

DSM strategies to reduce electricity costs on platinum mines

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Abstract

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Labour disruptions, operational cost increases, mineral price decreases and nationalisation are only a few of the financial risks faced by mining companies in South Africa. These risks are not only impacting the mining companies but have a rippling effect on the surrounding communities and the country's economy.

With the South African Platinum Group Metals (PGM) largely affected, platinum mining companies are reviewing all possible cost savings strategies. Together with the help of Eskom's Integrated Demand Management (IDM) programmes, various electricity cost savings strategies are being investigated. To date implemented DSM strategies have deemed themselves successful on numerous mines.

These DSM strategies range from replacing basic equipment to maintenance schedules. However, there is a need to evaluate DSM strategies specifically applicable to standard underground platinum mines. Therefore this study reviews several plausible DSM strategies for the largest service systems including compressed air, refrigeration, ventilation, water reticulation and dewatering systems on platinum mines.

The first step in the investigation evaluated each DSM strategy according to existing system operations and infrastructure. The second step determined the feasibility of each DSM strategies for specific platinum mine case studies. This was done by simulating the electrical energy impact and investigating the required infrastructure for each strategy. With the predicted results and required infrastructure, an estimated payback period and a five year financial prospect was calculated to determine the feasibility.

Three strategies were selected and successfully implemented on the platinum mine case study. With the delivered electrical energy impact the annual electricity cost savings was calculated at an average R14.5 million with the implementation of the three DSM electrical cost saving strategies. The study provides insight into selecting the best proven electricity cost savings strategy according to the layout and design of a platinum mine.

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Abbreviations

BAC	Bulk Air Cooler
COP	Coefficient of Performance
CTM	Critical Thermal Maximum
DSM	Demand Side Management
EEDSM	Energy Efficiency Demand Side Management
ESCO	Energy Service Company
GDP	Gross Domestic Product
IDM	Integrated Demand Management
M&V	Measurement and Verification
PGM	Platinum Group Metals
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive

Nomenclatures

General:

°C Degree Celsius

g Gram

h Hour

J Joule

k Kilo

K Kelvin

ℓ Litre

m Meter

M Mega

Pa Pascal

R Rand

s Second

t Tonne

W Watt

% Percentage

Chapter 2:

C Leak coefficient

C_p Specific heat constant

$\dot{m}$ Air mass flow rate

n Polytropic compression exponent

η Efficiency

p Pressure

$P_{electrical}$	Electrical power
$\dot{Q}$	Heat transfer rate
R	Gas constant
T	Temperature
w_{comp}	Compressor energy

Chapter 3:

D_{volume}	Dam volume
L	Dam level
$\dot{m}$	Water mass flow rate
t	Time

Chapter 4:*Integrated downstream and compressed control:*

$P_{electrical}$	Electrical power
p	Compressor delivery pressure
v	Compressor delivery volumetric flow
$\emptyset$	Average compressor delivery pressure coefficient
φ	Average compressor delivery volumetric flow rate coefficient
α	Compressed air interception coefficient

Load management:

P_{actual}	Actual electrical power
P_{normal}	Normal electrical power
α	Refrigeration and ventilation electrical profile scaling factor

Variable water flow control:

P_{scaled}	Scaled electrical power
$T_{ambient}$	Ambient temperature

$T_{hot\ dam}$	Hot dam temperature
$T_{cold\ dam}$	Cold dam temperature
v_{shaft}	Water flow rate to shaft
v_{BAC}	Water flow rate to BAC
a_i	Scaling parameter

Chapter 1

Introduction

The struggling platinum industry and the need for Demand Side Management (DSM)

Chapter 1: Introduction

1.1 The South African platinum mining industry

To date, South Africa is one of the leading mineral producing countries in the world, with a mineral reserve worth R20.3 trillion. Of these reserves 66.3% of South Africa's 2011 mineral exports came from Platinum Group Metals (PGM), coal and gold (Kearney, 2012). During 2011 the mining sector also contributed 8.8% of the direct Gross Domestic Product (GDP) (Yager *et al.*, 2013). And in 2012, the PGM mining sector alone accounted for 4.1% of the country's GDP and 9% of its merchandise exports (Baxter, 2014). Figure 1 illustrates the PGM contribution to the GDP.

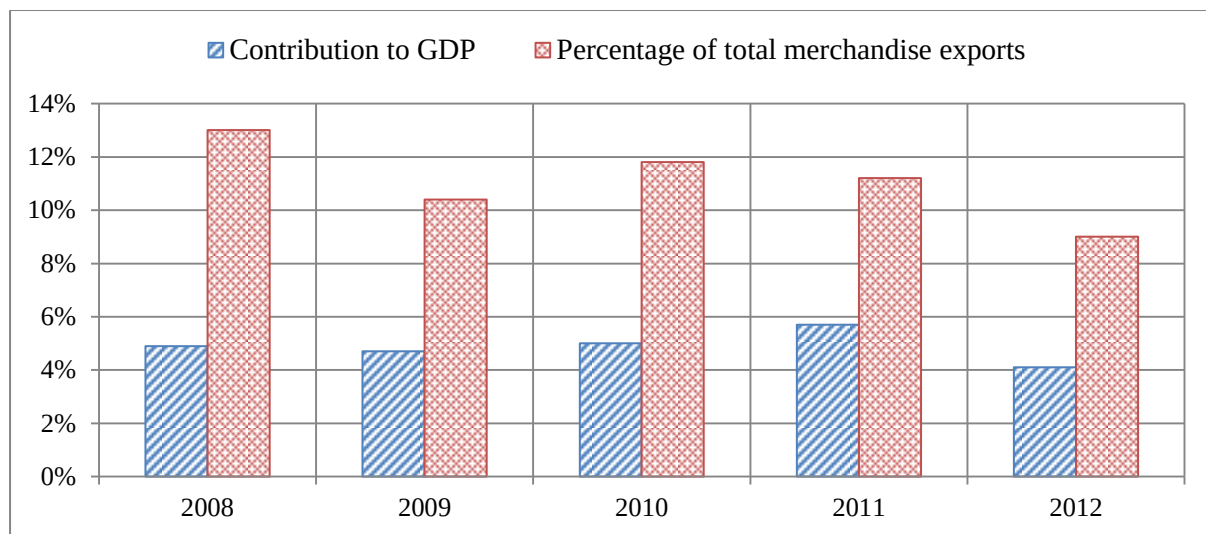


Figure 1: 2012 PGM mining economical contribution.

Platinum is currently considered as one of the scarcest metals in the world, with just over 200 metric tons being produced globally each year (Yang, 2009), with statistics showing that 72% of the world's platinum produce originated from South Africa (Yager *et al.*, 2013). However, the South African PGM production is annually declining by 0.4% due to lower global demand, increased domestic costs and labour disruptions (Baxter, 2014).

In 2014 the platinum producing companies in South Africa lost approximately R24 billion in revenues due to a five month labour disruption which started on 23 January 2014 (Platinum producers, 2014). Anglo American Platinum released a report claiming a 5.24 metric ton platinum loss within the first quarter alone (Anglo American, 2014). The labour actions are not only affecting production but also the platinum price which has seen a 12% decrease since 2011 (Magara, 2014).

To mitigate the losses, platinum mining companies are reviewing possible restructuring and lowering of costs and expenditures. However, if the financial deficit does not improve, extreme actions such as mothballing or selling of low production shafts will be taken (Baxter, 2014). When reviewing the 2011 costs and expenditures of the platinum mining sector, it is clear that the top three contributors

cannot be lowered without large scale restructuring. But the fourth largest contributor, electricity, can be further reviewed for possible cost reductions. A breakdown of the costs and expenditures of the platinum sector is displayed in Figure 2 (Baxter, 2014).

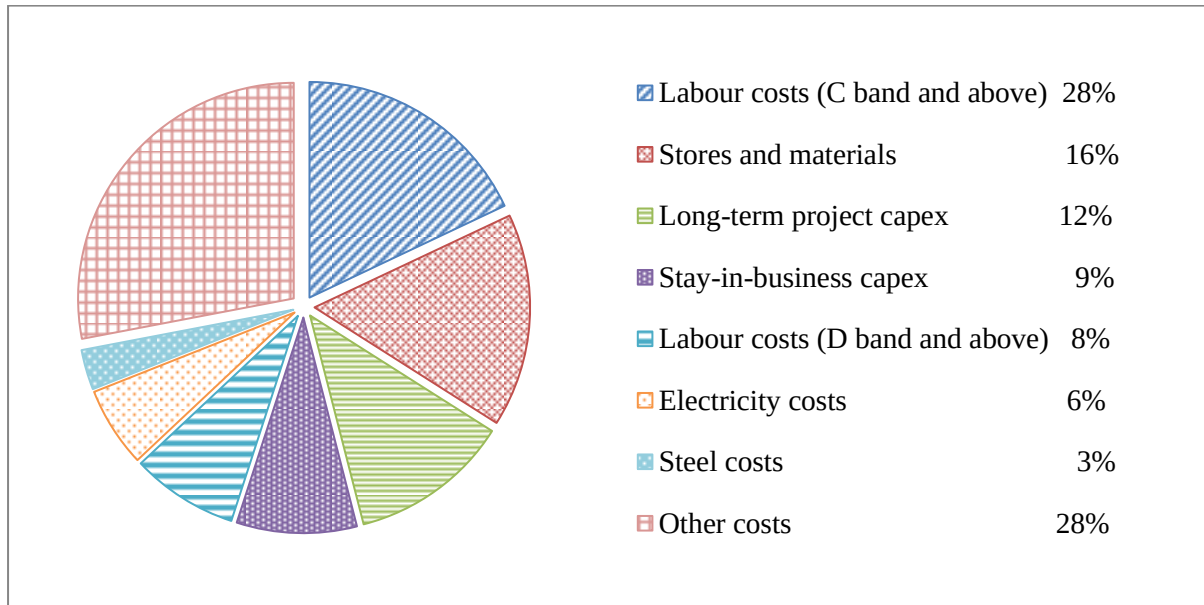


Figure 2: Costs and expenditures of the platinum sector (Baxter, 2014).

1.2 Reducing electricity costs through DSM strategies

Electricity is one of the most important commodities in the modern world and is slowly but surely becoming one of the most expensive commodities in South Africa. In 2013 Eskom introduced their new Multi-Year Price Determination (MYPD 3) plan three which includes an annual 8% tariff increase from 2013 to 2018. With this tariff increase, the current (2014/15) average electricity price of 70.75 c/kWh will increase to 89.13 c/kWh by 2018 (Creamer, 2013).

With the mining sectors consuming 14.1% of the total Eskom electricity sales, the tariff increase will only worsen the fragile financial state of mining companies and in turn the South African economy (Eskom Ltd., 2014). Therefore, platinum mining companies, such as Anglo American, together with Eskom have embarked on electrical energy savings projects to reduce the demand-side load (Anglo American, 2014). These electrical energy savings projects, also called Demand Side Management (DSM) Projects, form part of the Integrated Demand Management (IDM) Programme (Eskom Ltd., 2012).

DSM projects are subdivided into four categories namely Energy Efficiency DSM (EEDSM), Demand Response (DR), Energy Conservation Scheme (ECS) and Electricity Growth Management (EGM) (Eskom Ltd., 2014). The main focus of Energy Service Companies (ESCOs) and platinum mining companies are to implement EEDSM projects on high electrical energy consuming activities.

The typical electrical energy distribution of the underground mining sector is depicted in Figure 3 (Le Roux, 2005).

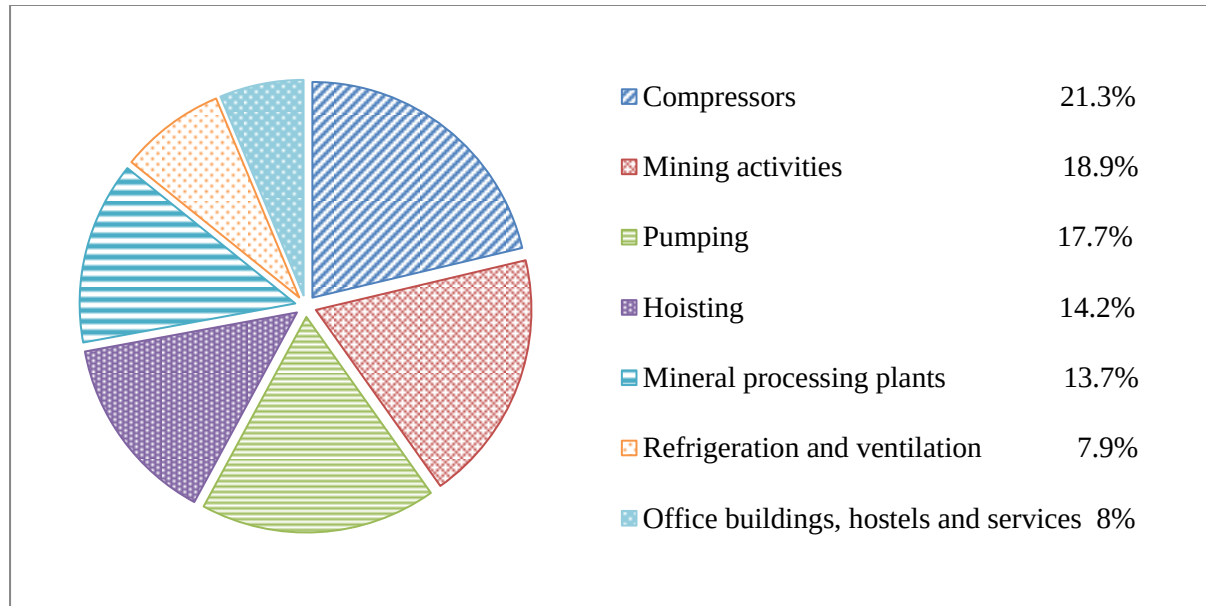


Figure 3: Electrical energy distribution of the mining sector (Le Roux, 2005).

The platinum mining operations can be divided into two categories; production and services (Schutte, 2013). Production includes all the activities such as drilling, blasting, sweepings etc. involved in mining the platinum ore. Whereas services include all the systems, i.e. compressed air, refrigeration, ventilation, hoisting and pumping that are utilised by the production activities. These five service systems are essential for any underground mine but consumes 61.1% of all the electrical energy supplied to the mining sector.

With the service systems consuming the majority of electrical energy, it presents the opportunity to investigate and possibly implement three different DSM interventions namely electrical energy efficiency, load management and peak clip strategies. Electrical energy efficiency strategies will reduce the load throughout the day according to the user demand. However, load management and peak clip will focus on reducing the load during periods of the day when the electricity tariffs are the highest.

Each of the DSM strategies will be implemented to accommodate the production schedules and the Eskom tariff structures. Figure 4 incorporates both the mining production schedules and the weekday 2014/2015 Eskom Megaflex electricity tariff plan (Eskom Ltd., 2014). The average electricity tariff for the high demand season (June - August) and the low demand season (September - May) was used in Figure 4 and will be used throughout the dissertation. The Eskom Megaflex electricity tariff plan for 2014/2015 is shown in Appendix A.

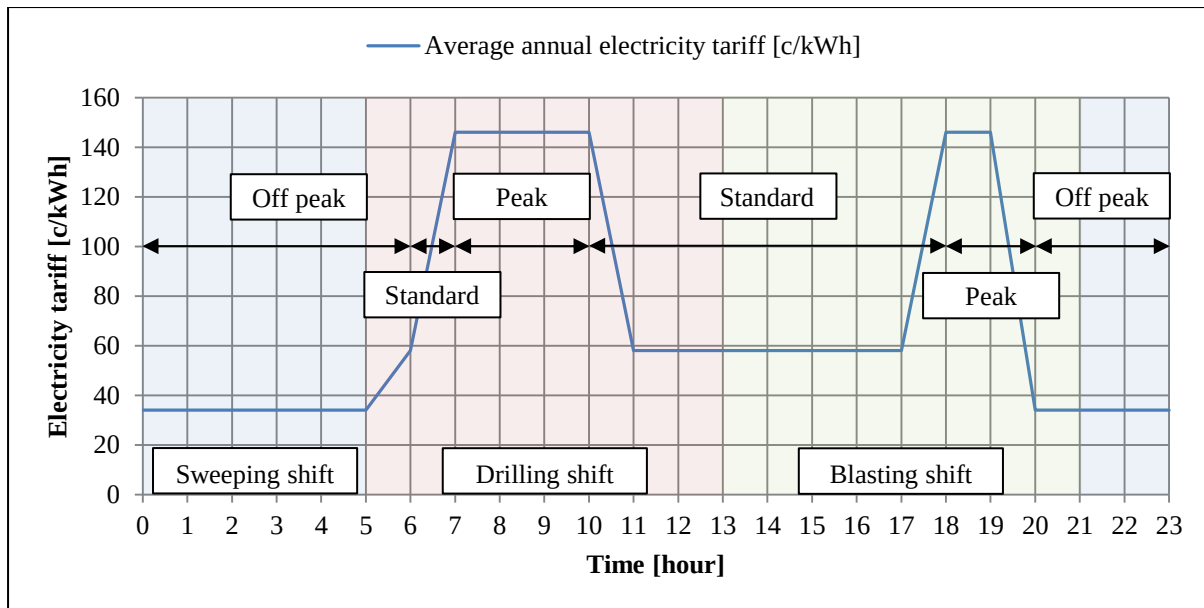


Figure 4: Average weekday Eskom Megaflex electricity tariff.

1.3 DSM potential on platinum mines

Until recently the price of electricity in South Africa was among the lowest in the world (NUS Consulting Group, 2007). This presented mining companies the opportunity to operate oversized auxiliary equipment to achieve maximum production without any concerns regarding electrical energy efficiency. With over 46% of the mining sectors electricity consumption being allocated to these systems, the potential for savings is substantial (Le Roux, 2005).

1.3.1 Compressed air systems

Compressed air is perhaps the most used and most expensive utility on any mine (Botha, 2011). Mining companies constantly overdesign compressed air systems to avoid any shortcomings due to the different requirements needed for each user. Not only are these systems overdesigned, but they are operated inefficiently due to a lack of supply and demand control. However, various DSM strategies implemented on compressed air systems have reported ample electrical energy savings.

These strategies have incorporated compressor control, downstream control and regular maintenance to achieve the savings (Schutte, 2013). This dissertation will investigate the feasibility of potential compressed air DSM strategies and implement them within the platinum mining sector.

1.3.2 Refrigeration and ventilation systems

With most South African platinum mines being situated within the Bushveld Igneous Complex, the Virgin Rock Temperatures (VRT) can increase up to 18°C per kilometre in depth (Venter, 2007). To overcome these temperatures and create a suitable underground working environment, platinum mines

utilise large refrigeration and ventilation systems. However, these systems are constantly operated at a maximum load throughout the day and year.

This presents the opportunity to investigate possible DSM strategies to reduce the electricity costs of these systems. The DSM strategies will incorporate load control and supply control in accordance with the mine health and safety regulations.

1.3.3 Water reticulation systems

Water is one of the essential utilities needed for underground mining. It has a wide variety of uses ranging from secondary cooling to suppression of dust (Schutte, 2013). However, any water within a mine, fissure as well as rain water, will accumulate at a central location at the bottom of the shaft. For dewatering, mining companies utilise large centrifugal pumps to move water from a central location, usually dams, to another until it reaches the surface (de la Vergne, 2003). The dewatering pumps, dams and piping networks all form the water reticulation system.

These water reticulation systems are usually manually operated without any specific control. This again presents the opportunity to investigate possible DSM strategies which will incorporate the automating of the entire water reticulation system. The automation will include proper control strategies to accommodate the Eskom Megaflex tariffs and mining schedules.

1.4 Objectives of this study

The current platinum crisis presents a vast need for system restructuring and optimisation interventions to mitigate the already fragile state. The objective of this study will be to investigate existing DSM strategies and adapt them specifically to underground platinum mines. The implementation of these DSM strategies will not only reduce the electricity costs but lower the operational overheads.

1.5 Dissertation overview

The overview of this dissertation is discussed below:

Chapter 1

The introduction provides background to the current South African platinum mining crisis and the intervention required to reduce operational costs. It outlines the typical underground mine electrical energy distribution and existing DSM strategies. The outcome of this chapter is to identify possible DSM strategies on compressed air, refrigeration, ventilation and water reticulation systems.

Chapter 2

In this chapter an overview of the typical compressed air, refrigeration, ventilation and water reticulation systems are presented and discussed in depth. Thereafter, potential electricity cost saving strategies through system improvements or alterations are investigated. The objective of this chapter is to provide a basis for the simulations and optimisation models in Chapter 3.

Chapter 3

The purpose of this chapter is to investigate the feasibility of implementing DSM strategies on several platinum mine case studies. These strategies are then simulated and optimised with the use of a thermal hydraulic simulation flow solver.

Chapter 4

This chapter provides insight into the implementation and integration of the DSM strategies. Hereafter, the results achieved from each case study is verified against the proposed results from Chapter 3.

Chapter 5

To conclude the dissertation, a review of the problem statement, processes followed to reach a valid solution and the findings are summarised in this chapter. Finally recommendations for future studies on electricity cost saving strategies for platinum mines are discussed.

Chapter 2

Investigation of possible DSM strategies

Classification of DSM strategies applicable to the platinum mining industry and its high electricity consuming service system

Chapter 2: Investigation of possible DSM strategies

2.1 Introduction

Chapter 1 briefly discussed the potential for electricity cost saving strategies on the significant electrical energy consuming systems of South African underground platinum mines. Chapter 2 investigates and provides background on the compressed air, refrigeration, ventilation and water reticulation systems of a typical underground platinum mine. Attention will then be given to possible electricity cost savings through the implementation of existing system alterations and/or improvements.

2.2 Compressed air systems

2.2.1 Compressed air usage throughout the mining industry

A compressed air system is of high importance to most underground South African mines. Compressed air is used throughout the mine from the drilling process all the way to the processing plant. Each of these processes has its own specific requirements in terms of flow, pressure and quality of air. Table 1 outlines the compressed air requirements for a variety of mining activities (Brake & Bates, 1999; Joubert, 2010; Snyman, 2011).

Table 1: The compressed air requirements of typical mining activities.

Process	Pressure [kPa]	Pressure Category	Flow [m ³ /h]	Flow Category
Agitation	400	Medium	1500	High
Drilling	450-600	High	160-1500	High
Workshops	250	Low	500	Medium
Hoisting	350	Medium	12	Low
Loading	350-860	High	93.6-1080	Medium
Refuge bays	200-300	Low	36 -300	Low
Cleaning	250	Low	2000	High
Tramming	350	Medium	12	Low
Pneumatic valves	350	Medium	12	Low
Plant equipment and instrumentation	450	High	288-2520	Medium-High
<300 kPa = Low pressure >350 kPa & <450 kPa = Medium pressure >450 kPa = High pressure <500 m³/h = Low flow >500 m³/h & <1500 m³/h = Medium flow >1500 m³/h = High flow				

Large multistage compressors are being used by South African mines to deliver the required amount of compressed air. These compressors deliver compressed air at a flow rate of 10 000 – 60 000 m³/h and a pressure of 500 – 600 kPa (Snyman, 2011).

A compressed air network can comprise of kilometres of piping on surface and underground to distribute the compressed air. Over these long distances the air will never reach the end user at the same (flow and pressure) condition as it was originally supplied by the compressors. This is due to a variety of factors such as auto compression, pipe friction losses, air leakages and unauthorised users. Some of these factors can be minimised with regular inspection and maintenance of the airline.

A typical air network will have multiple compressor houses with one or more compressors supplying air. These compressors will most likely vary in size and capacity and will be situated in compressor houses close to a compressed air user such as a shaft or a processing plant. Compressed air networks can be categorised as either a stand-alone system or a ring-feed system as illustrated in Figure 5 and Figure 6 (Joubert, 2010).

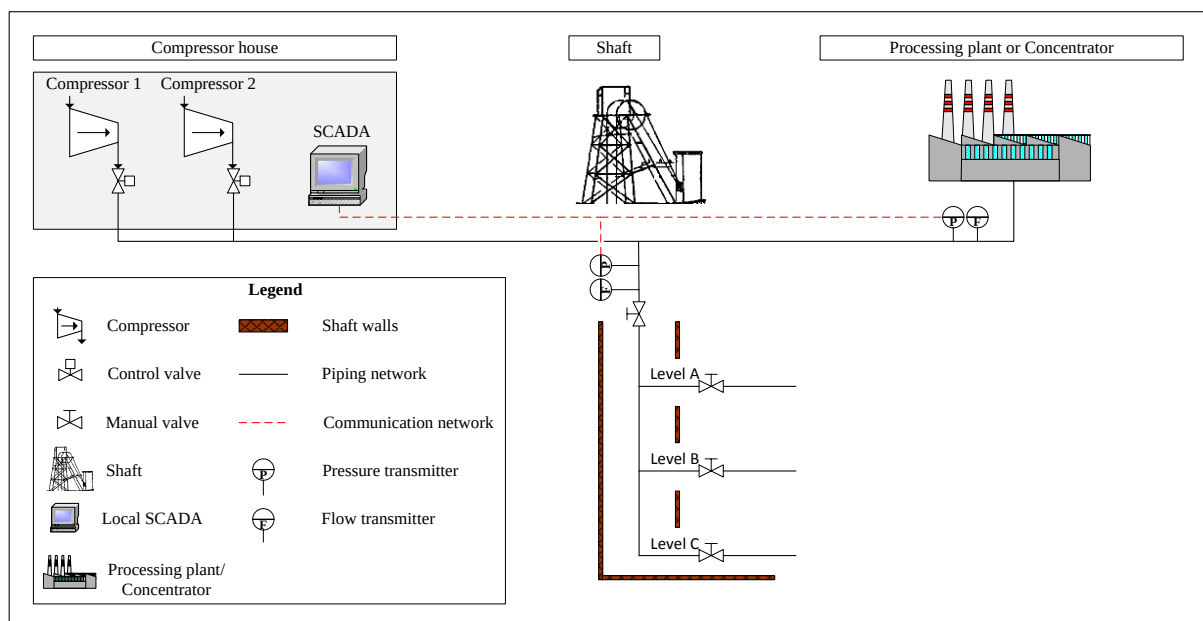


Figure 5: Typical layout of stand-alone compressed air network.

Stand-alone systems consist of a single airline from the supplier to the user. Whereas ring-feed systems utilise a closed ring airline where all the suppliers feed into and the users feed out of. Both these systems have their advantages and disadvantages but a ring-feed system is the most preferred. This is due to the fact that the compressed air supplies are spread throughout the network and this facilitates maintenance schedules without a complete shutdown.

All compressed air users can be grouped into categories of pressure and flow as shown in Table 1 (Schutte & Kleingeld, 2010). With different users demanding compressed air from the same network, it is difficult to supply compressed air at the required flow rate and pressure. Therefore mines schedule the run time of their compressors to pressurise the compressed air network according to the requirements of its highest user (Marais, 2012; Venter, 2012). The compressed air demand will also vary according to the working shifts of each mine. For instance, during drilling shifts a minimum

pressure of 480 kPa is required on surface and underground. While during non-drilling shifts a minimum pressure of 350 kPa is required for agitation and refuge bays (Snyman, 2011).

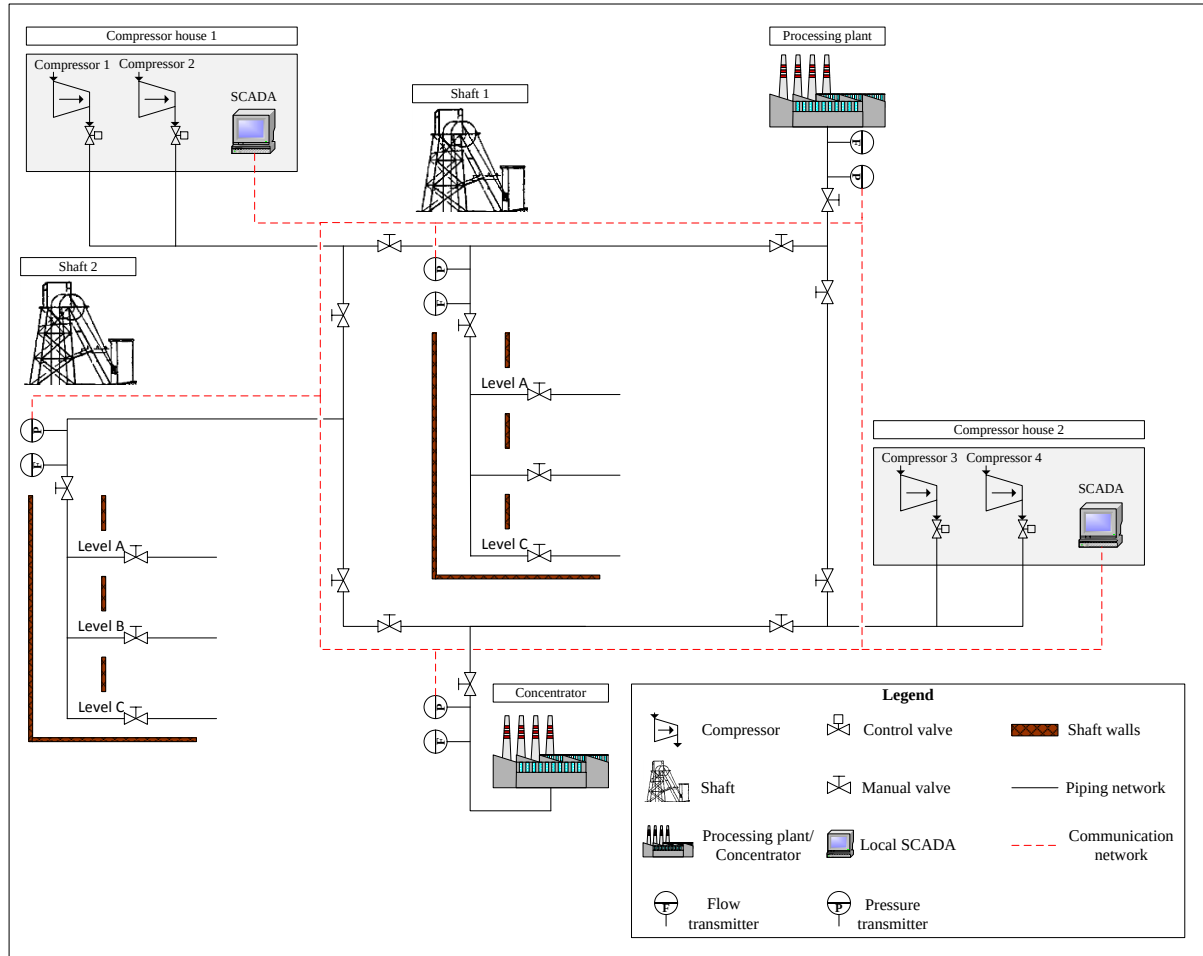


Figure 6: Typical ring-feed compressed air network.

The run schedules for the different compressors are determined by the demand during the day. But irregular compressed air usage during the day can result in compressors being started and stopped not according to their schedules. South African underground mines use either operators or automated control systems to start and stop compressors according to the pressure demand. Both controlling methods can result in high compressor power consumption with the frequent starting and stopping of compressors during peak and off-peak periods (Marais, 2012). An example of an inefficient compressor usage at platinum Mine B is illustrated in Figure 7.

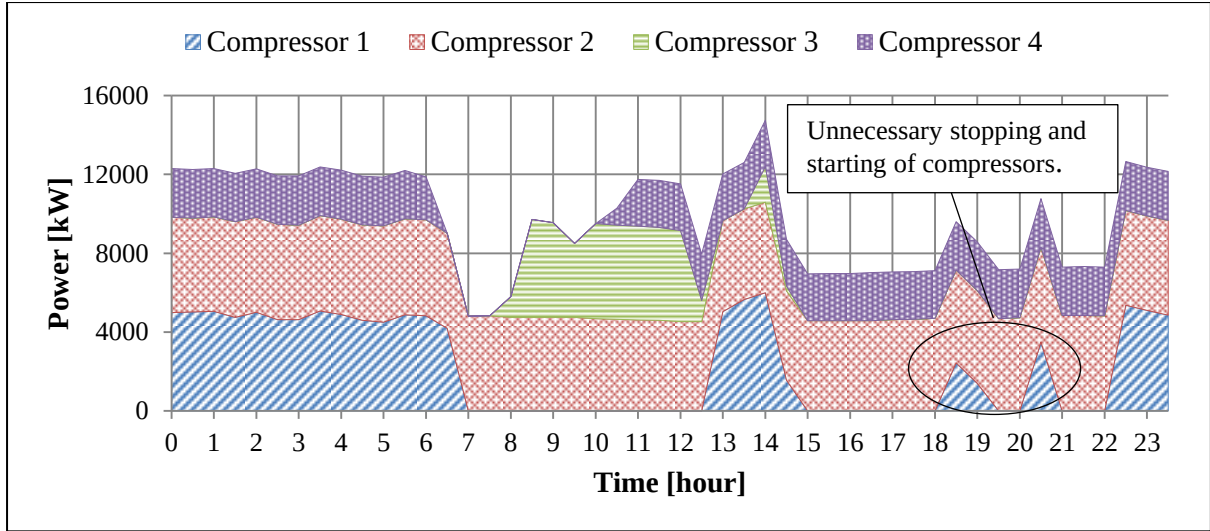


Figure 7: Inefficient compressor usage at Mine B.

To fully understand the impact of unnecessary compressor usage the focus has to be shifted to the electrical power consumption. Compressors not only vary in size and capacity but also in the amount of electrical power required to generate compressed air. Equation 1 can be used to estimate the theoretical electrical power required to generate compressed air at atmospheric conditions (101.3 kPa, 20°C) (Cengel *et al.*, 2011).

Equation 1:

$$P_{electrical} = \frac{\dot{m}_{air} w_{comp,in}}{\eta_{motor}}$$

Where:

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

$\dot{m}_{air}$ = compressed air mass flow rate (kg/s)

$w_{comp,in}$ = energy required to compress a unit mass of air (kJ/kg)

η_{motor} = efficiency of the electrical motor (90%)

From Equation 1 it is evident that by decreasing the compressed air mass flow rate, the electrical power will decrease as they are directly proportional. Furthermore Equation 1 shows that the motor's efficiency is inversely proportional to the electrical power. The electrical power is also dependent on the design of the compressor and the maintenance, which is incorporated into the electrical energy required to compress a unit mass of air (van der Zee, 2013). The electrical energy can be calculated using Equation 2 (Cengel *et al.*, 2011).

Equation 2:

$$w_{comp,in} = \frac{nRT_{in}}{\eta_{comp}(n-1)} \left[\left(\frac{p_{out}}{p_{in}} \right)^{(n-1)/n} - 1 \right]$$

Where:

$w_{comp,in}$ = energy required to compress a unit mass of air (kJ/kg)

n = polytropic compression exponent

R = gas constant (0.287kJ/kg.K)

T_{in} = inlet temperature (K)

η_{comp} = compressor efficiency

p_{out} = compressor discharge pressure (kPa)

p_{in} = compressor inlet pressure (kPa)

2.2.2 Compressed air system alterations and improvements

Studies have shown that between 20% and 50% of electrical energy savings can be realised with improvements on a compressed air system. Therefore, the following section will investigate and discuss compressed air improvement opportunities that can result in possible electricity cost savings (Hongbo & McKane, 2008; Joubert, 2010).

According to the first law of thermodynamics, the energy in a system is conserved and cannot be created or destroyed. The amount of energy used to compress air into a system will be equal to the energy used and lost by the system. Therefore, this section will first focus on reducing the amount of energy demand and losses in a compressed air system.

Air leaks

Leaks in a compressed air system can be a nuisance to most mine personnel, but leaks can be accountable for up to 20% of its total compressed air capacity (Hongbo & McKane, 2008). An air leak with a diameter of 10 mm might not seem large, but if unfixed it will have cost the mine approximately R86 000.00 per annum with the 2014 electricity rates (Eskom Ltd., 2014). Repairing an air leak is a small price to pay compared to the price of electricity. Figure 8 illustrates the amount of wasted electrical power and cost (Eskom 2014/2015 Megaflex tariffs) according to the diameter of the air leak (Eskom Ltd., 2014; van der Zee, 2013).

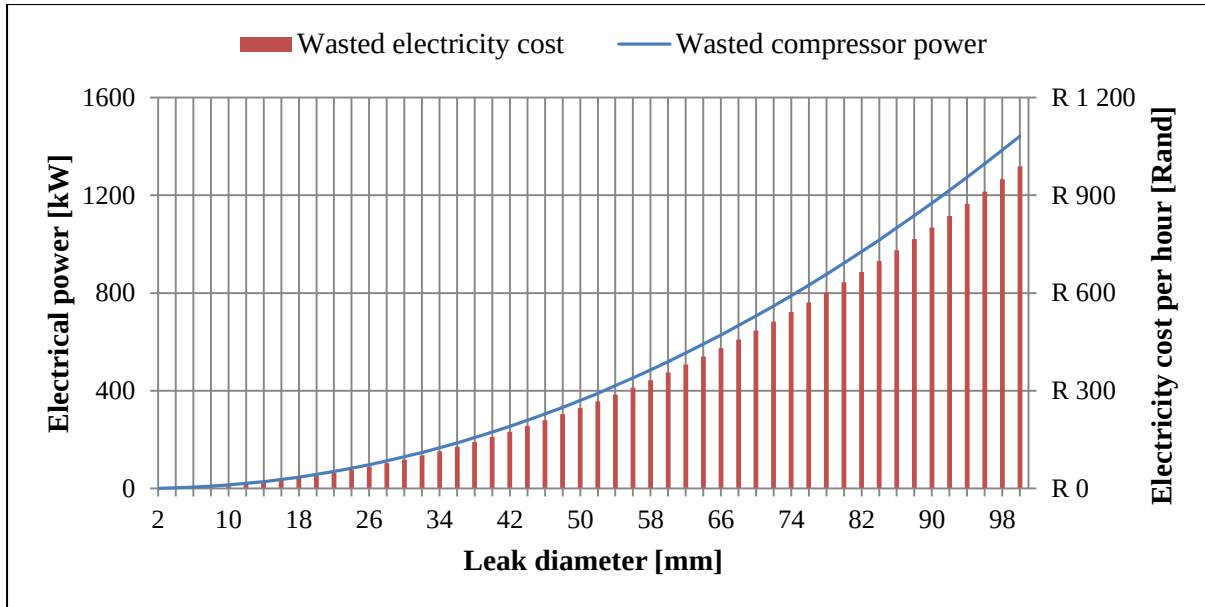


Figure 8: Compressed air leak wastage.

Figure 8 was calculated using both Equation 1 and Equation 2. The assumed parameters are:

n = polytropic compression exponent (1.4)

k = specific heat ratio for air (1.4)

R = gas constant (0.287 kJ/kg.K)

C = coefficient of leak (0.65)

T_{in} = inlet temperature (25°C)

T_{line} = line temperature (28°C)

p_{in} = compressor inlet pressure (87 kPa)

p_{line} = compressor discharge pressure (500 kPa)

η_{comp} = compressor efficiency (80%)

η_{motor} = motor efficiency (90%)

In addition to the wasted electrical power, air leaks can cause reduced tool efficiencies due to downstream pressure drops. Reduced air tool efficiencies will also lead to lower production, increased operating hours and additional maintenance (Hongbo & McKane, 2008). According to van der Zee it will be uneconomical to repair each small leakage due to the fact that the entire airline has to be isolated beforehand. Therefore, fixing large air leaks must receive the highest priority (van der Zee,

2013). Figure 9 shows an example of a surface air leak that has been poorly repaired by mine personnel on platinum Mine A.



Figure 9: Poorly repaired air leak at platinum Mine A.

Pneumatic equipment

Another possibility is to replace current pneumatic equipment with either electrical or hydropowered equipment. Figure 10 illustrates the average power consumption of pneumatic rock drills compared to electrical and hydropowered rock drills (Willis, 2008).

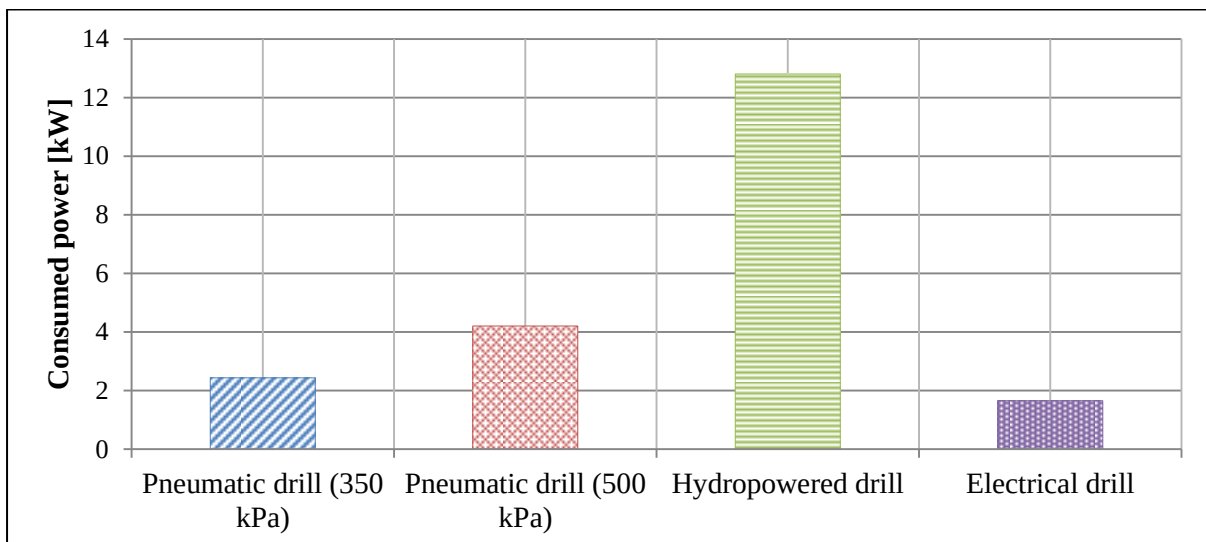


Figure 10: Rock drill power consumption (Willis, 2008).

Unfortunately studies performed at Anglo American Platinum in 2008 have shown that the operational cost of electrical rock drills would be approximately 28% more than pneumatic rock drills (Petit, 2006). A similar study confirmed these results by showing that the operational costs for

electrical rock drills can be up to 2.6 times more than pneumatic rock drills (Labuschagne, 2010). Although the results appear positive in terms of electrical power consumption, replacing pneumatic equipment will be uneconomical in terms of installation and operational costs.

Downstream control

Deep-level mines are notorious for over-pressurised air networks. The main reason for this is that some air networks feed multiple shafts and processing plants. Table 1 only outlines the required compressed air pressure and flow for when a process is in progress. When these processes end the air demand will change, but the supplied compressed air remains unchanged.

To eliminate or limit the above mentioned scenario three main strategies have been developed, namely: underground and surface-isolation, control and supply side control. Underground and surface-isolation is done by installing open/close isolation valves upstream on the supply airlines. The isolation valves will be controlled according to shift changes. Once a drilling shift has ended the valve will close isolating the supply air. When the next shift, for instance a cleaning shift starts, the isolation valve will open supplying the line with compressed air.

There are various methods for isolating an airline but the most frequently used method is manual isolation by designated personnel. The preferred method is a controlled isolation valve which can be opened or closed from a central point such as a control room to ensure isolation according to the schedule. These isolation valves can either be manually controlled by an operator or automatically controlled. Both these methods can be performed through a local Supervisory Control and Data Acquisition (SCADA) system (Joubert, 2010).

However, not all shafts can be isolated as there are refuge bays and loading bins that still require a constant pressure and flow rate. In order to solve this problem the isolation valve can be exchanged for a pressure/flow controlling valve. These valves will control the compressed air flow according to the downstream demand. A control valve will utilise an actuating positioner to control the valve according to the downstream pressure and flow readings (Joubert, 2010). Figure 11 shows an isolation and control valve setup that was installed on platinum Mine A.

In this setup a 250 mm control valve was utilised for refined control instead of a 450 mm control valve. Also due to the fact that only the downstream pressure would be affected, pneumatic actuating control valves were used and not electric actuating control valves.



Figure 11: Surface control valve utilised on Mine A.

Compressor control

The last optimisation methods focus on the supply side of a compressed air network. A compressor is designed to deliver compressed air at a specific pressure and flow but it is not limited to this design. Air is sucked into the compressor through the inlet valves where it is guided into the compressor through a set of guide vanes. Hereafter the air is compressed by rotor blades to a pre-set pressure and discharged into the air network through a controlling discharge valve. Before the air is discharged into the system, the compressor has to reach a high enough pressure to overcome back pressure from the system.

Each compressor is designed to operate within a set of stable parameters to prevent the compressor from entering its surge or choke point. Surge occurs once the flow through the compressor is too low to overcome the flow through the compressed air system and will result in flow reversal. Whereas at the choke point the inlet flow through the compressor is too high and a low head is developed. During this period the flow through the compressor will reach Mach 1.0. Both these conditions will cause extreme vibration and might damage the compressor and components (Barletta & Golden, 2004; Booyesen *et al.*, 2010; US DOE-OIT, 2003).

In order to prevent surge, a compressor is equipped with adjustable inlet valves, guide vanes and a blow-off valve. Once surge occurs the blow-off valve will immediately open to increase the flow through the compressor. The adjustable inlet guide vanes are also used during the start up to achieve

the desired inlet flow while the discharge and blow-off valves are closed (Blanchini & Giannattasio, 2002; US DOE-OIT, 2003; Willems *et al.*, 2002). Figure 12 illustrates the adjustable inlet guide vanes of a RI-565 Brown Boveri Sulzer 4 2876 m³/h centrifugal compressor.

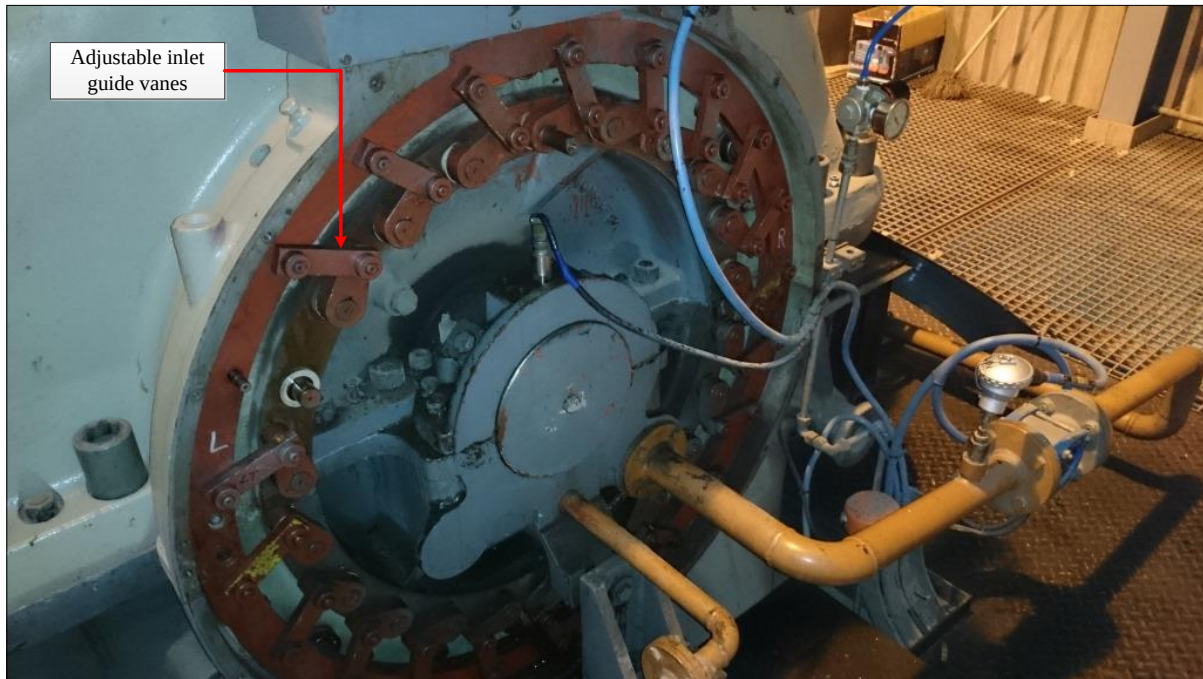


Figure 12: Photo of a Brown Boveri Sulzer centrifugal compressor guide vanes.

There are two methods of utilising the adjustable guide vanes and blow-off valves to reduce the amount of electrical power drawn by a compressor. These methods are either by placing a compressor in an unloaded state or by controlling the inlet vanes to reduce the delivery pressure.

The load/unload control of a compressor, known as constant-speed control, can be used to isolate the compressor from the compressed air system. This is done by closing the discharge valves and opening the blow-off valves. The compressor will still operate at a constant speed but will only consume up to 35% of its full-load capacity (US DOE-OIT, 2003). Unfortunately this controlling method can also be seen as energy wastage due to the compressed air being blown into the atmosphere.

Modulating control is the operation where the inlet valves are closed to vary the inlet air flow according to a pressure set-point. A more efficient control can be achieved by adjusting the inlet guide vanes angles to direct the inlet air straight into the impeller inlet. To prevent a compressor from entering a surge, the inlet vanes are limited to a minimum of 40% and maximum of 100% modulation. This modulating control has a direct effect on the discharge pressure and the electrical power consumed by the electrical motor (US DOE-OIT, 2003).

By combining the modulating control on a compressor with a programmable pressure profile, also called a Moore controller, a more effective compressed air supply can be achieved (Scheepers, 2011).

Figure 13 shows the reduction in consumed power and inlet air flow by applying modulating control and a Moore controller on a GHH Borsig centrifugal compressor.

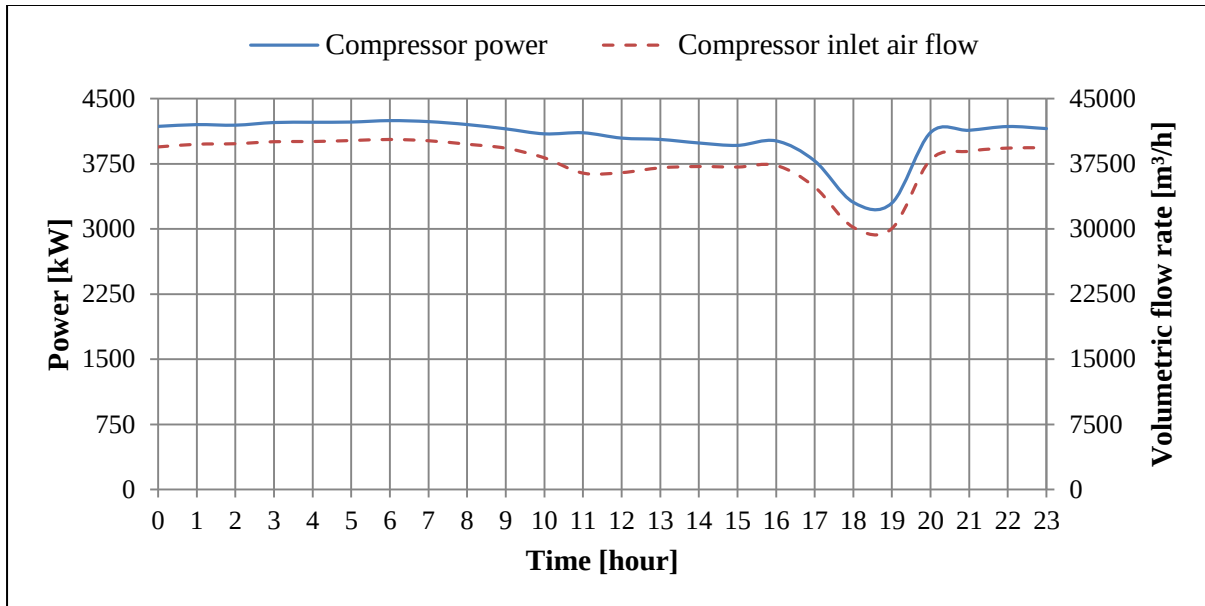


Figure 13: Modulating- and Moore-control implementation on a centrifugal compressor.

DSM projects on compressed air systems normally vary between electrical energy efficiency and a peak clip project. The type of DSM project depends on the compressed air demand and supply of a mine during the day. An electrical energy efficiency project will focus on optimising the compressed air system to reduce the total electrical energy consumption throughout the day. Whereas, a peak clip project will focus only on reducing the electrical energy consumption during the Eskom peak periods.

Chapter 3 will compare each system improvement according to the cost of the required infrastructure, the implementation period and the possible electrical energy savings. Thereafter, the DSM project selection will be discussed.

2.3 Refrigeration and ventilation systems

This section will discuss the function and operation of platinum mine refrigeration and ventilation systems. A short description of a typical platinum mine water reticulation system will also be provided as it runs concurrent with the refrigeration system.

2.3.1 Refrigeration and ventilation usage throughout the mining industry

Everyone and everything on the earth has a set of limitations. These limitations range from the temperature it can withstand to the mass it can uphold. Beyond these limitations failure is bound to occur whether it is a machine or a human. Therefore, a safe set of boundaries has been developed over the years for each and everything including humans. For underground mine workers these boundaries are being pushed to the limits every day.

One of the most important human boundaries is the Critical Thermal Maximum (CTM), which is the maximum temperature the human core can withstand, this ranges from 41.6°C to 42°C. Various studies have shown that in hot humid working condition the human core can easily reach temperatures above 39°C. However, when the human core reaches temperatures close to the CTM, dehydration and heat stroke becomes a reality (Bynum *et al.*, 1978; Kosaka *et al.*, 2004; Wyndham *et al.*, 1966).

An increase in working temperatures is not only dangerous for the health and safety of mine workers but it is inversely proportional to their performance (Le Roux, 1990). With this in mind the mining industry of South Africa introduced a maximum wet-bulb working temperature of 27.5°C. Another aspect to consider when choosing underground working conditions is the limitations of mining equipment. These limitations have been tested and will be specified by the manufacturers (Vosloo *et al.*, 2012). High operating temperatures for mining equipment will result in increased maintenance down time and operational costs.

High temperatures in underground mines are caused by a variety of heat sources. Some of these heat sources are wall- and blasted-rock, adiabatic compression, electromechanical equipment, explosives, as well as ground and service water (Nixon *et al.*, 1992). Of these heat sources, the rock walls of a mine are the largest source of heat. The VRT, depending on the thermal conductivity, can increase up to 18°C for every kilometre down (Gosh & Patterson, 1940; Nixon *et al.*, 1992).

It is, therefore that deep-level mines utilise large refrigeration and ventilation systems to optimise the underground working conditions. Figure 14 illustrates a simplified layout of a typical refrigeration and ventilation system that incorporates chilled water reticulation (Du Plessis, 2013; Schutte, 2007). Water reticulation systems will be discussed in detail in Chapter 2.4.

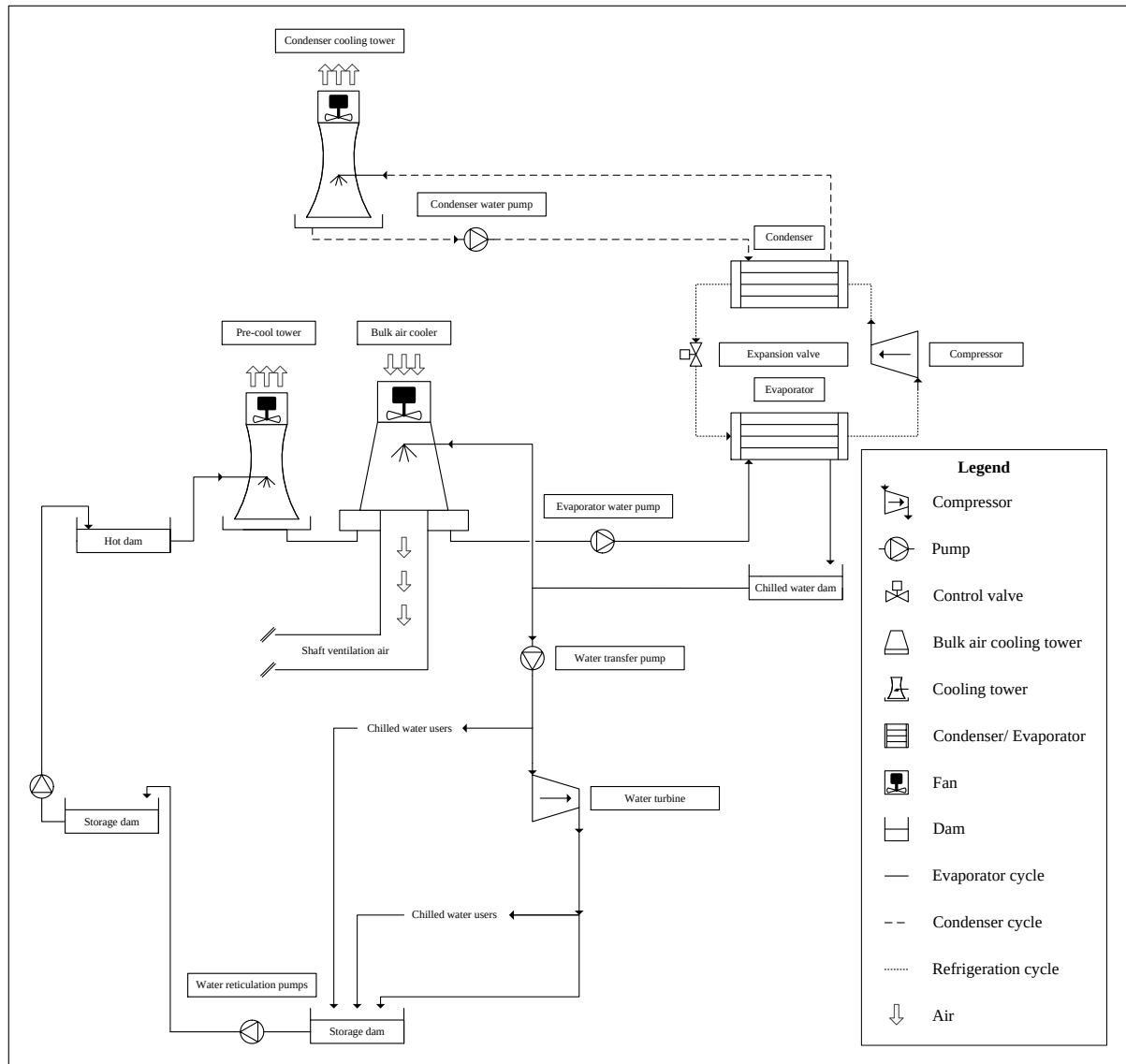


Figure 14: Typical mine refrigeration and water reticulation system layout.

Figure 14 is a generalised layout due to the fact that the cooling and chilled water requirements for each underground mine is unique. Refrigeration and water reticulation systems can be subdivided into closed- or semi-closed loop systems. Figure 14 represents a semi-closed loop system where chilled water is required underground for mining equipment, Bulk Air Coolers (BACs) and spot coolers. A closed loop system will only be utilised for ventilation purposes and not chilled service water (Du Plessis, 2013; Schutte, 2013).

To summarise a water reticulation system, chilled water is supplied to underground users at a surface temperature between 3°C and 6°C. After each end user, the water will flow to storage dams on various underground levels where it is pumped back to surface. Here the water is collected in a hot dam with temperatures ranging from 25°C to 35°C. The underground water requirements will vary according to the size of a mine and its operation during the day (Calitz, 2006; Du Plessis *et al.*, 2013).

Refrigeration system layout

A refrigeration system consists of an evaporator, condenser and refrigeration cycle. Within the refrigeration cycle, also known as a chiller, thermal energy is transferred from the evaporator to the condenser by means of a refrigerant fluid as seen in Figure 15. The two common refrigerant fluids used in the mining industry are ammonia or R134a. It is important to consider the working conditions of the fluid and the equipment to be used when selecting the appropriate refrigerant fluid (Borgnakke & Sonntag, 2009).

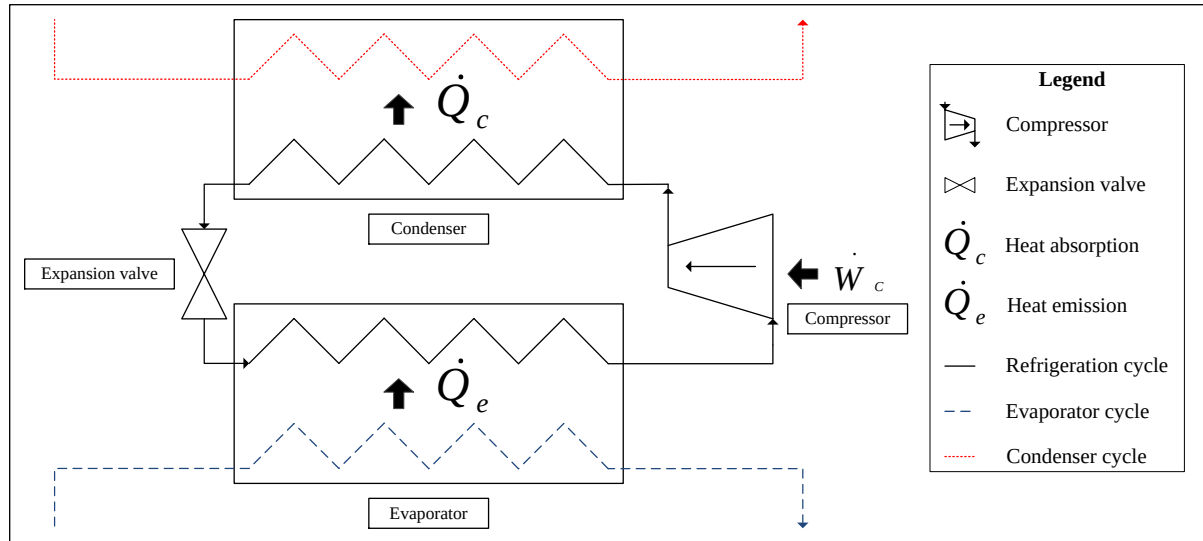


Figure 15: Vapour-compression cycle of a shell-and tube-heat exchanger.

As illustrated in Figure 15, after the thermal heat is transferred to the refrigerant vapour, from the evaporator water it is forced to the condenser by an electrical driven compressor. Within the condenser the thermal heat is transferred from the refrigerant to the condenser water. The refrigerant will also change from its vapour phase to a liquid phase due to the reduction in heat content - hence the use of an expansion valve to restore the refrigerant to a wet vapour with the reduction in pressure. Equation 3 can be used to determine the rate at which heat is transferred within the evaporator (Borgnakke & Sonntag, 2009).

Equation 3:

$$\dot{Q}_e = \dot{m}_w c_{p,w} (T_{w,o} - T_{w,i})$$

Where:

$\dot{Q}_e$ = rate of heat transfer (W)

$\dot{m}_w$ = mass flow rate (kg/s)

$c_{p,w}$ = specific heat of water at constant pressure (J/kg.K)

$T_{w,o}$ = temperature of water out (K)

$T_{w,i}$ = temperature of water in (K)

A similar equation can be used to determine the rate at which heat is absorbed in the condenser, refer to Equation 4.

Equation 4:

$$\dot{Q}_c = \dot{m}_w c_{p,w} (T_{w,o} - T_{w,i})$$

Where:

$\dot{Q}_c$ = rate of heat absorbed (W)

$\dot{m}_w$ = mass flow rate (kg/s)

$c_{p,w}$ = specific heat of water at constant pressure (J/kg.K)

$T_{w,o}$ = temperature of water out (K)

$T_{w,i}$ = temperature of water in (K)

Theoretically the total heat transferred in the evaporator must be equal to the heat absorbed in the condenser. This is called an adiabatic process and can only be used for theoretical calculations. In reality this process cannot be assumed as adiabatic as heat loss will occur.

Figure 15 represents a vapour-compression cycle but an ammonia absorption cycle can also be used for mine refrigeration systems. The ammonia absorption cycle exchanges the compressor for a liquid pump or a screw compressor. The liquid pump is used to pressurise an ammonia water solution through the cycle to a condenser. With the ammonia being absorbed in water, the specific volume will be less than that of a vapour which results in less work input required. Unfortunately the absorption

cycle is not entirely economically justifiable due to the amount of equipment and maintenance required as shown in Figure 16 (Borgnakke & Sonntag, 2009).

The guide vanes and slide valves of the compressor in a refrigeration cycle can be used to control the cooling load. This is achieved by altering the flow rate of the refrigerant throughout the cycle and therefore controlling the amount of heat transfer. The compressor control is based on the difference between a set-point and the actual value of evaporator outlet water temperature. By increasing the refrigerant flow rate, the electrical power usage and the cooling load will increase. Thus the electrical power usage of the compressor is directly related to the cooling load.

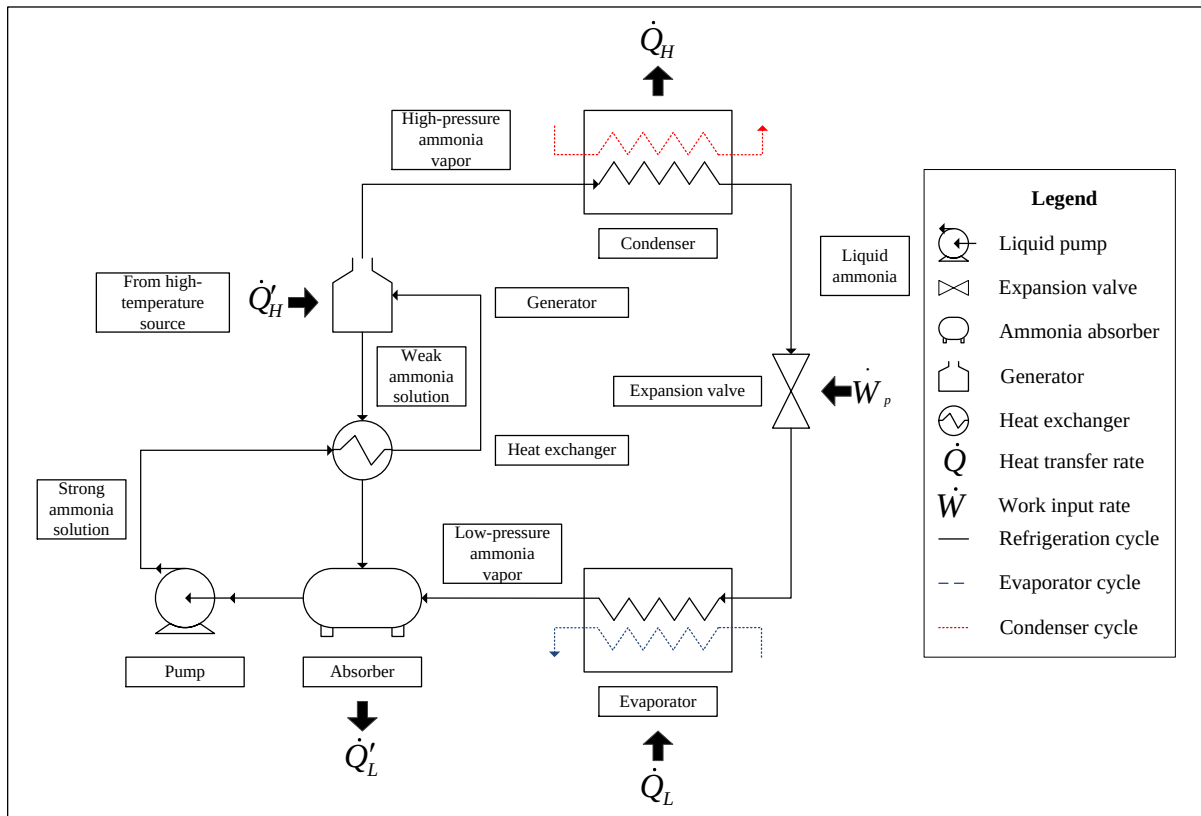


Figure 16: Ammonia absorption cycle.

With the rate of heat transfer in the evaporator and input electrical power of the compressor available, the cooling efficiency of the refrigeration cycle can be determined through Equation 5. The cooling efficiency, also known as the coefficient of performance (COP), indicates the amount of thermal cooling achieved for a unit of electrical power drawn by the compressor. A high COP value indicates an efficient energy usage and a low COP value the opposite (Du Plessis, 2013). Equation 5 can be used to determine the COP value for a single refrigeration cycle, chiller, or an entire refrigeration plant. This is done by substituting the electrical power input of a compressor by that of the entire plant (Borgnakke & Sonntag, 2009; Schutte, 2013).

Equation 5:

$$COP = \frac{\dot{Q}_e}{\dot{W}_c}$$

Whereas:

COP = coefficient of performance

$\dot{Q}_e$ = rate of heat transfer (W)

$\dot{W}_c$ = electrical power input (W)

As seen in Figure 15 and Figure 16, the purpose of a refrigeration cycle is to transfer heat from the water to the refrigerant fluid and vice versa. The same principle applies to the evaporator and condenser cycles. The one difference is that the heat is transferred between air and water through convection and/or evaporation.

The evaporator cycle uses a BAC to transfer heat from the ambient air to cold evaporator water. This is due to the temperature of the evaporator water being lower than the temperature of the ambient air. The result is cool dehumidified air at an average wet-bulb temperature of 7°C that is used for underground ventilation. A BAC will either be a forced draft or an induced draft BAC with fans at the air inlet or air outlet respectively. It is not necessary for a BAC to be vertical as horizontal BACs can be used if adequate space is available (Amsted Industries, 2011). Figure 17 shows a typical vertical BAC used on a mine refrigeration and ventilation system (McPherson, 1993).

The condenser cycle uses cooling towers to transfer heat from the hot condenser water to the ambient air. With the temperature of the ambient air being lower than that of the condenser water sensible heat transfer occurs, also known as convection. Not only does sensible heat transfer occur but latent heat transfer, also known as evaporation, occurs when the water changes from phases. A condenser cooling tower usually utilises induced draft with fans situated on top of the tower as shown in Figure 17 (Amsted Industries, 2011; McPherson, 1993).

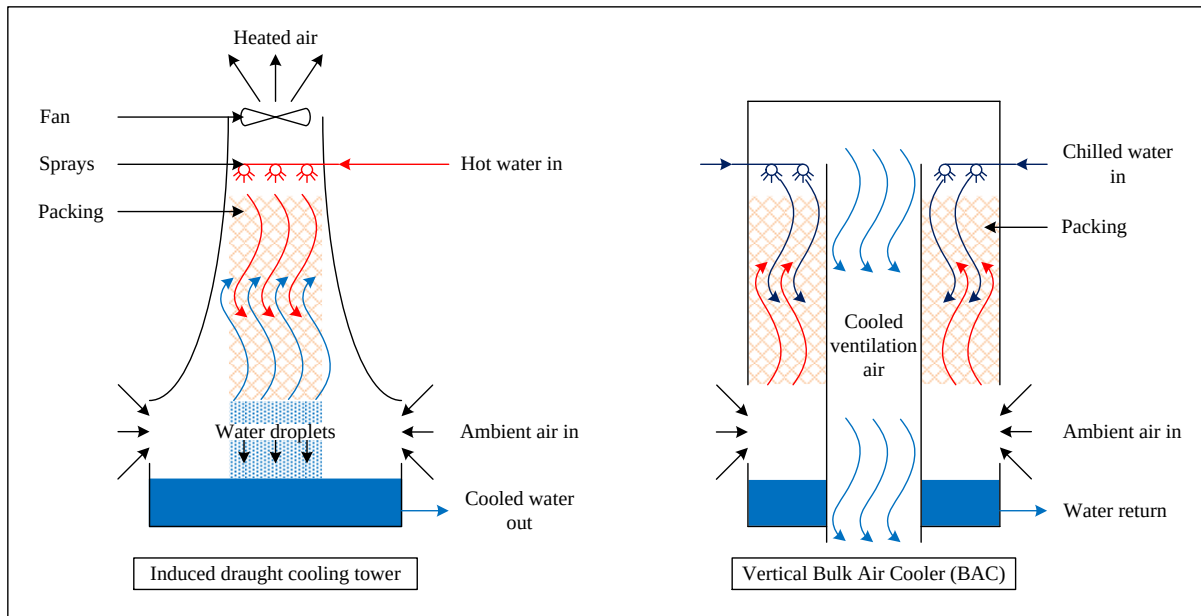


Figure 17: Typical cooling tower and vertical bulk air cooler (Amsted Industries, 2011; McPherson, 1993).

The numbered items below summarise the evaporator cycle of a typical refrigeration and ventilation system of mine.

1. The hot dam water is cooled to an average temperature of 30°C by a pre-cooling tower before it enters the evaporator cycle.
2. The water collected in the BAC sump enters the evaporator where the heat is transferred to the refrigerant fluid.
3. The water will now either be sent underground as service water or it continues to the BAC after being cooled to an average temperature of 2 °C by the evaporator.
4. Within the BAC, heat from the ambient air will be transferred to the cold evaporator water resulting in cool dehumidified ventilation air.
5. Large extraction fans at the return air way shaft draw the cool air from the BAC through the main shaft and mining levels.
6. The service water used through the mine is pumped to the surface hot dam after being utilised underground.

2.3.2 Refrigeration and ventilation system alterations and improvements

In general, a refrigeration and ventilation system is developed to produce either both cold service water and/or cool dehumidified ventilation air. Both these elements are essential for an underground mine to adhere to all the health and safety regulations. Unfortunately underground mine refrigeration and ventilation systems are operated inefficiently to adhere to these regulations. This presented opportunities for strategies to be implemented to improve the operational efficiencies and reduce the

energy demand. This section will summarise various strategies that have already been implemented and proven successful.

Load management

Load management refers to the efficient management of the cooling load to reduce the electrical costs. However, load management does not reduce the amount of electrical energy utilised during the day, but only the electrical costs. This is achieved by spreading the load evenly during the Eskom off-peak hours to reduce the load in the peak hours. The load reduction entails switching off the entire refrigeration plant if and only if the necessary preparations have been achieved. Figure 18 shows the normal electrical power and the proposed load management profile for Mine A.

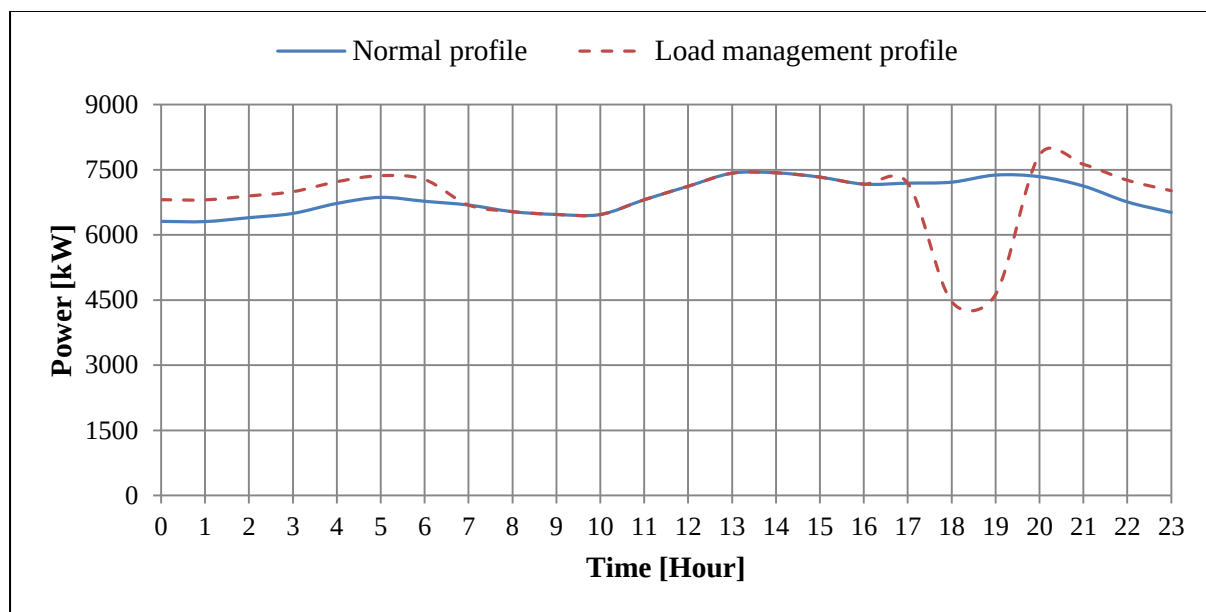


Figure 18: Load management power profile for Mine A.

The potential for a load management project can be identified by evaluating the refrigeration machine utilisation and thermal storage capacity. These two approaches have been developed and refined through numerous studies. The refrigeration machine utilisation is the percentage of electrical load used of the total installed capacity of the plant (van der Bijl, 2007). Whereas, thermal storage capacity refers the capacity to store sufficient cold water for underground usage during the Eskom peak hours (van der Zee, 2013).

A load management project will focus on using existing infrastructure to its maximum constraints during off-peak periods. This refers to the filling of chilled water dams to their maximum levels in order to supply underground usage during peak hours. The chilled water temperature should also be decreased to maximise thermal storage. An additional back-pass of chilled water to the hot dam or refrigeration machine will result in a decrease in compressor power consumption (ASHRAE, 1999; Calitz, 2006).

Refrigeration and ventilation supply control

The operating conditions for a refrigeration and ventilation system on a mine are similar to that of a compressed air system. Cold service water and ventilation air are oversupplied to ensure that there are no short comings (Du Plessis, 2013). However, with current technologies, such as variable speed drives (VSDs), the supply can be reduced in accordance with the underground demand (Yu & Chan, 2010).

Some underground mines implement primitive electrical energy saving strategies on the refrigeration machines by reducing the evaporator and condenser water flow. Unfortunately this is achieved by throttling isolation valves resulting in inefficient pump operation. Results published by van der Zee (2013) depicted a 45% reduction in evaporator pump power with the use of a VSD rather than throttling an isolation valve. Figure 19 shows the normal electrical power and the proposed flow control profile for Mine A.

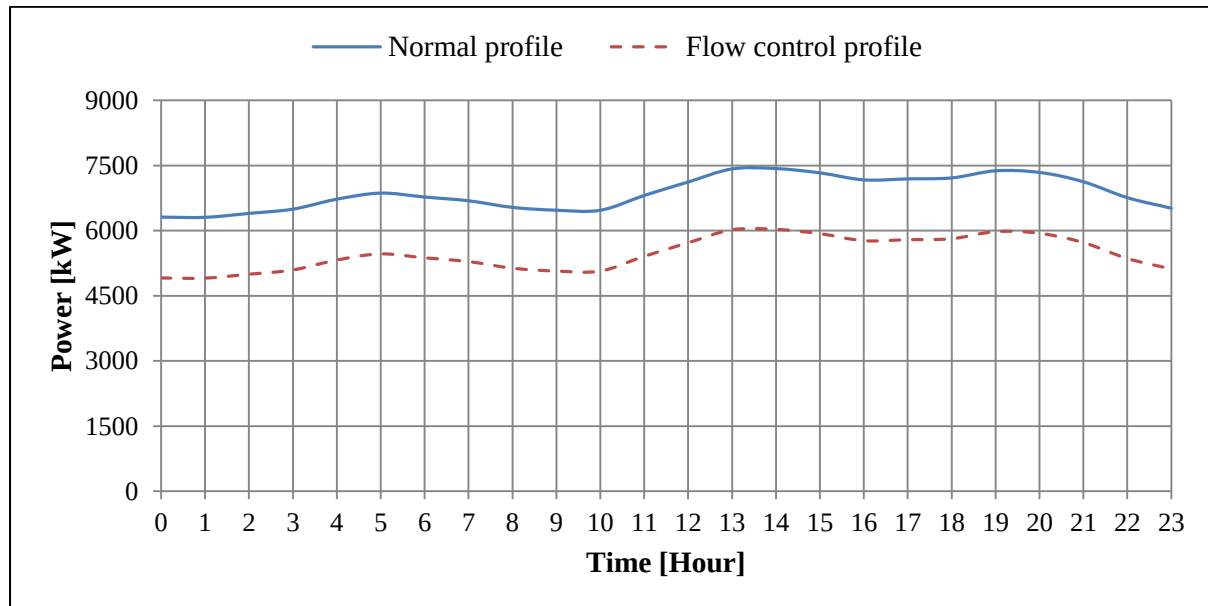


Figure 19: Flow control power profile for Mine A.

VSDs allow electrical motors to be operated at variable speeds and rotational forces. This is achieved by using a variation in output voltage, current and frequency, also known as pulse width modulation. Using VSD on electrical motors not only reduces the power consumption but increases the energy efficiency, power factor and operational life (Saidur *et al.*, 2012). Figure 20 illustrates the correlation between the potential electrical energy savings and average electrical motor speed reduction (Saidur, 2010).

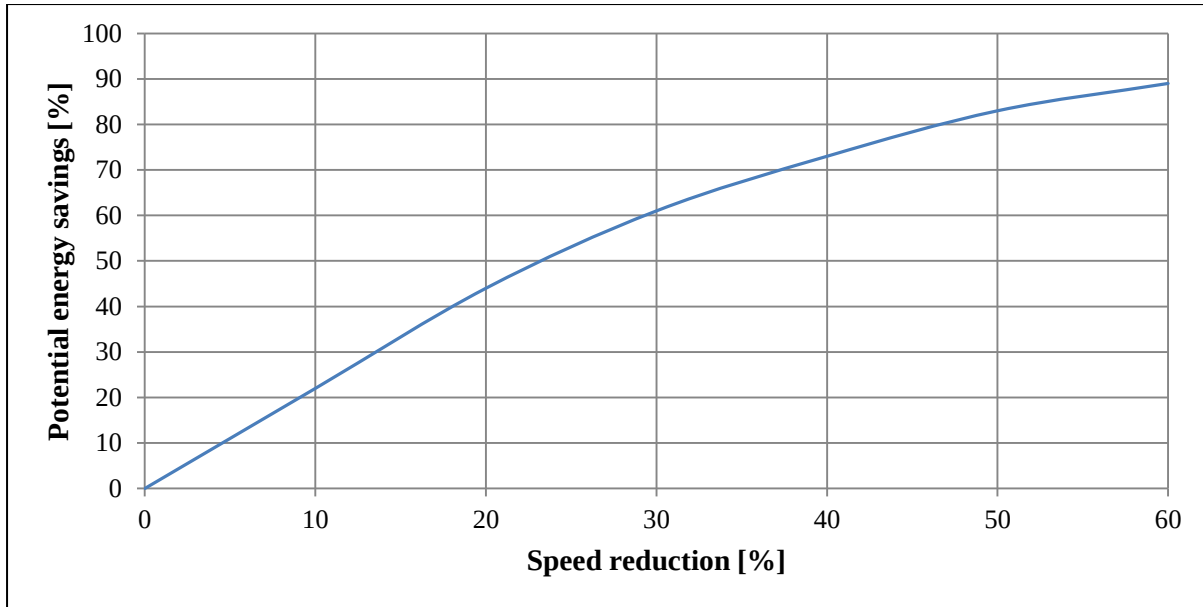


Figure 20: Potential electrical energy savings and electrical motor speed.

Various studies performed by Du Plessis (2013) show that a variable flow strategy has no or a negligibly small effect on the service delivery of a mine. In contrast a variable flow strategy can be accountable for electrical savings of up to 60% with only a 30% reduction in flow (Berkeley Law, 2008). The success of a variable flow strategy is directly dependent on the layout and operation of a refrigeration and ventilation system. Therefore each auxiliary component has been thoroughly discussed in Section 2.3.1. An example of the refrigeration and ventilation operational specifications of Mine C is depicted in Table 2 (Du Plessis, 2013).

Table 2: Specifications of the refrigeration and ventilation system on Mine C (Du Plessis, 2013).

Refrigeration and ventilation system	
Air inlet wet-bulb temperature [°C]	22
Water temperature from underground [°C]	30
Flow rate to underground [ℓ/s]	313
Chilled water dam temperature [°C]	6
Plant COP	5.00
Plant cooling capacity [kW]	42000
Barometric pressure [kPa]	90
Refrigeration machines	
Machine type	York
Cooling capacity per machine [kW]	13300
Evaporator outlet temperature [°C]	5.9
Condenser inlet temperature [°C]	18.5
Evaporator water flow rate [ℓ/s]	300
Condenser water flow rate per machine [ℓ/s]	600
Machine COP	6.65
Refrigerant	R134a
Compressor type	Centrifugal

Water pumps	
Number of evaporator pumps	4
Evaporator pump motor rating [kW]	90
Number of condenser pumps	5
Condenser pump motor rating [kW]	185
BAC return water pumps	
Number of return pumps	3
Return pump motor rating [kW]	75
Pre-cooling towers	
Number of pre-cooling towers	8
Water inlet temperature [°C]	28
Water outlet temperature [°C]	24
Condenser cooling towers	
Number of condenser cooling towers	4
Water inlet temperature [°C]	32
Water outlet temperature [°C]	27.5
Bulk air coolers	
Number of bulk air coolers	3
Water inlet temperature [°C]	3
Water outlet temperature [°C]	14
Air inlet wet-bulb temperature [°C]	22

Evaporator water flow control

Electrical energy savings on the evaporator cycle can be achieved with two different variable flow strategies. The first strategy is by reducing the water flow, to an acceptable minimum, through the evaporator. This will result in a reduced compressor and evaporator pump power consumption. The reduced compressor power consumption is due to the guide vanes controlling at a lower cooling load (Du Plessis *et al.*, 2013). The variable evaporator water flow control can also incorporate a more effective level control of the chilled water dam.

The second strategy on the evaporator cycle is to vary the cold water flow through the BAC to maintain a safe cooling air temperature. With the sessional change in ambient wet-bulb temperature, the amount of cooling needed during the winter will automatically be less. A reduction in compressors and pump power can be achieved by reducing the flow through the BAC according to the desired wet-bulb temperature.

Condenser water flow control

A variable flow strategy on the condenser cycle is greatly dependent on the COP of the refrigeration system. A reduction in flow can affect the COP negatively however, the amount of reduced pump power consumption is greater than the effect of a lower COP. Case studies performed by Arndt (2010) and van der Zee (2013) show savings of up to 40% and 21% respectively with a reduction in condenser water flow. Arndt (2010) also showed that a system COP under full load will stay unchanged with a flow reduction of up to 60%.

2.4 Water reticulation systems

Water reticulation by definition is a network of pipes supplying water to a net point (Oxford University Press, 2014). But a water reticulation system of a mine includes the refrigeration, ventilation and dewatering systems as they are all linked to a water network. This section will continue the detailed discussion on a mine's water reticulation systems and the possible strategies to reduce its electricity costs.

2.4.1 Water reticulation usage throughout the mining industry

As mentioned earlier there are two essential natural elements required for underground mining to take place. The first of these elements is cool ventilation air at a wet-bulb temperature below 27.5°C (Vosloo *et al.*, 2012). The second element is cold service water at a temperature of between 3°C and 6°C (Du Plessis *et al.*, 2013). Both these elements are produced by the surface refrigeration and ventilation system and will be used underground to create a suitable working environment. The cold service water will be used for secondary cooling, drilling and sweeping operations. A detailed layout of a typical mine water reticulation system is shown in Figure 21.

The entire operation of a water reticulation system in a mine is dependent on its depth. For instance a mine less than 1200 m deep will at times only require surface refrigeration systems. Whereas mines deeper than 1200 m, will most of the time require both surface and underground cooling systems (Biffi *et al.*, 2007). Underground cooling systems, also known as secondary cooling systems, consists of refrigeration systems, cooling cars and spot coolers (Vosloo, 2008). Figure 22 shows an example of a typical GNM cooling car used in underground mines.

At these extreme depths, the water supplied to underground will build up hydraulic pressure in the main supply column (van der Zee, 2013). To reduce the pressure various strategies are used. These strategies range from cascading dams to Pelton wheel turbines (Schutte, 2013). The operation of both these strategies is illustrated in Figure 21. The Pelton wheel turbine is the preferred strategy as it converts mechanical energy into shaft work (Vosloo, 2008).

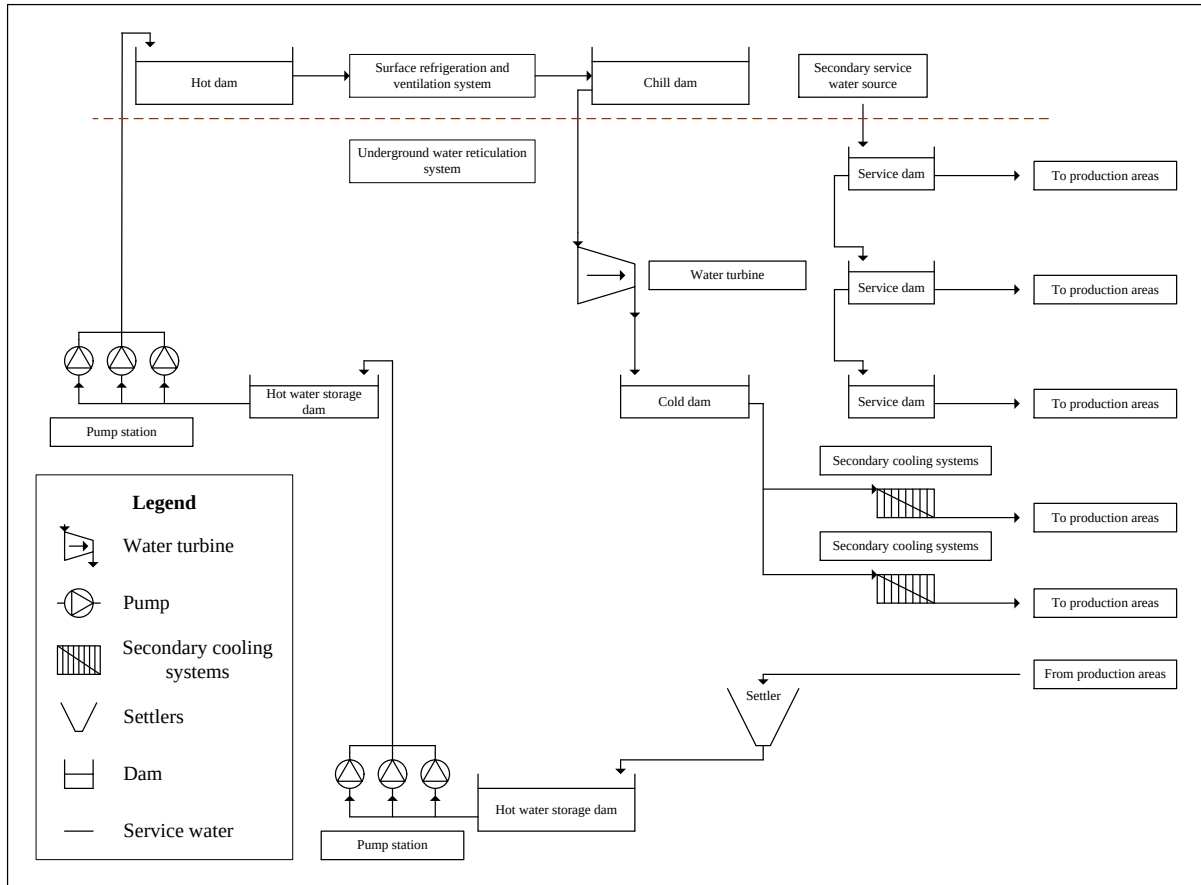


Figure 21: Typical mine water reticulation system.

The last service water utilisation operation is drilling and sweeping that occurs at the production areas of each level. From there the service water together with natural fissure water will flow through the return drains to various settlers. These settlers use flocculants to separate the water from any unwanted mud and rocks that can damage dewatering pumps and surface refrigeration systems (Vosloo, 2008). The removed mud will also be pumped to a surface processing plant to remove any platinum deposits.

After the water is purified by the settlers it will accumulate in hot water storage dams at the bottom of the shaft. Large dewatering systems consisting of pump stations and cascading dams are used to return the water to the surface refrigeration system (Schutte, 2013). Multistage high pressure pumps are used in these pump stations to overcome the static head. The optimum static head between pump stations is 600 m (de la Vergne, 2003). According to de la Vergne (2003) for a tonne of water to be pumped a 100 m every second, would require approximately 1 MW of power. The theoretical power required can however be calculated using Equation 6 (Sayers, 1990).

Equation 6:

$$P_h = \frac{\rho g Q h}{1000}$$

Where:

P_h = theoretical power (kW)

Q = volumetric rate (m³/s)

ρ = fluid density (kg/m³)

g = gravity (9.81m/s²)

h = total head (m)



Figure 22: Typical GNM cooling car.

2.4.2 Water reticulation system alterations and improvements

As described throughout this chapter most mining systems are operated inefficiently, water reticulation included. Therefore this section will investigate several opportunities to improve the efficiency of a water reticulation system and reduce the energy demand. Implementations of electrical energy saving strategies must not at any stage endanger the lives of personnel or influence the production.

Water leaks

The first step in reducing the energy demand within a water reticulation system is to improve the existing system. Water leaks in supply lines are a common cause for the reduced water supply pressure and excess pump power consumption. It can be estimated that a 50 mm leak can cost up to

R3 million worth of pump's electricity consumption per annum with the 2014 electricity rates (Eskom Ltd., 2014). This was achieved by combining theoretical power, Equation 6, and the volumetric flow, Equation 7, derived from Bernoulli's equation (White, 2008). Figure 23 depicts the ratio of wasted electrical power and electricity costs (Eskom 2014/2015 Megaflex tariffs) compared to the diameter of a leak, assuming a line pressure of 800 kPa.

Equation 7:

$$Q = \alpha A \sqrt{\frac{2(P_{inside} - P_{outside})}{\rho}}$$

Where:

Q = volumetric flow (m³/s)

ρ = fluid density (kg/m³)

A = leak area (m²)

P_{inside} = water pressure inside the pipe (kPa)

$P_{outside}$ = pressure outside the pipe (kPa)

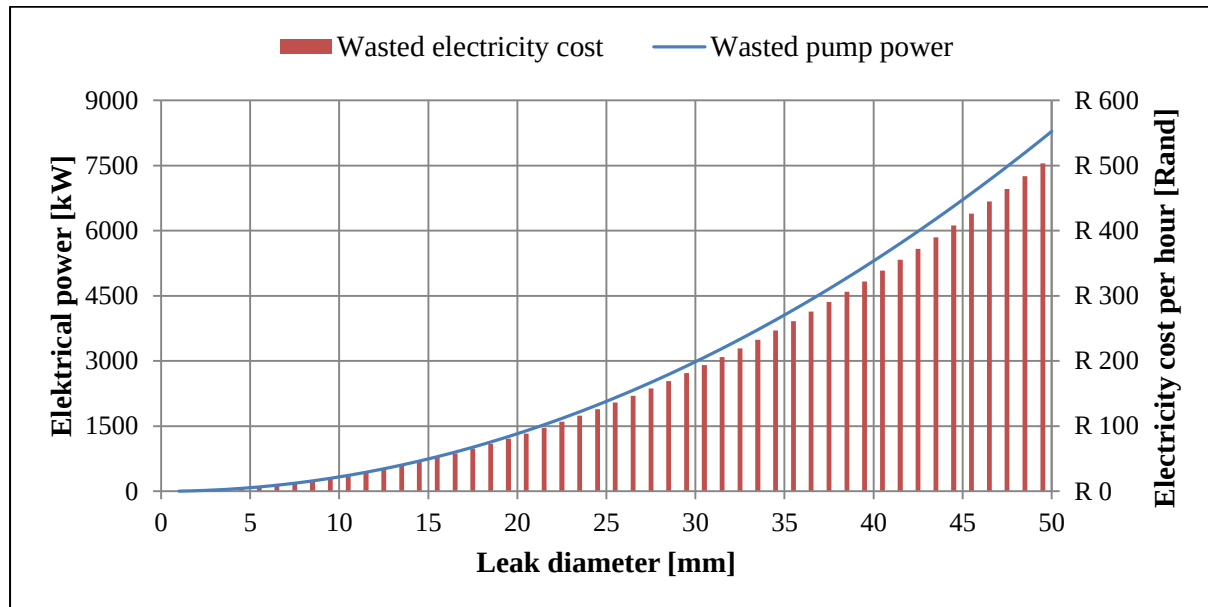


Figure 23: Water leak wastage.

Water wastage is not only due to leaks but also to unauthorised and non-production usage. Unfortunately managing water usage and wastage is a difficult task and seldom receives the attention it should. Therefore the next section will briefly discuss measures to reduce the quantity and pressure of water supply to the end users during non-production periods.

Supply control

Two strategies previously investigated by Vosloo (2008), Botha (2010) and van der Zee (2013) all showed positive cost savings results. These strategies focused on reducing the amount of water consumption during non-production periods. The two strategies are:

1. Isolation control,
2. Pressure control.

The first supply control strategy requires the isolation of water to an entire production level. Isolation of service water will only occur during the blasting shifts as it is only required during other shifts (Botha, 2010). Care must be taken when isolating an entire level as it could influence production or necessary downstream cooling systems. The isolation can be done by either a manual or automated valve system. Manual isolation valves would however rely on the discipline of mine personnel to isolate levels.

It would therefore be recommended to implement automated isolation valves that control according to a predetermined schedule. The actuator on an automated valve can either be pneumatic or electrical depending on the availability of compressed air or electricity. Numerous successfully implemented isolation control strategies have been reported and published.

The last supply control strategy is theoretically based on Equation 7 that states the volumetric flow rate is a radical function of the pressure. By reducing the pressure to an acceptable minimum, less water will be supplied to the end users. This is achieved by implementing pressure reducing valves that control on a pre-set downstream pressure (Botha, 2010). There are a number of PRVs available and each valve will deliver unique results. Figure 24 illustrates the results achieved on Mine C by implementing a pressure control strategy.

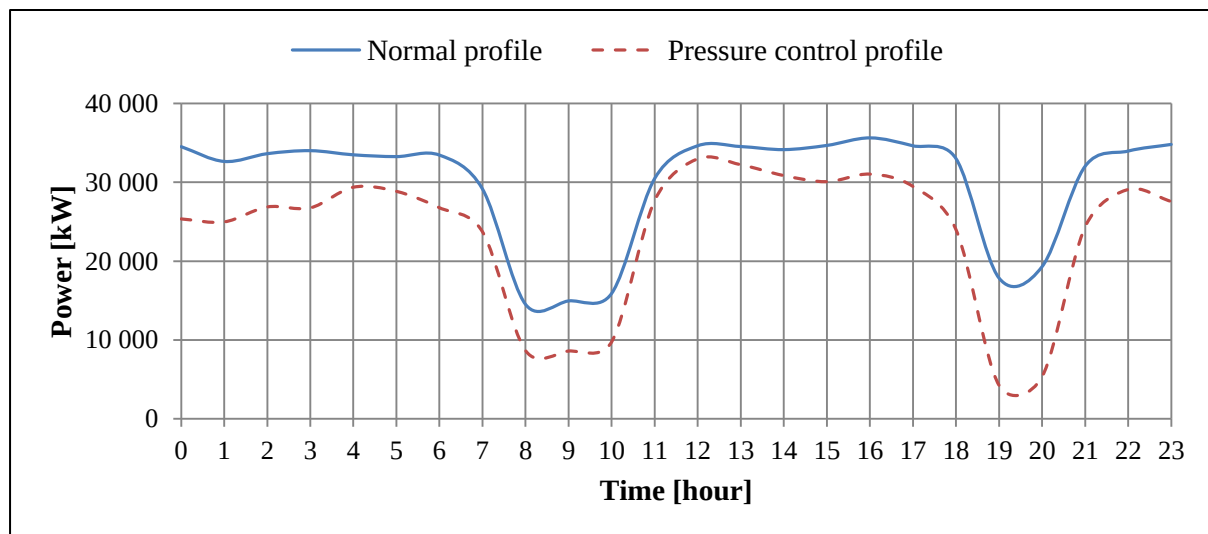


Figure 24: Pressure control implemented on Mine C.

System efficiencies

The next step in reducing the electrical energy demand is to optimise the efficiency of existing systems. This implies altering the operation schedule and pipe layout after the pumps. Underground pumping stations will normally consist of two or more high pressure pumps that receive water from a single manifold. Every pump has an overall efficiency curve that determines its optimum operational conditions. However, a pumping station will use multiple pumps to increase the flow and overcome the large static head (Sayers, 1990). With multiple pumps the overall efficiency curve is combined to form a system curve as seen in Figure 25.

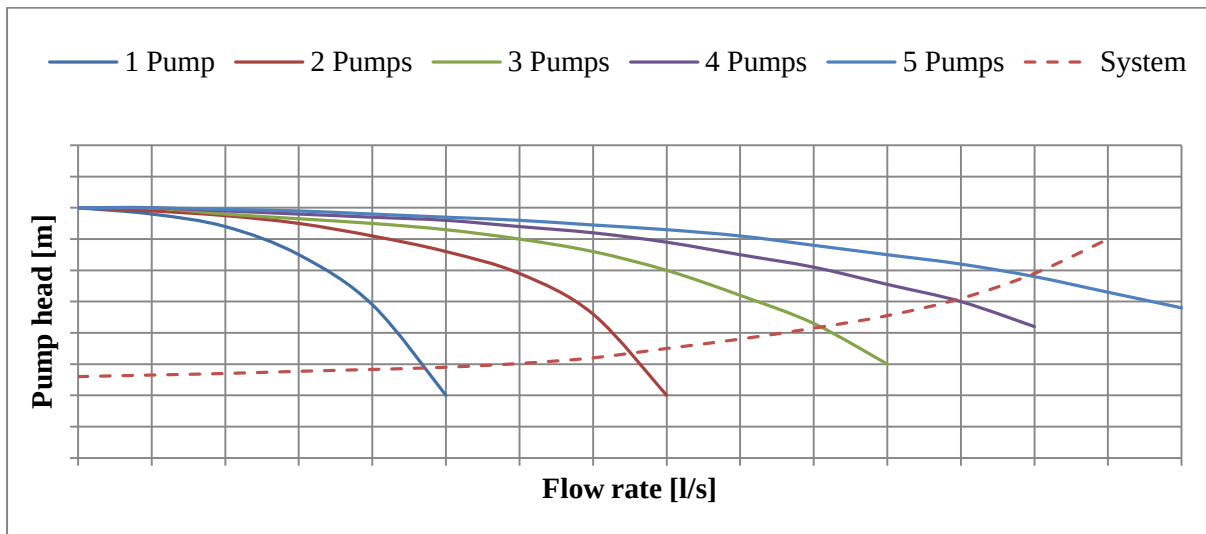


Figure 25: Multiple pumps performance curve.

It is clear that consideration has to be taken when selecting the combination of pump to deliver the desired output. The combination of pumps also refers to a series or parallel arrangement as indicated in Figure 26. A series arrangement will deliver an increased head where a parallel arrangement will increase the delivered flow (Sayers, 1990). Both these arrangements have their limitations and therefore selection should be made for increased efficiency.

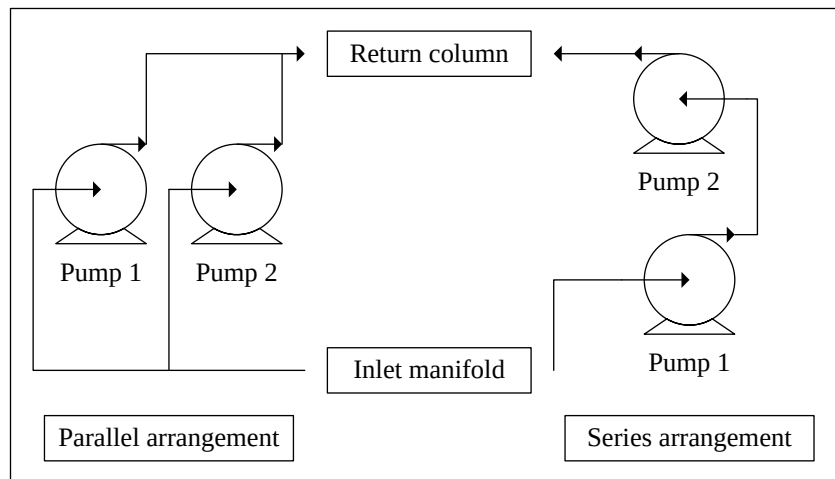


Figure 26: Parallel and series pump arrangements.

Load management

The load management for a water reticulation system refers to a similar concept as described in Section 2.3.2. The load during the high peak tariff periods is evenly spread throughout the lower off-peak tariff periods. For a water reticulation system this implies emptying the hot storage dams beforehand to minimise the risk of flooding when the pumps are switched off during peak periods. Precaution measures such as level sensors, alarms and automated pump starting must also be implemented to avoid flooding. Once the storage dams are emptied and precautions are in place the pumps can be switched off during the peak periods. A theoretical example of a 1 MW load management strategy on a water reticulation system is illustrated in Figure 27.

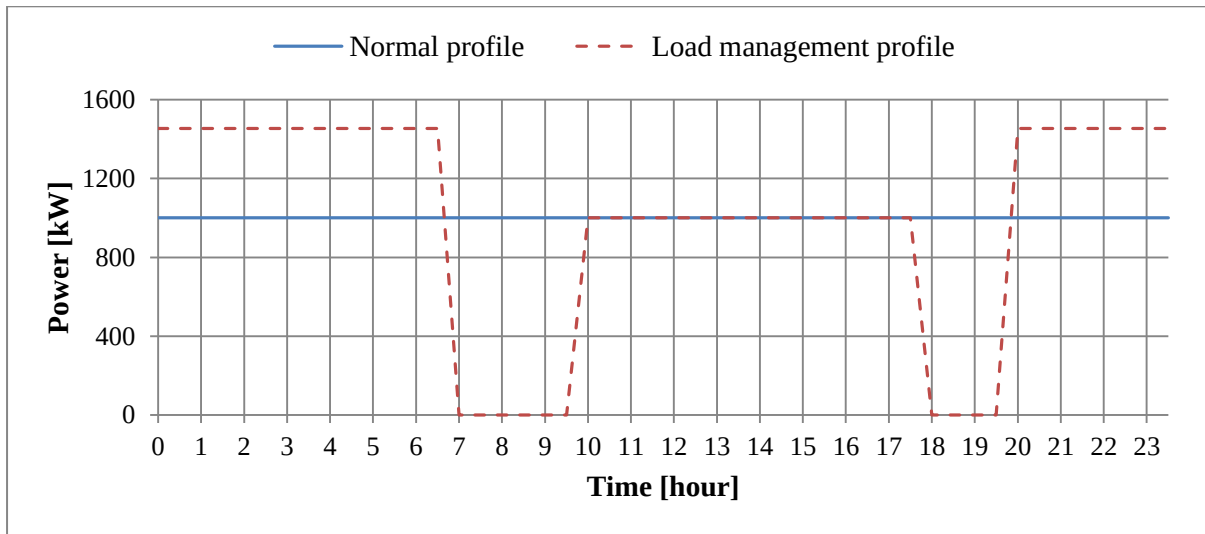


Figure 27: Theoretical 1 MW load management profile (van der Zee, 2013).

Figure 27 represents a 1 MW load management strategy for the morning peak period (07:00-10:00) and the evening peak period (18:00-20:00). The reduced load will be evenly spread from after the evening peak to before the morning peak period. The Eskom peak, off-peak and standard periods are as indicated in Figure 4 in Section 1.1.

2.5 Conclusion

Within this chapter the working of the three large electrical energy consumers of platinum mines were investigated. This was done to evaluate the possibility of implementing electricity cost saving strategies. The investigation delivered numerous possibilities but has shown that the operational limitations of each system have to be considered.

Investigations showed that with low cost system improvements such as leak repairs, regular maintenance and efficient operation schedules, electricity cost savings can be achieved on all three systems. It further showed that by reducing the demand according to the production and electricity tariff schedules, electricity cost savings can be achieved on the supply side.

For compressed air, control valves before the end users can be used to limit the air flow enabling the compressors to cut back on electrical energy consumption. With the use of variable speed technology on cooling auxiliaries, the supply of cooled ventilation air and cold water can also be reduced according to the demand. Lastly, by implementing isolation and pressure reducing valves on service water supply lines a more efficient usage can be maintained resulting in less pump electrical energy consumption.

Chapter 3

Evaluation of DSM strategies

Assessment of applicable DSM strategy on a platinum mine case study

Chapter 3: Evaluation of possible DSM strategies

3.1 Introduction

The previous chapter identified the possible areas of electrical energy savings. Therefore the next step in the process is to evaluate the feasibility of DSM strategies. This feasibility evaluation process is performed to ensure the success of the strategy and that important system parameters are not overlooked. These system parameters may cause a DSM strategy to either underperform or not perform at all.

This chapter will present the parameters of the three large electricity consumers. These details will thereafter be used to simulate the current and optimised system. The results of the simulation model must then be verified by performing an actual on-site test with the particular system. Once the strategies have been proven feasible then the proposal and implementation phase can commence.

3.2 Compressed air systems

3.2.1 System investigation

The investigation into a compressed air system starts at the collection and analysis of information. The information utilised must at all times be reliable and accurate. It must also be a full representation of the system on a typical production day. Information to be collected from a compressed air system is:

1. Compressor electrical power capacity (MW),
2. Compressor electrical power daily consumption (kW),
3. Compressor delivery flow rate (m^3/h),
4. Compressor delivery pressure (kPa),
5. Compressor control system (manual/automated),
6. Compressed air system layout,
7. End user flow rate requirements (m^3/h),
8. End user pressure requirements (kPa).

To establish the above mentioned data, temporary or permanent measuring equipment can be installed. However, temporary measuring equipment must be installed for a minimum of three months capture a more accurate representation of the system operations. Figure 28 shows examples of temporary power and air flow loggers. Once feasibility has been proven it is advised to install permanent power monitoring and logging equipment.



Figure 28: Temporary power and air flow loggers.

Compressor parameter

The electrical power consumption of a compressed air system is crucial in determining the average baseline. This baseline serves as a representation of the daily electricity consumption. It is also the first step in determining the feasibility of a DSM strategy. The daily baseline will to an extent indicate the compressor operational schedule. The electrical power baseline can be measured with temporary power loggers as shown in Figure 28 or acquired from the local SCADA.

The second purpose of a daily baseline is to measure the performance of a DSM strategy after implementation. This performance will be verified by an independent and registered measurement and verification (M&V) team appointed by Eskom. A full discussion on the performance verification process is provided in Chapter 4.

Furthermore, it is important to investigate the deliverable flow rates and pressures of compressors. The daily average of these deliverable values will be used to create a flow and pressure baseline. By combining the flow rate and pressure baseline with the power baseline, a full representation of the supply side can be portrayed. This will also assist in the correct scheduling of individual compressors once the demand baseline is established.

The last two individual compressor parameters to investigate are the level of automation and control. A manual operated compressor must rely on an operator to stop and start a compressor and its auxiliary equipment. However, in some cases mine operators are not disciplined to operate compressors efficiently. By automating the entire system, compressors can be operated according to the downstream demand. This automation incorporates stop/start, blow-off valve, inlet valve and guide vane control and in some cases protection against surge.

Compressed air system parameters

The system parameters to consider are the layout and compressed air demand. A system layout will indicate the approximate distance between air suppliers and users. Together with a daily demand baseline for each end user, the correct location of compressors can be established. This however, only applies to mines that plan to install new or relocate the existing compressors.

A daily demand baseline is calculated with the average air flow rate or pressure to each end user. These pressures and flow rates can be measured with temporary flowmeters and pressure transmitters. But for effective real time system monitoring, it is advised to install permanent measuring equipment.

3.2.2 System simulation and optimisation

Van der Zee (2013) and Marais (2012) both derived simplified sequences when selecting an appropriate optimisation strategy. These sequences start at a thorough system investigation to develop an overview of the system and its operations. Subsequently this leads to the selection of an optimisation strategy or strategies that would be feasible.

However, if a thorough investigation is not possible or proves unsuccessful van der Zee (2013) suggested the following optimisation strategies:

- Compressor selection according to efficiency and location,
- Efficient compressor running schedules (automated or manual operated),
- Controlling downstream demand according to minimum pressure,
- Supplying compressed air according to downstream demand.

If all the necessary system parameters are available it is advised to theoretically and empirically test the appropriate strategy. A theoretical test implies simulating the system for both the current and optimised operating conditions. A simulation can either be manually performed with the correct calculations or with complex simulation software packages. The simulation software to be use is the Process Toolbox (PTB)¹, a thermal hydraulic simulation flow solver.

An empirical test implies a manual test on the compressed air system replicating optimisation strategies. The reason for a manual test is to investigate how the system will react when it is placed under similar conditions. The advantage of these tests is that alterations can be made to achieve the most efficient strategy before implementation. This will reduce the probability of unforeseen costs and delays during installations and implementations.

¹ Process Toolbox thermal hydraulic simulation flow solver - TEMMI International (Pty) Ltd

3.2.3 Case study: Mine A

Mine A compressed air system investigation

Platinum Mine A was selected for the case study as it has an installed capacity of 23 MW and it's lack in electrical energy efficiency awareness. The large variety of available information provides the opportunity for a quick and easy feasibility evaluation. Mine A consists of five centrifugal compressors supplying compressed air to three vertical shafts, four decline shafts and two plants. The compressed air network of Mine A is illustrated in Figure 29 and the compressor parameters are provided in Table 3.

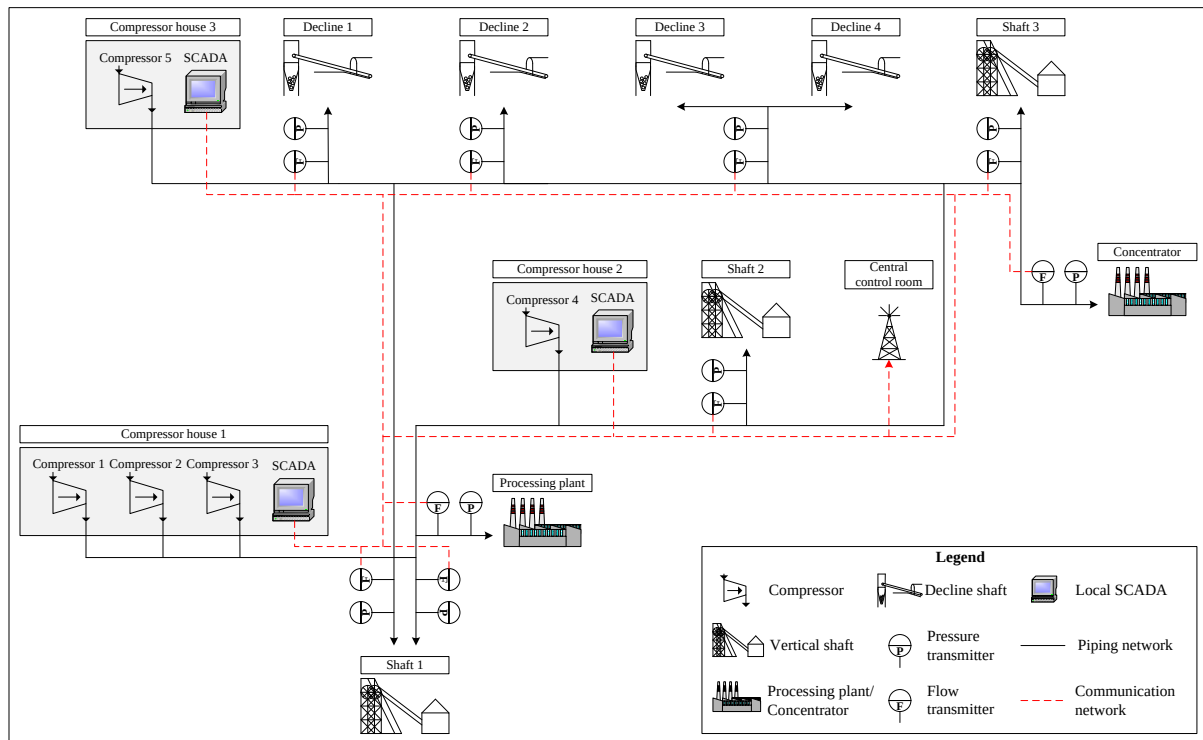


Figure 29: Mine A compressed air network layout.

Table 3: Mine A compressor parameters.

Number	Model	Automation	Surge protection	Installed capacity [kW]	Delivery pressure [kPa]	Delivery flow rate [m ³ /h]
1	GHH	Operator	None	4300	636	40 362
2	GHH	Operator	None	4300	622	45 426
3	GHH	Operator	None	4800	-	-
4	Sulzer	Operator	None	4800	629	41 117
5	GHH	Operator	None	4800	630	41 212

The compressed air is forced into an 11 km closed loop pipeline, also called an air ring. It is from this air ring that compressed air is supplied to each of the end users. As the five compressors are manually operated it is difficult to determine a fix operation schedule. However, the compressors are operated

according to ring pressure requirements. Figure 30 illustrates the average compressor power consumption and the corresponding average operation schedule.

The pressure requirement for the air ring is determined by the highest users at that specific time. This pressure is also used as the set-point at which the compressors must deliver compressed air. Figure 31 depicts the average ring pressure and current set-point pressure versus the proposed set-point pressure for Mine A.

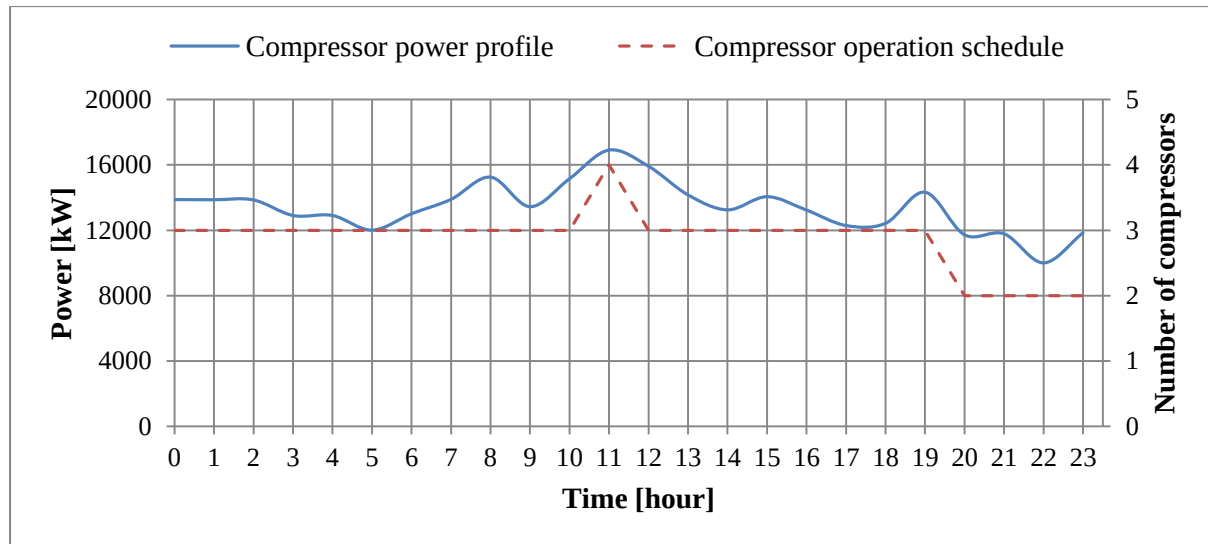


Figure 30: Mine A compressor power profile and operation schedule.

The current pressure set-points indicated in Figure 31 are set according to the daily scheduled mining activities. The typical requirements for the compressed air dependent mining activities are as stipulated in Table 1 (See Section 2.2.1). The large fluctuation in the average ring pressure during 04:00 and 13:00 is due to the drilling shifts demanding high flow rate and pressure.

As a result of pressure losses, such as air leaks, the ring pressure will not reach the desired surface set-point with the minimum compressor capacity. However, some of the pressure losses underground are recovered by a pressure increase caused by auto compression. Snyman (2011) reported an average pressure increase of 66 kPa at a depth of 2.2 km below surface.

Although the underground mining activities halt during blasting shifts, compressed air at 300 kPa is still required for refuge bays. The only significant compressed air user between 13:00 and 21:00 is the surface processing and concentrator plants. The agitation processes require compressed air at a minimum of 400 kPa and a flow rate of above 2000 m³/h, whereas the instrumentation can only function at a pressure of 450 kPa and a flow rate of 300 m³/h.

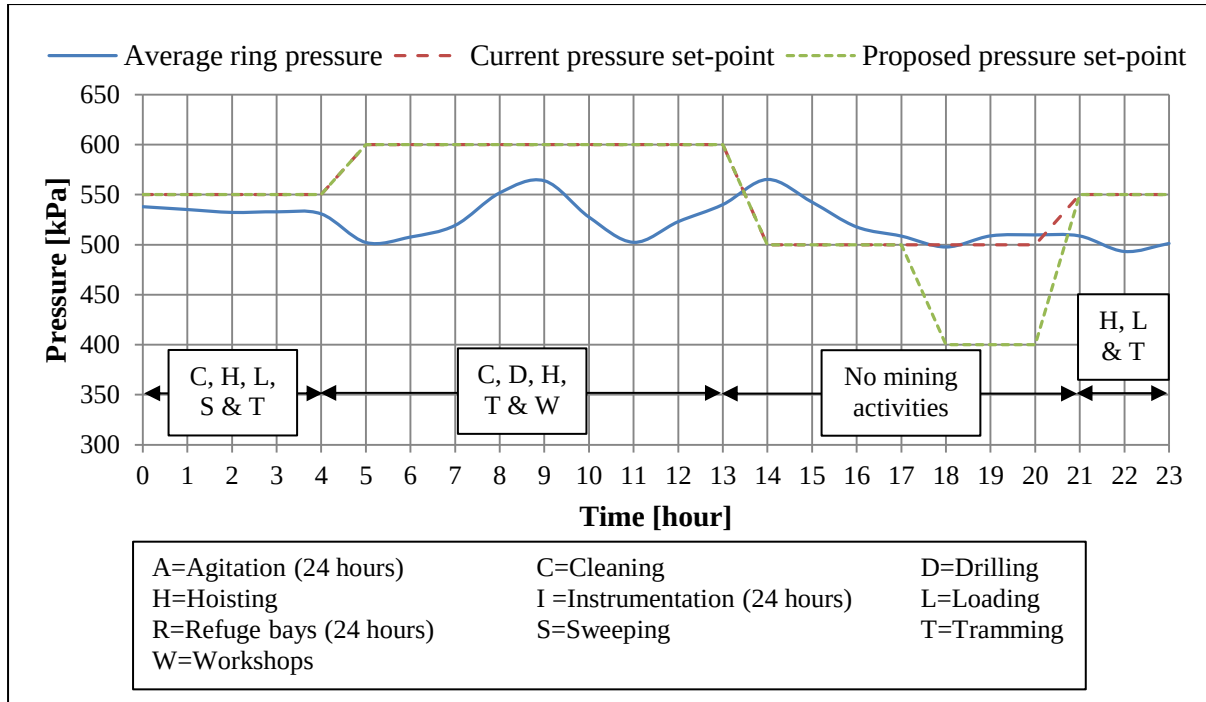


Figure 31: Mine A compressed air pressure requirements.

The low pressure set-point during 18:00 and 20:00 may cause instrumentation failure. However, with the correct flow supply through a smaller diameter pipeline a 50 kPa pressure increase is achievable. This pressure increase can easily be calculated with the simplified Bernoulli equation as indicated below:

Equation 8:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$

Where:

p_i = absolute pressure at reference point i (kPa)

ρ = density of air (kg/m³)

v_i = velocity at reference point i (m/s)

Mine A compressed air system simulation model

The first simulation for Mine A is performed to replicate the actual compressed air system. This simulation will serve as a base from which the optimisation models can be simulated from. The results of the optimisation models will also be measured against the results of the base model.

The procedure followed for the simulation model was:

1. Select the necessary profile data from the system to simulate,
2. Replicate the system layout within the simulation software and incorporate the profile data,
3. Simulate the model and alter if necessary,
4. Analyse the results to validate the simulations model.

The profile data required for the simulation is also referred to as system information in Section 3.2.1. From the system information gathered a layout was constructed in Process Toolbox² (PTB). Figure 32 illustrates the simplified compressed air simulation layout of Mine A.

Two assumptions were made to simplify the simulations. The first assumption is that Decline shafts 3 and 4, Shaft 3 and Plant 2 can be respectively combined as two users. This assumption is based on the fact that these users feed from the same air supply line. Therefore only two mass flowmeters and two pressure transmitters were utilised. The second assumption is the removal of the third compressor unit. This compressor unit has been out of service since the profile data collection period and will not be considered for the system investigations.

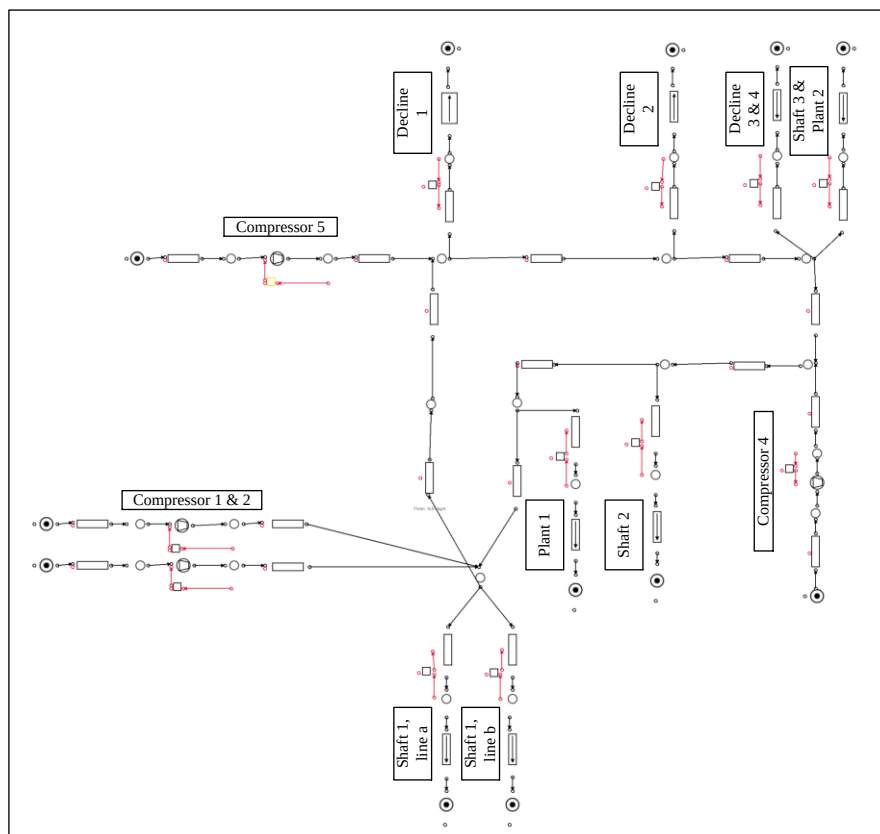


Figure 32: Compressed air system simulation of Mine A.

² Process Toolbox thermal hydraulic simulation flow solver - TEMMI International (Pty) Ltd

The compressed air system was simulated with the profile data of a typical production month. To validate this simulation the average simulated and actual power profiles was compared. The validation process delivered an accurate correlation coefficient of above 90%. Therefore the system simulation was deemed acceptable as it closely represented the actual compressed air baseline. The power profile comparison is shown in Figure 33.

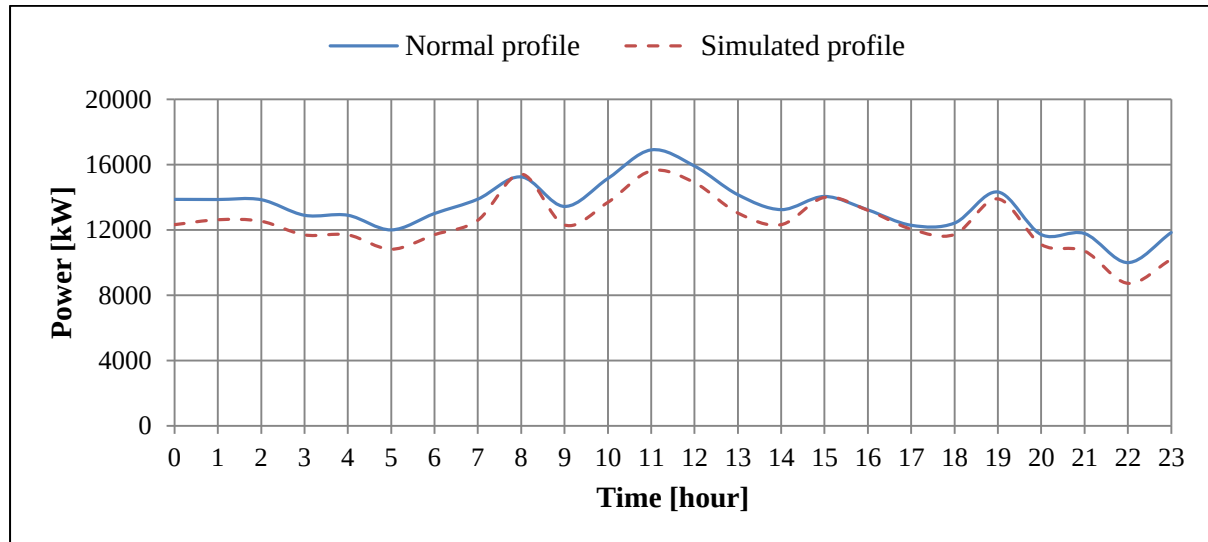


Figure 33: Compressed air system simulation power profile for Mine A.

With the supply side of the system simulation being validated, the next step is to verify the results at the demand side. The simulation delivered a total compressed air usage of 4037 kg/s for five working days compared to the actual 4167 kg/s. The difference between the total mass flows can be assigned to high volumes of condensed water within the actual compressed air system interfering with the mass flowmeter readings.

This assumption can be verified as only the plants utilise air driers before the mass flowmeters. Therefore their simulated and actual mass flow results deviate with less than 2 kg/s for the same five working days. Figure 34 illustrates the normal and simulated compressed air consumption for each end user.

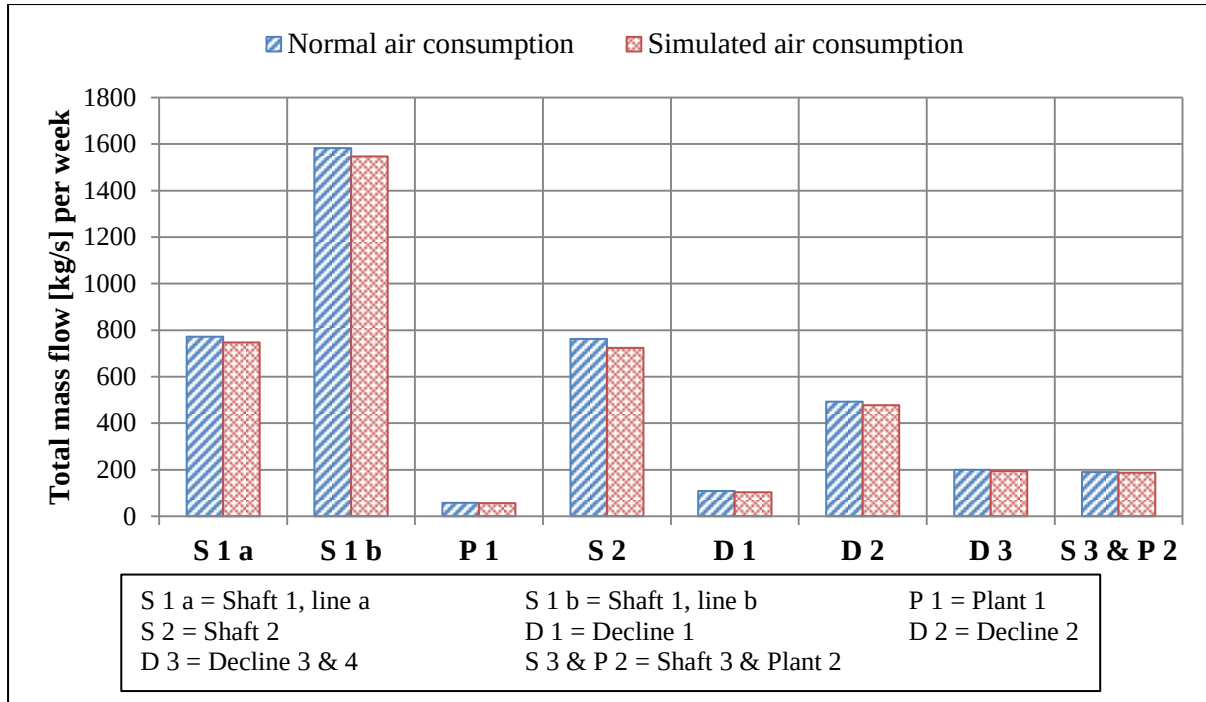


Figure 34: Actual compressed air mass flow vs. simulated compressed air mass flow for Mine A.

Mine A compressed air optimisation simulation models

The optimisation simulations will focus on the two control strategies as mentioned in Section 2.2.2. These simulations will also follow the procedures discussed and will be based on the system simulation layout as seen in Figure 32. The proposed infrastructure to achieve these optimisation strategies is illustrated in Figure 35.

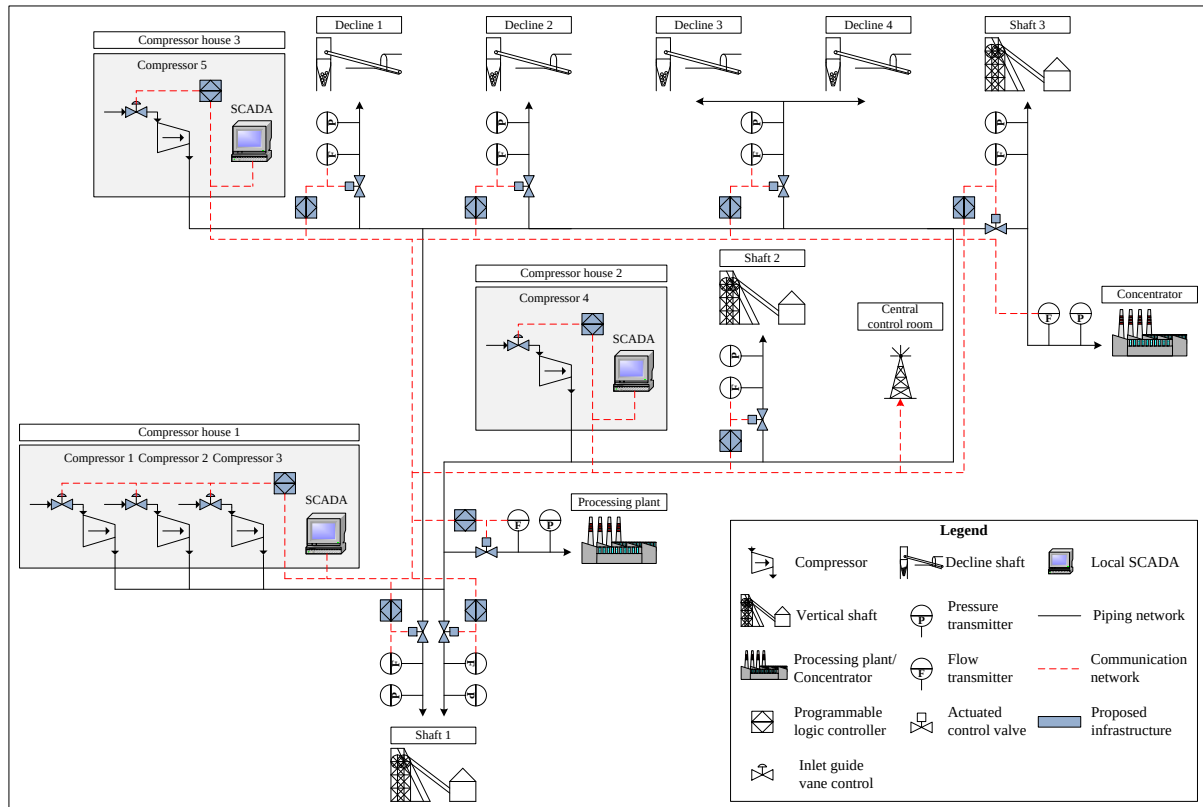


Figure 35: Mine A compressed air network and proposed infrastructure.

The two control strategies selected for simulation are the downstream and compressor control. Both strategies will utilise the function of predetermined set-point values. These set-point values will be simulated with the use of proportional and integral controllers (PI controllers) within PTB. These PI controllers are based on the same principle as an actual proportional integral derivative (PID) controller.

PID control is a closed loop system that calculates an error value through the difference between the set-point and the actual value. Figure 36 demonstrates the simple PID control loop of an actuated control valve (Krass, 2006). The PID controller together with the actual pressure value will determine the position at which the valve should be placed to achieve the desired set-point.

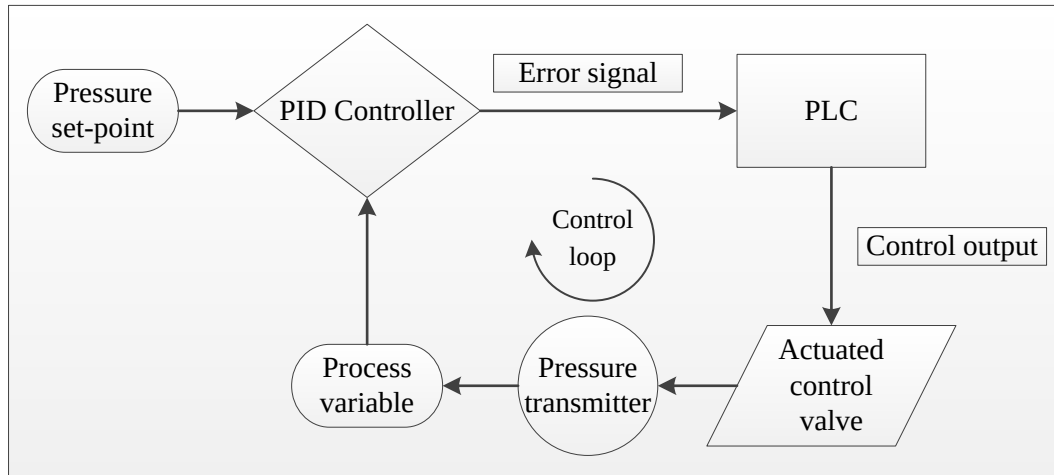


Figure 36: PID control example for Mine A (Krass, 2006).

Downstream control

The first optimisation simulation was performed to simulate the impact of reducing the downstream pressure. Once the downstream pressure has been reduced the ring pressure will increase to a point where the compressor delivery pressure can be reduced. If this functionality does not apply to the site then the option will be to possibly switch off or unload a compressor.

The simulation delivered an average system pressure reduction of 250 kPa. This large pressure reduction is caused by the lower set-point for all vertical and decline shafts. However, the pressure delivered to the plants stayed above 400 kPa during the peak period. The optimised average pressure for the downstream control simulation can be seen in Figure 37.

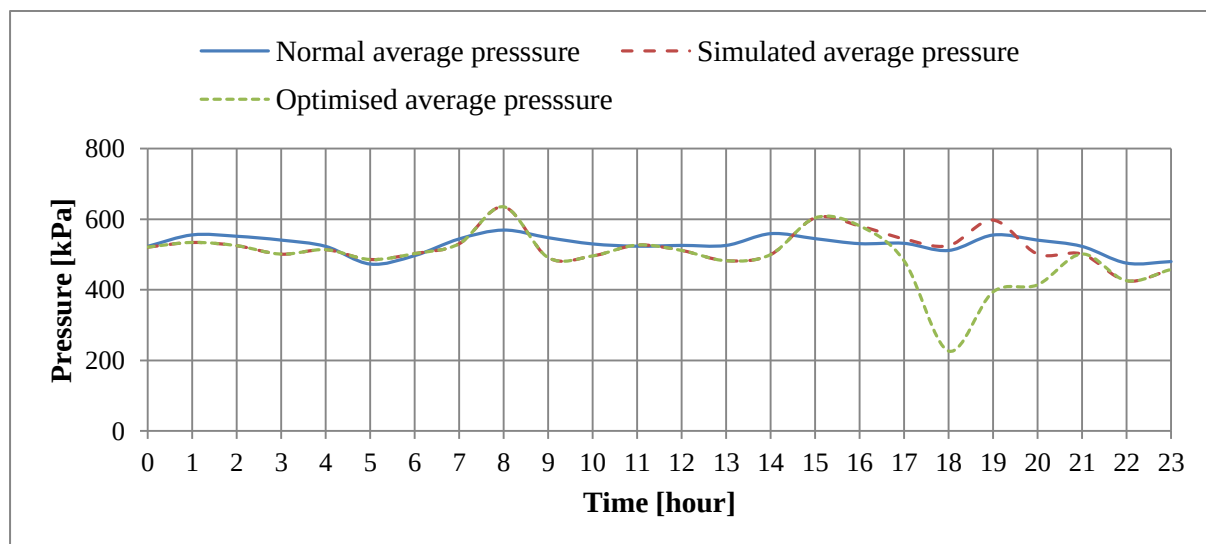


Figure 37: Simulated pressure with downstream control on Mine A.

The downstream control simulation resulted in an average electrical energy savings of 1.41 MW. This however, only represents a peak clip strategy and is illustrated in Figure 38. A larger savings potential is possible if this strategy is converted to electrical energy efficiency. For an electrical energy

efficiency strategy, it is advised to upgrade existing mass flowmeter for higher accuracy. Another option would be to install air drying equipment or water traps throughout the system to reduce the condensed water within the airlines.

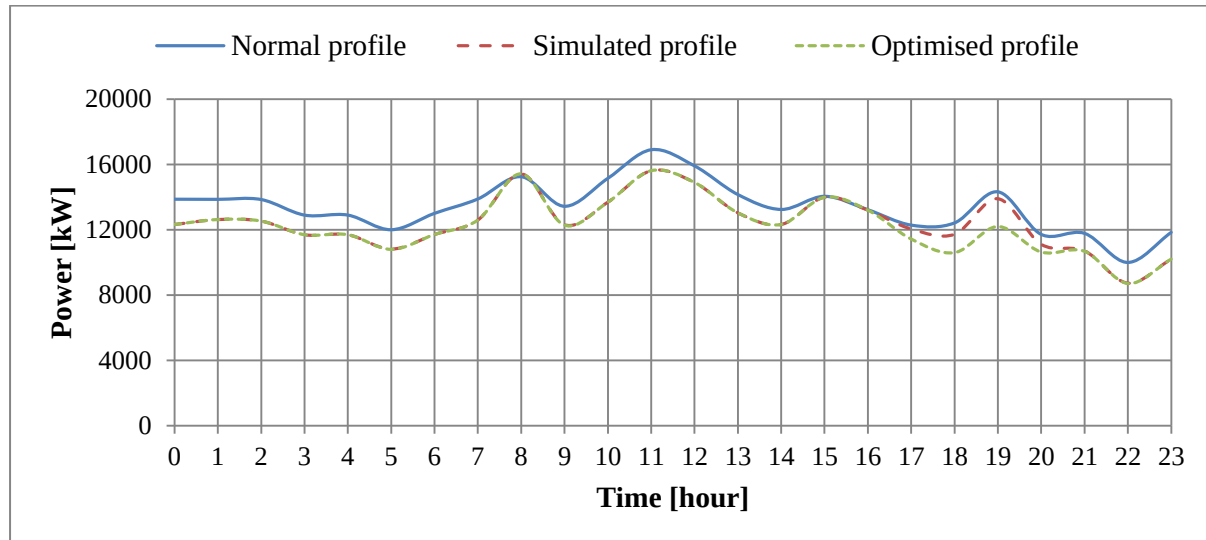


Figure 38: Mine A downstream control simulated power profile.

To implement a downstream control strategy on Mine A would be costly. A total of eight pneumatic actuated control valves with the necessary control equipment such as positioners and programmable logic controllers (PLCs) will be required. Furthermore according to the safety specifications of Mine A, an automated control valve must at all times be provided with a bypass valve.

It should also be noted that the air supply columns to vertical shafts 1 and 2 are 450 mm galvanized piping and 300 mm at Shaft 3. To increase the control capability, the pneumatic control valves will be placed on the 250 mm bypass line. This will allow the pneumatic solenoid open/close valve to be installed on the 450 mm main airline. An example of the control valve layout is shown in Figure 11.

The cost to implement downstream control on a Mine A accumulates to R4.89 million. The detailed quotation for implementing downstream control on Mine A is shown in Appendix C. Taking into account an annual electricity tariff increase of 8%, the estimated payback period for this strategy is 57 months. This immensely decreases the feasibility of implementing downstream control on Mine A. The results for optimisation through downstream control on Mine A is summarised in Table 4.

Table 4: Simulated results for downstream control on Mine A.

Downstream control simulated results	
Peak clip electrical energy savings	1.41 MW
Annual electricity cost savings	R 928 839.89
Installation cost	R 4 899 981.03
Duration of installations	4 months
Payback period	57 months

Compressor control

The second optimisation simulation performed was the compressor control strategy. This strategy entails reducing the compressor delivery pressure to decrease the electrical energy consumption. A full discussion into this strategy is provided in Section 2.2.2. Figure 39 illustrates a typical compressor controller (Matrikon Moore, 2010) for more information.

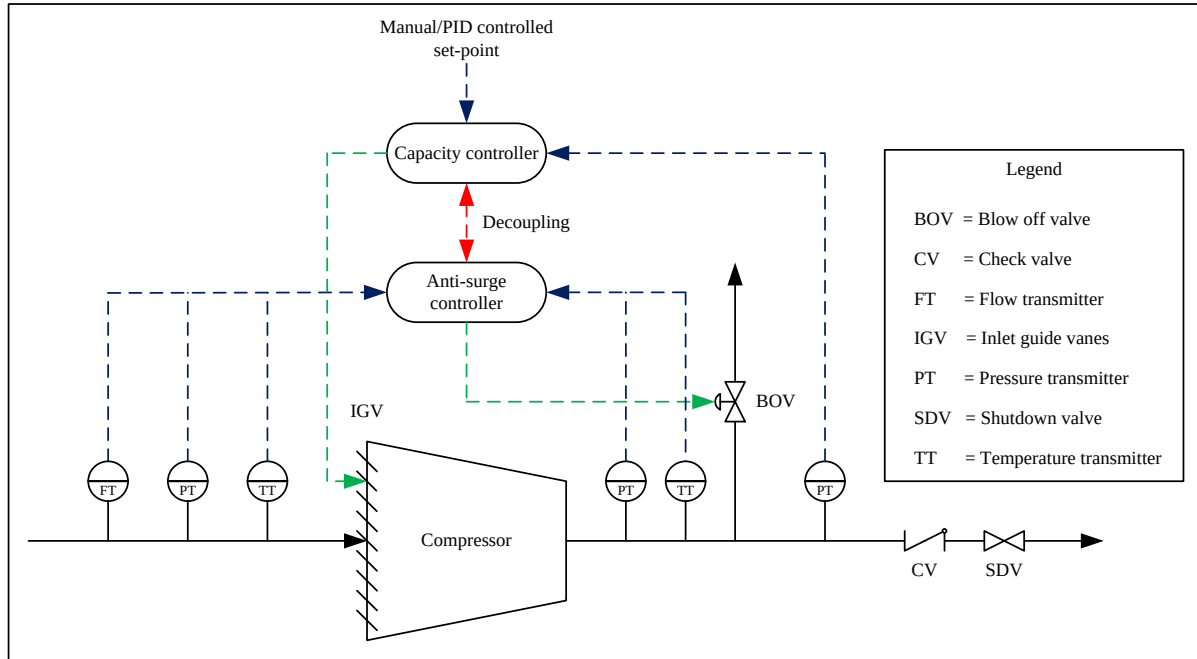


Figure 39: Moore compressor controller (Matrikon Moore, 2010).

The compressor controller, otherwise known as a capacity controller, varies the angle of the inlet guide vanes to obtain the desired delivery pressure. The compressor controller itself utilises a PID closed control loop to calculate the correct angle. For simulation purposes a PI controller within PTB will be used to replicate the compressor capacity control system.

With the use of PI controllers the compressors were set to control on a downstream pressure of 450kPa. This downstream pressure will be the average pressure before each end user. A 450 kPa set-point was selected to conform to the requirements of both plants. It was assumed that there is no existing downstream control and no air leakages. The reduction in delivery pressure at the compressors and the end users are compared in Figure 40.

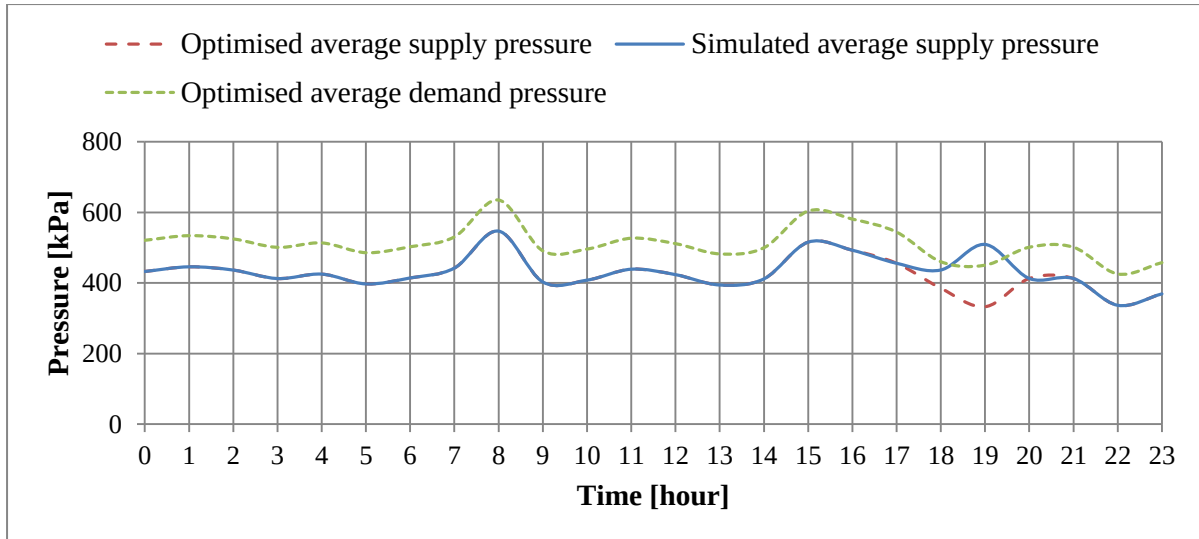


Figure 40: Mine A compressor control simulated delivery pressure.

The simulation delivered a potential 2.94 MW peak clip electrical energy savings per day. This strategy can also be applied as an electrical energy efficiency strategy. With a 2.94 MW peak clip reduction the electricity cost savings accumulates to over R1.93 million annually (Eskom 2014/2015 Megaflex tariffs) (Eskom Ltd., 2014). The impact of the simulated compressor control strategy on the power profile is shown in Figure 41.

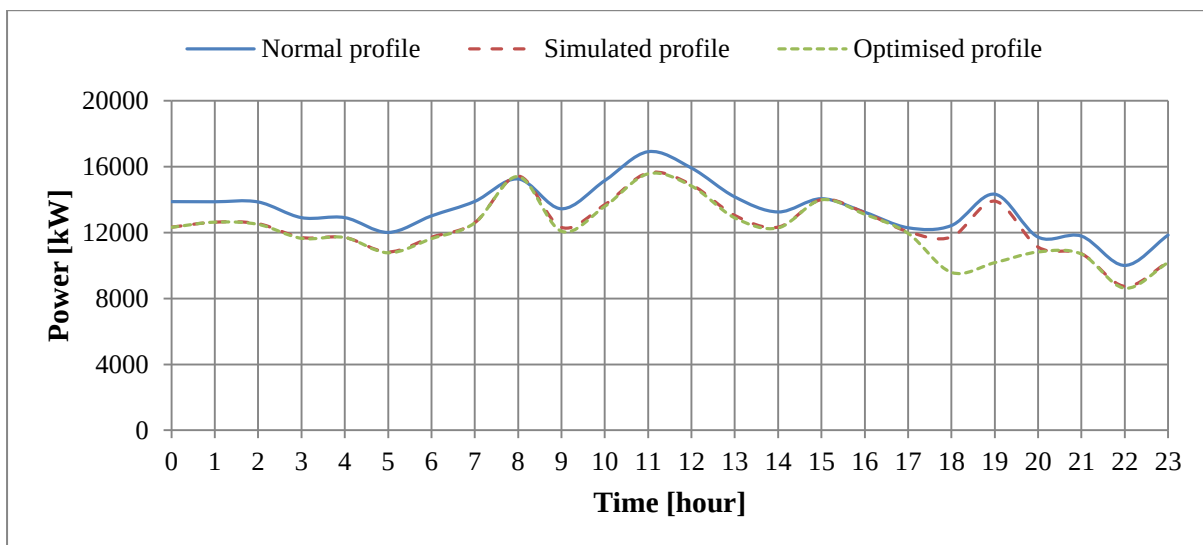


Figure 41: Mine A compressor control simulated power profile.

Although the feasibility of this strategy appears certain, possible high implementation costs can prevent the execution. The cost to implement a full compressor controller is estimated at R1.7 million per compressor. Fortunately Mine A already utilised a similar controller on all five compressors. This controller was however, only configured to prevent the compressors from entering surge conditions.

To fully profit from the current controller the following upgrades will have to be made:

1. Active surge control with surge curve plotting,
2. Independent set-point and inlet guide vane control.

The implementation cost of the compressor control upgrades for Mine A is estimated at R160,000. A detailed quotation quantifying the implementation cost is shown in Appendix C. With the low implementation cost and the large electricity cost savings, the payback period is calculated at 3 months. A two month implementation period was assumed for the payback period calculations. The results for implementing compressor control on Mine A are tabulated in Table 5.

Table 5: Simulated results for compressor control on Mine A.

Compressor control simulated results	
Peak clip electrical energy savings	2.94 MW
Annual electricity cost savings	R 1 933 089.18
Installation cost	R 158 567.50
Duration of installations	2 months
Payback period	3 months

Integration of downstream and compressor control

The last simulation performed was the integration of the downstream and compressor controller. By integrating the two strategies the demand and supply side could be controlled more efficiently. This allowed each user and supplier to be controlled independently but still maintain the system balance. The individual set-points selected are illustrated in Table 6.

Table 6: Mine A control set-points.

	Control set-point [kPa]
Compressor 1	450
Compressor 2	450
Compressor 4	450
Compressor 5	450
Decline 1	250
Decline 2	250
Decline 3 & 4	250
Shaft 1 line a	250
Shaft 1 line b	250
Shaft 2	250
Shaft 3	450
Plant 1	450
Plant 2	450

A 450 kPa set-point was selected for Shaft 3 due to the second plant utilising the same airline. The set-point for Plant 1 was also selected at 450 kPa as both plants require high pressure for instrumentation. This integration simulation delivered a new proposed electrical energy savings of 3.7 MW during the peak period. This reduction in electrical energy consumption is depicted in Figure 42.

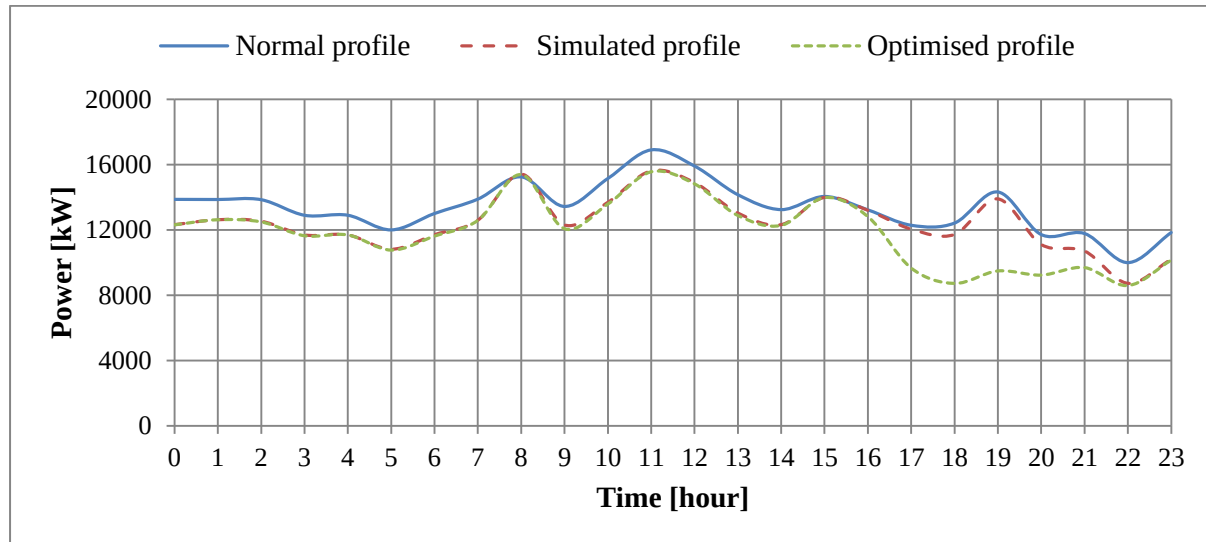


Figure 42: Mine A integration simulation results.

Therefore the payback period for this optimisation strategy is estimated at 28 months with an annual electricity cost saving of R2.43 million. The implementation cost of R5.06 million is assumed as the sum of the combined strategies. A detailed quotation quantifying the implementation costs is shown in Appendix C. For the payback period Eskom Megaflex electricity tariffs for 2014/2015 were taken with an average annual increase of 8% (Eskom Ltd., 2014). Table 7 summarises the savings results achieved with the integrated simulation.

Table 7: Simulated results for downstream and compressor control on Mine A.

Downstream and compressor control simulated results	
Peak clip electrical energy savings	3.70 MW
Annual electricity cost savings	R 2 434 857.47
Installation cost	R 5 058 548.53
Duration of installations	4 months
Payback period	28 months

3.2.4 Conclusion

With sufficient site specific information gathered a simulation model was constructed to represent the compressed air system of Mine A. The simulation model was verified and proven adequate to be adapted for further investigation models. Three applicable strategies selected from Chapter 2 were simulated to estimate the potential electrical energy and electricity cost savings.

The three simulations performed on the compressed air system of Mine A resulted in viable electricity cost savings. However, the high installation cost for downstream control decreases its financial feasibility leaving two feasible strategies for Mine A. The estimated payback periods for all three electricity cost saving strategies delivered from the financial feasibility analysis are illustrated in Figure 43.

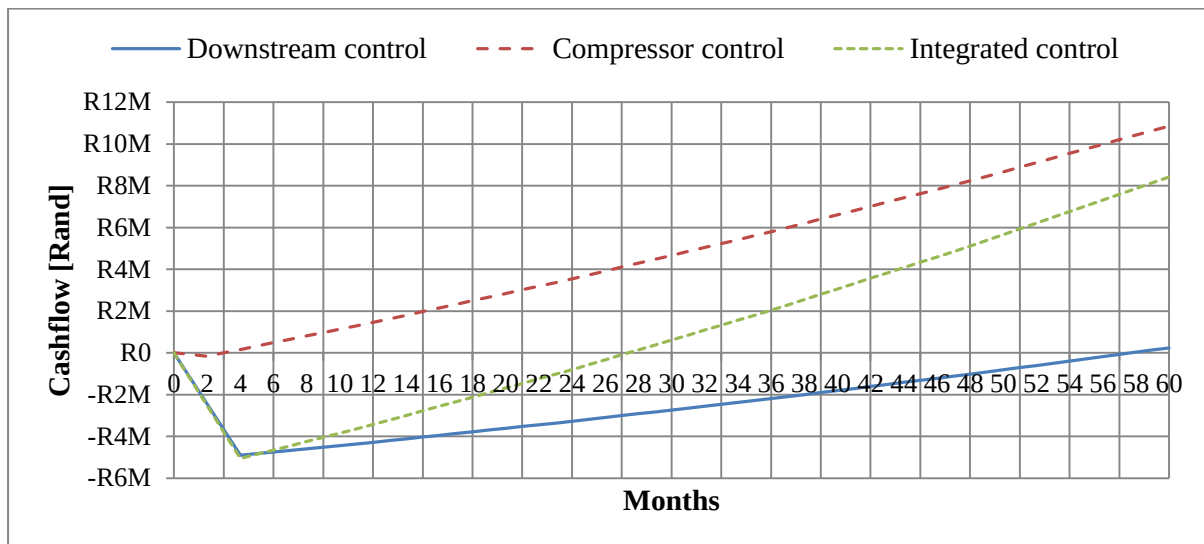


Figure 43: Estimated payback period for compressed air optimisation on Mine A.

3.3 Refrigeration and ventilation systems

3.3.1 System investigations

The investigation process on refrigeration and ventilation systems of platinum mines are performed in a similar sequence to that described in Section 3.2.1 for compressed air systems. The process starts at the collection of site specific information. Whereafter the system will be analysed and simulated with the collected information. These processes are performed to fully understand the functionality and parameters of the system. It should be noted that the information collected must at all times be reliable and accurate.

This investigation will focus on a refrigeration plant and its interaction (but also monitor the effects) between the mining and ventilation systems. Some refrigeration systems are utilised for cold ventilation air and cold service water or either one. The information to be collected from a refrigeration and ventilation system is:

1. Electrical power capacity of refrigeration machines and all auxiliary equipment (kW),
2. Electrical power consumption of refrigeration machines and all auxiliary equipment (kW),
3. Operational schedules,
4. Refrigeration and ventilation systems layout,
5. Design parameters (COPs, ℓ/s , kPa and $^{\circ}C$) of refrigeration machines and all auxiliary equipment,
6. Design parameters (ℓ/s , kPa and $^{\circ}C$) of BACs, pre-cooling and condenser cooling towers,
7. End user requirements (ℓ/s and $^{\circ}C$).

To obtain the above mentioned site specific information two methods will be utilised. The first method is to develop a general overview of the system and its parameters. This will be done by using a questionnaire developed by Du Plessis (2013). The second method will be to collect actual information from the system during operational hours. Actual information can be acquired from the on-site local SCADA if permanent logging equipment is installed. If permanent logging equipment is not available, temporary loggers can be used for this process.

Refrigeration and ventilation system parameters

Before a DSM strategy is investigated on a system, an energy audit is completed. Its purpose is to establish the consumed electrical power baseline. This consumption baseline will be used to determine the feasibility of a strategy. It will also be used after implementation to measure the performance of a strategy.

The baseline for a refrigeration and ventilation system is compiled by the electrical consumption of the entire system combined. This includes all refrigeration machines, auxiliary fans and pumps. An illustration of a typical refrigeration and ventilation system including the auxiliary equipment is shown in Figure 14.

The investigation continues with the collection of design parameters and actual deliverables. Again this will assist in the determining of operational conditions and schedules. A vital parameter to investigate is COPs of all refrigeration machines. During simulations these parameters will be used to determine the impact a strategy will have on the performance of the system once implemented.

Unlike compressed air, most refrigeration and ventilation systems have different running schedules during the year. This is due to temperature changes throughout the seasons. During hot summer months mine personnel will tend to utilise all available surface and underground refrigeration systems. But during winter months less refrigeration is required to achieve acceptable underground temperatures. In some cases only underground refrigeration systems are adequate. However, these operational schedules are not fixed and will vary according to the mine depth and location.

Dependant system parameters

All refrigeration and ventilation systems are used to decrease the temperatures of either service water or ventilation air. Therefore it is also important to investigate or determine the constraints of the dependant systems. The constraints for ventilation systems are the minimum and maximum working temperatures underground. To simplify the measuring of underground temperature the surface BAC temperature will be used as a reference temperature.

The two last constraints to investigate are the temperatures and flow rates of the service water. The reason for these constraints is that some mines use cold water for secondary refrigeration systems. Secondary refrigeration systems refer to underground BACs, cooling cars or in-line spotcoolers. Figure 22 illustrates a typical cooling car used by mines for underground cooling of ventilation air.

3.3.2 System simulation and optimisation model

Two simulation models will be performed for the refrigeration and ventilation systems. The first model will be to replicate the system for all operational conditions. The second model will be used to determine the system impact of variable evaporator and condenser flow control. Both models will be simulated using Process Toolbox (PTB)³, a thermal hydraulic simulation flow solver.

³ Process Toolbox thermal hydraulic simulation flow solver - TEMMI International (Pty) Ltd

3.3.3 Case study: Mine A

Mine A refrigeration and ventilation system investigation

For the feasibility simulation of an electricity cost savings strategy on a mine's refrigeration and ventilation system, platinum Mine A was selected. This section will provide the site specific information obtained from an in-depth site investigation, along with an operational description. The purpose of this first-off investigation is to provide a background from which simulations can be performed.

The surface refrigeration plant of Mine A consists of five refrigeration machines, each utilising an ammonia vapour-compression cycle for energy transfer. These refrigeration machines are used for the cooling of underground service water and ventilation air. The cooled service water is used underground for secondary refrigeration and ventilation. Information regarding the secondary systems is not available and will therefore not be considered for this investigation. A simplified layout of the surface refrigeration and ventilation system of Mine A is shown in Figure 44.

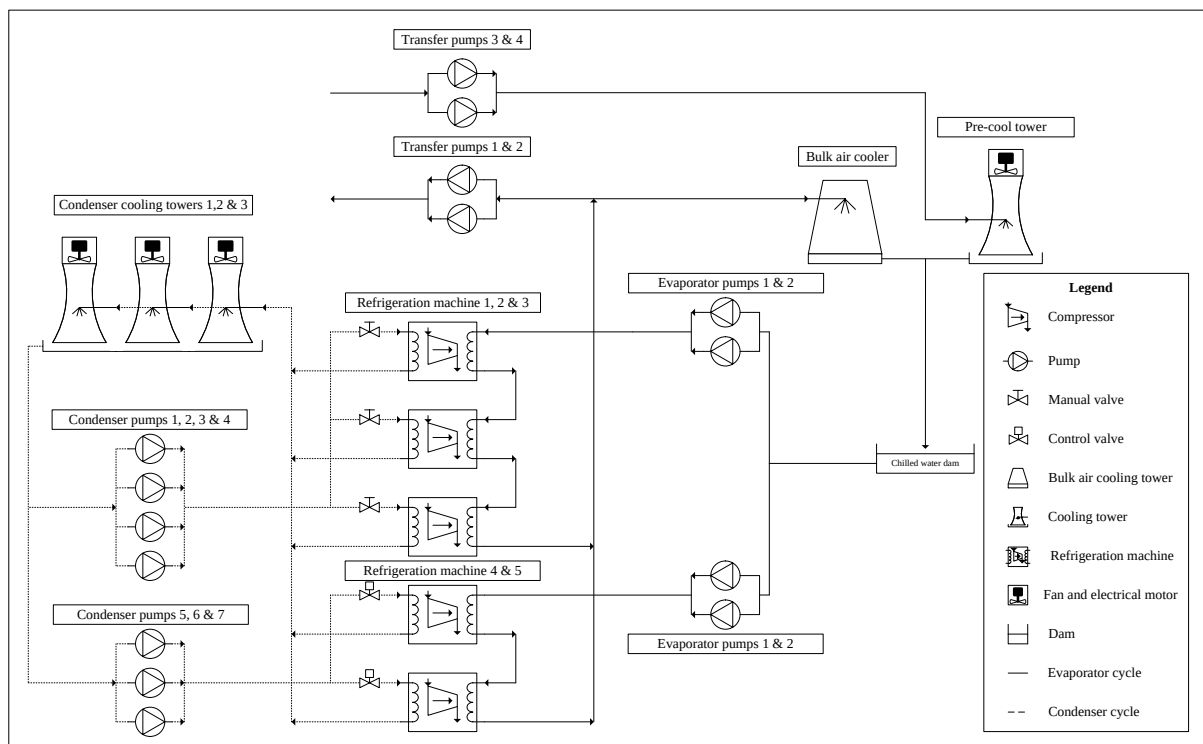


Figure 44: Mine A refrigeration and ventilation layout.

The first process of the refrigeration cycle is the cooling of warm service water. This water, at 28°C, is pumped from the mining shaft through the Pre-cool tower via two parallel pumps (Transfer pumps 3 and 4). After passing through the Pre-cool tower into the Pre-cool sump, at 23°C, it is fed through a levelling pipe to the BAC sump.

Within the BAC sump the water temperature further decreases to 10.5°C before entering the Chilled water dam. From the Chilled water dam, water is pumped by two parallel pump sets (Evaporator pumps 1, 2, 3 and 4) through the five refrigeration machines. The parallel pump configuration is used to increase the flow rate through the common manifold while maintaining a constant pressure difference across the pumps (White, 2008).

The five refrigeration machines are also divided into two sets. The first set consists of three refrigeration machines (1, 2 and 3) whereas the second consists of the last two machines (4 and 5). For this investigation the first three refrigeration machines will be classified as Plant 1 and the last two as Plant 2.

The refrigeration machines are designed to operate as a lead-lag system where the water enters at 12°C and leaves the system at 1°C. The detail parameters are tabulated in Table 8. After exiting the refrigeration machines at 1°C the water is pumped to either the Chilled water dam at the mining shaft or to the BAC. The cold water pumped to the Chilled water dam is manually controlled according to the dam level.

The secondary cold water flow is used for cooling of ventilation air within the BAC. Ambient air is drawn through the BAC and cooled to a saturated 8°C before entering the underground mining levels. The design of the BAC is an induced draught system utilising large extraction fans at various locations throughout Mine A. The extraction fans will not be investigated as they are not included in the optimisation strategy.

At present the refrigeration plants are operated according to seasonal changes. During warm summer months both refrigeration plants are operated with Plant 1 as the base load. Through the winter months only Plant 1 will be operational with one or two refrigeration machines. In order to achieve the correct design flow rates, manual water flow control with valve throttling is used. This control philosophy is kept constant regardless of a variation in water temperatures.

For the condenser cycle water, at 24°C, is pumped through the refrigeration machines by two sets of parallel pumps-again utilising the same control philosophy and parallel pump configuration as described for the evaporator cycle. After leaving the refrigeration machines at 28°C the water is pumped to three condenser cooling towers. Within the condenser cooling towers thermal heat transfer takes place to cool the condenser water to 23°C. Finally the water is collected in a common condenser sump where the cycle starts again.

Table 8: Mine A refrigeration and ventilation system parameters.

Refrigeration and ventilation system		
BAC outlet air temperature [°C]	7.7	
Water temperature to underground [°C]	2.38	
Water temperature from underground [°C]	21	
Flow rate to underground [ℓ/s]	100	
Flow rate from underground [ℓ/s]	100	
Chilled water dam temperature [°C]	12	
Chilled water dam capacity [Mℓ]	0.16	
Plant COP	5.00	
Plant cooling capacity [kW]	32507	
Barometric pressure [kPa]	90	
Refrigeration machines	Plant 1	Plant 2
Number of refrigeration machines	3	2
Machine type	Stal-Astra	York
Cooling capacity per machine [kW]	6532	6455
Evaporator inlet temperature [°C]	12	12
Evaporator outlet temperature [°C]	1	1
Condenser inlet temperature [°C]	24	24
Condenser outlet temperature [°C]	28.5	28.5
Evaporator water flow rate [ℓ/s]	425	280
Condenser water flow rate per machine [ℓ/s]	385	440
Machine COP	5.02	4.97
Refrigerant	Ammonia	Ammonia
Compressor type	Screw	Screw
Compressor rating [kW]	1300	1300
Water pumps	Plant 1	Plant 2
Number of evaporator pumps	2	2
Evaporator pump motor rating [kW]	400	200
Evaporator pump water flow rate [ℓ/s]	425	250
Evaporator pump pressure [kPa]	400	530
Number of condenser pumps	4	3
Condenser pump motor rating [kW]	400	250
Condenser pump water flow rate [ℓ/s]	370	390
Condenser pump pressure [kPa]	400	400
Transfer water pumps	Return pumps	Feed pumps
Number of transfer pumps	2	2
Transfer pump motor rating [kW]	75	75
Transfer pump water flow rate [ℓ/s]	150	150
Transfer pump pressure [kPa]	280	280

Pre-cooling towers	
Number of pre-cooling towers	1
Pre-cooling tower fan rating [kW]	75
Air flow per cell [kg/s]	265
Water inlet temperature [°C]	28
Water outlet temperature [°C]	23
Water flow rate [ℓ/s]	200
Sump capacity [Mℓ]	0.65
Condenser cooling towers	
Number of condenser cooling towers	3
Condenser cooling tower fan rating [kW]	90
Air flow per cell [kg/s]	500
Water inlet temperature [°C]	28.3
Water outlet temperature [°C]	24
Total water flow rate [ℓ/s]	1153
Sump capacity [Mℓ]	0.65
Bulk air coolers	
Number of bulk air coolers	1
Air flow per cell [kg/s]	420
Water inlet temperature [°C]	2
Water outlet temperature [°C]	12
Water flow rate [ℓ/s]	425
Sump capacity [Mℓ]	0.6
Air outlet wet-bulb temperature [°C]	8

Mine A refrigeration and ventilation system simulation model

The system simulation model as described in Section 3.2.3 is performed to imitate the actual system before an optimisation strategy is integrated, whereafter it will serve as a reference for applicable optimisation simulation models. The system simulation model was performed incorporating actual system operational inputs. These operational inputs include:

1. Ambient seasonal condition,
2. Seasonal operation schedules,
3. Chilled water demand and return service water,
4. Ventilation air specifications,
5. Internal system parameters (as seen in Table 8).

Due to the refrigeration and ventilation system only being fully utilised during weekdays, two typical summer and winter production days were selected for the simulation model. The necessary system historical data for the selected days were collected from the local SCADA at the refrigeration plant of Mine A. With all the necessary system data collected a model representing the systems of Mine A was constructed and simulated within PTB. The constructed PTB layout of the refrigeration and ventilation system of Mine A is provided in Appendix B.

With the system simulation model completed a verification process was performed to evaluate its accuracy against the actual system performance. A correlation coefficient of 95% was achieved with the comparison between the actual and the simulated electrical power baseline. This verification process mainly focused on the electrical energy consumption since the objective of this study is to evaluate various electricity cost savings strategies.

The system simulation model for the refrigeration and ventilation system of Mine A was separated into typical summer and winter simulations. The summer and winter operation schedules and parameters used for the system simulations of Mine A are provide in Table 9.

Table 9: Mine A refrigeration and ventilation system operation schedules and parameters.

	Summer (Sept -May)	Winter (June -Aug)
Number of refrigeration machines	4	2
Number of evaporator pumps	5	1
Number of condenser pumps	6	2
Average chilled water temperature to shaft [°C]	1.8	1.5
Average chilled water flow to shaft [ℓ/s]	110	90
Average hot water temperature from shaft[°C]	28	19
Average return hot water flow from shaft [ℓ/s]	110	90

Figure 45 illustrates the comparison between the actual and simulated summer baseline for the refrigeration and ventilation system. These actual and simulated baselines are a representation of a typical production summer weekday. The 2.6% deviation between the actual and simulated summer baselines can be ascribed to variances in the mechanical and thermal efficiencies calculated. This assumption is applicable to the 5.8% deviation of simulated winter baseline as well.

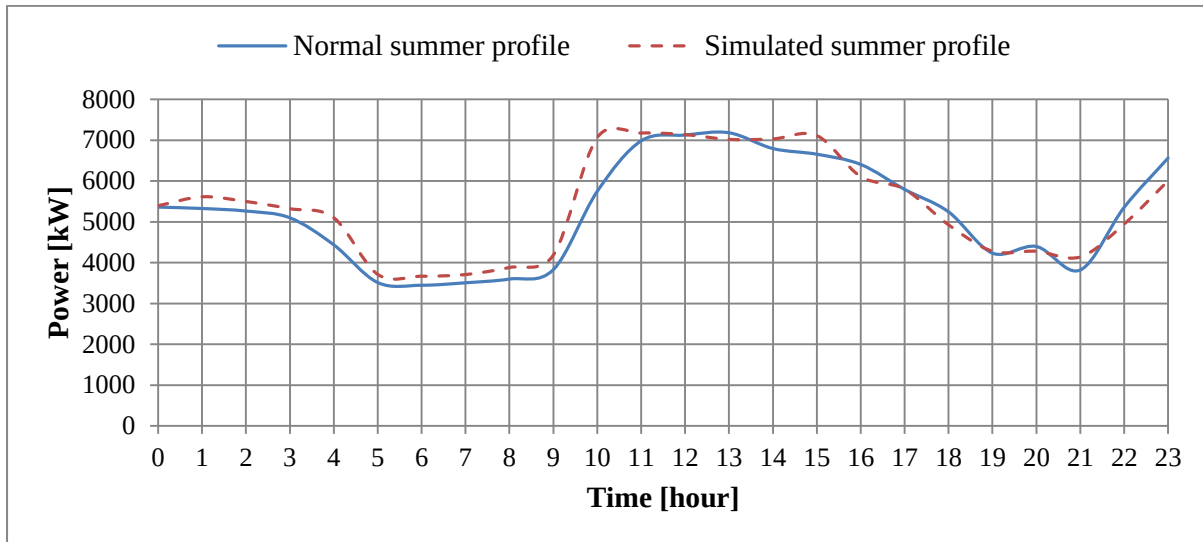


Figure 45: Mine A refrigeration and ventilation simulated summer power profile.

During the winter months the refrigeration and ventilation system consumes on average 46% less electrical energy compared to the summer months. However, the system operation remains inefficient and electrical energy and cost savings are possible. The simulated winter baseline achieved is shown against the actual winter baseline in Figure 46.

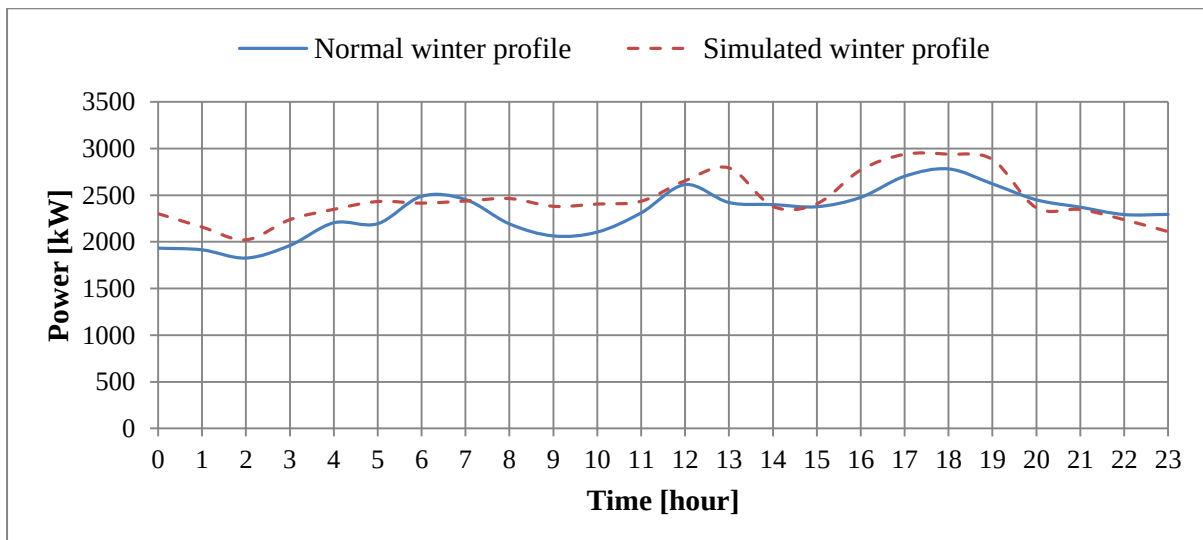


Figure 46: Mine A refrigeration and ventilation simulated winter power profile.

It is clear from evaluating Figure 45 and Figure 46 that the system simulations are accurate representations of the actual systems for both summer and winter seasons. Both simulations followed similar trends throughout the days with the change in ambient and operational conditions. Therefore the system simulation model for the refrigeration and ventilation system of Mine A was deemed accurate and adequate for further optimisation simulations.

Mine A refrigeration and ventilation optimisation simulation models

From the literature study presented in Chapter 2, two optimisation strategies applicable to the refrigeration and ventilation system of Mine A were selected for the feasibility investigation. Therefore the first process in determining the feasibility is to theoretically simulate each strategy. These simulations will be based on the already verified system simulation performed in the previous section.

For the two strategies to be adapted specifically for Mine A the following proposed infrastructure upgrade is required:

1. Six 400 kW VSDs for condenser water pumps 1 to 4 and evaporator water pumps 1 and 2,
2. Three 250 kW VSDs for condenser water pumps 5, 6 and 7,
3. Two 200 kW VSDs for evaporator water pumps 3 and 4,
4. One temperature sensor within the BAC,
5. The automation of the entire refrigeration and ventilation system.

The proposed infrastructure for Mine A is illustrated in Figure 47.

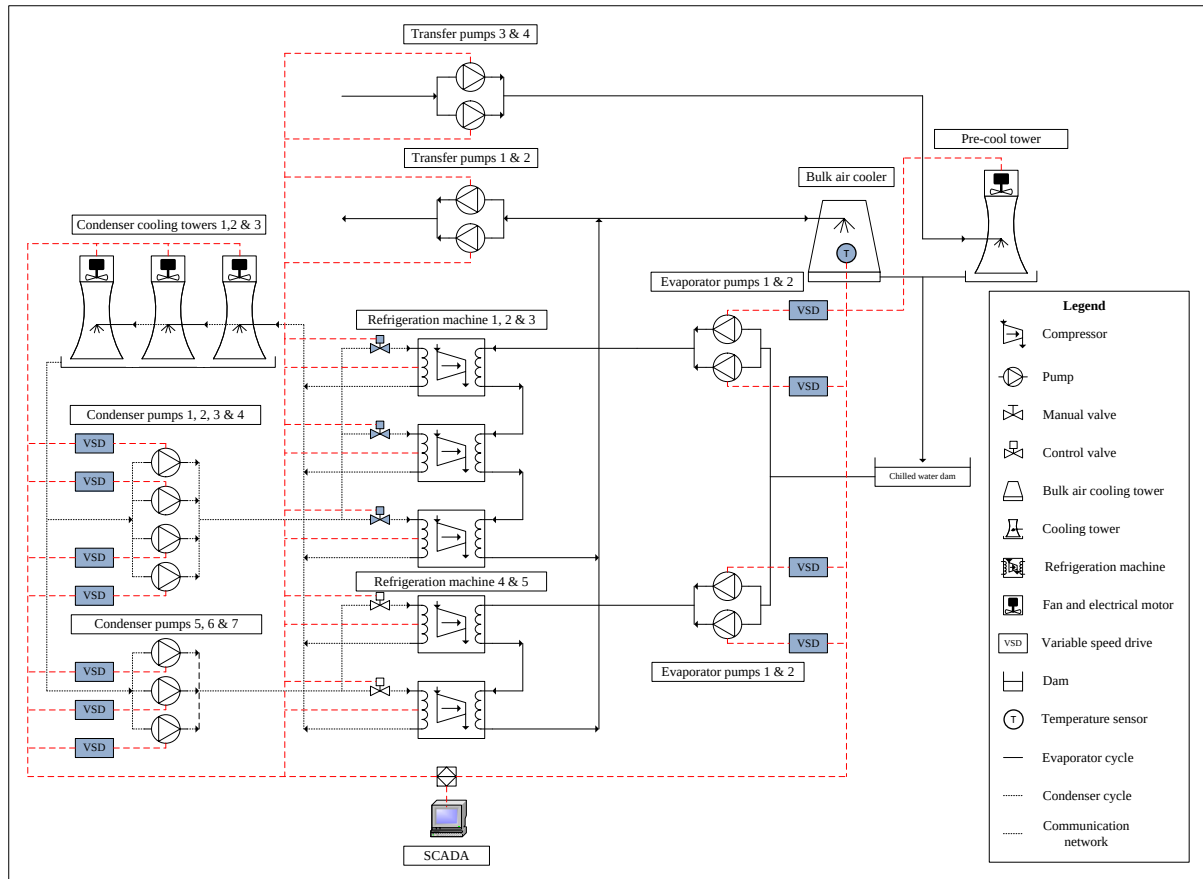


Figure 47: Mine A refrigeration and ventilation system and proposed infrastructure.

Load management model

The first strategy as discussed in Section 2.3.2 is a load management strategy. The strategy would be to shut down the refrigeration machines, condenser water pumps, evaporator water pumps (all but one), condenser cooling tower fans and pre-cool tower fans between 18:00 and 20:00. However, thorough monitoring of the relevant temperatures and dam levels would be required. This is to ensure the temperatures and dam levels do not exceed the maximum/minimum allowable constraints.

To simulate the load management strategy an optimisation simulation model was adapted from the system simulation. All ambient condition and system requirements for the optimisation model stayed unchanged. However, to ensure the model remained within the allowable constraints, two control philosophies were set aside.

The first control philosophy prepared the system for the load management strategy before the peak period (17:00 to 18:00). The preparation control philosophy followed was:

1. Decrease the evaporator water temperature to a minimum 0.8°C ,
2. Increase the cold dam level to a maximum 90%,
3. Decrease the hot dam level to a minimum 60%.

The second control philosophy monitored the system during the load management strategy (18:00 to 20:00). Although this strategy entails turning off the entire system one evaporator water pump continued running for cold water supply to the BAC. The control philosophy followed during the load management strategy was:

1. Shut down entire refrigeration and ventilation system except one evaporator water pump,
2. Maintain the BAC air temperature below a maximum of 12°C.,
3. If the BAC temperature increases above maximum temperature start the run sequence for one refrigeration machine together with the necessary auxiliary equipment,
4. If the BAC temperature continues to increase resume normal operations,
5. If the surface hot water dam level increases above the maximum 80% start the necessary water transfer pumps to the pre-cool tower,
6. If the surface cold dam level decreases below the minimum 60% start the necessary water transfer pumps from the BAC sump.

The simulated and optimised electrical energy consumption profiles for both a typical summer and winters day are illustrated in Figure 48 and Figure 49 respectively.

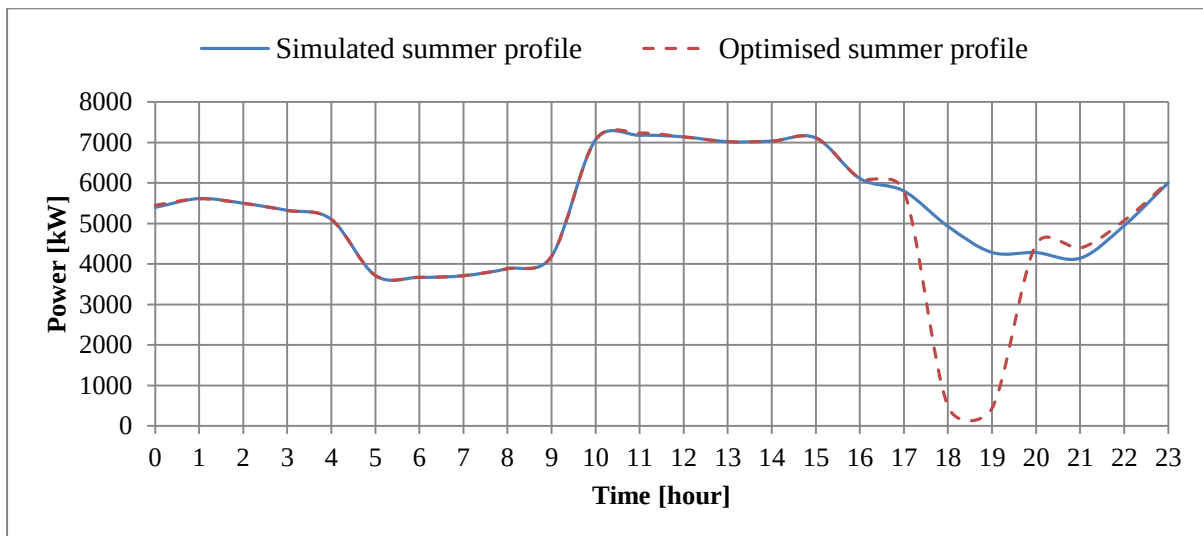


Figure 48: Mine A refrigeration and ventilation simulated load management summer power profile.

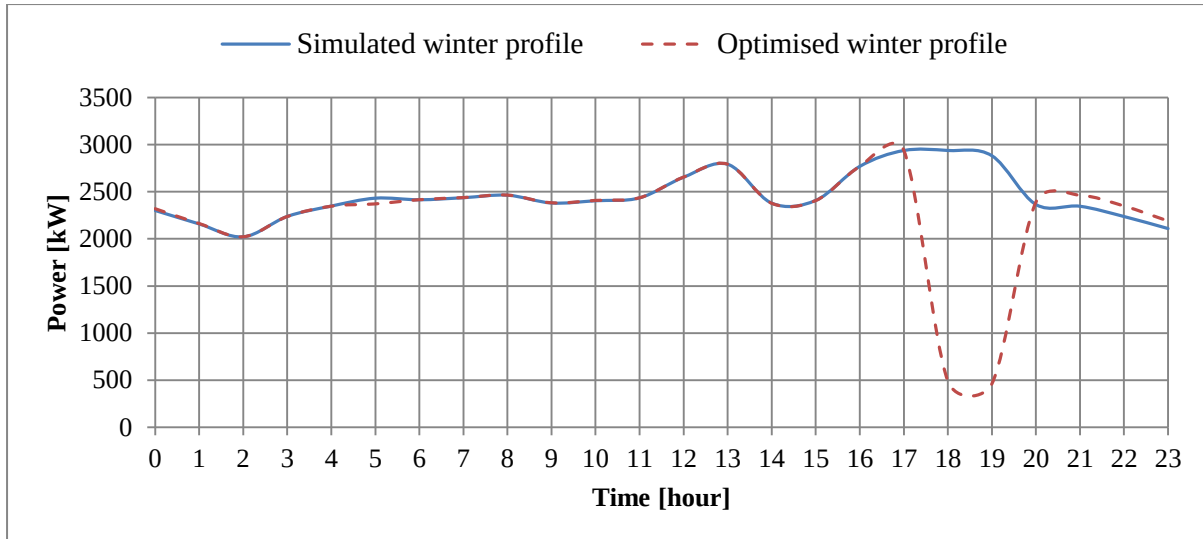


Figure 49: Mine A refrigeration and ventilation simulated load management winter power profile.

The optimised models delivered an average daily electrical energy impact of 4.15 MW for summer and 2.44 MW for winter. This accumulates to an average annual electrical energy impact of 3.72 MW if September to May are taken as summer months and June to August as winter months. The smaller reduction in electrical energy during 18:00 and 20:00 for the winter day can be ascribed to the already lowered operational requirements during winter months. The optimisation simulation model was performed while abiding to all the system constraints. Figure 50 indicates that the proposed BAC air wet-bulb temperature remained below the maximum 12°C for a typical summer day.

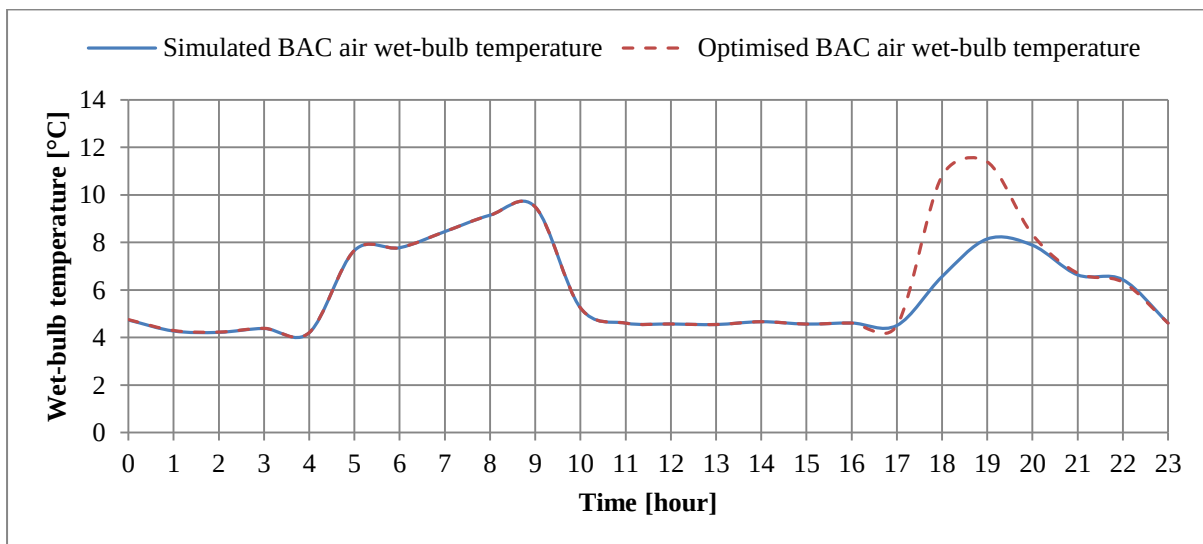


Figure 50: Mine A refrigeration and ventilation simulated BAC summer wet-bulb temperature.

It is estimated that the load management strategy will result in an annual R2.1 million electricity cost savings for Mine A if implemented. This annual electricity cost savings is calculated with the 2014/2015 Eskom Megaflex tariffs (Eskom Ltd., 2014). With the implementation cost accumulating to R0.99 million, the payback period for a load management strategy is estimated at eight months. A

detailed quotation for the proposed infrastructure is shown in Appendix C. The results for a load management strategy on Mine A are summarised in Table 10.

Table 10: Simulated results for a load management strategy on Mine A.

Load management simulated results	
Load management electrical energy impact	3.72 MW
Annual electricity cost savings	R 2 098 230.58
Installation cost	R 990 204.33
Duration of installations	2 months
Payback period	8 months

Condenser and evaporator water flow control model

The second optimisation strategy that was investigated on Mine A is a combination of condenser and evaporator water flow control. By combining these two strategies a more efficient system operation can be achieved, as well as an increase in the possibility of electrical energy savings. Both these strategies will be controlled via closed loop PID control logic similar to the PID control discussed in Section 3.3.2.

The electrical energy savings for this strategy will be achieved by utilising VSDs to control the condenser and evaporator water flow accordingly. Before implementing this strategy on the actual system, an optimisation simulation was performed to predict how the system will react. To imitate the use of VSDs on the water pumps, PI controllers within PTB were used to calculate the correct pump speed fraction. For the simulation two control philosophies were used for the condenser and evaporator cycles respectively.

The following control philosophy was utilised for the condenser water pump PI controllers:

1. Increase the pump speed once the water temperature difference over the condensers exceeds the temperature set-point.
2. Decrease the pump speed once the water temperature difference over the condensers drops below the temperature set-point.

The temperature difference set-point selected for the condenser water flow optimisation simulation is 5°C. The temperature difference described above is the difference between the outlet and the inlet condenser temperature of the refrigeration machines.

For the optimisation simulation of the evaporator water flow the following control philosophy was used:

1. Increase the pump speed once the BAC air temperature exceeds the temperature set-point.
2. Decrease the pump speed once the BAC air temperature drops below the temperature set-point.
3. Increase pump speed once cold dam level drops below minimum set-point.

This optimisation simulation model was adapted from the system simulation model. It delivered an average electrical energy efficiency savings of 2.45 MW for a typical summer day. The optimisation model was simulated without altering any system operations or constraints. The proposed typical summer day electrical energy savings through variable water flow is illustrated in Figure 51.

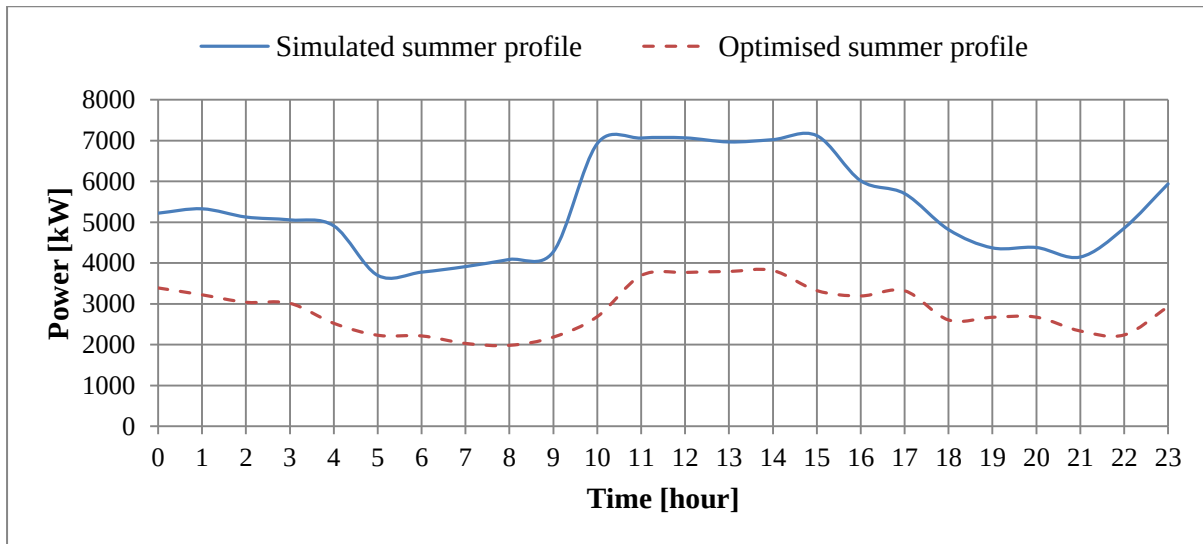


Figure 51: Mine A refrigeration and ventilation simulated variable water flow control summer power profile.

For the winter optimisation model the system operations were altered as specified in Table 11. This is due to the refrigeration system being operated inefficiently to achieve the desired deliverables. By altering the winter optimisation model accordingly a potential electrical energy efficiency saving of 0.84 MW was achieved. The electrical energy profile for the winter optimisation model is shown in Figure 52.

Table 11: Mine A refrigeration and ventilation optimised winter system operation schedules.

	Winter (June - Aug)
Number of refrigeration machines	1
Number of evaporator pumps	1
Number of condenser pumps	2

Although the estimated winter savings is significantly lower, the average percentage of electrical energy reduction for the winter day is 63% against the 54% for a summer day. With the combined

summer and winter optimisation simulation an annual electrical efficiency savings of 2.05 MW is achievable. This annual electricity savings was calculated assuming the nine summer months from September to May and three winter months from June to August.

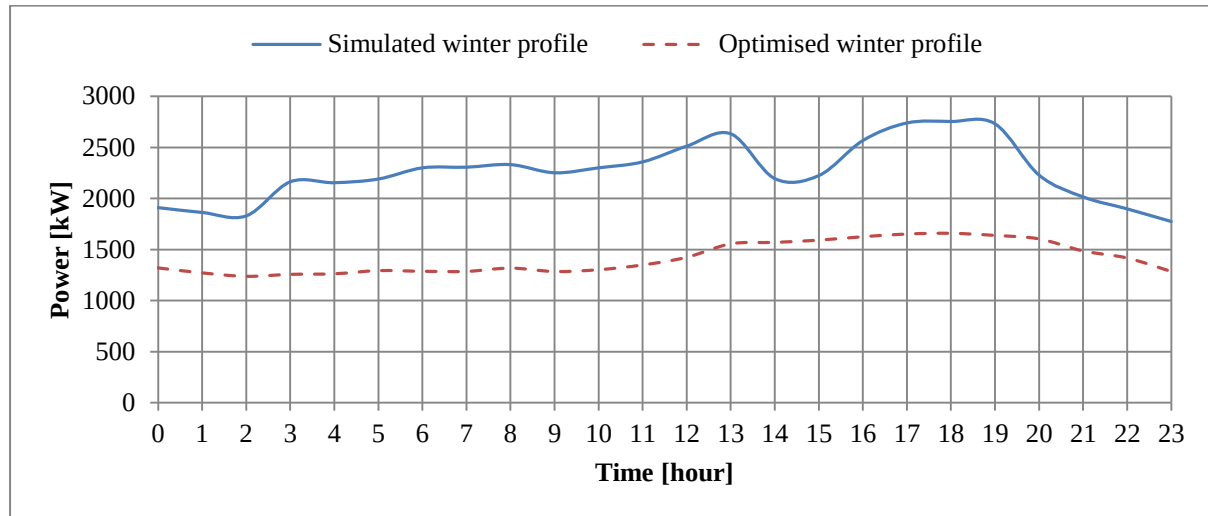


Figure 52: Mine A refrigeration and ventilation simulated variable water flow control winter power profile.

With the estimated 2.05 MW savings a potential reduction of R8.64 million in annual electricity cost can be achieved if variable water flow control is implemented on Mine A. However, with the high cost for VSDs the cost to implement this strategy is calculated at R3.44 million. A detail breakdown of the quotation for this strategy is shown in Appendix C. By quantifying the annual electricity cost reduction and an annual electricity tariff increase of 8%, a payback period of only nine months is expected. The results from the variable water flow control optimisation simulation model are tabulated in Table 12.

Table 12: Simulated results for variable water flow control on Mine A.

Variable water flow control simulated results	
Electrical energy efficiency savings	2.05 MW
Annual electricity cost savings	R 8 642 000.60
Installation cost	R 3 443 815.85
Duration of installations	4 months
Payback period	9 months

3.3.4 Conclusion

A suitable system investigation of the refrigeration and ventilation system of Mine A was performed. This established a general overview of the system and its operations. The constructed simulation model was verified against the actual measured system parameters and deliverables. Two optimisation models were adapted to represent the strategies and predict the potential electricity cost savings.

Both optimisation models performed for the refrigeration and ventilation system of Mine A delivered viable electricity saving. The load management strategy showed a potential 3.72 MW annual electrical energy reduction. Whereas the variable water flow strategy resulted in an annual electrical energy reduction of 2.05 MW.

A financial feasibility analysis estimated a payback period of seven months and nine months for the load management and variable water flow strategy respectively. The analysis was performed taking into account the current Eskom electricity tariff and an assumed 8% annual tariff increase. The estimated payback period for both strategies is depicted in Figure 53.

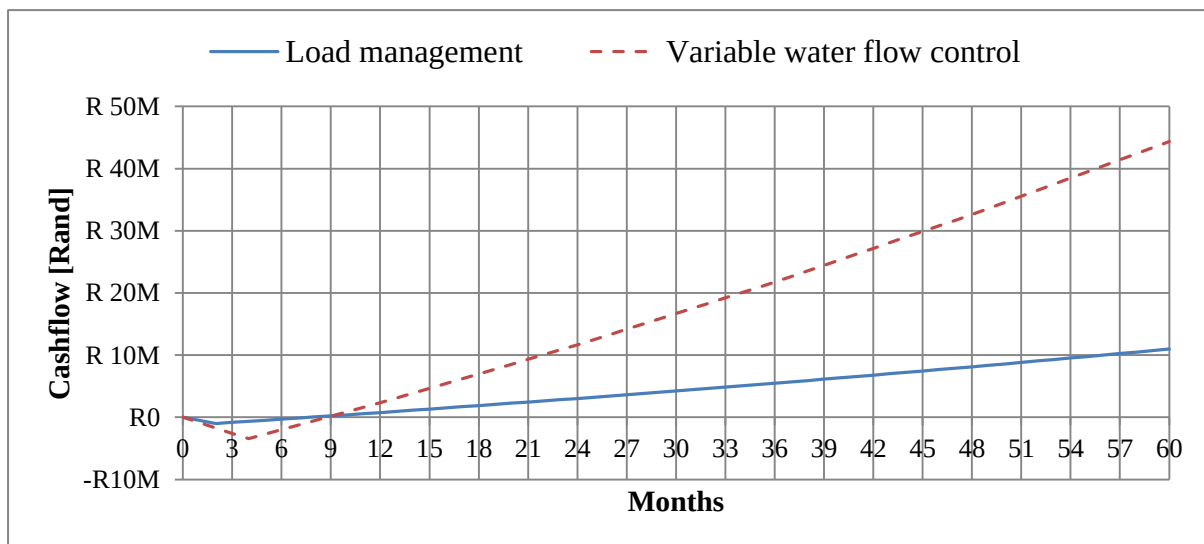


Figure 53: Estimated payback period for refrigeration and ventilation optimisation on Mine A.

3.4 Water reticulation systems

3.4.1 System investigation

A mine water reticulation system as described in Section 2.4.1 is interlinked with the refrigeration, ventilation and dewatering systems. With the investigation into a surface refrigeration and ventilation system completed, this section will focus on the combined underground water reticulation and dewatering systems.

The water reticulation operations used within platinum mines are to a great deal similar to that used within the gold mining industry however, they are smaller in scale due to the shallower depths (Mining Communications Ltd., 2009). Cold water is sent underground for mining operations such as drilling, sweeping and secondary cooling. After being used the water will flow to centralised hot water storage dams where it is pumped back to the surface refrigeration and ventilation system.

This however, is a simplified overview of a water reticulation system. There are more operations underground utilising the cold water. To perform a theoretical simulation of the system the following site specific information needs to be investigated:

1. Installed dewatering pump electrical power capacity (kW),
2. Dewatering pump electrical power consumption (kW),
3. Dewatering pump design parameters (ℓ/s and kPa),
4. Installed storage dam capacities (M ℓ),
5. Water reticulation system layout,
6. Water reticulation operational schedules,
7. End user requirements (ℓ/s , kPa and $^{\circ}C$).

The investigation process of a water reticulation system is similar to that described throughout this chapter. Specific site information can be collected by means of questionnaires or manual site inspections. Actual operational information is acquired through the use of permanent or temporary logging equipment. Figure 54 is an example of a temporary water flow logger used to measure the cold water supply to underground.

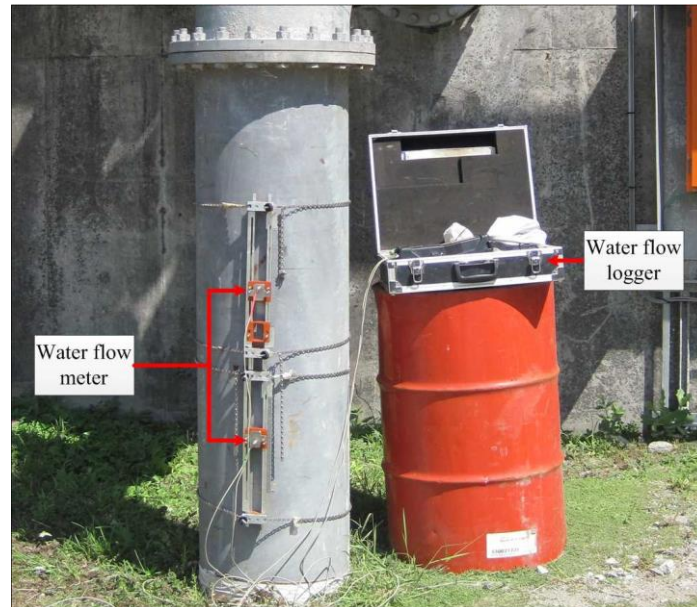


Figure 54: Temporary water flow logger.

3.4.2 System simulation and optimisation

Once all the site specific information has been collected and analysed a theoretical simulation can be developed to further investigate the possibility of electricity cost savings. This theoretical simulation can be performed using various thermal flow solvers such as Process Toolbox or KYPipe⁴. With the use of these thermal flow solvers, a system and an optimised simulation can be developed.

⁴ KYPipe. (2014) *Pipe2014: Water/Fluid (steady state)*. Available: <http://kypipe.com/kypipe>. [Accessed:1 September 2014].

3.4.3 Case study: Mine A

Mine A water reticulation system investigation

The water reticulation system of Mine A was selected as the case study for the investigation into possible electricity cost saving strategies. Therefore this section will provide the necessary site specific information of Mine A to develop a general overview of the system and its operations. The layouts of the water reticulation and dewatering systems are illustrated in Figure 55 and Figure 56.

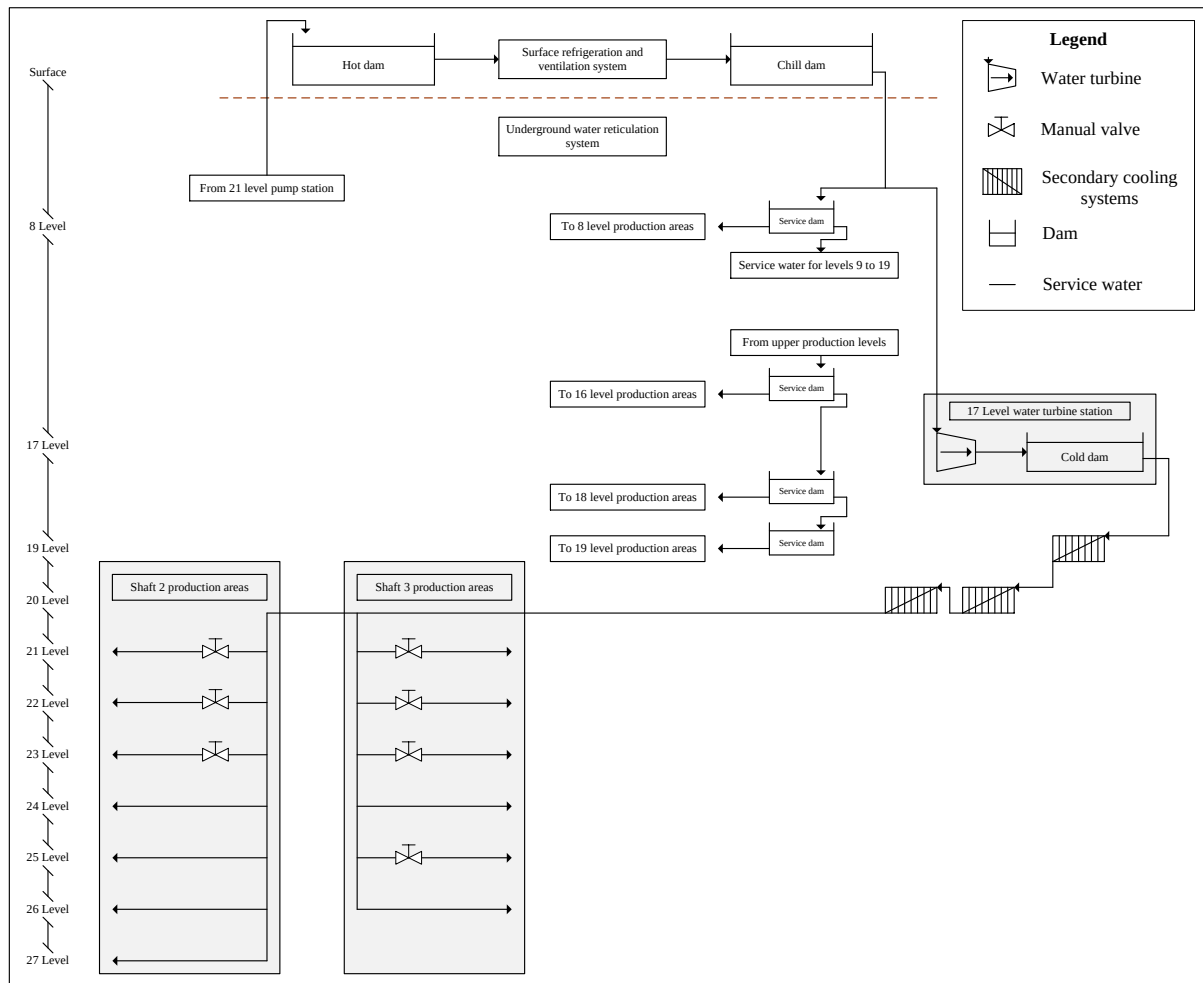


Figure 55: Mine A water reticulation system.

The water reticulation system of Mine A is an interlinked system with the surface refrigeration and ventilation system. Water cooled by the refrigeration system is mainly used underground by secondary cooling systems, on levels 19 and 20, and mining activities throughout each level. Therefore to minimise the increase in temperature of the cold water the reticulation system is separated into two sections.

For the first section water is gravity fed from the surface chilled water dam to the cascading service storage dams on levels 8 to 19. On these levels, water is supplied to the production areas where it is used for various mining activities. From here the service water together with natural fissure water and

water from Level 24 will flow through return drains to a 627 kℓ settler on Level 21. After passing through the settler the water accumulates in a 520 kℓ hot water storage dam.

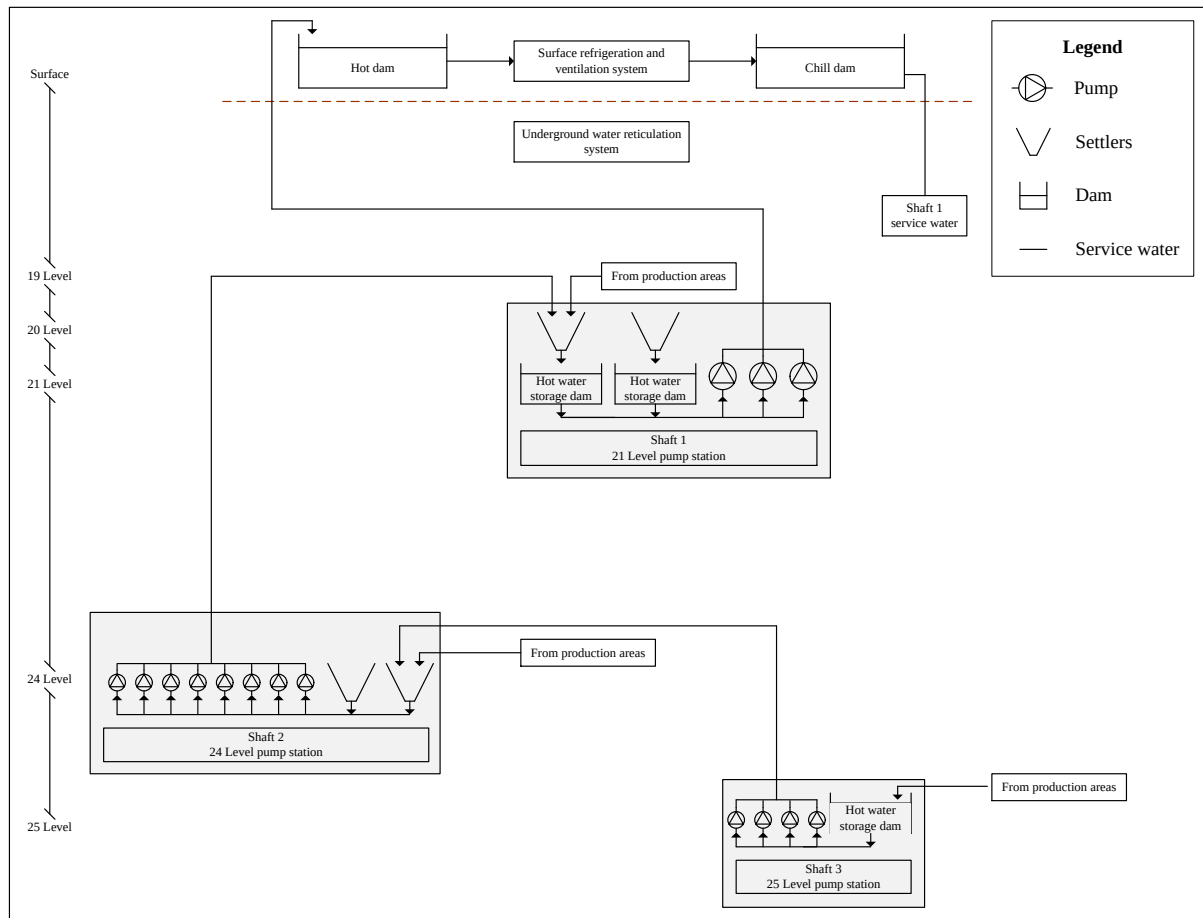


Figure 56: Mine A dewatering system.

Figure 56 illustrates two 627 kℓ settlers and two 520 kℓ hot water storage dams working as two separate water storage units on Level 21. However, the second storage unit is only used for redundancy and cannot be included in the strategy. After being collected, three 800 kW multistage dewatering pumps are used to return 9.8 Mℓ of hot water per day to the surface refrigeration plant. Figure 57 shows the average electrical energy consumption profile of the dewatering pumps.

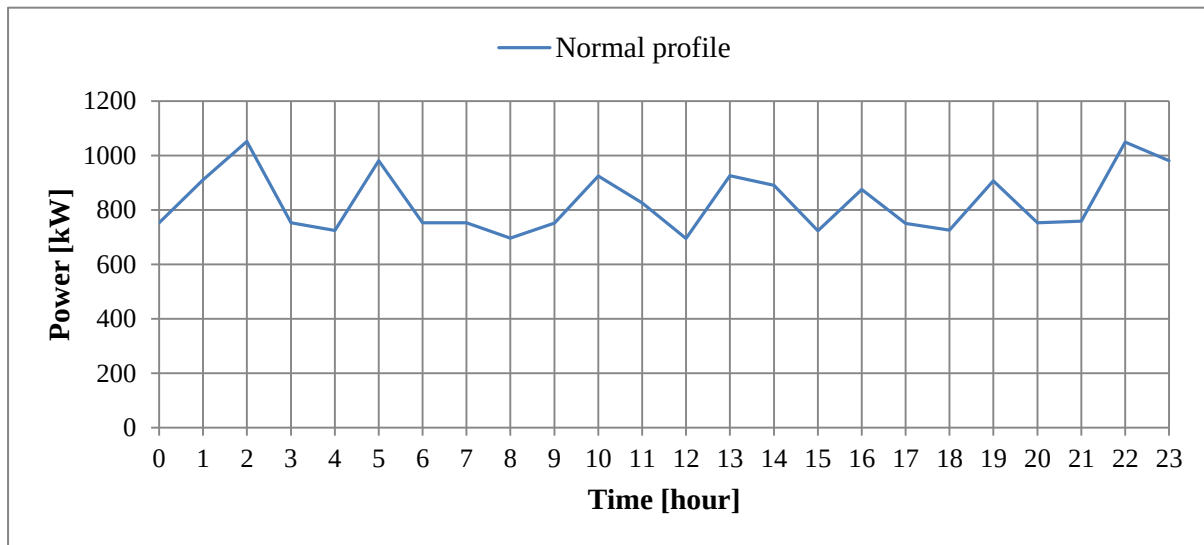


Figure 57: Mine A water reticulation power profile.

The second section of the water reticulation system is situated on levels 17 to 28. Before entering the 3288 kℓ cold water dam on Level 17, the cold water passes through a needle valve controlled Pelton turbine. The Pelton turbine is used to reduce the hydraulic pressure build up cause by the extreme depths. However, the key reason this process is used is to eliminate the temperature increase caused by the cascading dam system.

With the cold supply water still at a relatively low temperature it is used by three secondary cooling systems located on levels 19 and 20. These cooling systems are used to lower the ambient air temperature to 15°C, 17°C and 19°C respectively. These secondary cooling system parameters were determined from data collected at the local SCADA control system. Once the water leaves the last cooling system it is gravity fed to lower production levels.

These production levels are situated at two separate mining shafts namely Shaft 2 and 3. The water reticulation layout, including storage dams and pump stations, of these two shafts are also illustrated in Figure 55 and Figure 56. Although the service water is used at different production areas, it is in the end pumped back to the collection dam on Level 21. Figure 58 illustrates the water inlet and outlet flow rates compared to the Level 21 collection dam level for a typical production day.

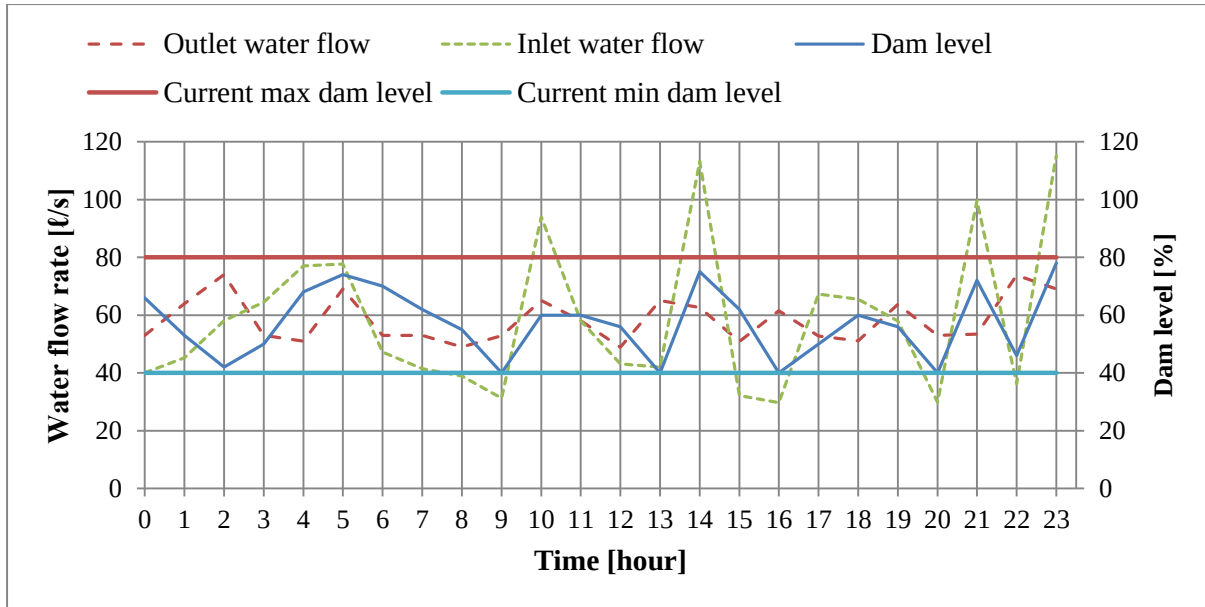


Figure 58: Mine A 21 level collection dam level vs. inlet and outlet flow rates.

The water used by the production areas of Shaft 3 accumulates in a 214 kℓ hot water dam on Level 25. From here the water is pumped by four small 200 kW pumps to the settlers at Shaft 2. These settlers are again used as two separate storage units with one only used for redundancy.

With the necessary site specific information gathered the proposed electricity cost saving strategies could be investigated. The first strategy investigated was the load management strategy. As discussed in Section 2.4.2 this strategy entails shifting the electrical load during the peak period to the off-peak periods. This investigation started at theoretically calculating the Level 21 hot water dam level if a load management strategy was implemented. The theoretical calculation was done with the use of Equation 9 (Schutte, 2007).

Equation 9:

$$L_2 = \frac{\left[\left(\frac{L_1}{100} \right) \times D_{volume} + (\dot{m}_{in} - \dot{m}_{out}) \times 3600 \times t \right] \times 100}{D_{volume}}$$

Where:

L_2 = new dam level (%)

L_1 = old dam level (%)

D_{volume} = dam volume (ℓ)

$\dot{m}_{in}$ = water flow rate in (ℓ/s)

$\dot{m}_{out}$ = water flow rate out (ℓ/s)

By theoretically calculating the proposed hot water dam level it was estimated that the dam would reach its maximum allowable level (90%) within 96 minutes. This calculation was made with the average inlet water flow rate data collected from the SCADA system utilised by Mine A. The proposed hot water dam level and inlet and outlet flow rates for only the evening peak period load management are displayed in Figure 59.

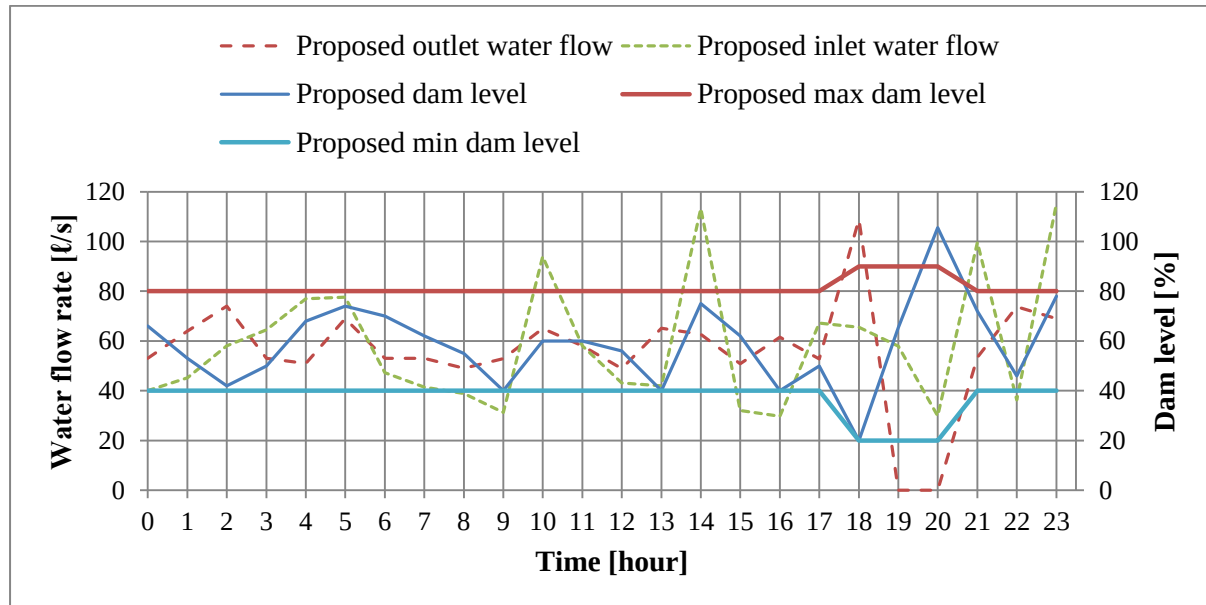


Figure 59: Mine A 21 level collection proposed dam level vs. proposed inlet and outlet flow rates

Due to the estimated time of 96 minutes being less than the two hours required, the maximum load that can be shifted was calculated at 730 kW. This delivered an estimated annual electricity cost savings of only R130 098. During the site investigation it was noted that for a load management project to be implemented, the following infrastructure would be required:

1. Automation of all dewatering pumps,
2. Electric control actuated open/close vales after each dewatering pump,
3. Control PLCs and fibre communication.

From the quotations received it was calculated that the automation of the three large dewatering pumps on Level 21 alone would cost R1.65 million. A detailed quotation is provided in Appendix B. With the annual electricity cost reduction and implementation cost calculated, it was estimated that the strategy would only be paid back after nine years, decreasing its financial feasibility substantially. This estimation was calculated with the 2014/2015 Eskom Megaflex tariff plan, incorporating an annual 8% tariff increase.

3.4.4 Conclusion

To conclude, the investigation of the water reticulation system of Mine A presented particular system limitations. The first of which is the low electrical energy profile, compared to the compressed air and refrigeration systems, allowing minimum possible electricity cost savings. The second is the small hot water storage capacity and the short time it would take to reach the maximum allowable limit, inducing the risk of flooding. Therefore, with the low expected electricity cost savings, shortage of existing infrastructure and high health and safety risks, the financial feasibility ultimately decreases to the least plausible solution.

3.5 Conclusion

In this chapter, a study investigating the feasibility of reducing the electricity costs of three high electricity consumers of a typical platinum mine were presented. The three high electricity consumers investigated was the compressed air, refrigeration and ventilation and water reticulation systems. The primary case study for these investigation was platinum Mine A.

Sufficient site specific information and background were presented and utilised to construct the system simulation models. The results achieved from each simulation model were compared to the actual system performance to verify its accuracy. The verification process delivered correlation coefficients ranging between 90% and 95%.

Once verified the simulation models were adapted according to the selected electricity cost reduction strategies. These models were used to investigate the feasibility of these strategies and to predict the reduction in electricity costs.

When comparing the strategies for a compressed air system the integration between downstream control and compressor control delivered the highest electricity cost reduction. With a potential annual electricity cost reduction of R2.43 million the payback period is estimated at 28 months. This intensely increases its feasibility as an electricity cost savings strategy for typical platinum mine compressed air systems.

The simulation models for load management and variable water flow control on a refrigeration and ventilation system both presented viable electricity cost savings. The high implementation cost of R3.44 million for variable water flow control is severely outweighed by its annual electricity cost reduction of R8.64 million. An estimated R2.1 million reduction in electricity cost was also achieved by the load management model.

The investigation into the water reticulation system of Mine A however, presented a different outcome. Due to the lack of infrastructure and low possibility of electricity cost savings, implementing either one of the strategies would result in high implementation cost with minimum benefits. The investigations into possible electricity cost savings on the water reticulation system of Mine A resulted in a low financial feasibility and were therefore stopped.

To conclude, this study presented three viable electricity cost reduction strategies. All three strategies were proven financially feasible and would achieve high electricity cost reductions. With the feasibility proved it was decided to validate the study by the implementing these strategies on Mine A.

Chapter 4

Verification and validation of DSM strategies

Validation of results from platinum mine case study

Chapter 4: Implementation and verification of DSM strategies

4.1 Introduction

Throughout Chapters 2 and 3, possible electricity cost saving strategies have been investigated and developed for the platinum mining industry. By quantifying the possible reduction in electricity costs of various strategies, a theoretical financial feasibility analysis was completed for each strategy. With the feasibility proven, three strategies with the highest possibility of electricity cost savings were selected for implementation on Mine A.

This chapter will first provide a swift overview of the implementation phase, including detailed lists of the equipment utilised during implementation. Thereafter the results achieved by each strategy will be verified according to the protocols set out by the Corporate Services Division Assurance and Forensic Department of Eskom (den Heijer, 2009).

These protocols are set in place to serve as guidelines for the independent auditing firms, also known as M&V teams. M&V teams are contracted directly by Eskom to measure and verify the savings realised by the various ESCOs. It is the M&V team's responsibility to measure and determine the electrical energy profile before and after the implementation of DSM strategies (Xia & Zhang, 2012). Once the implementation is completed the auditing firms utilise the electrical energy profile to verify the savings achieved (US Department of Energy, 1996).

4.2 Compressed air systems

4.2.1 Implementation of optimisation strategies

From the investigations performed in Section 3.2 it was decided to implement the new integrated control strategy due to its high electrical cost savings and short payback period. This integrated control strategy entails the installation of high pressure control valves before the end users and implementing compressor control on the five existing compressors. The integration of these two strategies will allow a more effective control of the compressed air system as a whole and increase the possibility of electricity cost savings. For detail regarding the layout of the compressed air system of Mine A and the location of the proposed infrastructure, refer to Figure 35.

A detailed list of the equipment, also known as a bill of quantities, required for the integration of downstream and compressor control is tabulated in Table 13. This bill of quantities was approved and accepted by the appropriate engineering management of Mine A. Furthermore, an exception was agreed upon to implement a separate control SCADA, hence the constant communication failure of the current on-site control SCADA. After the approval, various contractors were appointed to complete the new installations and integration of new and old control systems.

Table 13 displays a list of equipment and does not include the labour required for the installations and integration of control systems. The labour required for the integrated control system includes:

1. PLC engineering and installations,
2. WinCC SCADA engineering and commissioning,
3. Valve and pipe assembling and on-site installations,
4. Surge controller design, configuration and on-site commissioning.

Table 13: Integrated control strategy bill of quantities for Mine A compressed air system.

Item	Specification	Quantity
PLC units	Siemens Simatic S7-300, CPU 314C-2PN/DP with 192kb internal memory, Ethernet Profinet interface, integrated PS307 power supply (120/230V AC input, 24V DC/5A output), 128kb Simatic S7 micro memory card and S7-open Modbus/TCP for PN-CPU single license	6
Additional PLC analog input	Simatic S7-300, analog input SM 331 with 1x20 pin remove/insert w.backplane bus	2
Additional PLC analog output	Simatic S7-300, analog output SM 332 with 1x20 pin remove/insert w.backplane bus	2
SCADA system	Simatic WinCC advanced V11 SP2 Engineering-SW, Simatic WinCC runtime advanced 128 powertags V11 SP2 Runtime-SW, including single USB license key class A and executable inder Windows XP (32 bit)/Windows 7 (32/64 bit)	1
Wireless network bridges	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Dehnguard M TT 2P 275 din mount surge arrestor and clearline 100 base 1 port RJ45 surge arrestor	9
Wireless network repeaters	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Ubiquiti AirMax Rocket M5 5GHz Hi Power 2x2 MIMO, Ubiquiti AirMax 5GHz Omni (10dBi) with POE Injector 9 - 36VDC Input and 24VDC 19W POE Output	2
Wireless access point	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Ubiquiti AirMax Rocket M5 5GHz Hi Power 2x2 MIMO, Ubiquiti AirMax 5GHz Sector (16dBi, 120 deg), POE Injector 9 - 36VDC Input and 24VDC 19W POE Output, including Moxa EDS-508A industrial managed Ethernet switch	2
Control valves (450 mm)	450 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	2

Item	Specification	Quantity
Control valves (200 mm)	200 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	5
Control valves (150 mm)	150 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	1
Solenoid valves (450 mm)	450 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single actin fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	3
Solenoid valves (400 mm)	400 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	1
Solenoid valves (400 mm)	300 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	1
Air flow meters	CS mass flow meter - VA 400- max version	8
Pressure transmitters	IFM - PN5 pressure switch with digital display	8

Downstream control

Installations of the integrated control strategy on the compressed air system of Mine A started with the installation of control valves at each of the end users. However, due to financial constraints the control of compressed air to Plant 1 was removed from the scope. This decision was based on Plant 1 being the lowest compressed air user and requiring the highest pressure during 18:00 and 20:00. Figure 60 shows the two 200 mm pneumatic actuated control valves with their 450 mm solenoid valves installed before Shaft 1.



Figure 60: Downstream control valves installed on Mine A compressed air system.



Figure 61: Air mass flow meters and pressure transmitters installed on Mine A compressed air system.

Figure 61 shows the air mass flow meters and pressure transmitters utilised for controlling the downstream compressed air to Shaft 1. The next phase of installations involved the installation of the six Siemens PLCs together with the necessary wireless network communication to the central control room. Figure 62 illustrates the Siemens PLC and network communication panel installed at Decline 2.



Figure 62: PLC unit installed on Mine A compressed air system.

Compressor control

Figure 63 illustrates the pneumatic actuated inlet guide vane controller with a Siemens positioner utilised on Compressor 1 for the current surge prevention. The new compressor control system as described in Section 3.2.3, will use a delivery pressure set-point to control the position of the inlet guide vanes.



Figure 63: Pneumatic actuated inlet guide vane controller of Compressor 1 at Mine A.

Integration of control philosophy

After the installation of equipment, the integration between the current and new control systems were implemented and fully commissioned. The final control parameters and constraints were determined during the commissioning phase through accurate testing on the integrated system.

The downstream pressure set-points selected and agreed upon by the mine for each of the end users are as specified in Section 3.2.3. Figure 64 illustrates the decrease in downstream pressure of Shaft 3 according to the selected pressure set-point. The position of the control valve is also indicated in Figure 64.

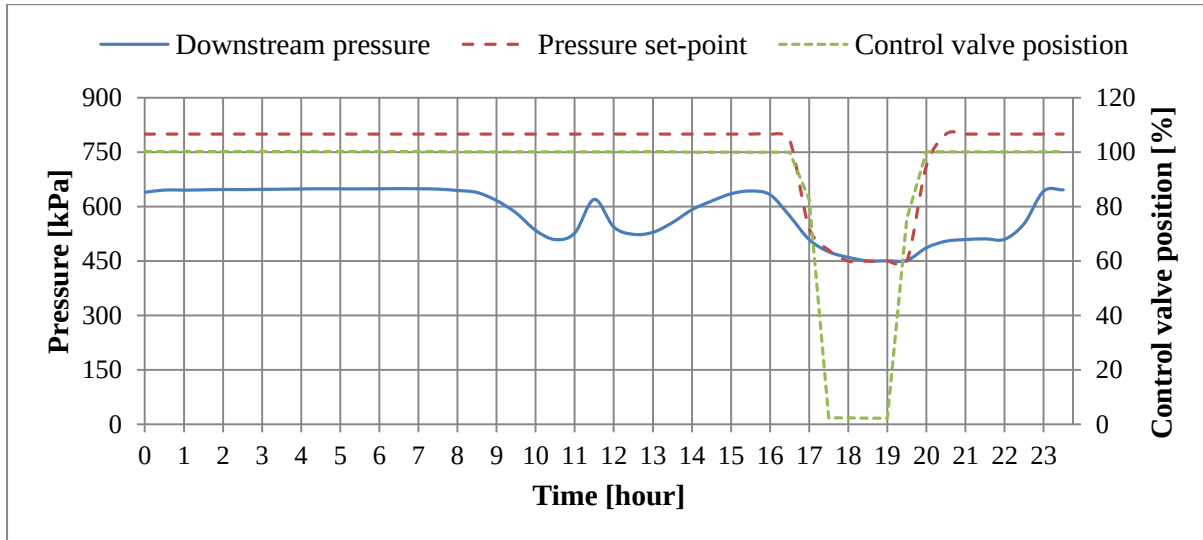


Figure 64: Downstream pressure control of Shaft 3 compressed air control valve on Mine A.

Before the implementation of the new compressor controller, the compressors were frequently stopped and started due to the fluctuation in system pressure. Although the compressors were set to deliver a predetermined pressure, once system pressure increases above the delivery pressure, the blow-off valves of the running compressors tend to open. This was due to the existing control system opening the blow-off valves to prevent the compressors from entering surge conditions instead of controlling the inlet guide vanes according to the surge curve.

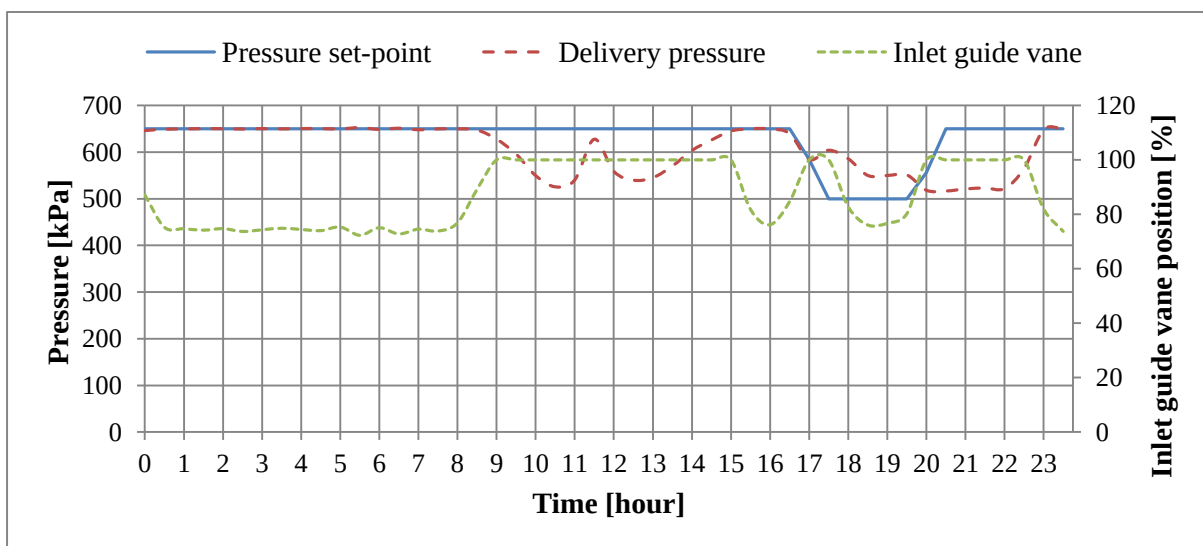


Figure 65: Compressor 4 delivery pressure control on Mine A compressed air system.

Figure 65 shows the position of inlet guide vanes for a typical production weekday used to control the delivery pressure according to the pressure set-point and the system pressure. The fluctuation in compressor electrical power consumption according to delivery pressure for the same production weekday is illustrated in Figure 66.

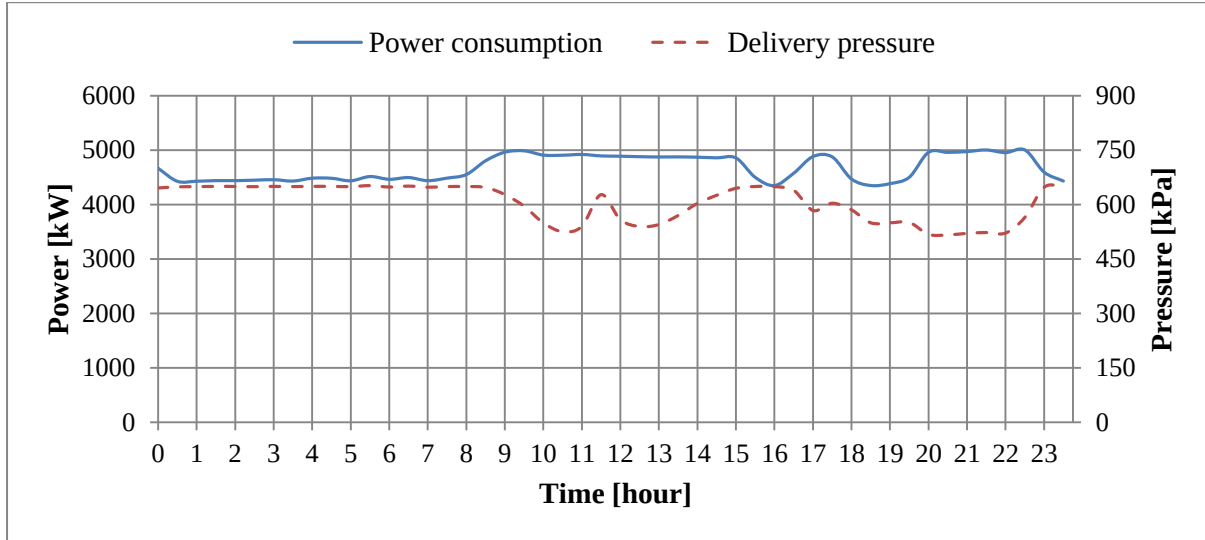


Figure 66: Compressor 4 power consumption vs. delivery pressure on the compressed air system of Mine A.

4.2.2 Verification of results

With the integrated compressor control implemented on the compressed air system of Mine A the next step in the process is the verification of results achieved. This process, as discussed earlier within the chapter forms part of the independent M&V team's responsibilities.

The verification of a DSM strategy is performed by comparing the normal electrical energy profile before implementation with the post-implementation electrical energy profile. The normal electrical energy profile was developed with a regression model that incorporates daily production changes. The regression model developed by the M&V team is shown in Equation 10.

Equation 10:

$$P_{electrical} = \alpha + \phi p + \varphi v$$

Where:

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

p = average compressor delivery pressure (kPa)

v = average compressor delivery volumetric flow rate (m³/h)

ϕ = average compressor delivery pressure coefficient

φ = average compressor delivery volumetric flow rate coefficient

α = interception coefficient

With the use of the regression model the daily electrical energy profile can be scaled to accommodate high or low production days. Table 14 tabulates the specific scaling coefficient parameters for weekdays, Saturdays and Sundays as proposed by the M&V team.

Table 14: Compressed air profile scaling coefficient parameters proposed by M&V team.

Compressed air profile scaling coefficients	Weekdays	Saturdays	Sundays
Average pressure coefficient [$\emptyset$]	22.527	0.917	20
Average volumetric flow rate coefficient [φ]	0.706	0.328	0.309
Interception coefficient [α]	2640	3634	2003

The electrical energy profile for the compressed air system of Mine A was determined by using the electrical feeder data and appropriate compressor delivery data (June 2013 to August 2013). The compressor delivery data was collected from the individual SCADA systems at the three compressor houses. Figure 67 illustrates the electrical energy profiles developed by the M&V team for weekdays, Saturdays and Sundays.

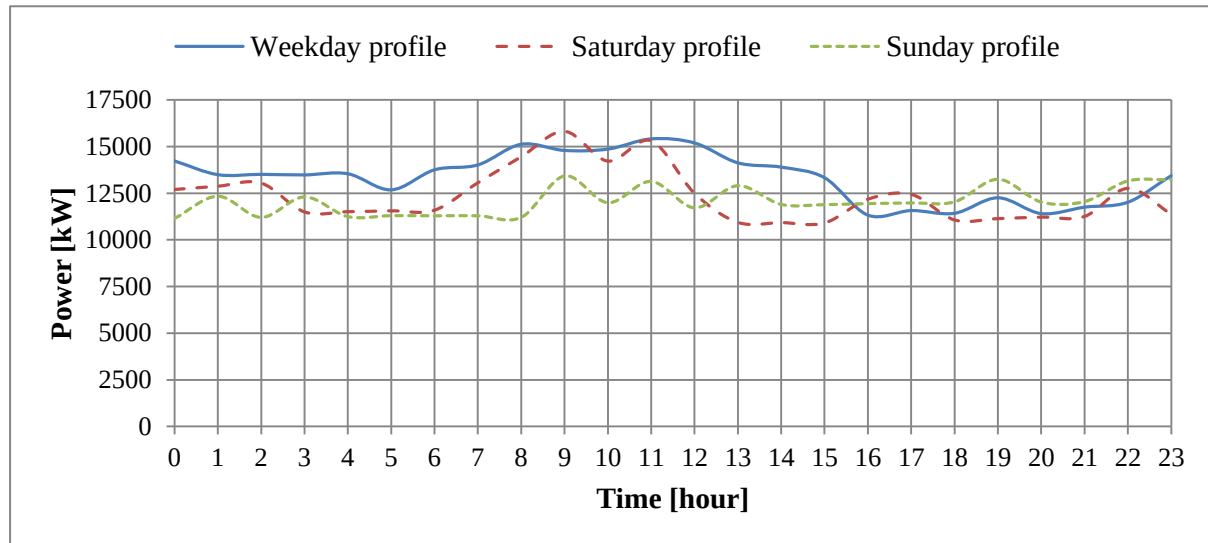


Figure 67: Average electrical energy profiles for the compressed air system of Mine A.

After the integrated downstream and compressor control was implemented on Mine A, the verification procedure delivered an average of 4.35 MW reduction in electrical energy consumption. Compared to the 3.70 MW proposed in Section 3.2.3 the actual savings is 15% higher. The actual electrical energy reduction was realised during the first performance assessment month (August 2014). Due to the dissertation being compiled before the completion of all three of the performance assessment months being completed, only the first month will be used for verification. The actual

electrical energy consumption profile compared to the normal electrical energy consumption profile is shown in Figure 68.

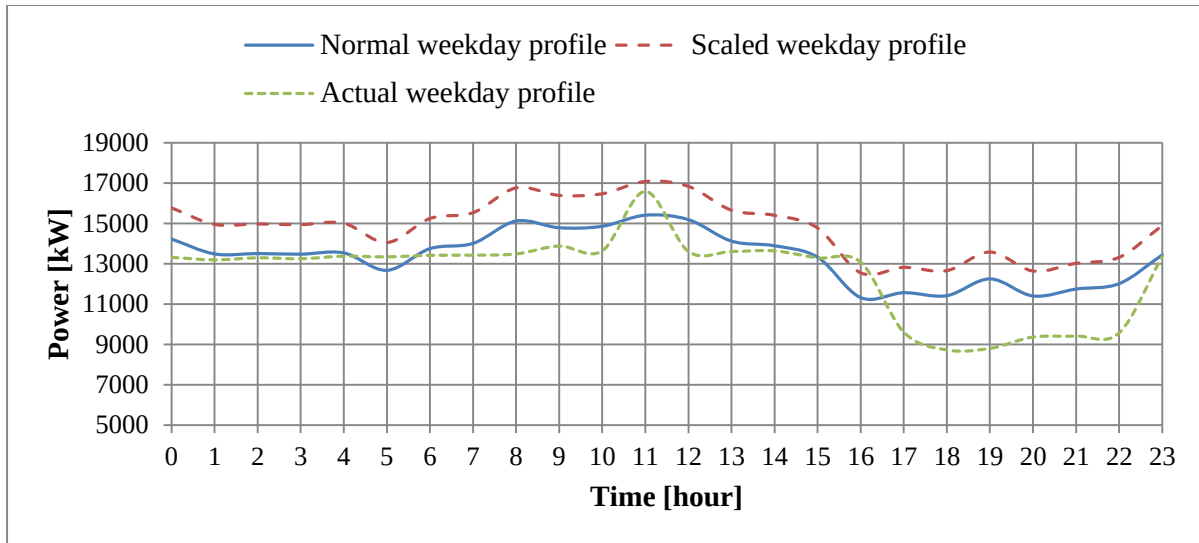


Figure 68: Mine A compressor electrical energy consumption before and after integrated strategy.

4.2.3 Conclusion

To conclude, the verification process of the DSM strategy delivered an average daily electrical energy reduction of 4.35 MW on the compressed air system of Mine A. The investigation and simulation of the DSM strategy for the compressed air system of Mine A has been verified with the actual achieved results by an independent M&V team. It is therefore proven that the implementation of an integrated downstream and compressor control strategy has the potential to reduce the electricity costs of a typical platinum mine. The post-implementation results for the integrated downstream and compressor control strategy on Mine A are tabulated in Table 15.

Table 15: Mine A compressed air system savings summary.

	Proposed	Achieved
Integrated downstream and compressor control		
Electrical energy peak clip savings	3.70 MW	4.35 MW
Possible annual electricity cost savings	R 2 434 857.47	R 2 861 184.94

4.3 Refrigeration and ventilation systems

4.3.1 Implementation of optimisation strategies

The two optimisation strategies investigated for potential electricity costs savings on a refrigeration and ventilation system were load management and variable water flow control on the condenser and evaporator cycles. After optimising the verified simulation model of Mine A, potential savings of 3.72 MW for load management and 2.05 MW for variable water flow control was calculated. Mine A was selected as a case study for the implementation of the two optimisation strategies to further validate the study.

For the implementation of these two strategies on Mine A, an upgrade to the existing system was required. These upgrades did not in any manner interfere or affect the normal system operations or endanger any personnel underground. The equipment required for the upgrade of the existing refrigeration and ventilation system will be discussed in the section below and is listed in Table 16. Refer to Figure 47 for the layout of the proposed infrastructure on the refrigeration and ventilation system of Mine A.

Load management

The pneumatic actuated control valve shown in Figure 69 was installed on the condenser water cycles before the first refrigeration machine. With the control valves installed, separate automated starting and stopping of refrigeration machines will be possible. Before the control valves were installed operators were supposed to close manual valves once a refrigeration machine has stopped. The reason for this is to prevent warm condenser water from flowing back into the refrigeration machine. However, this routine was never consistently followed and for the load management strategy to be successful this routine was automated.



Figure 69: Pneumatic actuating control valve installed on the condenser water cycle of Mine A.

Condenser and evaporator water flow control

Due to financial constraints and the high implementation cost for this strategy it was decided to remove two VSDs from the original scope. The two VSDs removed would have been for Evaporator pump 4 (200 kW) and Condenser pump 7 (250 kW). This decision was based on the following:

1. Both pumps are utilised as spare pumps and can replace a similar size pump without replacing the installed VSD.
2. If operated correctly, each pump will only contribute a maximum of 4% to the total electrical energy reduction.

The system upgrade is essentially comprised of the installation of VSDs on three evaporator pumps and six condenser pumps. It also included the installation of a temperature sensor within the BAC, automation of condenser fans and transfer pumps and the installation. The last system upgrade was the installation of pneumatic actuated control valves on the condenser water cycle before the three of the refrigeration machines.



Figure 70: 200 kW and 250 kW VSDs installed on the condenser and evaporator water pumps of Mine A.

Figure 70 illustrates the two 250 kW VSDs for the condenser water pumps and a 200 kW VSD for the evaporator water pump. Two of the 400 kW VSDs for the condenser and evaporator water pumps are shown in Figure 71.



Figure 71: 400kW VSDs installed on the condenser and evaporator water pumps of Mine A.

The last installation entailed mounting a temperature sensor within the BAC. This sensor was installed to monitor the temperature increase during the load management period and for the evaporator water flow control. The control philosophy for both the load management and evaporator water flow control strategy will be discussed in next section.

Table 16: Load management and variable water flow strategy bill of quantities for Mine A refrigeration and ventilation system.

Item	Specification	Quantity
Load management		
Control valves (450 mm)	450 mm Air Torque slimline PN16 cast iron wafer type butterfly valve, EPDM liner, ST/ST disc with double acting fail safe open pneumatic actuator. Namur mount with 5/2 way 24 V DC solenoid valve, switchbox with 2 mechanical limit switches for open/close feedback	3
Remote IO	Siemens Profibus DP IM253-1 for ET 200M including digital input 32DI (120 V AC isolated) and digital output 32DO (120 V/1 A AC isolated) Analog input 8AI (14-bit 20mS isolated)	1
Remote IO panel	1000 x 1000 x 300 Stainless steel double door enclosure including cable trays and tray fixings	1
Junction box panel	600 x 600 x 210 Stainless steel double door enclosure including cable trays and tray fixings	3
Condenser water flow control		
VSD (400 kW)	Allen Bradley PowerFlex 750-Series 400 kW (600 V/595 A) AC Drives, including circuit breakers, line and motor choke	4
VSD (250 kW)	Allen Bradley PowerFlex 750-Series 250 kW (600 V/355 A) AC Drives, including circuit breakers, line and motor choke	2

Evaporator water flow control		
VSD (400 kW)	Allen Bradley PowerFlex 750-Series 400 kW (600 V/595 A) AC Drives, including circuit breakers, line and motor choke	2
VSD (200 kW)	Allen Bradley PowerFlex 750-Series 200 kW (600 V/295 A) AC Drives, including circuit breakers, line and motor choke	1
Ambient weather station	Testo 6681 Industrial humidity transmitter with Testo 6611 climate probe. 0/4 to 20 mA and 0 to 1/5/10 V output (2/4-wire) including Profibus DP module	1
BAC temperature station	Testo 6681 Industrial humidity transmitter with Testo 6611 climate probe. 0/4 to 20 mA and 0 to 1/5/10 V output (2/4-wire) including Profibus DP module	1

Integration of control philosophy

To realise the electricity costs savings proposed in Section 3.3.3, the same control philosophy utilised in the optimisation simulations were implemented on the actual systems. However, to implement the same control philosophy on the actual system required the determining of certain system parameters and constraints. The system parameters and constraints determined during the commissioning phase are tabulated in Table 17.

Table 17: Mine A load management and variable water flow control parameters.

Evaporator water flow control	
Minimum flow [ℓ/s]	240
Maximum flow [ℓ/s]	550
Minimum VSD frequency [Hz]	38
Maximum VSD frequency [Hz]	50
Cold dam maximum level [%]	90
Cold dam minimum level [%]	70
Condenser water flow control	
Minimum flow [ℓ/s]	350
Maximum flow [ℓ/s]	550
Minimum VSD frequency [Hz]	40
Maximum VSD frequency [Hz]	50
Transfer water control	
Shaft cold dam maximum level [%]	80
Shaft cold dam minimum level [%]	60
Shaft hot dam maximum level [%]	85
Shaft hot dam minimum level [%]	35

The system parameters tabulated above was either determined manually or was specified by the relevant mine personnel. The VSD and water flow set-points were determined by lowering the VSD

frequency until the minimum evaporator or condenser flow was reached. A safety margin of 50 ℓ/s was allowed for both the evaporator and condenser water flows. Further results achieved from the manual VSD parameter tests are shown in Appendix E.

4.3.2 Verification of results

To verify the electrical energy savings realised by the implementation of the DSM strategies on the refrigeration and ventilation system of Mine A, M&V teams were contracted by Eskom. Due to the load management and variable water flow strategies being implemented separately each strategy will be evaluated independently. However, for these strategies the same pre-implementation electrical energy profile will be used but with different profile scaling methods. Figure 72 depicts the electrical energy profiles developed prior to implementation.

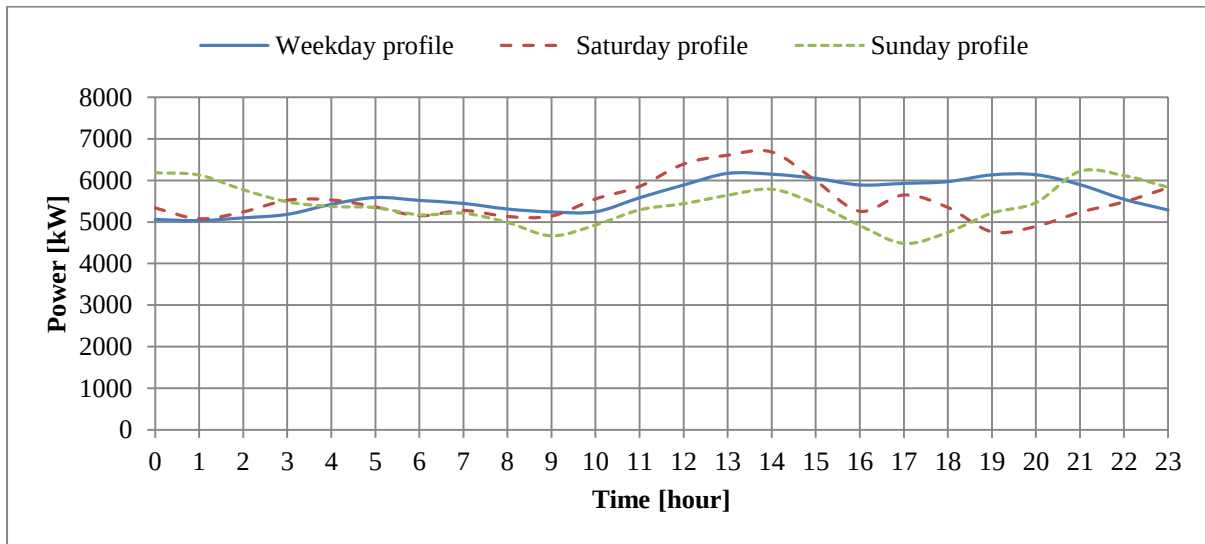


Figure 72: Average electrical energy profiles for the refrigeration and ventilation system of Mine A.

Load management strategy

The profile scaling method selected to verify results of the load management strategy will incorporate daily changes in the electrical energy consumption. This will be achieved by multiplying the pre-implementation electrical energy profile with a daily calculated profile scaling factor. Equation 11 illustrates how the scaling factor is calculated.

Equation 11:

$$\alpha = \frac{\sum_{j=1}^{24} P_{actual_j}}{\sum_{j=1}^{24} P_{normal_j}}$$

Where:

P_{actual_j} = actual 24 hour electrical power (kW)

P_{normal_j} = normal 24 hour electrical power (kW)

α = scaling factor

Once the load management strategy was implemented on Mine A an average daily electrical energy impact of 4.04 MW was realised. With the increase in electrical energy impact the new annual electricity cost savings was calculated at R2 514 250. The electrical energy load management results were verified using the profile scaling method developed by the M&V team. The verified results for the load management strategy on Mine A are shown in Figure 73.

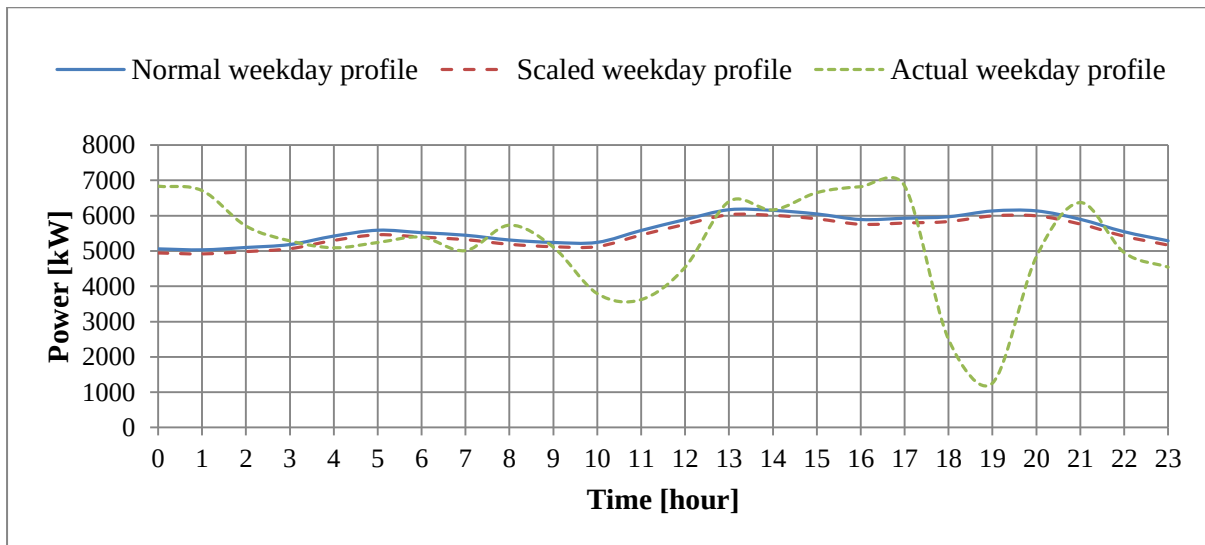


Figure 73: Mine A refrigeration and ventilation electrical energy consumption before and after load management strategy.

Variable water flow strategy

Due to the variable water flow strategy being an electrical energy efficiency strategy, a different profile scaling method was developed by the M&V team. Due to the variable water flow strategy being dependent on the ambient and production conditions, a scaling method was selected to compensate for these factors accordingly. The profile scaling method developed by the M&V is displayed in Equation 12.

Equation 12:

$$P_{scaled} = a_0 + a_1 T_{ambient} + a_2 T_{hot\ dam} + a_3 T_{cold\ dam} + a_4 v_{shaft} + a_5 v_{BAC}$$

Where:

P_{scaled} = scaled electrical power (kW)

$T_{ambient}$ = ambient temperature (°C)

$T_{hot\ dam}$ = hot dam temperature (°C)

$T_{cold\ dam}$ = cold dam temperature (°C)

v_{shaft} = water flow rate to shaft (ℓ/s)

v_{BAC} = water flow rate to BAC (ℓ/s)

a_i = scaling parameters ($i = 1,2,3,4$ and 5)

With the new variable water flow strategy implemented on Mine A, an average 40% and 20% reduction in condenser and evaporator pump power consumption was achieved respectively. The power consumption for a typical summer weekday of the first evaporator pump is shown in Figure 74. The increase in power consumption after the twelfth hour was caused by two factors. The increase in BAC outlet air temperature above the 5°C temperature set-point was the first reason for an increase in evaporator water flow.

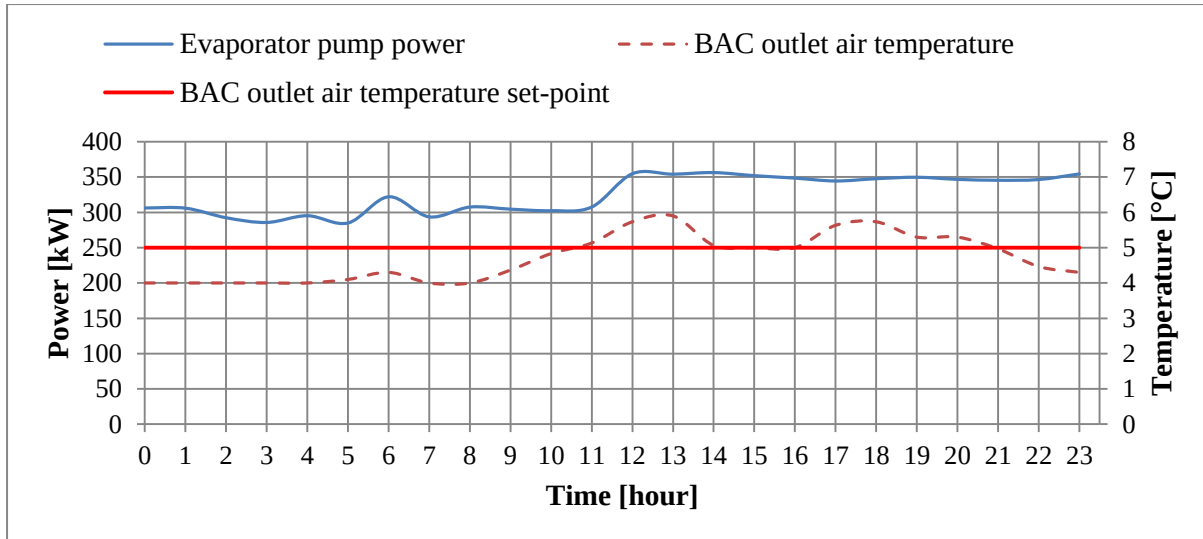


Figure 74: Mine A post-implementation variable evaporator water flow control.

The second reason for the increase was due to the cold dam level dropping below minimum set-point. The cold dam level for the same typical summer weekday is shown in Figure 75. Figure 74 and Figure 75 are good representations of the control philosophy utilised for the variable water flow control on the evaporator cycle of Mine A.

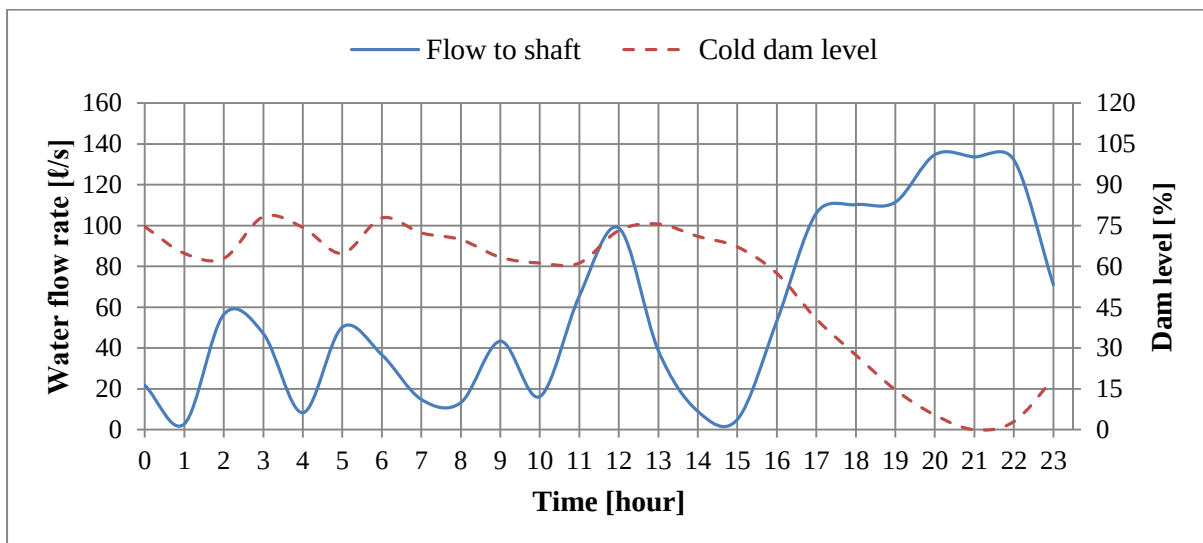


Figure 75: Mine A post-implementation daily water flow to shaft and cold dam level.

After implementing the variable water flow strategy and integrating the condenser and evaporator control philosophies, an average of 2.65 MW electrical energy reductions was realised. With the increased reduction in electrical energy consumption it was re-estimated that an average annual electricity cost savings of R9 206 000 can be realised. The post-implementation electrical energy consumption for the refrigeration and ventilation system of Mine A is shown in Figure 76.

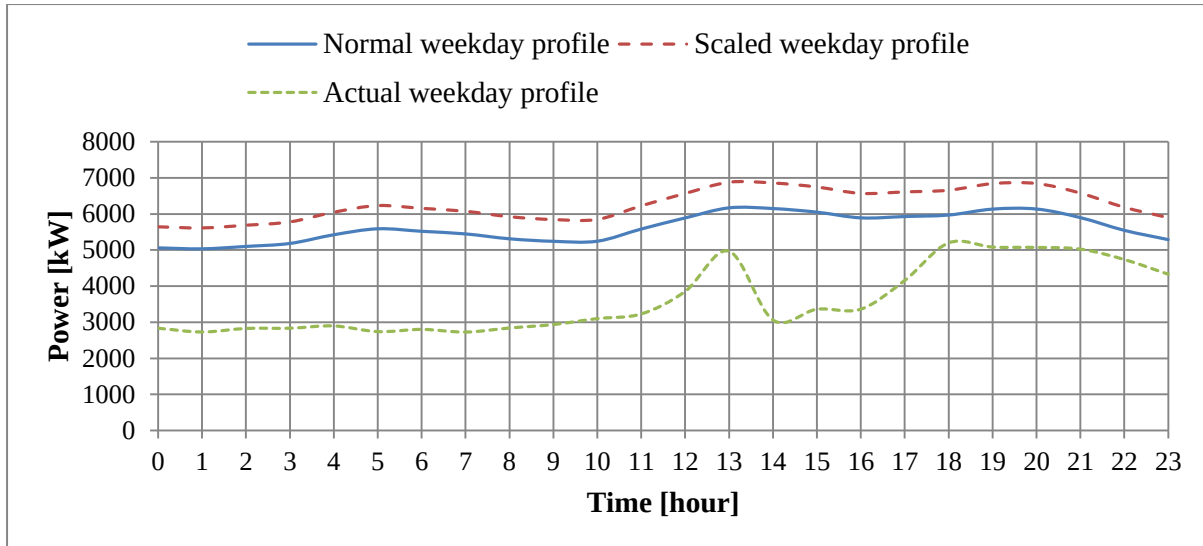


Figure 76: Figure 73: Mine A refrigeration and ventilation electrical energy consumption before and after variable water flow strategy.

4.3.3 Conclusion

Both strategies have proven to reduce the electricity costs of the refrigeration and ventilation system of Mine A. These electricity cost saving strategies were successfully implemented without compromising any health and safety regulations. This was achieved with the integration of the existing and proposed control philosophies, as specified in Section 3.3.3. Table 18 compares the proposed with the actual electrical cost reduction results

Table 18: Mine A refrigeration and ventilation system savings summary.

	Proposed	Achieved
Load management		
Electrical energy impact	3.72 MW	4.04 MW
Annual electricity cost savings	R 2 098 230.58	R 2 514 246.62
Variable water flow		
Electrical energy efficiency savings	2.05 MW	2.65 MW
Annual electricity cost savings	R 7 695 035.75	R 9 205 753.26

4.4 Conclusion

To conclude this chapter, three electrical cost saving strategies investigated and implemented on Mine A have realised significant savings. The integrated downstream and compressor control strategy delivered an average 4.35 MW peak clip electrical energy reduction. This accumulates to an annual electricity cost saving of R2.86 million.

The compressed air electrical energy saving was achieved with the supply and demand philosophy. By reducing the compressed air demand, less electrical energy is required at the supply end. It was estimated that with an implementation cost of R5.06 million, the strategy would be paid back within 25 months. The re-estimated payback periods for all three strategies are illustrated in Figure 77.

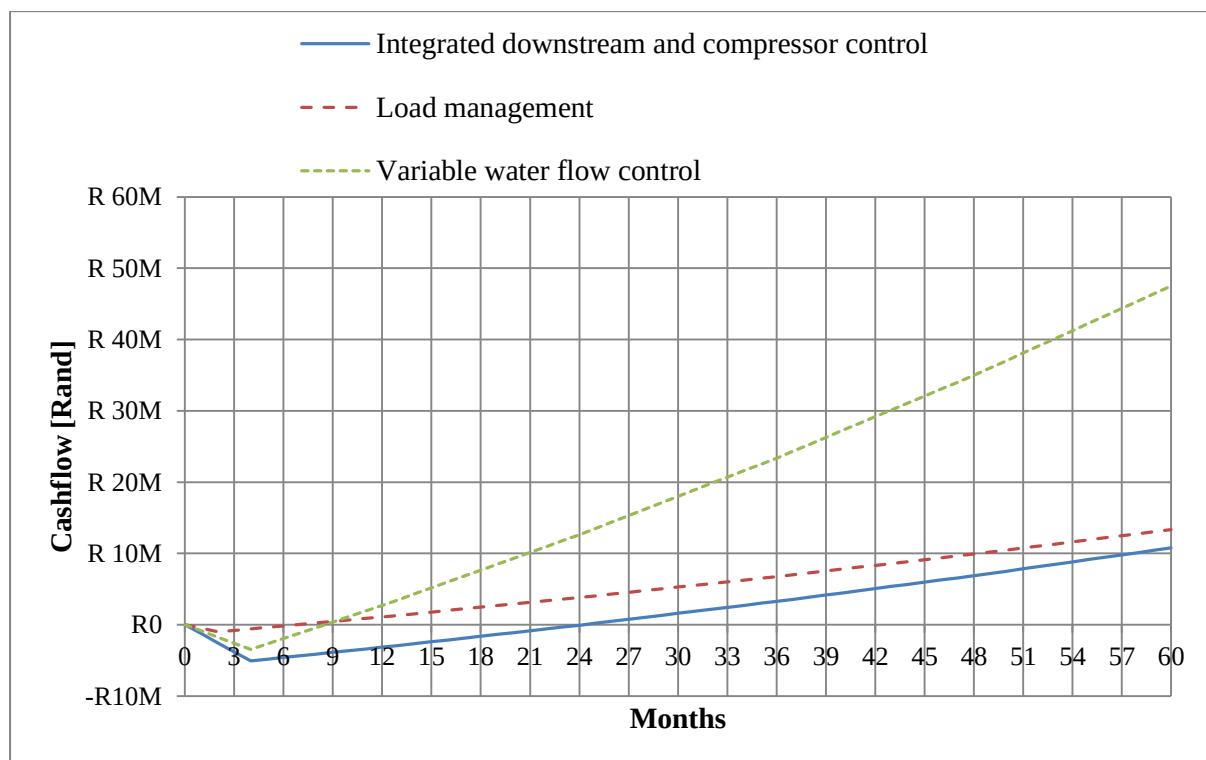


Figure 77: Mine A post-implementation payback period results.

Two electrical cost saving strategies were investigated and implemented on the refrigeration and ventilation system of Mine A. The load management and variable water flow strategy both produced ample electricity cost savings. A 4.04 MW load reduction between 18:00 and 20:00 was achieved by implementing the load management strategy. The annual electricity cost savings was estimated at R2.51 million against the simulated R2.1 million annual reduction. This delivered an estimated payback period of seven months for the load management strategy.

The last electrical cost savings strategy investigated and implemented was the variable water flow strategy. Although the implementation cost for this strategy ranged second highest, it delivered an astounding 2.65 MW energy efficiency savings. The strategy comprised of reducing the condenser and evaporator water flow to supply the required chilled water and ventilation air cooling. To summarise, an estimated annual electricity cost savings of R14.58 million can be realised if the three strategies continue to control the electrical energy consumption of Mine A throughout the year. A summary of the electricity cost savings results is provided in Table 19.

Table 19: Mine A post-implementation electricity cost savings results.

	Simulated	Actual
Integrated downstream and compressor control		
Electrical energy impact [MW]	3.7	4.35
Electricity cost savings	R 2 434 857.47	R 2 861 184.94
Estimated payback period [months]	28	25
Load management		
Electrical energy impact [MW]	3.72	4.04
Electricity cost savings	R 2 098 230.58	R 2 514 246.62
Estimated payback period [months]	8	7
Variable water flow control		
Electrical energy impact [MW]	2.05	2.65
Electricity cost savings	R 8 642 000.60	R 9 205 753.26
Estimated payback period [months]	9	9
Total estimated annual electricity cost savings	R 13 175 088.65	R 14 581 184.82

Chapter 5

Conclusion and recommendations

Review of study performed and recommendations for future studies

Chapter 5: Conclusion and recommendations

5.1 Conclusion

Large production losses, mineral price decreases and increased expenditures are raising concerns throughout the South African platinum mining sector. Therefore, platinum mining companies are looking at any and all possibilities of reducing operational costs. Together with the help of Eskom, these mining companies are investigating the financial benefits of implementing DSM strategies.

The aim of this dissertation was to investigate a combination of DSM strategies applicable to the platinum mining sector. By dividing the platinum mining operations into production and services, the electrical consumption of the three highest service consumers were identified. The three high consumers identified were compressed air, refrigeration and ventilation and pumping systems. With the high consuming service system known, a number of platinum mines within the Bushveld Igneous Complex were investigated for potential DSM strategies. This investigation delivered a list of potential platinum mines, as shown in Table 20.

Table 20: High electricity consuming platinum mines.

Mine	System	Installed capacity	Possible electrical energy impact	EEDSM project type
Mine A	Compressed air	23 MW	3.7 MW	Peak clip
Mine C	Compressed air	13 MW	1.2 MW	Peak clip
Mine D	Compressed air	33 MW	2 MW	Peak clip/energy efficiency
Mine E	Compressed air	18.2 MW	0.75 MW	Peak clip
Mine F	Compressed air	57.4MW	3.5 MW	Peak clip
Mine A	Refrigeration and ventilation	10.6 MW	3.7 MW	Load management
Mine D	Refrigeration and ventilation	6.4 MW	2.8 MW	Load management
Mine A	Refrigeration and ventilation	10.6 MW	2.1 MW	Energy efficiency
Mine D	Refrigeration and ventilation	6.4 MW	1 MW	Energy efficiency
Mine G	Refrigeration and ventilation	8.5 MW	2.7 MW	Energy efficiency

With the high consumers identified, knowledge regarding the specific systems and their operations were obtained to provide a suitable background. The background then served as a basis from which applicable system improvements and DSM strategies could be evaluated. Once all the electricity cost saving strategies were evaluated, an applicable case study, Mine A, was selected from the list of potential platinum mines.

The feasibility investigation led to the development of theoretical simulation models which represented the selected systems of Mine A. To verify the accuracy of the models, simulated electrical energy profiles were compared to the actual electrical energy consumption profiles. With correlation factors of 90% and above achieved, each model was verified as accurate and suitable for optimisation investigations.

Each of the system optimisation simulations delivers promising results, except for the water reticulation systems. With limited thermal storage capacities underground and low electrical energy consumption, investigations resulted in low feasibility for electrical cost saving strategies.

However, the investigation of possible strategies on the compressed air and refrigeration and ventilation systems delivered positive results. The integrated downstream and compressor control strategy proposed an annual R2.43 million electrical cost reduction on the compressed air system. Whereas the load management and variable water flow strategies proposed annual electricity cost reductions of R2.1 million and R8.64 million respectively.

Hence the high feasibility results, each of the strategies was implemented on the actual systems of Mine A. The implementation of these strategies did not affect any mine operations, productions or service deliveries.

The annual electricity cost savings on the service delivery systems of Mine A was estimated at an average R14.5 million with the implementation of three electrical cost saving strategies. The actual daily results from the implemented strategies were presented in Chapter 4. The high electricity cost saving achieved and low financial payback periods proves that the implementation of DSM strategies can reduce the electricity costs of struggling platinum mines.

5.2 Recommendations

The DSM electricity cost saving strategies investigated throughout this dissertation focused on specific platinum mining systems during certain time periods of the day. This was due to the DSM strategies partially being funded by the Eskom IDM programme that focuses on the Eskom high demand peak periods.

However, if these initiatives are driven and funded solely by platinum mining companies, the investigations can potentially be broadened to incorporate all systems without any time period limitations. Future electrical cost reduction investigations can be performed on the following systems:

1. Underground refrigeration and ventilation systems,
2. Winder systems,
3. Process plant systems,

4. Underground compressed air systems.

Other studies have also shown the potential to reduce electricity costs without the implementation and installation of expensive equipment. These electricity cost saving strategies mainly focus on maintaining the existing systems or altering the operation for higher efficiencies. Some of these low cost strategies were investigated and mentioned throughout the dissertation.

Chapter 6

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Chapter 6: References

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Appendix

Additional information utilised throughout the dissertation

Appendix A

The 2014/2015 annual Eskom Time Of Use (TOU) tariff structure for non-local authority rates is illustrated in Figure 78.

Transmission zone	Voltage	Active energy charge [c/kWh]										Transmission network charges [R/kVA/m]	
		High demand season [Jun - Aug]						Low demand season [Sep - May]					
		Peak	Standard	Off Peak	Peak	Standard	Off Peak	Peak	Standard	Off Peak	Peak	Standard	Off Peak
		VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl
≤ 300km	< 500V	204.55	233.19	62.23	70.94	33.97	38.73	66.98	76.36	46.22	52.69	29.46	33.58
	≥ 500V & < 66kV	201.33	229.52	60.99	69.53	33.12	37.76	65.68	74.88	45.20	51.53	28.68	32.70
	≥ 66kV & ≤ 132kV	194.96	222.25	59.06	67.33	32.07	36.56	63.60	72.50	43.77	49.90	27.77	31.66
	> 132kV*	183.75	209.48	55.66	63.45	30.23	34.46	59.94	68.33	41.25	47.03	26.18	29.85
> 300km and ≤ 600km	< 500V	206.21	235.08	62.48	71.23	33.93	38.68	67.27	76.69	46.31	52.79	29.38	33.49
	≥ 500V & < 66kV	203.34	231.81	61.60	70.22	33.45	38.13	66.34	75.63	45.65	52.04	28.96	33.01
	≥ 66kV & ≤ 132kV	196.88	224.44	59.64	67.99	32.38	36.91	64.22	73.21	44.19	50.38	28.04	31.97
	> 132kV*	185.58	211.56	56.22	64.09	30.52	34.79	60.53	69.00	41.66	47.49	26.43	30.13
> 600km and ≤ 900km	< 500V	208.27	237.43	63.08	71.91	34.25	39.05	67.94	77.45	46.76	53.31	29.66	33.81
	≥ 500V & < 66kV	205.38	234.13	62.22	70.93	33.79	38.52	67.00	76.38	46.11	52.57	29.25	33.35
	≥ 66kV & ≤ 132kV	198.88	226.72	60.25	68.69	32.71	37.29	64.87	73.95	44.65	50.90	28.32	32.28
	> 132kV*	187.45	213.69	56.78	64.73	30.84	35.16	61.15	69.71	42.08	47.97	26.70	30.44
> 900km	< 500V	210.36	239.81	63.74	72.66	34.61	39.46	68.63	78.24	47.23	53.84	29.97	34.17
	≥ 500V & < 66kV	207.43	236.47	62.83	71.63	34.11	38.89	67.66	77.13	46.56	53.08	29.54	33.68
	≥ 66kV & ≤ 132kV	200.88	229.00	60.85	69.37	33.04	37.67	65.52	74.69	45.10	51.41	28.61	32.62
	> 132kV*	189.29	215.79	57.37	65.40	31.17	35.53	61.78	70.43	42.53	48.48	27.00	30.78

Distribution network charges					
Voltage	Network access charge [R/kVA/m]		Network demand charge [R/kVA/m]		Urban low voltage subsidy charge [R/kVA/m]
	VAT incl	VAT incl	VAT incl	VAT incl	VAT incl
< 500V	R 11.63	R 13.26	R 22.05	R 25.14	R 0.00
≥ 500V & < 66kV	R 10.67	R 12.16	R 20.23	R 23.06	R 0.00
≥ 66kV & ≤ 132kV	R 3.81	R 4.34	R 7.05	R 8.04	R 9.39
> 132kV*	R 0.00	R 0.00	R 0.00	R 0.00	R 9.39

Customer categories	Service charge [R/Account/day]		Administration charge [R/POD/day]	
	VAT incl	VAT incl	VAT incl	VAT incl
> 1 MVA	R 133.50	R 152.19	R 60.17	R 68.59
Key customers	R 2,616.06	R 2,982.31	R 83.55	R 95.25

Reliability service charge [c/kWh]		
Voltage		VAT incl
< 500V	0.27	0.31
≥ 500V & < 66kV	0.26	0.30
≥ 66kV & ≤ 132kV	0.25	0.29
> 132kV*	0.23	0.26

Electrification and rural network subsidy charge [c/kWh]		Affordability subsidy charge [c/kWh] payable by non-local authority tariffs	
All seasons		All seasons	
	VAT incl		VAT incl
5.20	5.93	2.07	2.36

Reactive energy charge [c/kVarh]			
High season		Low season	
	VAT incl		VAT incl
9.40	10.72	0.00	0.00

Figure 78: Appendix A; 2014/2015 Eskom Megaflex tariff rates.

Appendix B

Figure 79 shows the PTB simulation model utilised during the pre-implementation investigations.

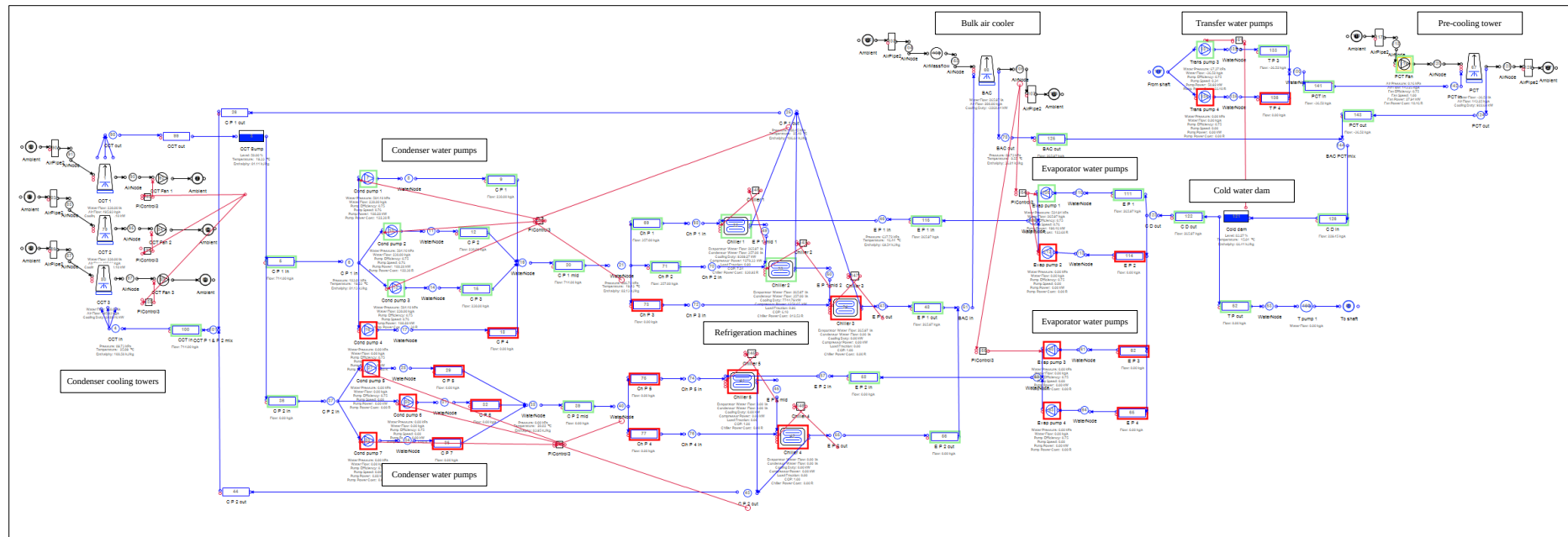


Figure 79: Appendix B; Mine A refrigeration and ventilation system simulation model.

Appendix C

The selected quotations for downstream control and compressor control are tabulated in Table 21.

Table 21: Appendix C; Mine A downstream and compressor control quotations.

Item	Description	Quantity	Total
Simatic S700-300 components	Simatic S7-300, Rail	6	
	Simatic S7-300 Stabilised power supply	6	
	Simatic S7-300, CPU 314C-2PN/DP compact CPU with 192 kbyte working memory	6	
	Simatic S7, Micro memory	6	
	Simatic S7-300, Front connector with screw contacts	12	
	Simatic S7- Open modbus/TCP for PN-CPU single license	6	
	Simatic S7, PC adapter USB F. Connection of S7-200/300/ 400, C7; with USB-able (5M)	6	
	Simatic S7-300, Analog input SM 331	2	
	Simatic S7-300, Analog output SM 332	2	
			R 353 281.00
SCADA control system	Simatic WinCC advanced V11 SP2 Engineering-SW	1	
	Simatic WinCC runtime advanced 128 powertags SP2 runtime-SW	1	
			R 85 329.00
PLC installation	PLC enclosure	6	
	Supply cable	600	
	Communication cable	600	
	Labour	12	
	P&Gs	12	
			R 171 750.00
Telemetry	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Dehnguard M TT 2P 275 din mount surge arrester and clearline 100 base 1 port RJ45 surge arrester	9	
	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Ubiquiti AirMax Rocket M5 5GHz Hi Power 2x2 MIMO, Ubiquiti AirMax 5GHz Omni (10dBi) with POE Injector 9 - 36VDC Input and 24VDC 19W POE Output	2	
	Ubiquiti AirMax PowerBridge M5 (5GHz, 25dBi, 27dBm), Ubiquiti AirMax Rocket M5 5GHz Hi Power 2x2 MIMO, Ubiquiti AirMax 5GHz Sector (16dBi, 120 deg), POE Injector 9 - 36VDC Input and 24VDC 19W POE Output, including Moxa EDS-508A industrial managed Ethernet switch	2	
			R 337 648.00

Engineering	PLC engineering	20	
	PLC FAT	2	
	WinCC SCADA engineering	10	
	On-site testing and commissioning	5	
	Documentation	7	
	Travel	35	
			R 650 219.00
Control valves	450 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	2	
	200 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	5	
	150 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator, Siemens valve positioner for control function with feedback. Including pipe sections	1	
Solenoid valves	450 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single actin fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	3	
	400 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	1	
	300 mm Air Torque butterfly valve, EPDM liner, ST/ST disc with single acting fail safe open actuator complete with solenoid and switchbox for open/close contacts. Including pipe sections	1	
Air flow meters	CS mass flow meter - VA 400- max version	8	
Pressure transmitters	IFM - PN5 pressure switch with digital display	8	
			R 3 301 754.03
Total compressed air downstream control			R 4 899 981.03
Compressor controller	Surge controller design and configuration on 5 compressors	6	
	Surge controller commissioning and surge curve design	6	
	Travel	6	
	Accommodation	6	
	Surge controller commissioning	12	
	Travel	6	
	Accommodation	6	
Total compressor control			R 158 567.50

The quotations for the load management and variable water flow strategy are shown in Table 22.

Table 22: Appendix C; Mine A load management and variable water flow quotation.

Item	Description	Quantity	Total
Load management			
Control valves	450 mm Air Torque slimline PN16 cast iron wafer type butterfly valve, EPDM liner, ST/ST disc with double action fail safe open pneumatic actuator. Namur mount with 5/2 way 24 V DC solenoid valve, switchbox with 2 mechanical limit switches for open/close feedback	3	
			R 528 597.00
Instrumentation	Yellow Asi cable (roll E74100)	1	
	Black Asi cable (roll E74110)	1	
	Asi splitter (used to extend existing cable) (AC3000)	3	
	Asi Air Box 2 in 2 out (AC5227)	3	
	M12 wire able plug (E11504)	6	
	Asi cable end glands (E70413)	1	
	Asi fly leads	6	
	Air pipe to valve	100	
			R 39 333.00
Remote IO panel	1000x1000x300 S/S enclosure Double door	1	
	Trunking, din rail, fixtures & misc	1	
	Terminals, double with fuse module	80	
	Panel wire assorted colours	2	
	220v-110v~ control transformer	1	
	Mini circuit breaker 1 Pole supply (in 220v DB)	1	
	Mini circuit breaker 2 Pole incomer	1	
	Mini circuit breaker 1 Pole control transformer input	1	
	Mini circuit breaker 1 Pole control transformer output	1	
	Mini circuit breaker 1 Pole Profibus adaptor	1	
	Mini circuit breaker 1 Pole IO rack	1	
	Mini circuit breaker 1 Pole field 110v 1	1	
	Cable tray - wire mesh	1	
	Glands (power supply and coms)	4	
	Glands (multicore to buckets)	1	
	Tray fixings	1	
	2.5mm 3 core SWA PVC	15	
	Profibus cable	10	
	1mm 24 pair PVC SWA (2xpump - run, trip, start, & spare)	100	

Remote IO panel	1mm 12 pair PVC SWA (3xInstrotech + 3x vibration switches in Cond room)	80	
	Siemens remote IO equipment	1	
	6ES7390-1AE80-0AA0 - DIN rail 480 mm	1	
	6ES7153-1AA03-0XB0 - IM 153-1 for ET 200M, Profibus DP	1	
	6ES7321-1EL00-0AA0 - Digital input 32DI, 120V AC; isolated	1	
	6ES7392-1AM00-0AA0 - Front connector, 40-pin, with screw contacts	1	
	6ES7307-1EA01-0AA0 - Load current supply PS 307; AC 120/230V, DC	1	
	24V, 5A 1 R 2,967.32 R 2,967.32	1	
	6ES7322-1FL00-0AA0 - Digital output 32DO, 120V AC, 1A; isolated	1	
	6ES7392-1AJ00-0AA0 - Front connector, 20-pin, with screw contacts	1	
	6ES7331-7KF02-0AB0 - Analog input 8AI; 14-bit; 20ms; isolated	1	
	Profibus plug	1	
			R 136 418.84
Junction box panel	1600x600x210 S/S enclosure	1	
	Trunking, din rail, fixtures & misc	1	
	Terminals, double with fuse module	12	
	Glands (existing temp plus 3 spare for vibration switches)	12	
	Glands (multi-core)	2	
	Misc.	1	
			R 23 320.20
Labour	General installation	30	
	PLC and SCADA software engineering	10	
	Commissioning	1	
	Documentation	1	
	Travel	40	
			R 262 534.29
Total load management			R 990 203.33

Variable water flow control			
400 kW VSDs	Allen Bradley PowerFlex 750-Series 400 kW (600 V/595 A) AC Drives. Including circuit breakers, line and motor choke.	4	
250 kW VSDs	Allen Bradley PowerFlex 750-Series 250 kW (600 V/355 A) AC Drives. Including circuit breakers, line and motor choke.	2	
Instrumentation	Glands	40	
	Lugs	48	
	Misc.	7	
	Profibus D-Sub 9-pin attached vertical connector with Diagnostics	6	
	Additional Earth Leakage unit	6	
	3-Core 300mm cable from switch gear to drive panel	100	
	70mm Earth cable	100	
	6GK1503-3CB00 - Siemens OLM Multi Mode		
Fibre optic cable	4 Core MM HDD fibre	100	
	Midcoulper	4	
	1 Meter ST unjacketed pigtail	8	
	Splice and OTDR	4	
	Splice box complete	2	
			R 1 900 621.34
400 kW VSDs	Allen Bradley PowerFlex 750-Series 400 kW (600 V/595 A) AC Drives. Including circuit breakers, line and motor choke.	2	
200 kW VSDs	Allen Bradley PowerFlex 750-Series 200 kW (600 V/295 A) AC Drives. Including circuit breakers, line and motor choke.	1	
Instrumentation	Glands	15	
	Lugs	24	
	Misc.	4	
	Profibus D-Sub 9-pin attached vertical connector with Diagnostics	3	
	Additional Earth Leakage unit	3	
	3-Core 300mm cable from switch gear to drive panel	40	
	70mm Earth cable	40	
Ambient weather station	Testo 6681 Industrial humidity transmitter with Testo 6611 climate probe. 0/4 to 20 mA and 0 to 1/5/10 V output (2/4-wire) including Profibus DP module	1	

BAC temperature sensor	Testo 6681 Industrial humidity transmitter with Testo 6611 climate probe. 0/4 to 20 mA and 0 to 1/5/10 V output (2/4-wire) including Profibus DP module	1	
			R 923 219.51
Labour	General installation	30	
	PLC and SCADA software engineering	80	
	Commissioning	100	
	Documentation	1	
	Travel	120	
			R 619 975.00
Total variable water flow control			R 3 443 815.85

Appendix D

The results delivered after the implementation of the various DSM strategies on the service operation of Mine A is tabulated in Table 23, Table 24 and Table 25 respectively.

Table 23: Appendix D; Mine A integrated downstream and compressor control strategy post-implementation results.

Hour	Normal consumption [kW]	Actual consumption [kW]
0	15774	13323
1	14958	13198
2	14978	13300
3	14944	13254
4	15012	13381
5	14056	13346
6	15248	13424
7	15537	13431
8	16765	13492
9	16396	13883
10	16477	13646
11	17085	16590
12	16841	13614
13	15662	13611
14	15406	13642
15	14776	13297
16	12555	13083
17	12826	9615
18	12664	8734
19	13586	8809
20	12646	9372
21	13028	9420
22	13323	9580
23	14900	13360

Table 24: Appendix D; Mine A load management strategy post-implementation results.

Hour	Normal consumption [kW]	Actual consumption [kW]
0	4944	6835
1	4918	6711
2	4983	5707
3	5064	5287
4	5299	5091
5	5460	5241
6	5392	5393
7	5322	5011
8	5190	5731
9	5122	5109
10	5125	3793
11	5454	3623
12	5754	4539
13	6027	6401
14	6009	6163
15	5911	6653
16	5756	6821
17	5792	6841
18	5833	2497
19	5993	1257
20	5996	4837
21	5763	6371
22	5419	4957
23	5167	4543

Table 25: Appendix D; Mine A variable water flow strategy post-implementation results.

Hour	Normal consumption [kW]	Actual consumption [kW]
0	5643	2833
1	5613	2730
2	5687	2827
3	5780	2834
4	6048	2897
5	6232	2739
6	6154	2801
7	6074	2727
8	5923	2840
9	5845	2935
10	5849	3101
11	6225	3229
12	6567	3853
13	6879	4967
14	6858	3059
15	6746	3360
16	6570	3361
17	6611	4157
18	6657	5198
19	6840	5082
20	6843	5073
21	6577	5025
22	6184	4737
23	5898	4330

Appendix E

During the commissioning of the variable water flow strategy on Mine A, the minimum water flow parameters with the corresponding VSD frequencies were determined. The results for the condenser and evaporator pumps of the first plant is illustrated in Figure 80 and Figure 81 respectively.

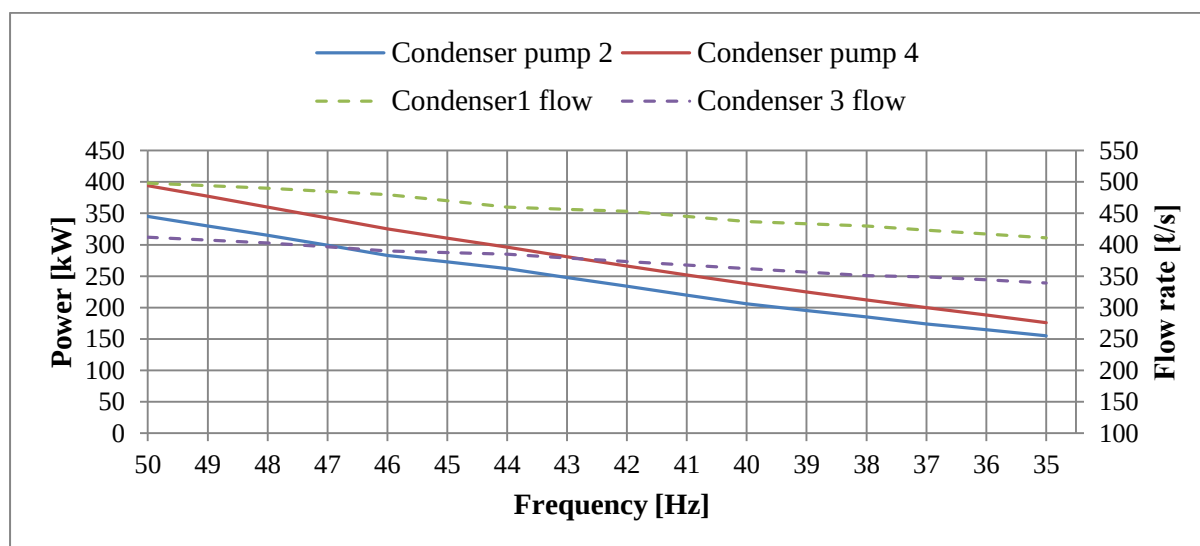


Figure 80: Appendix E; Mine A manual condenser water flow test 1.

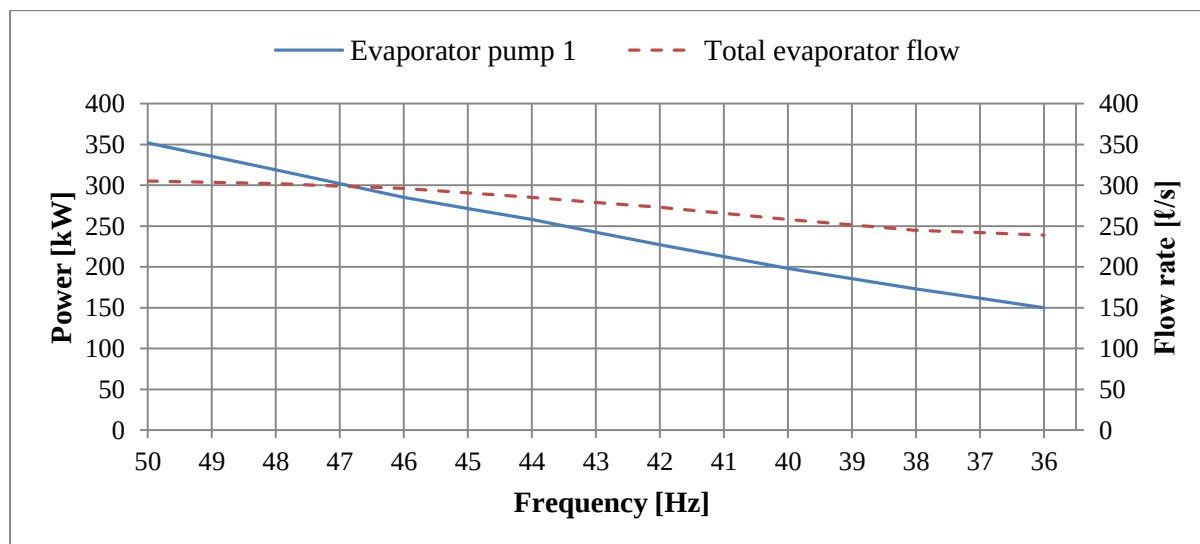


Figure 81: Appendix E; Mine A manual evaporator water flow test 1.