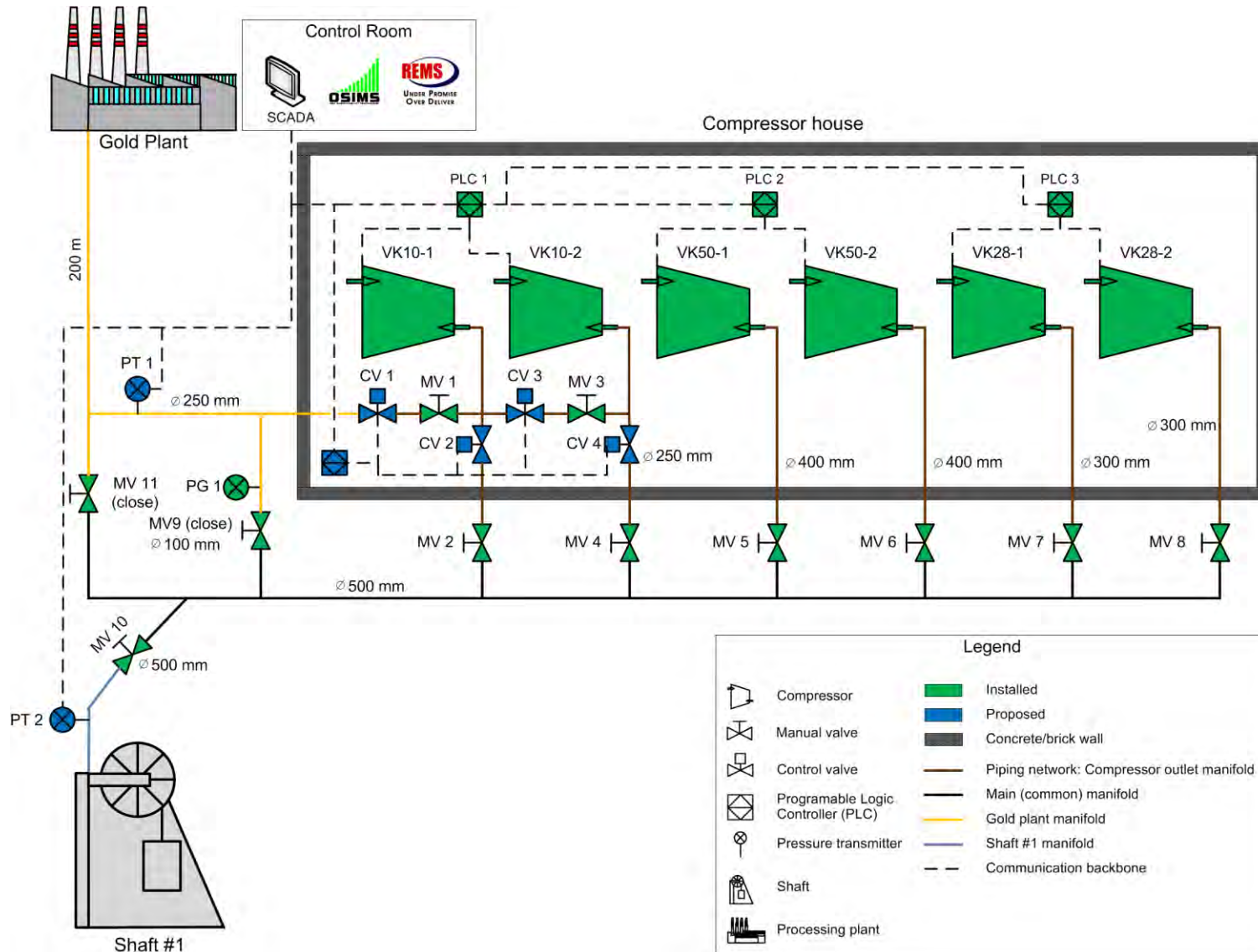


Figure 3.12 – Case Study 1: Surface layout after optimisation methods are applied.

With reference to Figure 3.12, the proposed control philosophy according to which the network had to be controlled on surface was as follows:

1. Compressors

- 1.1. VK10-1 and VK10-2 would be run on a permanent basis during low airflow demand periods to supply compressed air to the gold plant. The maximum demand of the gold plant was below the combined supply capacity of the compressors. Therefore, sufficient air would be available at all times.
- 1.2. The remaining compressors could be used to supply compressed air to Shaft #1. One compressor could be stopped whenever the operating compressors supplied excess air and output could not be reduced further.
- 1.3. Compressor set points had to be set according to the required supply. The set points for compressors VK10-1 and VK10-2 had to be set according to the minimum demand of the gold plant. The set points of the remaining compressors had to be set according to the minimum demand of Shaft #1.

2. Control valves

- 2.1. One pressure set point would be sent to the installed PLC which would control the valves on the surface. This set point had to be the pressure requirement of the gold plant.
- 2.2. Control valves CV 2 and CV 4 should be controlled according to the pressure reading from pressure transmitter PT 1. The valve should open if the average reading was above the pressure set point of the gold plant. This would allow any excess air to be supplied to the manifold supplying Shaft #1 with air.

3. Safety interlocks

- 3.1. All control valves were fail-to-open which means that when the pressure supply to the relevant valve actuator was not adequate, or the power supply to the actuator failed, the valve would open automatically.
- 3.2. When the compressed air requirement of the gold plant could not be met, and both the control valves CV 1 and CV 2 were fully closed, the set points to all compressors would be changed to the greater minimum demand of all surface areas and all the control valves would open.

3.4.3 Theoretical analysis – Estimated power savings

According to the power baseline shown in Figure 3.10 a minimum and maximum average daily saving of 6.0 MW and 7.5 MW could be realised. This was, however, unrealistic since flow losses due to air leaks, agitation, refuge bays, workshops and cleaning equipment had been neglected. Typical losses due to these factors is

To compensate for this it was assumed that the minimum flow demand was determined by the requirement of the loaders. The resulting, expected minimum power consumption and anticipated power saving profiles are shown in Figure 3.13. As shown the baseline power was given in terms of total minimum power demand, total minimum expected saving and total possible additional savings.

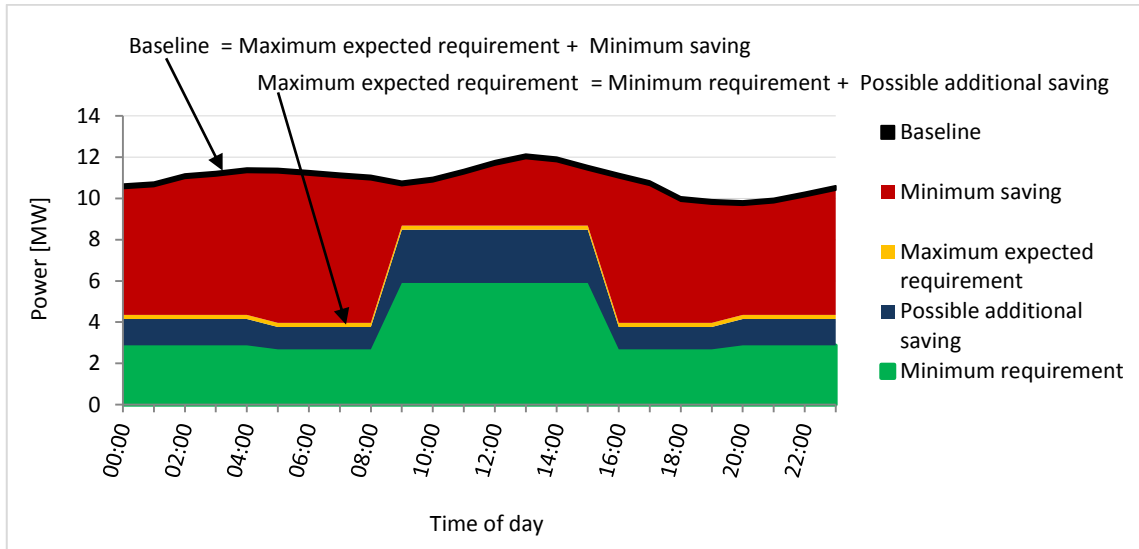


Figure 3.13 – Case Study 1: Accumulated expected power usage and saving profiles.

The baseline daily average power consumption was 10.6 MW. As shown in Figure 3.14 the expected maximum average daily power consumption (which was calculated by adding the minimum requirement and possible additional electrical savings) was 5.6 MW. Thus, the power consumption would be realised if a minimum average daily saving of 5.0 MW was achieved. This would be achieved if compressed air was supplied to match maximum expected demand.

An additional saving of 1.8 MW could be achieved if compressed air supply was accurately controlled according to the minimum demand which was estimated to be 3.8 MW. This would result in a total saving of 6.8 MW.

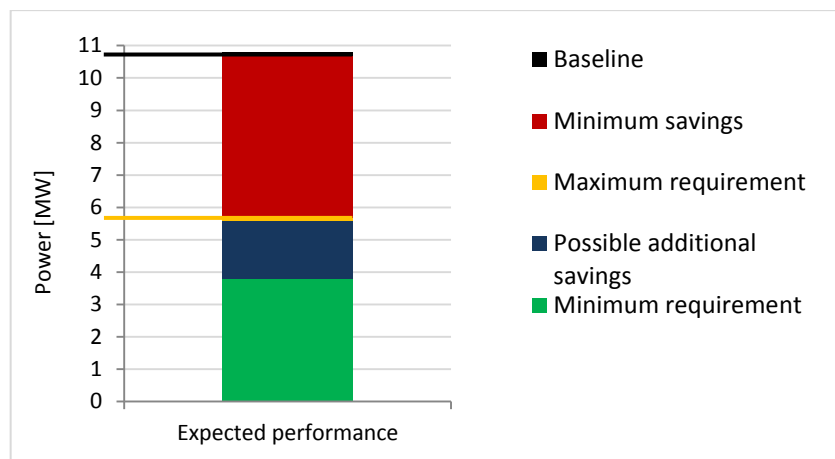


Figure 3.14 – Case Study 1: Estimated average daily power usage, minimum saving and possible additional savings.

3.5 Results

The first proposal for integrating methods of reducing compressed air usage was presented during February 2010. After verification the final proposal was approved during May 2010. The following month orders for installing required equipment and development were placed with subcontractors.

Figure 3.15 shows the weekday average power usage of the compressors. This was calculated by dividing the total kilowatt-hours consumed during working weekdays by the number of weekday hours. An initial average daily saving of 1.6 MW was realised between 01 March 2011 and 30 June 2011. This saving was realised due to manual controlled experimental tests optimising compressed air supply set points which commenced after the first-off proposal. These tests resulted in a permanent optimised compressed air supply schedule being followed by control room operators.

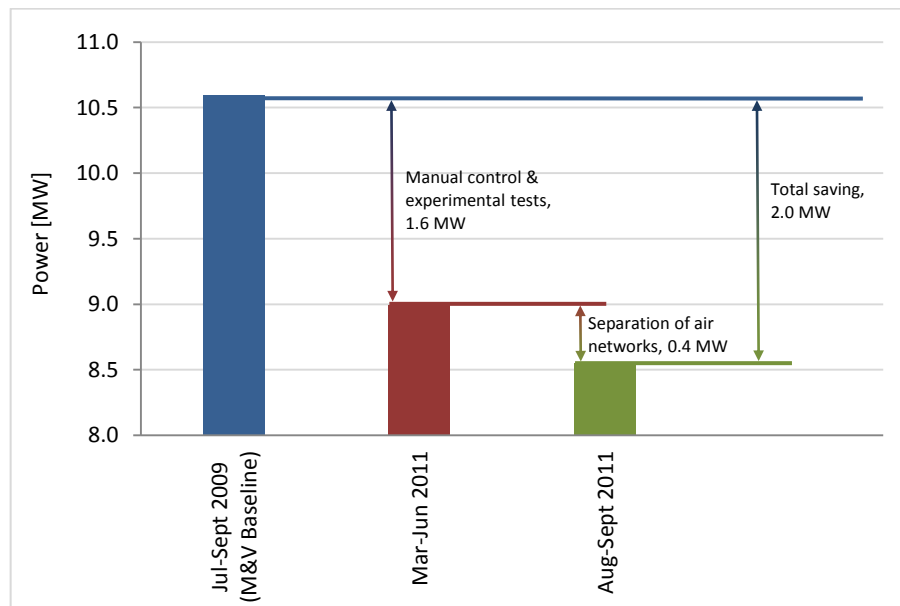


Figure 3.15 – Case Study 1: Power demand of compressors during implementation of saving interventions.

Hardware installations required for full optimisation according to the proposal were finalised during July 2011. Final tests and implementation were done during August 2011 such that full automatic control of the system commenced at the end of August 2011. An additional average saving of 0.4 MW was realised during August 2011 and September 2011. This was due to full implementation of the compressed air network optimisation which included the separation of air supply manifolds. This allowed mining personnel to reduce the pressure and flow supplied to Shaft #1 during low demand periods. Figure 3.16 shows the resulting power usage compared to the expected requirements and baseline.

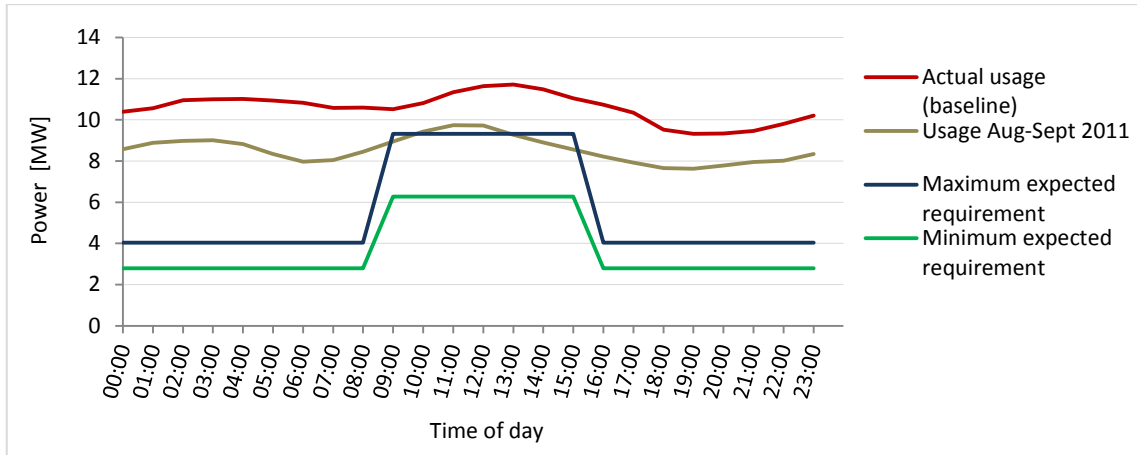


Figure 3.16 – Case Study 1: Power profiles.

3.6 Conclusion

Initial investigations took place from 01 July 2009 to 30 September 2009. During this period the compressed air system was analysed and power baseline profiles developed. An average weekday daily power usage baseline of 10.6 MW was measured.

After investigations proposals were submitted and confirmed through experimental tests, proposed optimisation methods were approved and finalised during May 2010. Optimisation methods applied included: optimised supply pressure control, underground flow control, implementation of a leakage documentation system and the division of air networks.

Experimental tests were conducted to optimally control the delivery pressure set points of compressors to optimise pressure supplied on surface according to the minimum requirement. This resulted in a saving of 1.6 MW, an approximate 15% reduction of the original baseline. This minimum requirement was determined by the greatest minimum requirement of major sections of either the processing plant or mining shaft.

Pressure supply optimisation was further improved by allowing compressors to supply air to each major section individually. Full implementation commenced at the end of July 2011. This resulted in an additional saving of 0.4 MW, approximately 4% of the baseline.

Air leaks were documented and repaired on an ongoing basis. CALDS, the documentation system that was implemented, created awareness of air leaks and resulted in repairs being carried out more frequently.

By restricting availability of compressed air a total power saving of 2 MW, approximately 19% of the measured baseline, was realised. However, a minimum saving of 5 MW was expected.

Investigations showed that the underground control valves proved to be unreliable and did not regulate the flow accurately. This was due to the flow meters not measuring the flow rates correctly due to a large amount of moisture in the compressed air supply lines which resulted in limited control of the air system.

Despite increases in production during 2011 the overall compressed air usage and power requirement was reduced. It is expected that the air consumption of Shaft #1 could be reduced further by providing accurate control of air supplied to mining levels. This will require the following to be done:

1. Installation of pressure transmitters downstream of control valves on each underground mining level.
2. Repairing control valves installed on underground mining levels.
3. Infrastructure that will allow compressed air system data to be monitored and captured continuously.

4 Case Study 2: Integrating various energy saving initiatives

4.1 Introduction

Figure 4.1 shows the surface site layout for Case Study 2 before project implementation. This study was conducted at a different mining site than the first study. The layout included three mining shafts and one gold plant. All valves on surface were in the fully open position and compressed air was supplied from the compressor house located at Shaft #1 via a common manifold.

Compressed air savings were achieved through the implementation of similar methods implemented in Case Study 1 – with the exception of the method in which underground control valves were controlled. During this case study all sections of the compressed air network were continuously monitored and controlled. Unlike Case Study 1 both pressure and flow was considered in the control loops. This allowed for full integrated control of the compressed air system which caused a significant increase in energy savings.

4.2 First-off Investigation – Overview of compressed air network

4.2.1 Instrumentation and data logging

Instrumentation installed onsite (such as flow meters, pressure transmitters, ammeters, voltmeters and electrical power meters) were used to obtain site data. The data was used to measure the performance of energy saving initiatives.

After calibration, a correction factor of 1.16 was used to obtain accurate compressor motor power readings logged by the SCADA. This factor was determined by calculating actual power usage from the ammeter and voltmeter readings, and comparing the results with the power logged on the SCADA.

The correction factor used on power readings was verified by calculating the expected total power consumption of compressors using the average delivery pressure and total flow and comparing results with the corrected power readings.

Results showed that the expected total power consumption calculated from the average delivery pressure and flow was within 6% of the corrected power readings.

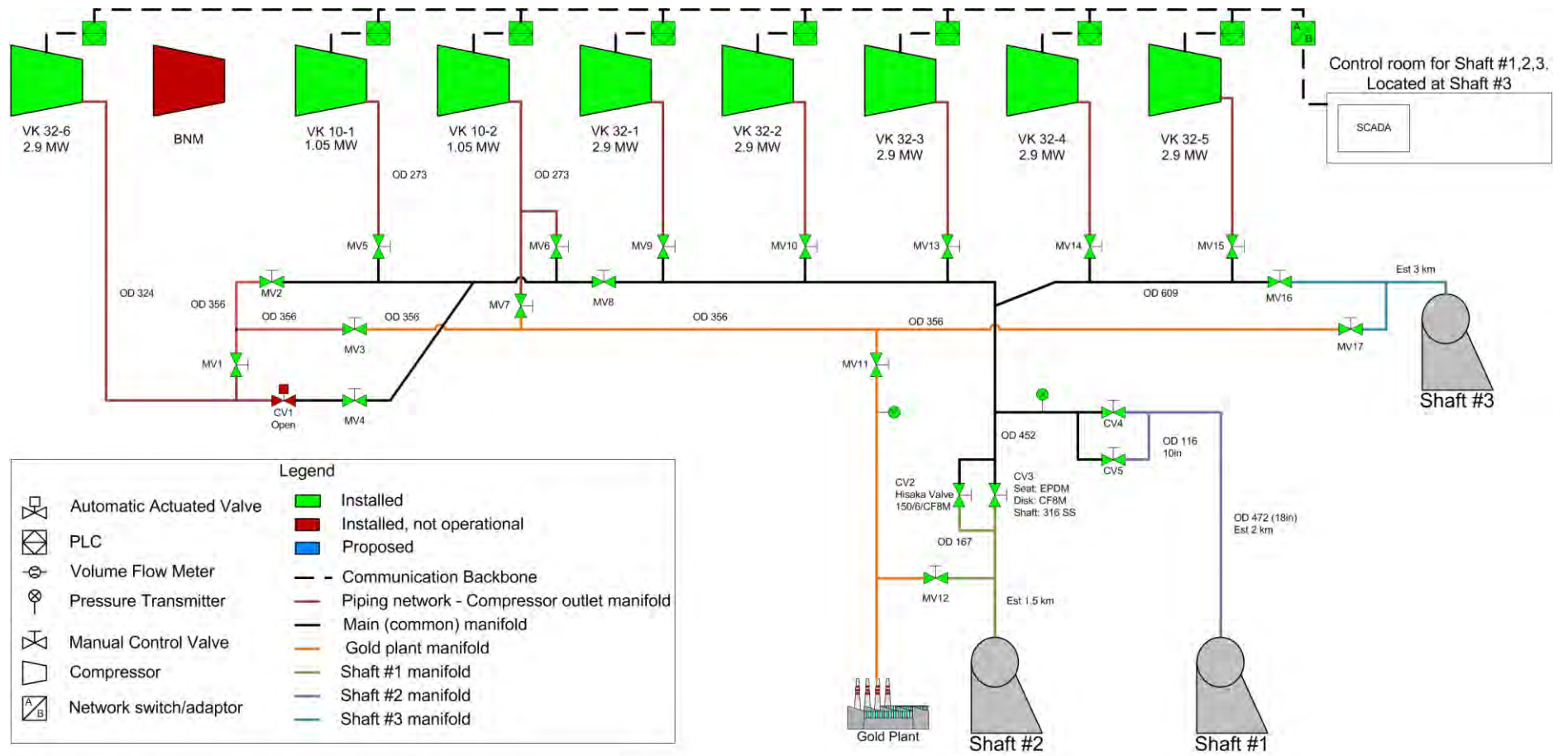


Figure 4.1 - Case Study 2: Surface site layout before project implementation.

4.2.2 Surface layout

The initial surface layout is shown in Figure 4.2 and Figure 4.1. As indicated in Figure 4.1 there were a total of eight compressors. These compressors included two VK10 compressors (with an installed capacity of 1.05 MW each) and six VK32 compressors (with an installed capacity of 2.9 MW each). The total installed capacity was 19.5 MW. Compressor ratings are indicated in Table 4.1. Note that these ratings are specified at normalised conditions where air pressure was taken as 101.3 kPa and temperature as 20°C.

Table 4.1 – Case Study 2: Ratings of installed compressors.

Compressor	Quantity	Installed capacity [MW]	Rated inlet flow rate [m ³ /h]	Totals	
				Installed capacity [MW]	Flow rate [m ³ /h]
VK10	2	1.05	10 000	2.1	20 000
VK32	6	2.9	32 000	17.4	192 000
Total	8			19.5	212 000

Compressed air was supplied via an intricate piping system referred to as the air network. This network allowed air to be supplied from the compressors to end-users and consisted of several kilometres of piping.

Compressors, in parallel, supplied air into a single manifold, referred to as the main manifold, which was then separated into four manifolds. Each manifold supplied air to a different section on surface. The manifolds were all interconnected. All valves were fully opened so that compressed air was naturally shared between the manifolds.

Volumetric flow meters were installed on each compressor's inlet manifold and pressure transmitters at each compressor's discharge manifold. A pressure gage was installed on the main manifold. All compressor instrumentation and pressure transmitters were connected to relevant PLCs located in the compressor house. These PLCs allowed compressors to be stopped and started from the SCADA located in the control room at Shaft #3. Compressor IGVC was also incorporated in the PLCs. All instrumentation was monitored from the SCADA.

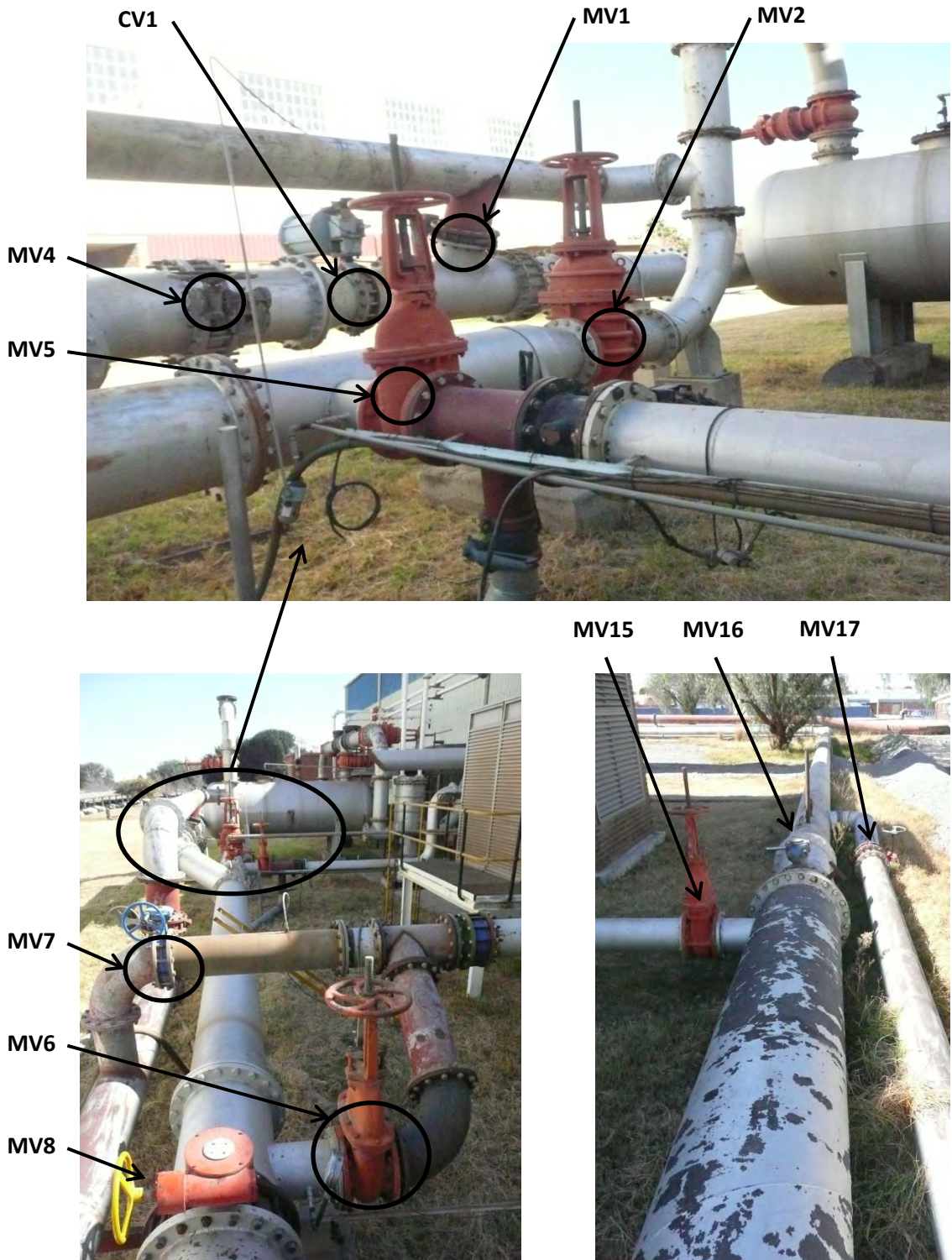


Figure 4.2 – Case Study 2: Valves installed on surface at 1# compressor house.

Note:

MV – Manual Valve

CV – Control Valve

4.2.3 Underground layout

Figure 4.3 shows the overall underground layout before project implementation. There were 17 working levels spaced approximately 50 m vertically apart. Mining levels were located approximately from 700 m to 1 400 m below surface.

A control valve was installed on each of the 17 mining levels approximately 100 m from the shaft entrance on the respective levels. A pressure transmitter and a flow transmitter were also installed upstream of the valve as shown in Figure 4.13. Data obtained from these transmitters were also shown on the SCADA in the control room located at Shaft #3.

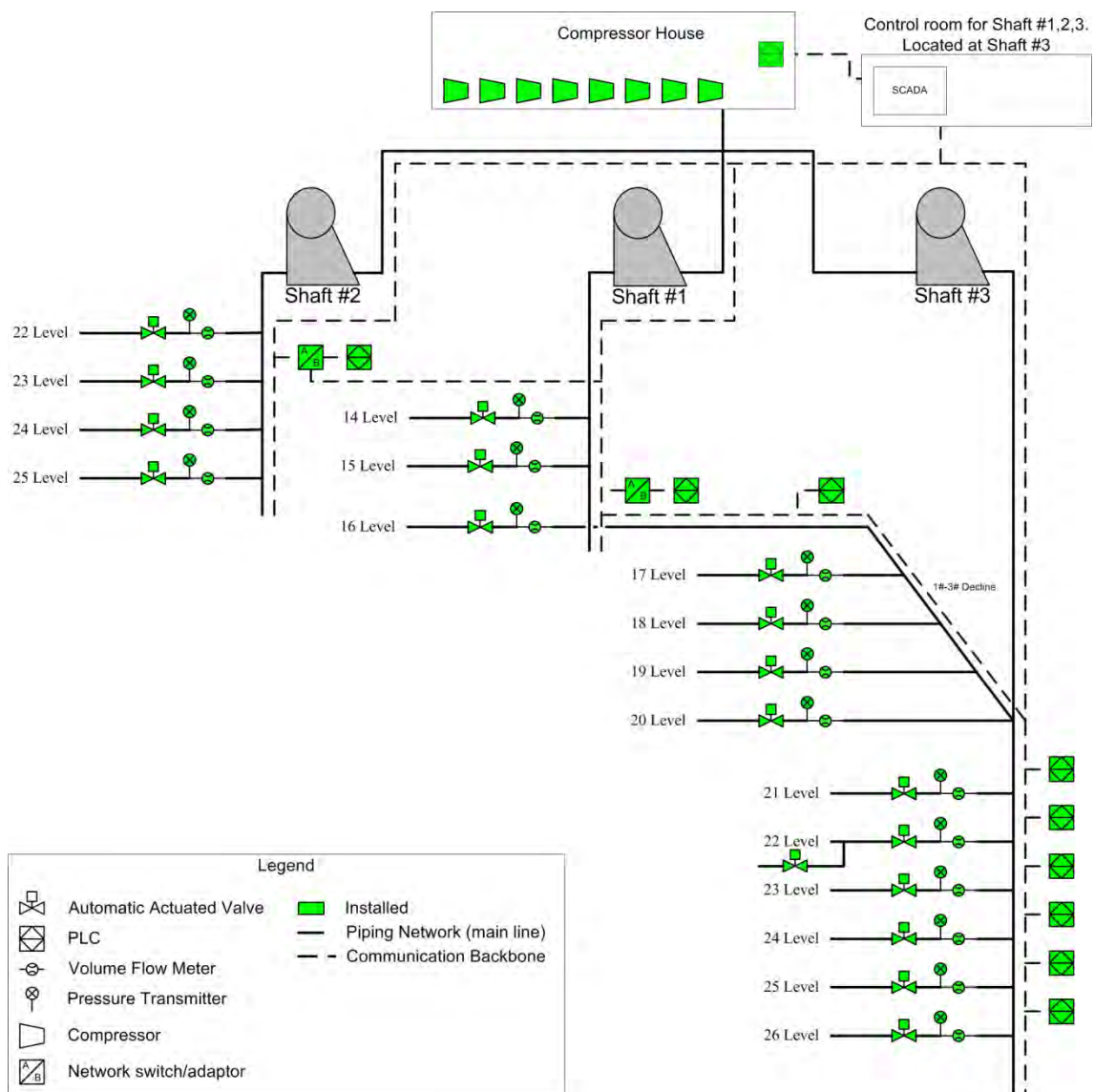


Figure 4.3 – Case Study 2: Underground layout before project implementation.

4.2.3.1 Compressed air requirement and electrical energy demand

The typical daily schedule for mining activities as well as the respective compressed air requirements are shown in Table 4.2.

Table 4.2 – Case Study 2: Typical daily mining activity schedule.

Time	Activity	Compressed air requirement	
		Pressure [kPa]	Airflow
07:00 – 13:00	Sweeping, drilling and cleaning, hoisting.	440	High
13:00 – 20:00	No mining activity. Ventilation, refuge bays, agitation, tramming, hoisting.	250	Low
20:00 – 04:00	Zalgieter loaders, tramming, hoisting.	400-450	High. Requires 4 m ³ per operational cycle (load, collect and unload)
04:00 – 07:00	No mining activity. Ventilation, refuge bays, tramming, hoisting.	250	Low

4.2.3.2 Compressed air requirement of Shaft #1 and Shaft #2

An average total of 108 pneumatic rock drills were operated simultaneously during drilling shifts (typically each day 07:00 – 15:00) on Shaft #1 and Shaft #2 combined. These drills required 350 – 400 kPa air pressure to operate efficiently. Each drill consumed compressed air at 160 – 210 m³/h. Thus, the total estimated compressed air consumption of rock drills varied from 17 280 m³/h to 22 680 m³/h.

16 loaders were used on these two shafts combined during loading shifts (typically 20:00 – 04:00). The loaders required air at 450 – 500 kPa with each loader consuming compressed air at approximately 420 – 500 m³/h. The total compressed air requirement of loaders ranged from 6 720 m³/h to 8 000 m³/h.

A total of 56 pneumatic cylinders were operated for approximately six hours per day. The cylinders were used to operate loading boxes on each level. Each cylinder had a piston diameter of 250 mm and a stroke of 1.2 m. Each cylinder required compressed air at 350 – 400 kPa and consumed air at approximately 42.4 m³/h. The total average compressed air requirement of pneumatic cylinders – calculated over a 24-hour profile – was 594 m³/h.

Other pneumatic cylinders were also used, but could have been disregarded due to the fact that they were not operated frequently and consumed only small volumes of air. Compressed air requirements for agitation and leaks resulting from poorly maintained piping and open ends would also have been disregarded. These air losses were not easily quantified due to relevant site data being unavailable.

Figure 4.4 shows the minimum and maximum pressure requirements of Shaft #1 and Shaft #2 combined. An average pressure loss of 36 kPa was measured between the compressor delivery pressure on surface, and the pressure measured by the pressure transmitters installed on underground levels upstream of the control valves. This loss was experienced due to the mining levels being relatively close to surface, and compression due to gravitational forces not being large enough to exceed the pipe wall friction.

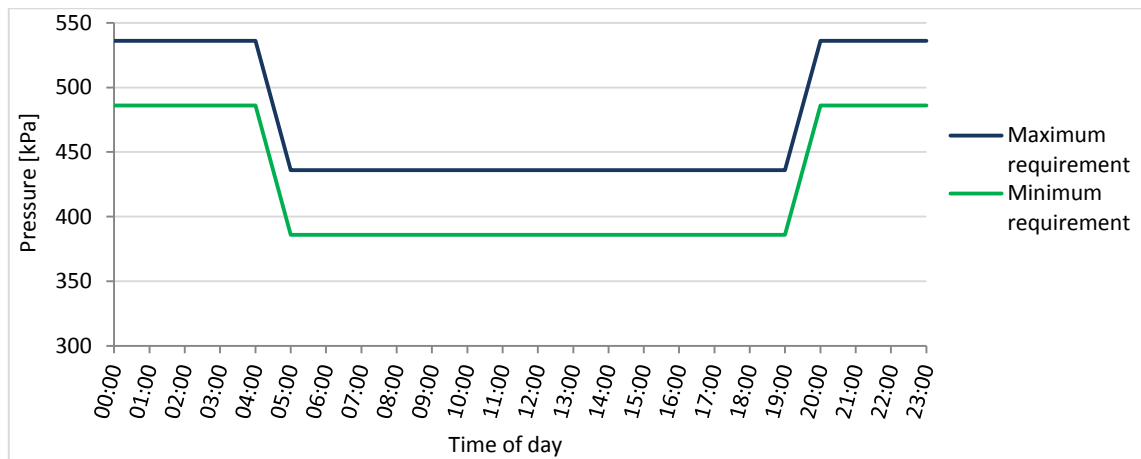


Figure 4.4 – Case Study 2: Shaft #1 and Shaft #2 compressed air pressure requirement on surface.

Figure 4.5 indicates the flow requirement of Shaft #1 and Shaft #2 combined. Note that, as stated previously, the minimum flow requirement did not take the flow required for agitation, refuge bays and air leaks into account.

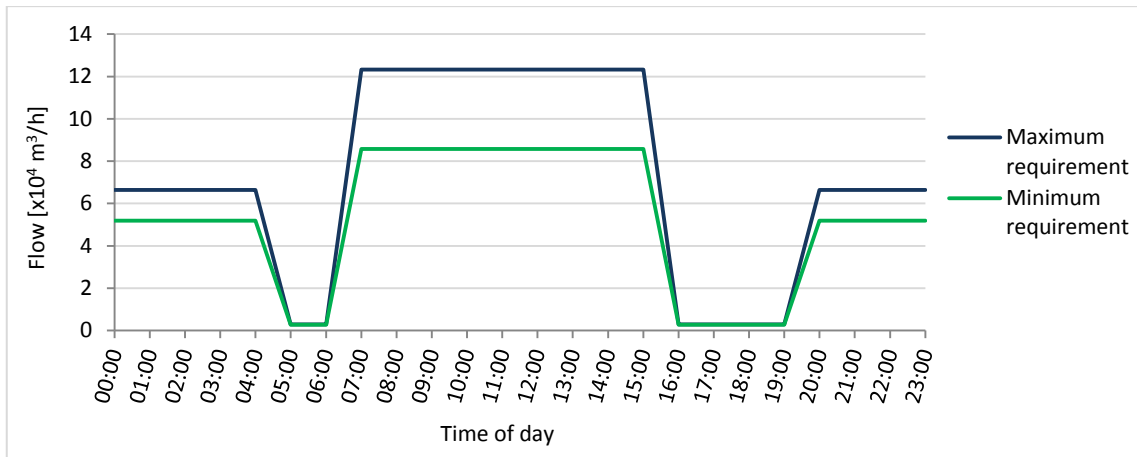


Figure 4.5 – Case Study2: Shaft #1 and Shaft #2 compressed air normalised flow requirements.

4.2.3.3 Compressed air requirement of Shaft #3

Shaft #3 made use of hydro-powered rock-drills which did not require any compressed air. However, four pneumatic loaders into account used on Shaft #3. Each loader required compressed air at 450 – 500 kPa and consumed compressed air at 420 – 500 m³/h. Compressed air for these loaders were sourced from Shaft #1. Thus, when optimising the air network the total air requirement of 1 680 – 2 000 m³/h for these loaders would be added to the air requirement of Shaft #1 and Shaft #2.

Twenty pneumatic cylinders, which operated for about 12 hours per day, were used on Shaft #3. An additional two pneumatic cylinders were operated for a period of 21 hours per working weekday on the belt level of Level #27. All cylinders had a piston diameter of 250 mm and a stroke of 1.5m. Each cylinder required compressed air at 400 kPa and consumed air at approximately 53 m³/h. The total average compressed airflow requirement of pneumatic cylinders was calculated as 625 m³/h.

The minimum and maximum delivery pressure requirements of Shaft #3 on the surface were 480 kPa and 530 kPa respectively. This was due to an average pressure loss of 30 kPa measured between the compressor delivery pressure on surface and the pressure measured by pressure transmitters installed on the upper underground levels upstream of control valves.

The total estimated minimum and maximum flow requirements for Shaft #3 remained constant at 3 811 m³/h and 4 120 m³/h respectively.

4.2.3.4 Compressed air requirement of the gold processing plant

The gold plant situated at Shaft 1# operated 24 hours each day and required compressed air at 450 – 500 kPa, with the compressed airflow demand ranging from 1000 m³/h to 1500 m³/h. This air was mainly used to operate pneumatic actuators and for agitation and oxidation.

The minimum and maximum delivery pressure requirements of the gold plant were 465 kPa and 505 kPa respectively. This was 25 kPa more than the requirement at the gold plant due to the pressure loss between the compressor delivery pressure on surface and the pressure measured by pressure transmitters installed at the gold plant. This pressure loss correlated well with expected pressure loss, as shown in Figure 2.9, for a pipe of 1 km in length and with an internal diameter of 250 mm.

The total minimum and maximum estimated flow requirements for the gold plant remained constant at 5 795 m³/h and 9 433 m³/h respectively.

4.2.3.5 Total compressed air requirement

Figure 4.6 shows the minimum and maximum pressure required on surface for Case Study 2. Due to the pressure loss between surface and underground levels the minimum pressure required on surface was higher than the minimum pressure required underground.

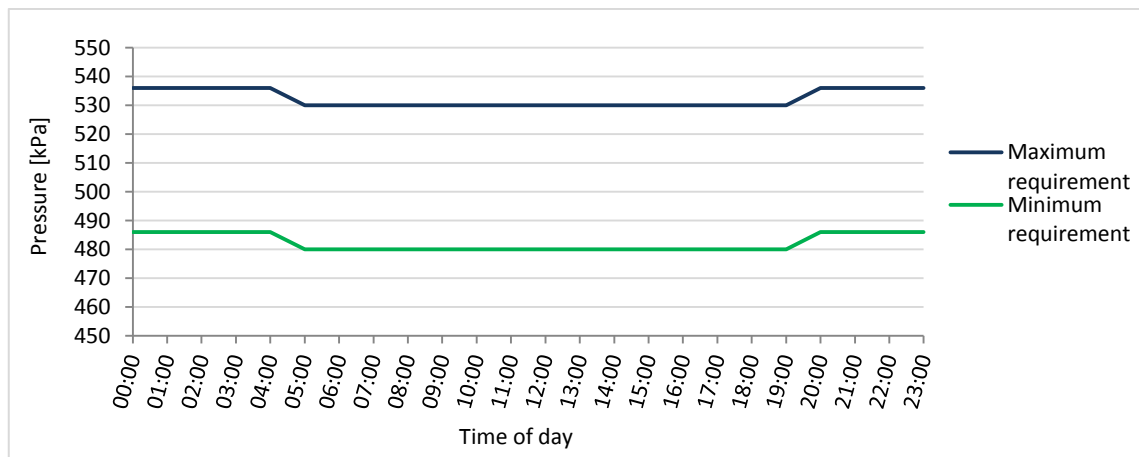


Figure 4.6 – Case Study 2: Minimum and maximum compressed air pressure required on surface.

Figure 4.7 shows the total estimated compressed airflow requirement for Case Study 2. This requirement did not take any additional air leaks into account. As stated previously, the air requirement of agitation underground and refuge bays had also been neglected.

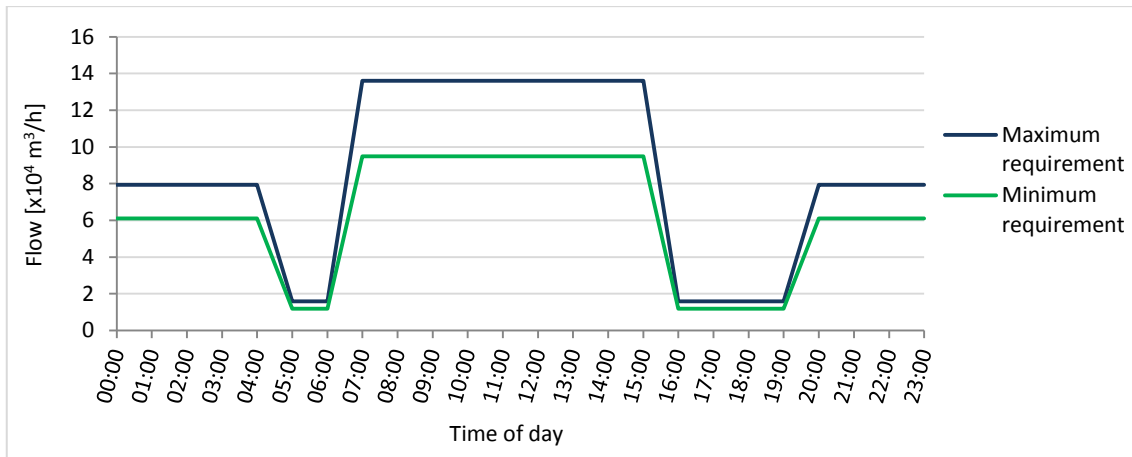


Figure 4.7 – Case Study 2: Total compressed airflow requirement.

4.2.3.6 Electrical energy required to meet compressed air demand

The estimated power required to produce compressed air according to the pressure and flow demand is shown in Figure 4.8. This was calculated assuming an overall compressor efficiency of 72%.

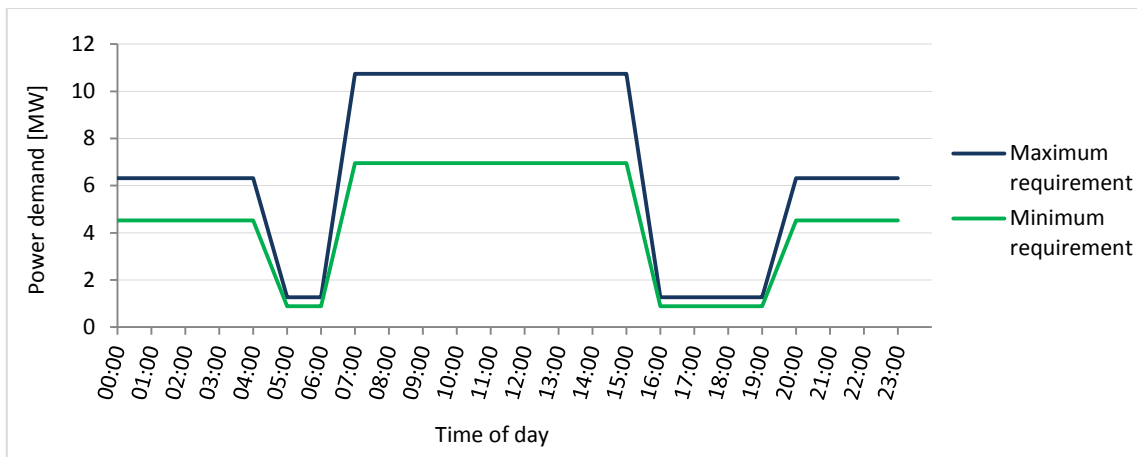


Figure 4.8 – Case study 2: Minimum and maximum power requirement.

4.2.3.7 Defining baselines

Initial investigations on this case study commenced during January 2009. The three-month period from 01 January 2009 to 31 March 2009 is referred to as the baseline period. During this period compressor power consumption, delivery pressure and flow were measured at two-minute intervals.

The data was processed into average weekday hourly profiles, similar to the method employed in Case Study 1. These profiles were referred to as the baseline profiles and formed the basis against which the performance of optimisation methods was measured. An M&V team was assigned to verify and approve these baselines.

4.2.3.8 Comparing compressed air supply with required demands

Figure 4.9 and Figure 4.10 show the baseline compressed air pressure and flow. The figures indicate that maximum demands were not only met at all times, but were generally exceeded.

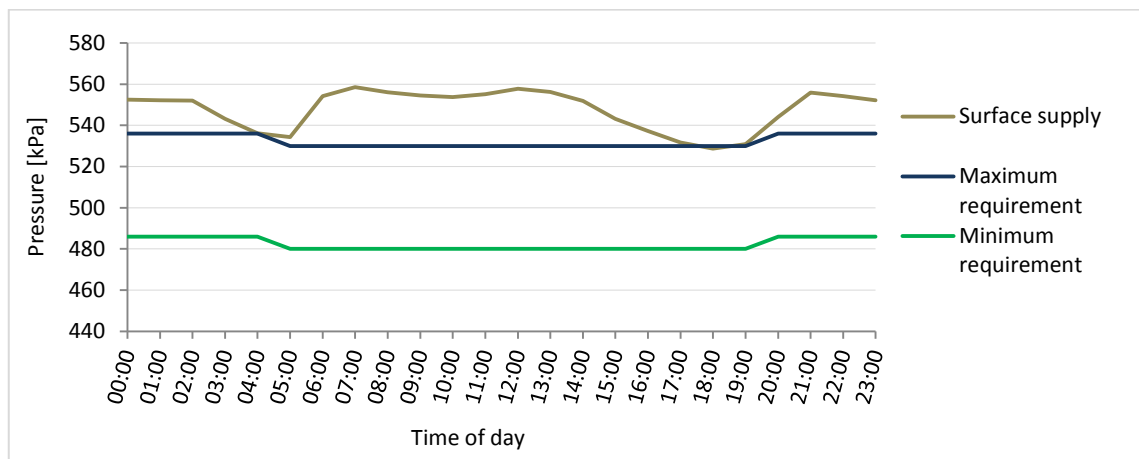


Figure 4.9 – Case Study 2: Pressure supplied from 01 January 2009 – 31 March 2009.

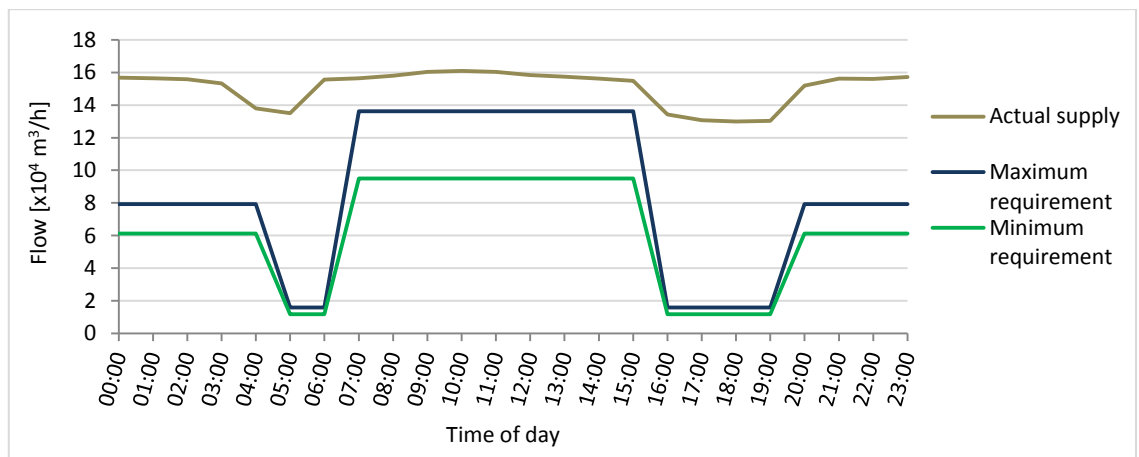


Figure 4.10 – Case Study 2: Compressed airflow supplied from 01 January 2009 – 31 March 2009.

Figure 4.11 shows the power baseline. Due to the compressed air supply that exceeded maximum demand, actual power consumption exceeded maximum expected demand on a permanent basis. This showed that the compressed air network could be significantly optimised.

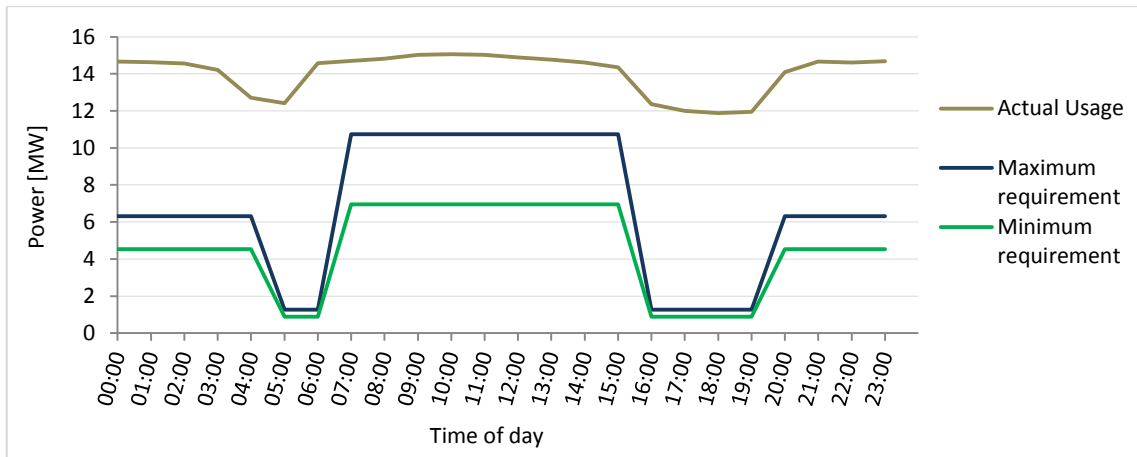


Figure 4.11 – Case Study 2: Power consumption during January 2009 – March 2009.

4.3 Proposal – Demand optimisation and equipment selection

4.3.1 Considering methods of optimisation

Table 4.3 summarises the methods that were considered for reducing compressed air demand and increasing compressed air supply efficiency.

Table 4.3 – Case Study 2: Considering methods for reducing compressed air demand.

Description	Solution
Methods of reducing compressed air demand.	
1. Reducing compressed air demand of authorised equipment use.	
1.1. Replacing pneumatic equipment with alternative nonpneumatic equipment.	1.1.1. Pneumatic rock drills have been replaced with hydro-powered rock drills on Shaft #3.
	1.1.2. Consider replacing pneumatic cylinders on Shaft #3 with hydro-powered cylinders. This was not feasible due to the shaft layout requiring additional infrastructure.
	1.1.3. Consider replacing pneumatic equipment on Shaft #1 and Shaft #2 with hydro-powered equipment. Not feasible due to high cost related to additional infrastructure requirement.

Case Study 1: Considering methods of reducing compressed air demand (continued).

Description	Solution
Methods of reducing compressed air demand (continued).	
1.2. Reducing pressure requirement of pneumatic equipment.	Consider replacing pneumatic cylinders on Shaft #3 with cylinders having a larger diameter piston. This was not feasible due to the high cost of replacing pneumatic cylinders.
2. Reducing unauthorised equipment use.	
2.1. Optimising operation time and schedule of pneumatic equipment.	Optimise compressor set points for each mining shaft and the gold plant.
2.2. Restricting compressed air supply during certain time intervals.	Install and repair underground control valves to control compressed air pressure supplied to each mining section.
3. Reducing air leaks.	
3.1. Regular maintenance and inspection of piping network.	Implement CALDS.
3.2. Blanking off of unused sections.	Already implemented on levels where mining activities are no longer conducted.
Methods of increasing compressed air supply efficiency.	
4. Optimising the air network.	
4.1. Correct sizing of piping system.	Replace piping section on Shaft #3, Level 27.
4.2. Separation of air networks.	Separate network to allow supply pressure to be reduced to Shaft #1 and Shaft #2 during low demand periods.
4.3. Maintaining network components.	Already in place.
5. Optimising air compression.	
5.1. Implement an optimised control system incorporation IGVC.	Already implemented.
5.2. Reducing compressor inlet air temperature.	Not considered practical at this site.
5.3. Installing after- and intercoolers.	Intercoolers are installed between compressor stages.
6. Optimising electrical motors driving compressors.	
6.1. Using high-efficiency electrical motors.	Motors are 90% efficient and will not be replaced.
6.2. Implement VSDs.	Not feasible due to high cost related to VSDs.
Legend	
	Methods not feasible or practical.
	Additional methods implemented.

4.3.2 Applying optimisation methods

4.3.2.1 Method 2- Reducing unauthorised equipment use

Compressed air optimisation methods (such as compressor supply pressure control) have been implemented before this study commenced which resulted in a reduction of compressed air consumption through authorised and unauthorised equipment use.

This was done by means of changing the compressor pressure supply set points according to the varying compressed air demands. The effects of this energy saving project on compressed air supply delivery pressure is shown in Figure 4.12. The result was a reduction in supply pressure during certain times of the day.

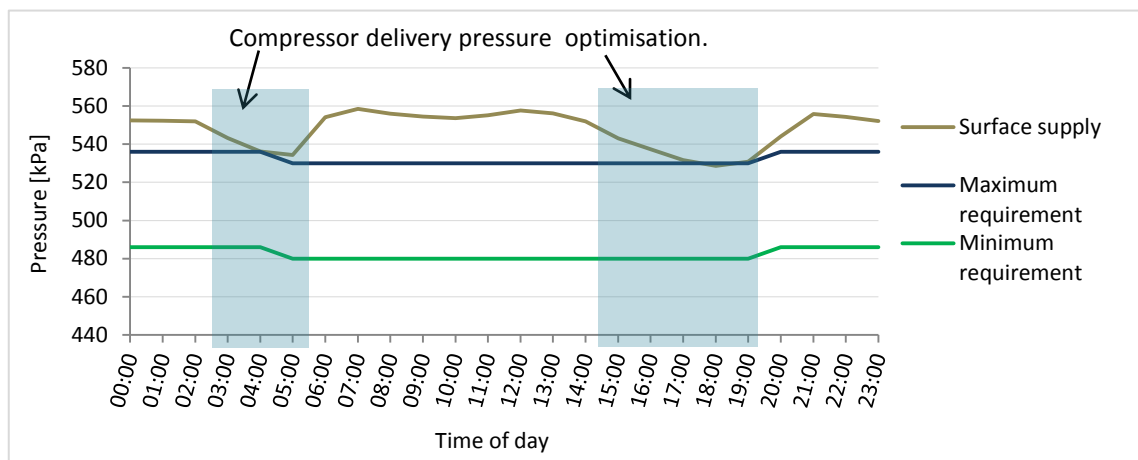


Figure 4.12 – Case Study 2: Average compressed air pressure supplied during January 2009 – March 2009.

Supply pressure remained above the required maximum despite the reduction in supply pressure due to implementation of these optimisation methods. Airflow also exceeded the maximum requirement as shown in Figure 4.10.

In order to reduce excessive air usage, control valves (similar to those shown in Figure 4.13) were installed on the air network of each underground mining level. These valves were installed before this study commenced to regulate the flow supplied to each individual mining level. Each valve regulated the flow, measured from a flow meter installed upstream of the control valve, whenever a predetermined value was exceeded.

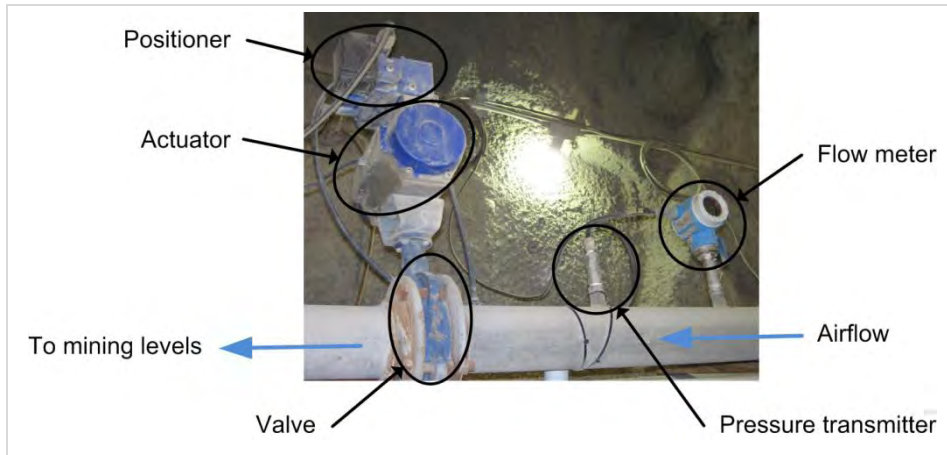


Figure 4.13 - Case Study 2: Underground control valve setup.

Figure 4.14 shows the average flow supplied to underground mining levels on Shaft #1 and Shaft #2 combined after implementation of underground control valves. As indicated the flow supplied to underground mining levels exceeded the maximum expected demand for all time periods despite control valves restricting flow during low demand periods. Further investigation revealed that this was due to inaccurate readings from flow meters as a result of the large moisture content in the compressed air supply line.

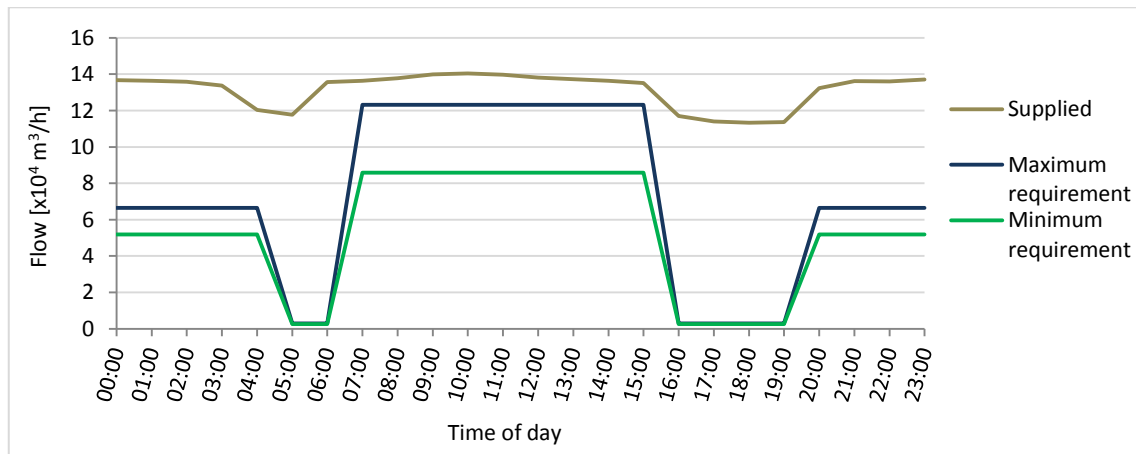


Figure 4.14 – Case Study 2: Average flow requirement and supply to Shaft #1 and Shaft #2 combined from 01 January 2009 to 31 March 2009.

It was proposed as part of this study that each underground control valve must be controlled according to the pressure, instead of the flow supplied downstream of the control valve. The proposal was based on the fact that pressure transmitters are much more reliable and robust than flow meters and would provide sustainable accurate readings according to which control valves could be controlled. By restricting the pressure supplied to a mining level the maximum flow rate of compressed air that could be obtained on that level would also be reduced. This follows from the Bernoulli flow principle [36].

Since the proposal only allowed for the pressure to be regulated, the possibility existed that volumetric flow would increase without restriction if the control valve remained fully open. To avoid this scenario alarms had to be programmed into the SCADA which had to inform control room operators when the flow increased beyond a certain maximum. This allowed personnel to respond by restricting the flow and investigating the situation.

4.3.2.2 Method 3 – Reducing air leaks

Similar to Case Study 1, investigations revealed that a large amount of air leaks were present on the air network. Air leaks were found on surface near the compressor house, in mining shafts, on mining levels and in the gold plant and continue to exist. Implementation of CALDS was also proposed for this case study.

4.3.2.3 Method 4 – Optimising the air network

Separating the network into a high- and low-pressure side is similar to the method discussed for Case Study 1 in Section 3.4.2.3.

Since Shaft #3 and the gold plant combined required a much lower maximum flow rate than Shaft #1 and Shaft #2 combined, the majority of compressors should be available to supply Shaft #1 and Shaft #2. The proposed compressed air network layout for creating two separate supply manifolds is shown in Figure 4.15 - Figure 4.17,. Proposed changes included closing certain manual valves and installation of one PLC, four control valves, pressure transmitters and flow meters.

With reference to Figure 4.17 the proposed control philosophy according to which the network should be controlled on surface was as follows:

1. Compressors
 - 1.1. VK32-5 and one VK10 would be run on a permanent basis to supply compressed air to Shaft #3 and the gold plant. The maximum combined system demand between these two sections was below the combined supply capacity of the compressors. Therefore, sufficient air would be available at all times. VK32-6 should serve as the backup compressor for VK32-5.
 - 1.2. The remaining compressors could be used to supply compressed air to Shaft #1 and Shaft #2. Whenever the operating compressors supplied excess air and output could not be reduced further, one compressor could be stopped.
 - 1.3. Compressor set points had to be set according to the required supply. The set points for compressors VK32-5, VK32-6, VK10-1 and VK10-2 had to be set according to the greater minimum demand between Shaft #3 and the gold plant. The set points of the

remaining compressors had to be set according to the minimum demand of Shaft #1 and Shaft #2.

2. Control valves

- 2.1. One pressure set point would be sent to the installed PLC which would control the control valves on surface. This set point had to be the higher pressure requirement between Shaft #3 and the gold plant.
- 2.2. Control valves CV 1 and CV 4 should remain fully opened. These valves would serve as backups for control valves CV 2 and CV 3. If CV 2 failed, CV 1 would take over control; and if CV 3 failed, CV 4 would take over control.
- 2.3. Control valves CV 2 and CV 3 should be controlled according to the average measurement obtained between pressure transmitters PT 3 and PT 4. The valves should open if the average reading is above the pressure set point of Shaft #3 and the gold plant. This would allow any excess air to be supplied to the manifold providing Shaft #1 and Shaft #2 with air.

3. Safety interlocks

- 3.1. All control valves were fail-open. That is, when pressure supplied to the relevant valve actuator was not adequate or power supply to the actuator failed, the valve would open automatically.
- 3.2. If the compressed air requirement of Shaft #3 and the gold plant can not be met and both control valves CV 2 and CV 3 are fully closed the set points to all compressors should be changed to the greater minimum demand of all surface areas and all control valves should open.

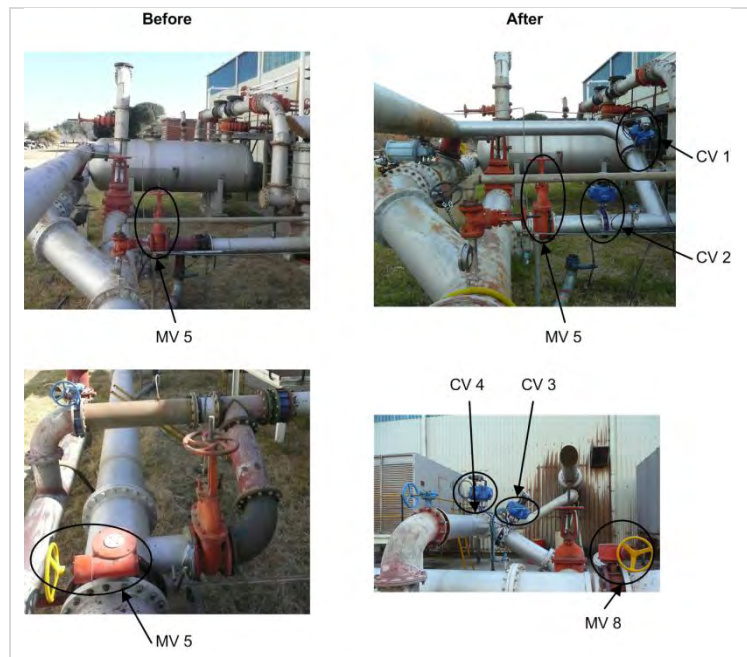


Figure 4.15 - Case Study 2: Control valves installed on surface.

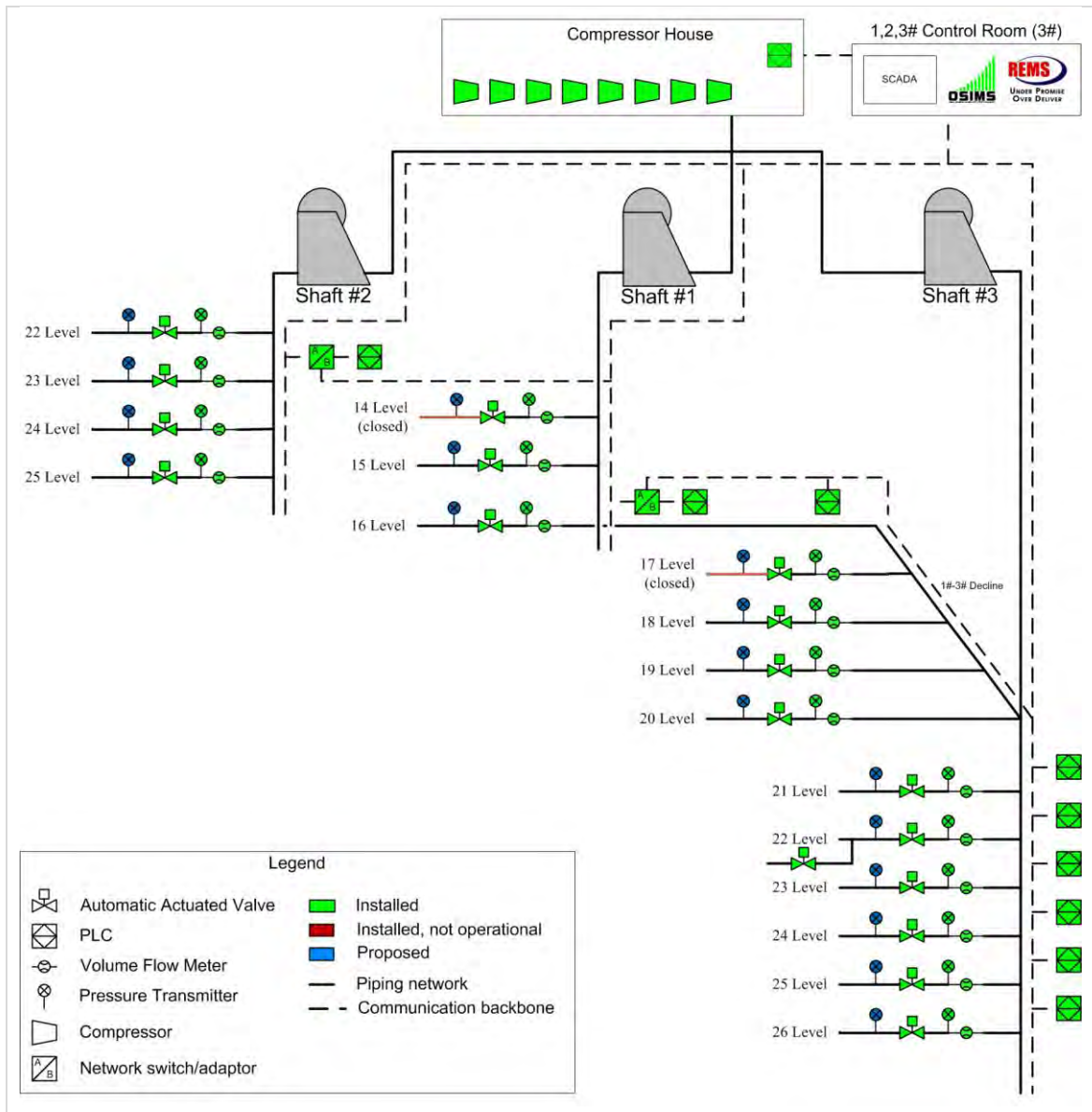


Figure 4.16 - Case Study 2: Underground installations.

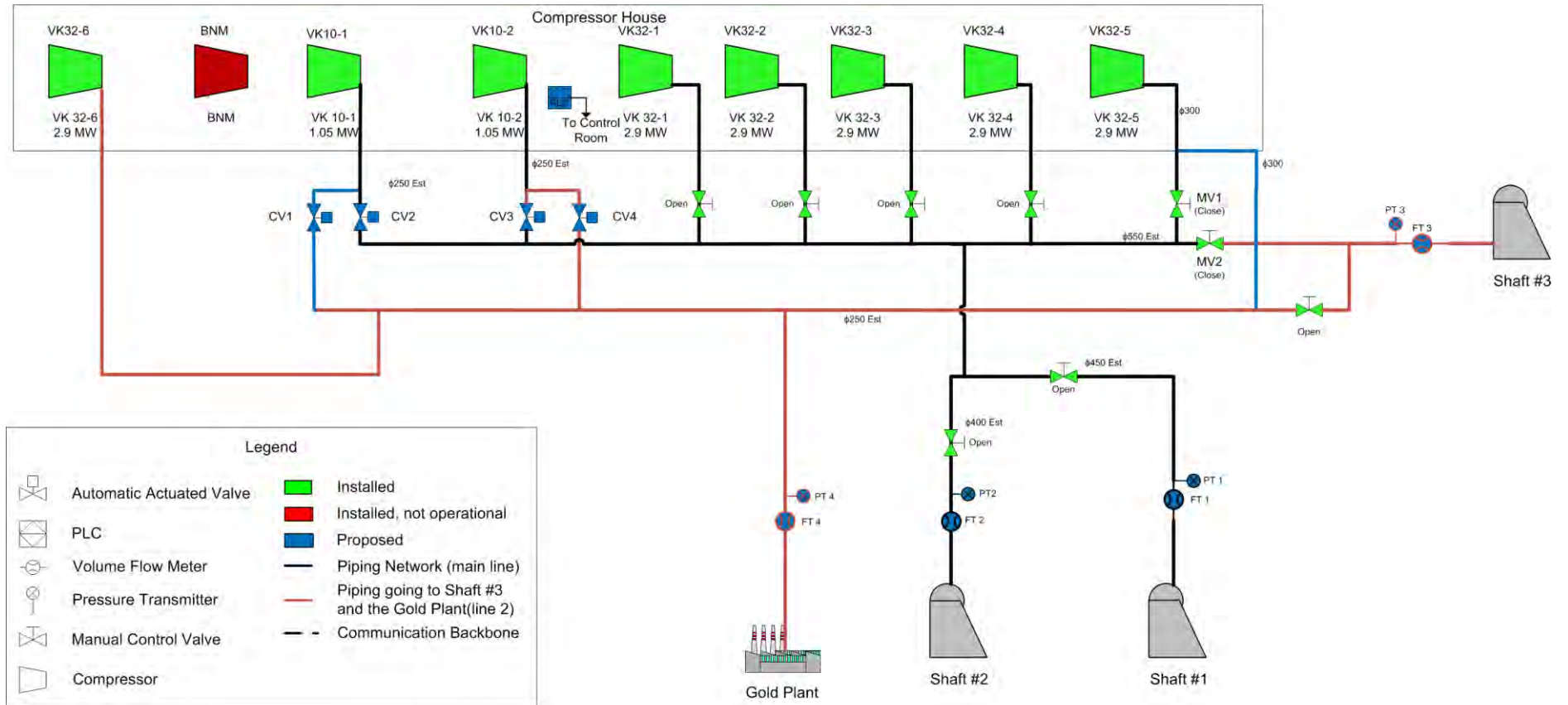


Figure 4.17 – Case Study 2: Proposed changes to the surface air network.

4.3.3 Theoretical analysis – Estimated power savings

According to Figure 4.11 a minimum and maximum average saving of 7.3 MW and 9.5 MW could be realised respectively. These savings were, however, overoptimistic since flow losses due to air leaks, agitation, refuge bays, workshops and cleaning equipment had been neglected.

Similar to Case Study 1, it would be assumed that the minimum flow demand was determined by the requirement of the loaders. The resulting, expected minimum power consumption and anticipated power saving profiles are shown in Figure 4.18. As shown the baseline power supplied could be broken down into the sums of total minimum power demand, total minimum expected saving and total possible additional savings for each of the major sections supplied with compressed air.

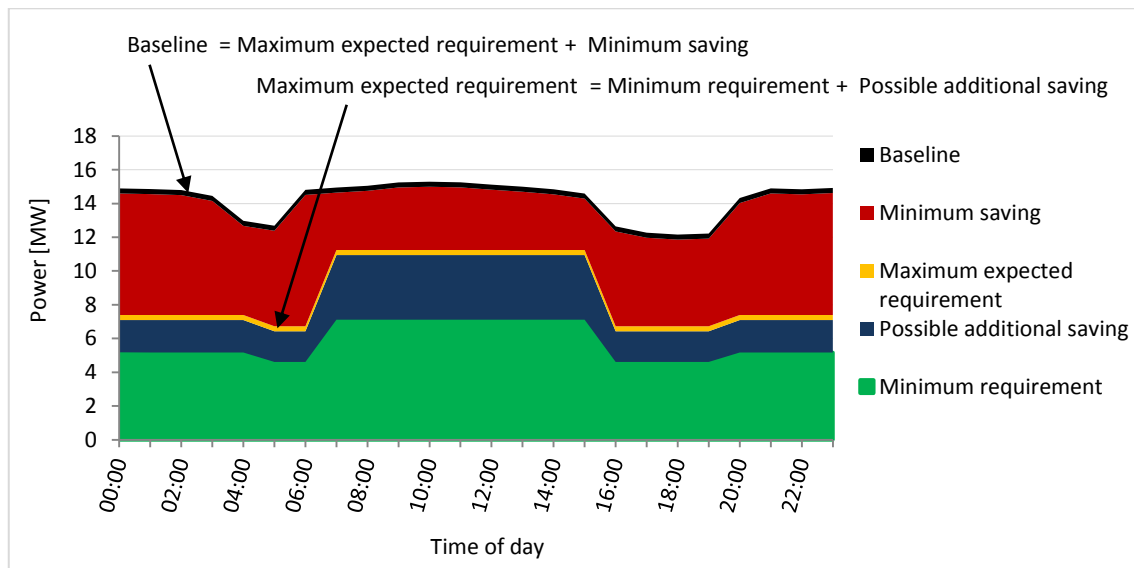


Figure 4.18 – Case Study 2: Accumulated expected power usage and saving profiles for Case Study 1.

The average daily baseline power consumption was 14.0 MW. As shown in Figure 4.19 the expected maximum average daily power consumption – which was calculated using the same method used in Case Study 1 – was 8.3 MW. If the power consumption was lowered from the baseline to this maximum expected demand of 8.3 MW, the minimum expected saving of 5.3 MW was achieved.

A possible additional saving of 2.6 MW could be achieved if the compressed air supply was accurately controlled according to the minimum demand which was estimated to be 5.8 MW.

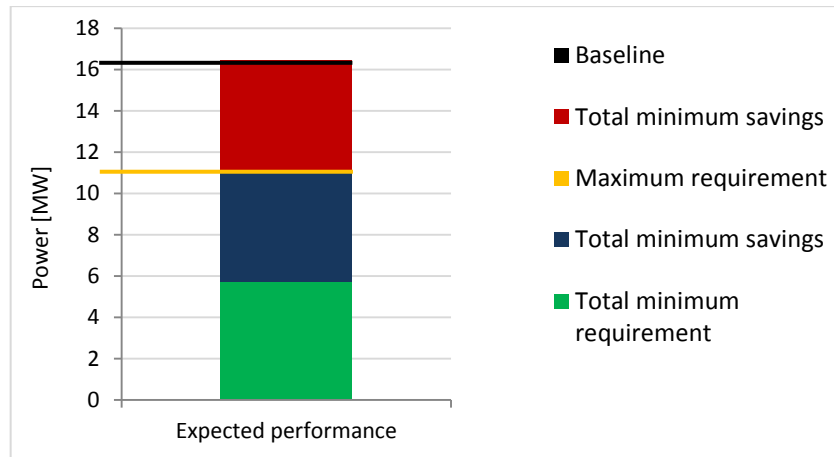


Figure 4.19 – Case Study 2: Estimated average daily power usage, minimum saving and possible additional savings.

As shown in Figure 4.20 expected savings were mostly obtained by optimising supply to Shaft #1 and Shaft #2. Thus, it was critical that the compressed air supply to these sections was controlled accurately according to the expected demand.

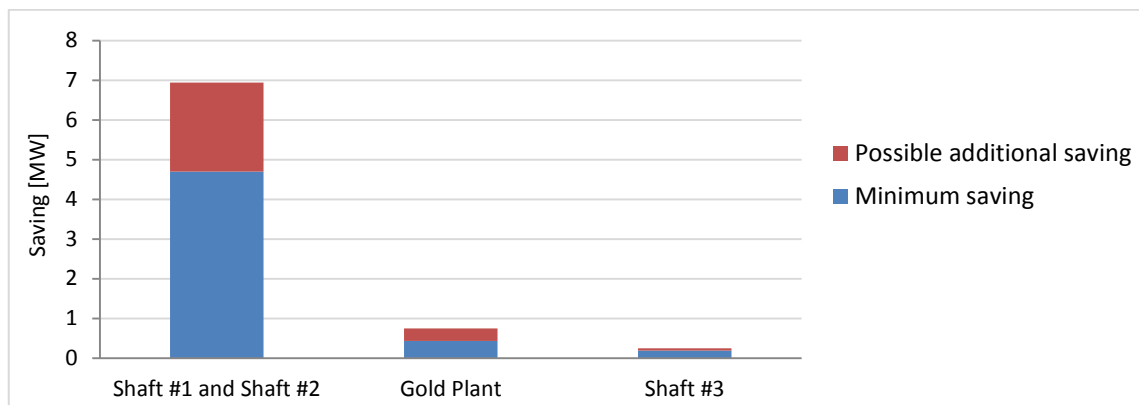


Figure 4.20 – Case Study 2: Breakdown of expected power savings for Case Study 1.

4.4 Results

The first proposal for integrating methods of reducing compressed air usage was presented during October 2009. Hereafter, the proposal was discussed with mining personnel and altered. Verification investigations commenced during January 2010 and, similar to Case Study 1, the final proposal was approved by May 2010. Orders on subcontractors for installing required equipment and development were placed during June 2010.

Figure 4.21 shows the total weekday average power usage of compressors. An initial average daily saving of 1.8 MW was realised between 01 January 2010 and 31 March 2010. This saving was realised due to manual controlled experimental tests optimising compressed air supply set

points which commenced after the first-off proposal. These tests resulted in a permanent optimised compressed air supply schedule being followed by control room operators.

Hardware installations required for full optimisation according to the proposal were finalised during January 2011. Due to optimised control of underground control valves an additional saving of 3 MW was realised. During this testing period it was found that the control valve actuators installed on surface did not operate correctly and had to be replaced. For this reason the air network could not be fully optimised and separation of air networks could not be implemented.

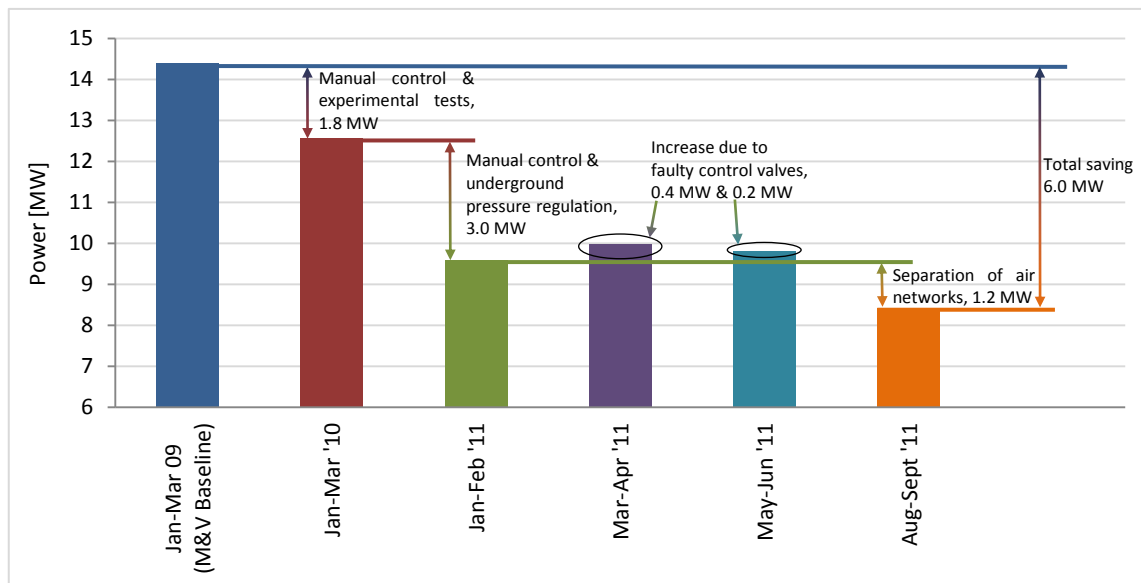


Figure 4.21 – Case Study 2: Power usage of compressors during implementation of saving interventions.

Furthermore, during March 2011 some underground control valves failed to operate effectively. This was due to positioners that malfunctioned as result of the high moisture content in the underground supply lines. These positioners were eventually replaced during July 2011.

Data obtained during July was not considered due to mining activity that was drastically reduced during this period. This was due to the mine being closed during certain time intervals because of fatality incidents and mass-action labour strikes that commenced.

Surface control valves that were found to be incorrectly specified were replaced during July 2011. Final tests and implementation were also done during July and full automatic control of the system commenced towards the end of July 2011. An additional average saving of 1.2 MW was realised between 01 August 2011 and 30 September 2011. This was due to full implementation of compressed air network optimisation which included the separation of air

supply manifolds into high- and low-pressure systems. Figure 4.22 shows the resulting power usage compared to the expected requirements and baseline.

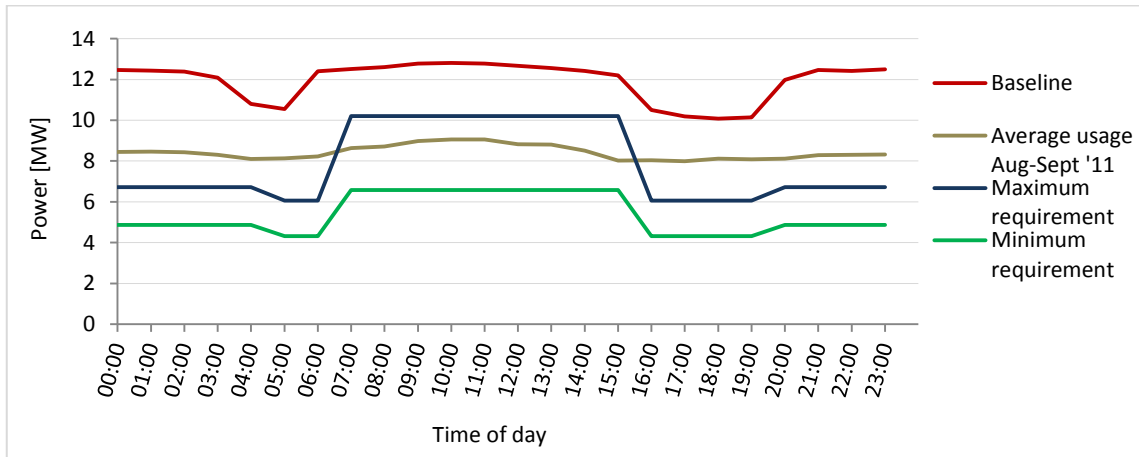


Figure 4.22 – Case Study 2: Power profiles .

Implementation of air network separation allowed mining personnel to reduce the pressure and flow supplied to Shaft #1 and Shaft #2 during low demand periods. It resulted in additional saving during August and September 2011.

Figure 4.23 shows the pressure requirement and supply to Shaft #1 and Shaft #2 during baseline and final project implementation. The figure shows that the pressure management showed a significant improvement over the original baseline. Pressure supplied remained below 500 kPa for most periods and followed the minimum demand during non-drilling periods.

Tests showed that although pneumatic drills could operate with air at 350 – 400 kPa, mining personnel was not satisfied with these low pressures. For this reason supply pressure was increased during drilling periods.

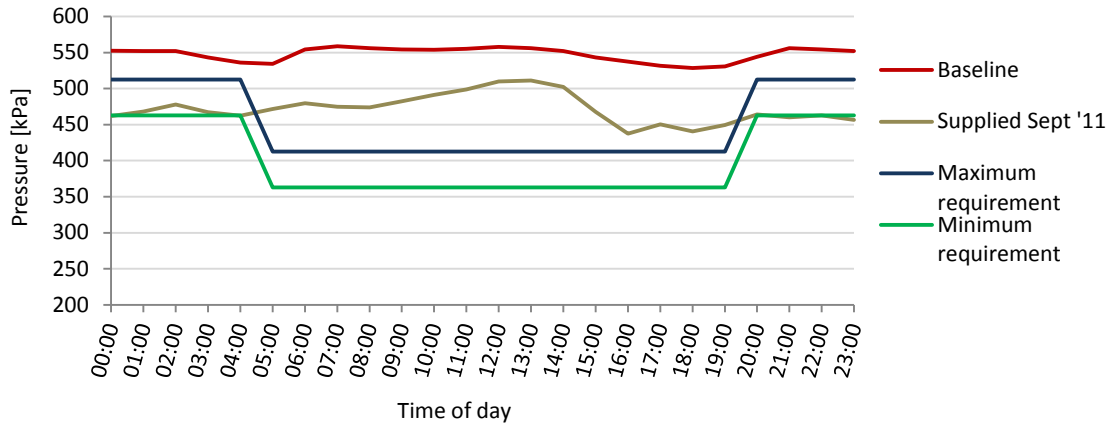


Figure 4.23 – Case Study 2: Average surface pressure requirement and supply to Shaft #1 and Shaft #2 after implementation of all saving initiatives.

Figure 4.24 shows the flow requirement and supply of Shaft #1 and Shaft #2. The figure indicates that management of the airflow consumption of the shafts improved a great deal compared to the original baseline.

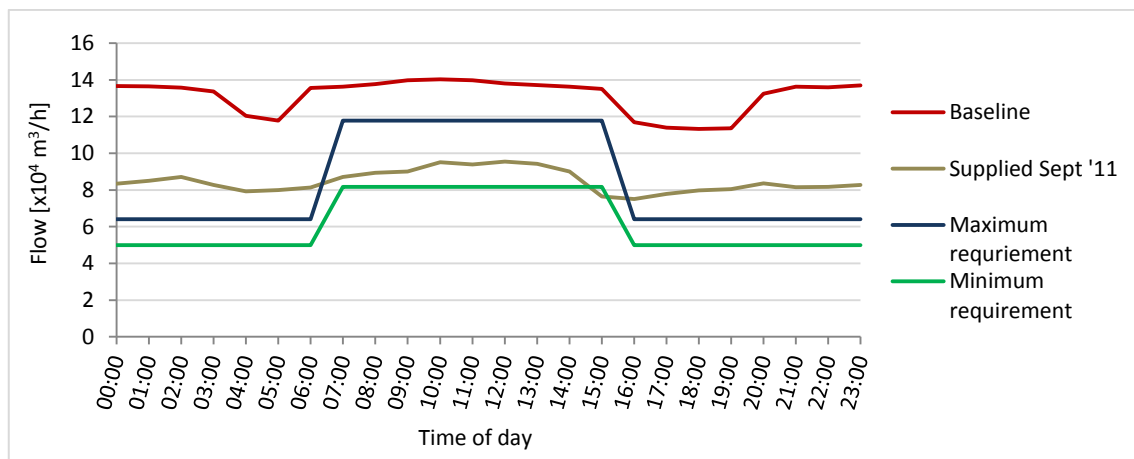


Figure 4.24 – Case Study 2: Average daily airflow consumption of Shaft #1 and Shaft #2 after implementation of saving interventions.

Figure 4.25 shows the pressure requirement and supply to Shaft #3 and the gold plant combined during baseline and final project implementation. The figure shows that the pressure was managed above the required minimum at all times and never reached the maximum expected requirement.

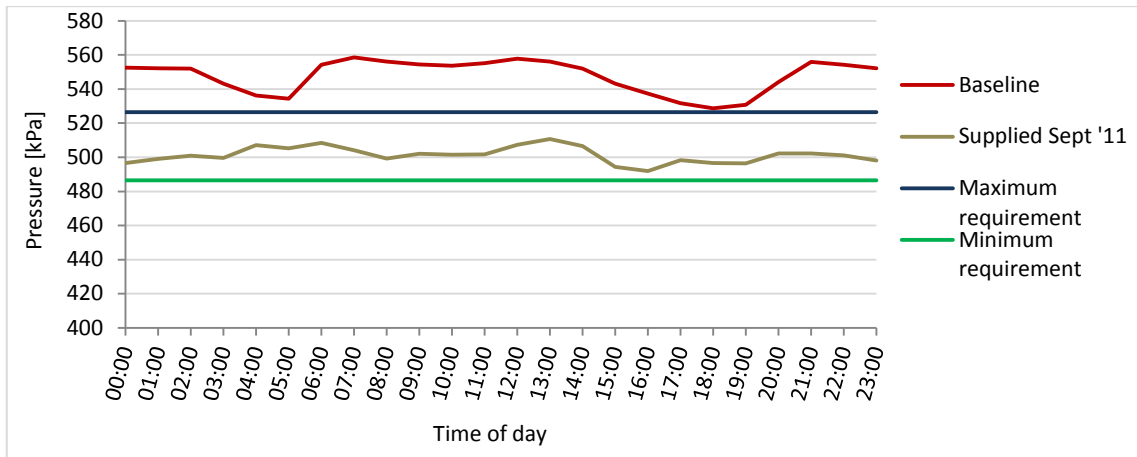


Figure 4.25 – Case Study 2: Average surface pressure requirement and supply to Shaft #3 and the gold plant after implementation of all saving initiatives.

Figure 4.26 shows the total flow requirement and supply of Shaft #3 and the gold plant combined. The figure indicates that management of the airflow consumption of these sections improved a great deal compared to the original baseline and never reached maximum expected demand.

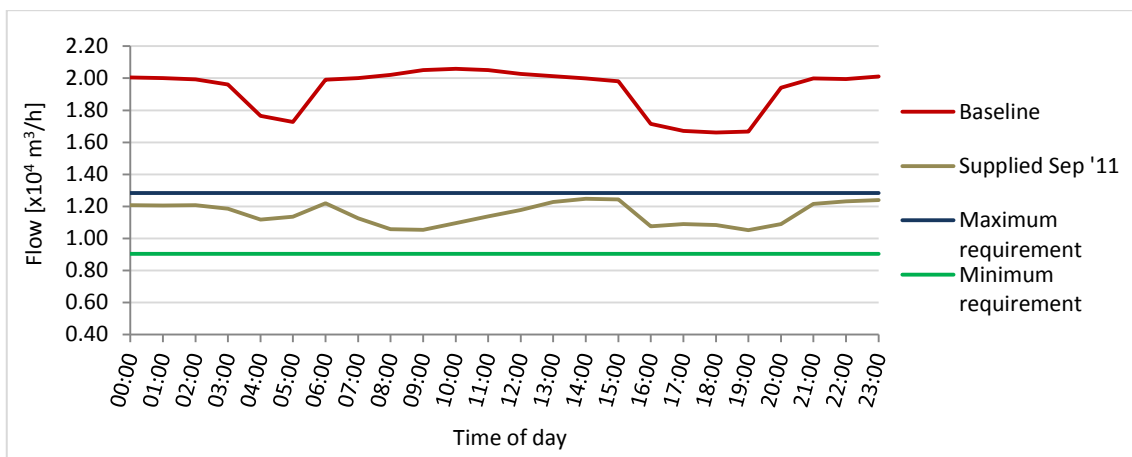


Figure 4.26 – Case Study 2: Average total flow requirement and supply to Shaft #3 and the gold plant after implementation of saving initiatives.

4.5 Conclusion

Initial investigations commenced during January 2009 and proceeded until end March 2009. An average weekday daily power usage baseline of 14.4 MW was measured.

The delivery pressure set points of compressors were optimised. This resulted in a saving of 1.8 MW, which was approximately 13% of the original power baseline.

The compressed air consumption of authorised and unauthorised equipment used was reduced significantly by optimising compressed air pressure supply. This was implemented in two stages during different time periods. Stage 1 of pressure supply optimisation, where air pressure supplied to each underground mining section was restricted individually, was operational from January 2011. Flow meters were used to raise alarms should the flow through a section exceed the maximum flow allowance. This stage of pressure supply optimisation resulted in a saving of 2.9 MW, approximately 21% of the power baseline.

Stage 2 of the pressure supply optimisation was implemented on surface. The single compressed air system was separated into two distinct high- and low-pressure systems. This resulted in a saving of 1.2 MW, approximately 8% of the power baseline.

Air leaks were documented and repaired. CALDS created a strong awareness of air leaks and resulted in greater attention given by personnel to maintenance and repairs of these leaks.

By restricting availability of compressed air a total power saving of 6 MW, approximately 42% of the measured baseline, was realised. Pressure and flow supplied to Shaft #1 and Shaft #2 were improved on average by 11% and 35.5% respectively. Pressure and flow supplied to Shaft #3 and the gold processing plant were improved by 8.5% and 60% respectively. Total airflow consumed by compressors was reduced by 40 000 m³/h, approximately 30% of the baseline.

Despite increases in production during 2011, the compressed air usage and power requirements were reduced significantly. The air consumption of Shaft #1 and Shaft #2 could be reduced further; however, additional savings that could be realised without major new developments would be small and would not justify related costs and effort.

By implementing integrated control the air supplied to each end-user could be continuously controlled and monitored. This resulted in a significant increase in savings compared to limited control implemented in Case Study 1.

5 Conclusion and recommendations

5.1 Conclusion

Studies showed that 14.5% of the total energy produced in South Africa was consumed by the mining sector and another 26.6% by the industrial sector. Furthermore, 10% of this energy was consumed to produce compressed air.

Many studies have focused on reducing electrical energy required to produce compressed air. However, these studies focused on single methods in isolation. This study investigated the effect of combining these methods to obtain maximum energy savings. Further investigations were done to determine how these methods could specifically be applied to typical South African mines. Thus, the study included industrial sectors, but focused on the mining sector in particular.

Two different mining sites were considered as case studies. Each case study utilised a plant air compressed air network layout which supplied air to at least one mining shaft and one gold processing plant.

Certain optimisation methods were already implemented before these case studies commenced.

Application of additional methods to reduce compressed air energy requirements were analysed for each site. This was done by first doing a detailed site investigation. Various methods were then considered to optimise the compressed air system. Electrical energy savings and costs were then evaluated. Graphs, showing initial baseline power profiles, were presented together with the electrical power profiles showing the proposed electrical energy savings. Practical application methods were discussed with mining personnel, and finally implemented after the proposed initiatives were approved.

Although proposed solutions for both studies were similar, a unique proposal was presented for each study. Both studies incorporated pneumatic-actuated, variable-opening control valves to control compressed air supplied to end-users. In the first study, only the compressed air supplied directly from the compressors on the surface was controlled.

In the second case study, where integrated control was applied, air pressure supplied on surface and to the each individual underground mining level was controlled. Both case studies also included further control optimisation, such as separation of air manifolds to allow multiple header supply pressures.

The implemented systems were tested and optimised for a minimum period of three consecutive months, referred to as the performance assessment (PA). During this period training was also given to mining personnel. After the PA period the system was officially handed over to the mine.

During initial investigations the energy usage of compressors were measured and captured at two-minute intervals over three consecutive calendar months. From this data the reference power baseline – averaged out over a typical 24-hour working weekday – was established. Similarly, where possible, compressed air pressure and flow data was also recorded to establish appropriate baselines. It was against these baselines that the performance of the energy saving initiatives was measured.

Table 5.1 shows a comparison between the two case studies and their limitations. In Case Study 1, due to a limited budget, full optimisation could not be implemented. This resulted in limited application of energy saving methods and control of air supply. Results showed that where full integration could be implemented savings were doubled.

Case Study 2 did not have the same budget constraint and the full integrated control of air supply could be implemented. The average 24-hour power usage for this study was measured as 14 MW. Minimum and maximum savings were estimated to be 5.3 MW and 7.9 MW respectively. A final saving of 6.0 MW, approximately 42.9% of the baseline, was realised. Maximum savings could not be obtained due to the malfunctioning instrumentation controlling the air supply.

Pressure and flow transmitters installed during Case Study 2 allowed compressed airflow and pressure supply to be monitored at each underground mining level. This resulted in the following benefits:

1. Continuous monitoring of compressor power usage allowed personnel to make use of the most efficient compressors.
2. Irregular peaks in flow consumption allowed mining personnel to effectively identify air leaks and unauthorised use of compressed air on each mining level.
3. By monitoring the pressure supplied to underground mining levels the required compressor delivery pressure could be accurately determined.
4. Pressure transmitters allowed sustainable control of air underground. Flow meters allowed maximum flow supplied to be limited, however these instrumentation were not reliable or accurate.

Table 5.1 – Comparison of energy saving initiatives.

Description	Limited control	Integrated control	Cost per item
Infrastructure requirement			
Power loggers	Required		Medium
Pressure loggers	Required only at compressor outlets	Required on all sections	Low
Flow loggers	Only on compressor inlets or outlets	On all sections	Medium – High
Maintenance	Low	High	Medium
Continuous monitoring capabilities			
Power	Limited to power logger readings that must be downloaded from meters installed in the substation supplying electrical energy to compressors	Continuous monitoring from the SCADA	Medium – High (depending on IT infrastructure installed on site)
Pressure	Limited to compressor delivery pressure	Compressor delivery pressure and pressure supplied to all sections	
Flow	Limited to compressor delivery flow	Compressor delivery flow and flow delivered to all sections	
Production activities	Limited indication of total air consumption and related cost of production activities	Detailed breakdown of compressed air consumption and related cost of activities conducted at each section	Cost of production activities and air leaks increase where monitoring capabilities are limited.
Air leaks*	Indication of air leaks limited to analysing total air consumption	Air leaks can be identified at a specific section by analysing the usage at the specific section	

*Although fixing air leaks is a very basic energy management principle it is seldom properly implemented in the mining environment.

Comparison of application of energy saving initiatives (continued).

Description	Limited control	Integrated control	Cost per item
Control capabilities			
Compressor pressure set points	Each compressor delivery pressure set point can be changed individually		Medium – High
Compressed air supplied to major sections	Control limited to pressure supply	Possibility of controlling both pressure and airflow supplied	Medium – High
Compressed air supplied to subsections	Limited to control of air supplied to major sections	Control pressure and flow supplied	Pressure control: Low Flow control: Medium – High
Performance			
Actual savings	19%	42%	
Sustainability of savings	Medium – low	Medium – high	

5.2 Limits of this study and recommendations for future work

Although the focus of this study was on producing an integrated solution for typical South African mines, it is expected that these results could be applied to any industry that use compressed air. Future studies should focus on combining similar methods of air network optimisation in industrial plants.

Proposed solutions for optimising compressed air networks did not include optimising production schedules. Since electrical energy cost in South Africa is dependent on the time of use, further savings can be realised by changing the time at which high energy-demand production activities are conducted.

Since a large amount of compressed air is wasted due to negligence and the careless attitude of personnel, incentives or enforcing procedures could be introduced. Better and more frequent training of mine personnel is strongly recommended to motivate the staff.

A CALDS was implemented on each of the case studies. This system only allows the documenting of located air leaks. The actual location of each leak is determined by manual inspection. The viability of sourcing or developing a leak-detection system that could accurately locate the position of a leak would add significant value to the CALDS.

This study did not include increasing the efficiency of pneumatic equipment. Additional savings can be realised by increasing the efficiency of pneumatic drills, loaders and cleaning hoses and/or nozzles.

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Appendix A - Calculations

A.1 Calculations related to Section 2

A.1.1 Air consumption of a pneumatic cylinder

The air consumption for a single stroke of a pneumatic cylinder can be calculated as follows:

$$V = \frac{\pi}{4} D^2 S$$

Equation A.1 – Volume of a cylinder.

Where

V – Volume [m³] consumed for a single stroke of length S.

D – Diameter of piston inside the cylinder [m].

S – Stroke length [m].

Consider a cylinder with piston diameter of 200 mm and a stroke of 1 m. The volume of air consumed (V) is calculated as follows:

$$V = \frac{\pi}{4} D^2 S = \frac{\pi}{4} (0.2)^2 (1) = 31.42 \times 10^{-3} \text{ m}^3$$

If the time t_s to complete a single stroke is taken as ten seconds and the cylinder is operated constantly for a period T_{op} of one hour, the total volume consumed becomes:

$$V_{1h} = V \frac{T_{op}}{t_s} = (31.42 \times 10^{-3}) \frac{(1 \times 60 \times 60)}{(10)} = 11.3 \text{ m}^3$$

A.1.2 Flow rate compressed air produced by compressors

The delivery volume flow rate of air delivered by a compressor can be calculated from known inlet and outlet conditions using the perfect gas law [35]. The calculation can be done as follows:

$$\frac{P_i V_i}{T_i} = \frac{P_d V_d}{T_d}$$

Equation A.2 – Ideal gas law (1).

Where

P – Air pressure [kPa].

V – Volume flow rate (or volume) [m³/s] or respectively [m³].

T – Absolute temperature [K]. $x[^\circ\text{C}] = 273.15 + x [K]$.

i – Denotes inlet (initial) conditions.

d – Denotes outlet (final) conditions.

Consider a compressor consuming ambient air (101.3 kPa and 20°C) at a rate of 10 000 m³/h (2.78 m³/s) and compress it to 500 kPa. The final temperature is 30°C. The delivery volume flow rate then becomes:

$$\frac{P_i V_i}{T_i} = \frac{P_d V_d}{T_d}$$

$$\therefore V_d = \frac{P_i V_i T_d}{T_i P_d} = \frac{(101.3 \times 10^3)(2.78)(273.15 + 20)}{(273.15 + 30)(500 \times 10^3)}$$

$$= 0.545 \text{ m}^3/\text{s} \text{ (1961 m}^3/\text{h)}$$

It can be seen that the delivery volume flow rate is inversely proportional to the pressure ratio and directly proportional to the temperature ratio.

A.1.3 Friction losses on compressed airflow due to piping

Pressure loss of fluid flowing through a pipe can be calculated as follows:

$$\Delta P = \rho g h_f$$

Equation A.3 – Pressure due to head.

Where

ΔP – Pressure drop [kPa] due to friction in piping.

ρ – Density of the fluid [kg/m³].

g – Gravitational acceleration. This is taken as 9.81 m/s².

h_f – Head loss [m] due to friction.

The density of air is calculated using the ideal gas law:

$$\rho = \frac{P}{RT}$$

Equation A.4 – Ideal gas law (2).

Where

ρ – Air density [kg/m³]

P – Absolute air pressure [kPa].

R – Gas constant taken as 0.287 kJ/kg-K.

T – Absolute air temperature [K].

Head loss due to friction is calculated using the Darcy-Weisbach equation [36]:

$$h_f = f \frac{L v^2}{d 2g}$$

Equation A.5 – Darcy-Weisbach equation for head loss.

Where

- h_f – Headloss [m].
- f – Friction factor.
- L – Length of piping [m].
- d – Inner diameter of pipe [m].
- v – Flow velocity [m/s].

The friction factor (f) can be determined by using various methods. Commonly, the Moody-chart or Colebrook-White equation is used. The Colebrook-White equation is defined as follows:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{e}{3.74d} + \frac{2.51}{Re\sqrt{f}} \right)$$

Equation A.6 – Colebrook-White equation for friction factor.

Where

- f – Friction factor.
- e – Absolute pipe roughness [m] (typical pipe-roughness values shown in Table A.1).
- d – Inner diameter of pipe [m].
- Re – Reynolds number of flow.

Table A.1 – Typical pipe roughness.

PIPE MATERIAL	ROUGHNESS (e) [mm]
Riveted steel (max)	9
Riveted steel (min)	0.9
Riveted steel (average)	4.95
Commercial steel / welded steel	0.045
Cast iron	0.26
Galvanised iron	0.15
Asphalted cast iron	0.12
Wrought iron	0.045
PVC, drawn tubing, glass	0.0015
Concrete (max)	3
Concrete (min)	0.3
Concrete (average)	1.65

Data courtesy of [38].

The Reynolds number can be calculated as follows:

$$Re = \frac{\rho v d}{\mu}$$

Equation A.7 – Reynolds number.

Where

- Re – Reynolds number.
- ρ – Density of the fluid [kg/m^3].
- v – Flow velocity through pipe [m/s].
- d – Inner diameter of pipe [m].
- μ – Dynamic viscosity of fluid [Ns/m^2].

Assuming isothermal flow the head loss can be adjusted for compressible flow in pipes [39]:

$$h_{f,comp} = \left| \frac{h_f}{kM^2 - 1} \right|$$

Equation A.8 – Head loss in compressible flow.

Where

- h – Headloss [m]. “f” refers to friction loss where compressibility effects are disregarded. “f,comp” refers to the friction loss where compressibility effects are accounted for.
- k – Specific heat ratio of fluid (taken as 1.4 for air).
- M – Mach number of flow.

A.1.4 Air loss through unwanted air leaks

Determining exact volumetric flow rates through leaks present in piping is beyond the scope of this study. For approximation purposes flow through air leaks will be treated as flow through an orifice. Flow through an orifice can be calculated as follows [39]:

$$\dot{V} = \frac{18.166PD^2}{\sqrt{1.8T + 0.33}}$$

Equation A.9 – Volumetric airflow through an orifice.

Where

- \dot{V} – Volumetric flow through orifice [m^3/s].
- P – Upstream gage pressure [kPa].
- D – Orifice inner diameter [m].
- T – Absolute air temperature [K].

Consider flow through a diameter 5 mm air leak where air is initially compressed at 500 kPa and 20°C. Flow rate through this air leak is calculated as:

$$\dot{V} = \frac{18.166PD^2}{\sqrt{1.8T + 0.33}} = \frac{18.166(500)(0.005)^2}{\sqrt{1.8(273.15 + 20) + 0.33}} = 9.882 \times 10^{-3} \text{ m}^3/\text{s}$$

A.1.5 Electrical power required to produce compressed air

Power required for polytropic compression of air can be calculated as follows [40]:

$$W_C = \dot{m} \frac{nRT_1}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1/n)} - 1 \right] \quad \text{Equation A.10 – Power required for polytropic compression (1).}$$

Where

W_C – Work input [kW] required to compress gas.

\dot{m} – Mass flow rate [kg/s] of the gas being compressed.

n – Polytropic exponent.

R – Universal gas constant taken as 0.287 kJ/kg-K.

T_1 – Inlet temperature [K].

P – Absolute pressure [kPa] (subscript ‘1’ denotes inlet conditions and ‘2’ outlet conditions).

Mass flow through the compressor is calculated by:

$$\dot{m} = \rho \dot{V} \quad \text{Equation A.11 – Mass-flow rate.}$$

Where

\dot{m} – Mass-flow rate [kg/s].

ρ – Air density [kg/m³] calculated by Equation A.4.

\dot{V} – Volumetric airflow rate [m³/s].

The power required for polytropic compression of air can be calculated by substituting air density as calculated by the perfect gas law (Equation A.4) into Equation A.11 and rearranging Equation A.10 as follows:

$$W_C = \frac{nP_1\dot{V}_1}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1/n)} - 1 \right] \quad \text{Equation A.12 – Power required for polytropic compression (2).}$$

Compressor and motor-efficiencies should be included in order to find the actual power consumed. This can be calculated by:

$$W_m = \frac{W_C}{\eta_c \eta_m}$$

Where

W_m – Power [kW] consumed by the electrical motor.

W_c – Power [kW] required to compress the air.

η – Efficiency (subscript ‘c’ refers to the compressor and ‘m’ to the electrical motor).

Consider a gas to be compressed from 20°C, 101.3 kPa to 40°C, 600 kPa with an inlet flow rate of 10 000 m³/h.

Air density at inlet can be calculated as follows:

$$\rho = \frac{P}{RT} = \frac{(101.3)}{(0.287)(273.15 + 20)} = 1.204 \text{ kg/m}^3$$

Mass flow through the compressor is calculated:

$$\dot{m} = \rho \dot{V} = (1.204) \left(\frac{10\,000}{60 * 60} \right) = 3.35 \text{ kg/s}$$

Assuming a polytropic exponent of 1.3, power required for compression can be calculated:

$$\begin{aligned} W_c &= \dot{m} \frac{nRT_1}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1/n)} - 1 \right] \\ &= (3.35) \left[\frac{(1.3)(0.287)(273.15 + 20)}{(1.3) - 1} \right] \left[\left[\frac{(600)}{(101.3)} \right]^{[(1.3)-1/1.3]} - 1 \right] \\ &= 619 \text{ kW} \end{aligned}$$

Assuming a compressor efficiency of 0.8 and motor efficiency of 0.9 the final power consumption is calculated as:

$$W_m = \frac{W_c}{\eta_c \eta_m} = \frac{(619)}{(0.8)(0.9)} = 860 \text{ kW}$$

This is the estimated electrical power consumption required to compress atmospheric air at 20°C and 101.3 kPa to 600 kPa absolute pressure (approximately 500 kPa gage pressure) at a mass-flow rate of 3.35 kg/s. This calculation does not include any electrical power required for auxiliary equipment such as oil pumps which is usually also installed on compressors.

Figure A.1 shows calculated power required to compress air from atmospheric conditions (20°C and 101.3 kPa) to several final absolute pressures for different initial volumetric flow rates. Figure A.2 shows estimated power consumption to compress air at a rate of 10 000 m³/s

(atmospheric conditions). Actual data obtained from case studies have been included to show the accuracy of calculations. As can be seen the calculations correspond well to actual measured values.

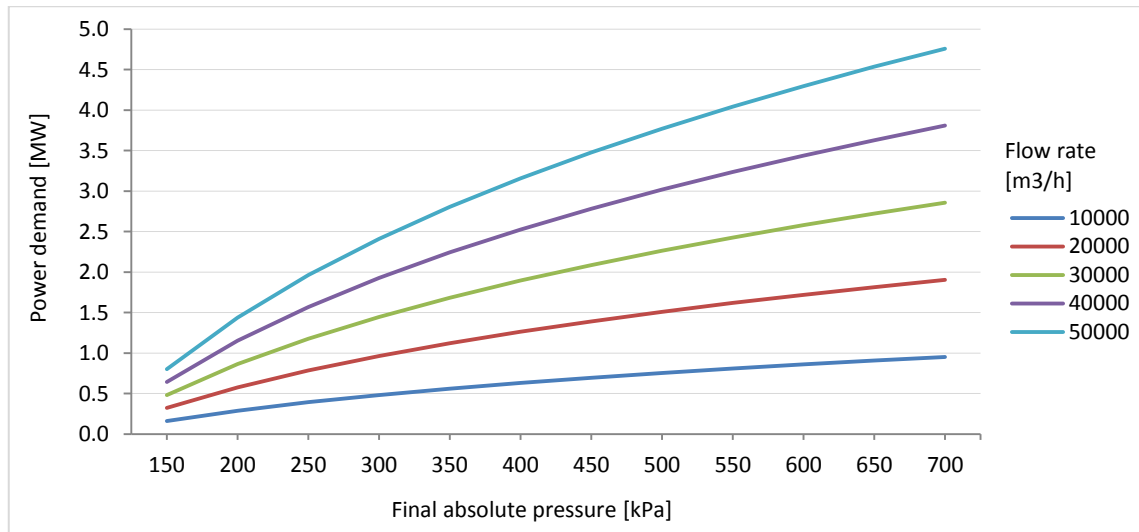


Figure A.1 – Estimated electrical power required to produce compressed air.

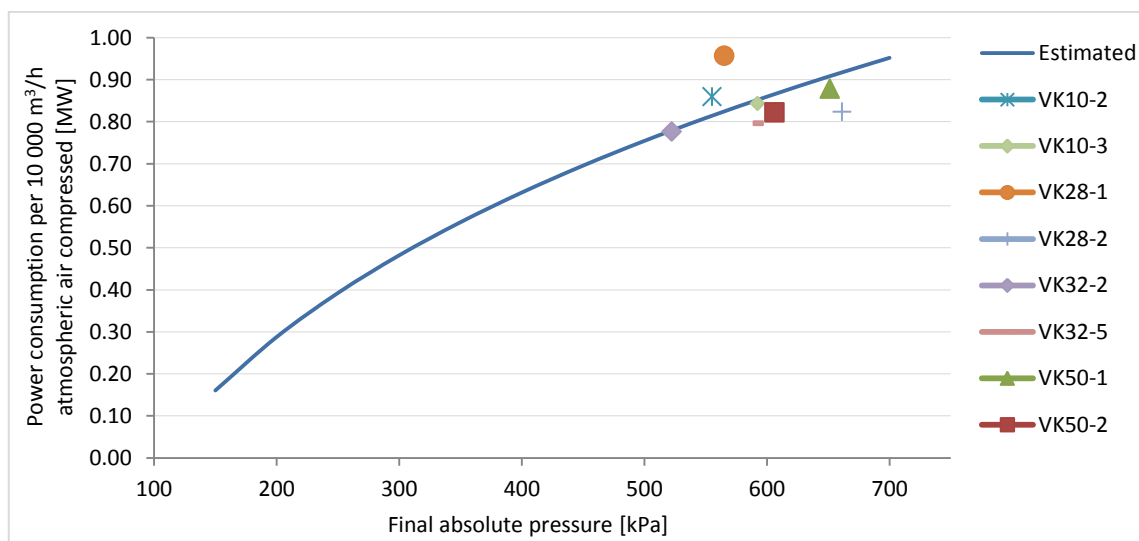


Figure A.2 – Estimated power required to produce compressed air compared to actual data.

As indicated in Figure A.2 the estimated power consumption, W_{act} , for compressing atmospheric air at a rate of 10 000 m³/h can be approximated by:

$$W_{Act} = 2 \times 10^{-9}P^3 - 4.3 \times 10^{-6}P^2 + 3.69 \times 10^{-3}P - 0.3 \text{ [kW]} \quad \text{Equation A.13 – Power required to compress air at } 10\,000\text{m}^3/\text{h}.$$

Where P is the final absolute pressure of the compressed air.

Equation A.14 can be used to estimate the electrical power (W) required to compress air at any specified atmospheric flow rate.

$$W = W_{10} \frac{\dot{V}_{req}}{10\,000} \text{ [kW]}$$

Equation A.14 – Power required to compress air.

Where

W_{10} – Electrical power required to compress air at 10 000 m³/h as calculated by Equation A.13.

\dot{V}_{req} – Volume flow rate (atmospheric conditions) air required [m³/h].

A.2 Calculations of correction factors related to case study 2

A.2.1 Correction factor on compressor power measurements

A correction factor for compressor power measurements taken from the SCADA were calculated according to the procedure below. Note that power consumed by auxiliaries are excluded.

1. Calculating actual power consumed

$$P = \sqrt{3}VI \cos(\sigma) \text{ [W]}$$

Equation A.15 – Three-phase power calculation.

where:

P – Actual electrical power usage of the compressor motor [W]

V – Electrical voltage supplied to the compressor motor [V]

I – Electrical current drawn by die compressor motor [A]

σ – Phase angle between the voltage and current. The term $\cos(\sigma)$ is commonly known as the Power Factor and was measured as 0.92.

Voltage and current readings of were obtained from the electrical cabinet supplying the compressor with electrical power. The actual power usage is calculated as:

$$P = \sqrt{3}VI \cos(\sigma) = \sqrt{3}(6500)(240)(0.92) = 2\,486 \text{ kW}$$

2. Comparing actual power consumed with measurements shown on the SCADA

Electrical power usage of the compressor as shown on the SCADA were noted during the same point in time that actual electrical supply readings were taken. The power correction factor to be applied of the measurements shown on the SCADA is calculated as follows:

$$P_{Corr} = \frac{P_{Act}}{P_{SCADA}} = \frac{2486}{2097} = 1.19$$

Equation A.16 – SCADA Power correction factor.

The average power correction factor between all six compressors was calculated as 1.16.