

Challenges faced during implementation of a compressed air energy savings project on a gold mine

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Abstract

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Demand side management (DSM) initiatives have been introduced by Eskom to reduce the deficit between the electricity generation capacity and the electricity usage within the country. DSM projects enable Eskom to reduce electricity demand instead of increasing generation capacity. DSM projects are more economical and can be implemented much faster than constructing a new power station.

One particular industry where DSM projects can be implemented is on mines. Mines consume about 14.5% of South Africa's electricity. Producing compressed air, in particular, is one of the largest electricity users on mines. It consumes 17% of the electricity used on mines. The opportunity, therefore, arises to implement DSM projects on the compressed air system of mines. Not only do these projects reduce Eskom's high electricity demand, but they also induce financial and energy savings for the mine itself.

However, during the implementation of a compressed air energy savings project, various challenges arise. These include, among others, operational changes, control limitations, industrial actions and installation delays. All of these can lead to a project not being delivered on time, within budget or with quality results.

The purpose of this study is to investigate and address various problems that occur during the implementation of such a compressed air energy savings project. The study shows that although these problems have an impact on the results achievable with the project, significant savings are still possible.

Project savings are achieved by reducing the amount of compressed air that is supplied, thereby delivering sufficient compressed air while minimising the amount of compressed air being wasted. During this study, a gold mine's compressed air network was optimised. The optimisation resulted in an evening peak-clip saving of 2.61 MW. This saving was achieved daily between 18:00 and 20:00 when Eskom's electricity demand was at its highest. It is equivalent to an annual cost saving of R1.46 million based on Eskom's 2014/2015 tariffs. When savings from all periods throughout the day are taken into account, the project will produce an annual cost saving of R1.91 million.

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“I can do all things through Christ who strengthens me.”

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Nomenclature

Abbreviation		Definition
AC	–	Alternating Current
DN	–	Diameter Nominal
DSM	–	Demand Side Management
ESCO	–	Energy Service Company
IDM	–	Industrial Demand Management
M&V	–	Measurement and Verification
NERSA	–	National Energy Regulator of South Africa
PID	–	Proportional-Integral-Derivative
PLC	–	Programmable Logic Controller
PMBOK	–	Project Management Body of Knowledge
SCADA	–	Supervisory Control and Data Acquisition
TOU	–	Time of Use
VSD	–	Variable Speed Drive

Unit of measure		Description
c/kWh	–	Cent per kilowatt-hour
GW	–	Gigawatt
GWh	–	Gigawatt-hour
kg/m ³	–	Kilogram per cubic metre
kg/s	–	Kilogram per second
kJ/kg·K	–	Kilojoule per kilogram per kelvin
kPa	–	Kilopascal
kW	–	Kilowatt
ℓ/min	–	Litre per minute
m	–	Metre
m ²	–	Square metre
m ³ /h	–	Cubic metre per hour
mm	–	Millimetre
m/s	–	Metre per second
MW	–	Megawatt

Symbol		Description
A	–	Area
C_p	–	Specific heat constant
g	–	Gravitational acceleration
h	–	Difference in height
k	–	Polytrophic exponent
$\dot{m}$	–	Mass flow of air being compressed
P	–	Power
p	–	Pressure
Q	–	Volume flow
T_{in}	–	Absolute inlet air temperature
v	–	Velocity
W_e	–	Electric power
X	–	Variable position
η_c	–	Efficiency of compressor
η_m	–	Efficiency of electric motor
ρ	–	Density of fluid or air

Chapter 1: Background



1

This chapter introduces the electricity situation in South Africa. The need and importance of demand side management initiatives are highlighted. This leads to the goals of this study.

¹ *Figures not contributing to the academic value of the dissertation will not be referenced in the bibliography. Footnotes will be used.*

Picture courtesy of <http://www.alstom.com/Global/Grid/Resources/Images/Engineered%20Grid%20solutions/Transmission%20Lines.jpg>

1.1) Electricity situation in South Africa

Electricity supply capacity, cost and access play a vital role in the South African economy and are critical for economic growth, social development and poverty alleviation [1]. Eskom, the largest electricity utility in Africa and among the top 15 largest utilities globally, generates 95% of the total electricity used in South Africa. Eskom also generates approximately 45% of the electricity used in Africa [2].

Between 2005 and 2013, Eskom increased its generation capacity by more than 6 GW [2], [3]. This forms part of the Eskom expansion programme to increase electricity capacity by 17.1 GW between 2005 and 2020 [4].

Three of the main power stations currently being built are the Medupi, Kusile and Ingula power stations [5]. The key challenge facing the capital expansion programme is remaining on schedule in the face of contractor issues and labour action [3]. The commissioning of Medupi power station, which was scheduled to start operating its first unit in 2012, has been extended until the end of 2014 when only a limited amount of power will be generated. The power station is only expected to be fully operational in 2015 [6].

According to Collin Matjila, former Eskom Interim Chief Executive, Unit 1 of the Kusile power station will only be commissioned during the 2015/2016 financial year. Unit 3 of the Ingula power station is forecasted to be synchronised during the second half of 2015. Eskom, therefore, expects that for the remainder of 2014, especially during the winter months, it will be challenging to meet the country's demand [5].

Another big concern is the fact that almost two-thirds of Eskom's power stations are past the midpoint of their expected operating lives and, therefore, require higher levels of planned maintenance [3].

1.2) Electricity usage on South African gold mines

Market capitalisation of mining companies continues to decrease year-on-year. Gold-mining companies, particularly, are hit the hardest of all the mining sectors [7]. According to economic strategist Chris Hart, one of the biggest concerns for the mining sector is the price of electricity. Between 2007 and 2012, average electricity cost to the mining sector as a whole rose 238% – from 18c/kWh in 2007 to 61c/kWh in 2012 [8].

These costs are increasing continuously each year. On 28 February 2013, the National Energy Regulator of South Africa (NERSA) approved an 8% average electricity price increase per annum for the next five years [9]. This was after Eskom handed in an application on 18 October 2012 applying for a 16% increase for the 2013/2014 yearly period [3], [9].

The mining industry uses about 14.5% of the country's electricity [4]. The industry consists of about 1 000 mining customers to which 31 611 GWh of electricity was sold in the 2013 financial year [2]. Figure 1 illustrates the electricity usage of the various sectors in the country.

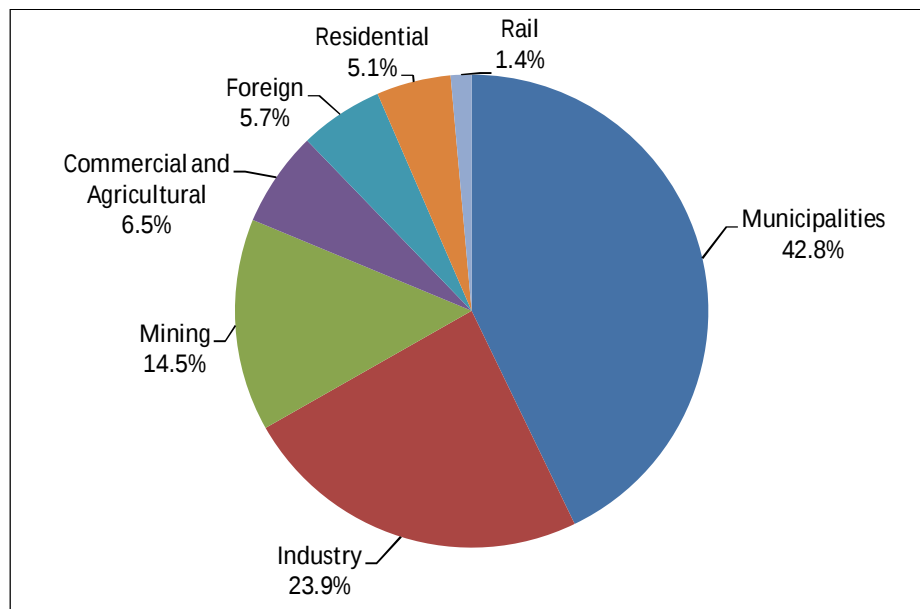


Figure 1: South Africa electricity usage per sector [4]

Gold mines are the largest electricity users within the mining sector, consuming 47% of the electricity consumed in the mining industry [10]. One of the largest electricity consumers on mines is compressed air. Figure 2 shows that compressed air accounts for 17% of electricity used on mines in South Africa [10].

While new power stations are being built to increase the capacity of the national electrical grid over the long term, demand side management (DSM) initiatives were introduced by Eskom to ensure short-term security of electricity supply [11].

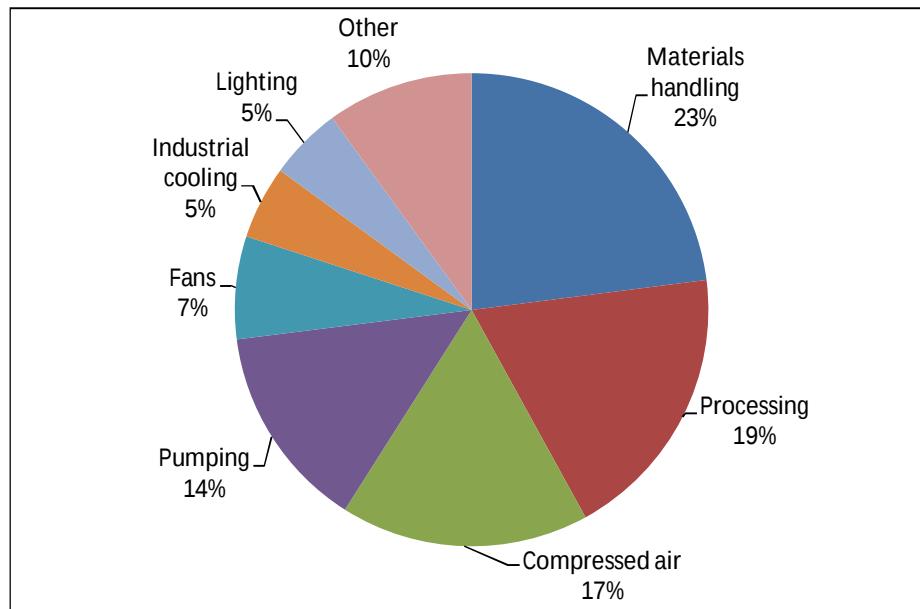


Figure 2: Electricity consumers on mines [10]

DSM initiatives are also known as Integrated Demand Management (IDM) initiatives. Since the mining industry consumes 14.5% of the country's electricity, it is reasonable to conclude that the South African mining industry has significant potential for DSM initiatives.

1.3) DSM initiatives

DSM is defined as the planning, implementing and monitoring of activities to encourage consumers to use electricity more efficiently, including both the timing and level of electricity demand [12].

The main reason for DSM programmes is that the national load peaks daily between 07:00 and 10:00, and then again between 18:00 and 20:00, as can be seen in Figure 3. A significant peak can specifically be seen during these times in the winter months and is mainly caused by the residential sector. Eskom, therefore, introduced a variable pricing structure, also known as the time-of-use (TOU) tariff pricing structure that is intended to be cost reflective. This was implemented to encourage consumers to use electric equipment outside the peak periods in support of the DSM programme [13].

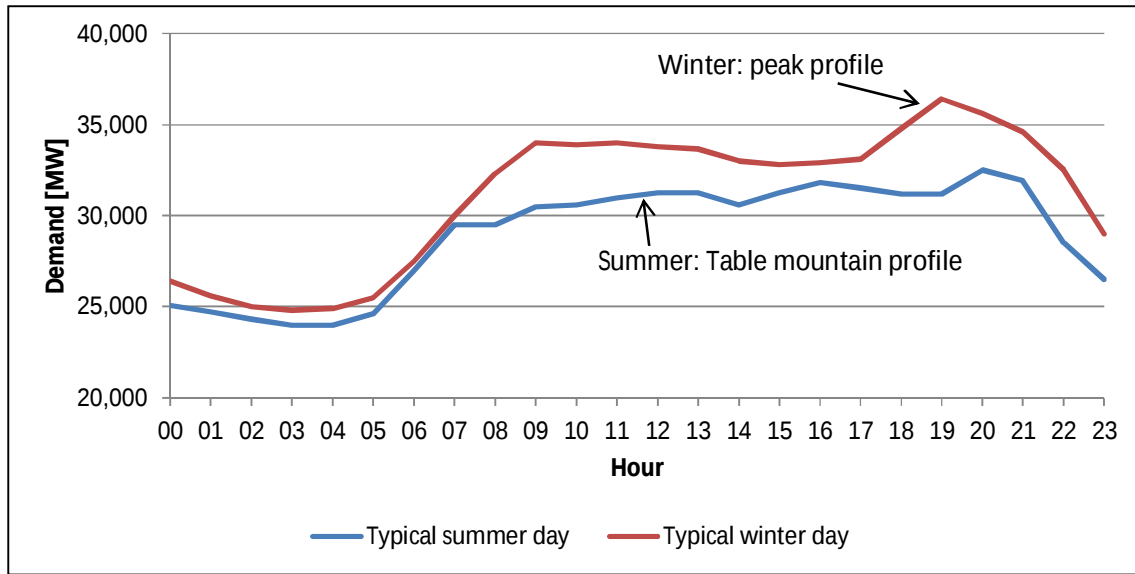


Figure 3: Summer and winter electricity load profiles (adapted from [3])

The tariffs are based on time-of-day usage, with the most expensive periods being the peak time periods [14]. This structure encourages consumers to use electric equipment during the least expensive periods, known as off-peak periods.

The various tariff structures are primarily grouped into three non-municipal classes, namely, urban, residential and rural tariffs [14]. Each of the various structures is made to fit the needs of various consumer groups. The mining and industrial sectors are placed in the urban tariff structure. One of these urban tariff structures is called the 'Megaflex' structure [14]. This structure is designed for sectors with continual operations and, therefore, it is used by the majority of mines in South Africa.

The tariff structure consists, firstly, of three different time-dependent periods during a day. The different periods are called the peak, standard and off-peak periods. The peak period is weekdays between 07:00 and 10:00 and then again between 18:00 and 20:00 [14]. This is typically the period during which people get ready to go to work and when industries start its activities and the period after work when home appliances such as ovens, televisions and heaters are used.

Secondly, the tariff structure is based on the different types of day, namely, weekdays, Saturdays and Sundays [14]. Figure 4 displays the three different costing periods for weekdays, Saturdays and Sundays.

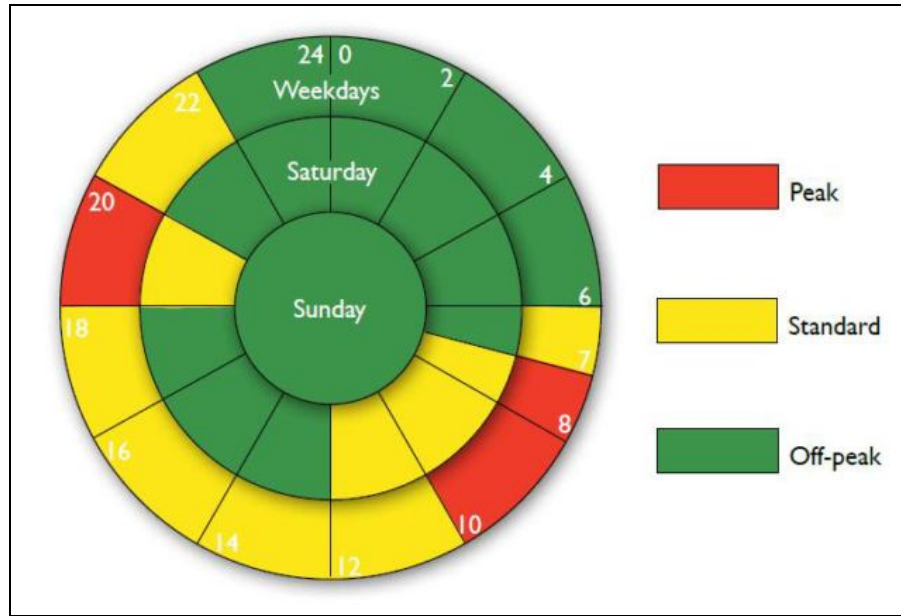


Figure 4: Eskom TOU tariff pricing structure [14]

Lastly, the tariff structure is based on seasonal changes. The structure is divided into summer and winter profiles. The winter profile ranges from June to August and the summer profile ranges from September to May [14].

Electricity tariffs are higher during winter profile months than during summer profile months, especially during peak periods. The seasonal tariff changes are also applicable to standard and off-peak periods. Table 1 illustrates the different costs per unit during the various periods for both the summer and winter profiles.

Table 1: Eskom 2014/2015 electricity tariffs [14]

Time of day	Low-demand season September–May [c/kWh]	High-demand season June–August [c/kWh]
Off-peak	30.97	35.77
Standard	48.82	65.87
Peak	70.93	217.44

The key objective of DSM projects is to improve energy efficiency by reducing the average cost of generating electricity. Added benefits of DSM projects include reducing greenhouse gas emissions as well as creating jobs [15].

There are three different types of DSM project [15]:

- **Energy efficiency** projects are based on reducing the overall power usage over a complete 24-hour period.
- **Load shifting** projects focus on reducing the electricity consumption away from the residential demand periods towards the off-peak periods. The total amount of power used during the 24-hour period would still be the same.
- **Peak clipping** projects focus on reducing the electricity usage only during the peak periods. Consumer demand remains unchanged for the remainder of the day.

Between 1 April 2013 and 30 September 2013, Eskom achieved evening peak-demand savings of 117 MW and annualised energy savings of 306 GWh with the DSM programme [3].

1.4) Challenges associated with the implementation of energy savings projects

During the six months between 1 April 2013 and 30 September 2013, Eskom spent R700 million on IDM initiatives (also known as DSM initiatives) [3]. These funds, with the help of energy service companies (ESCOs), were used to implement energy savings projects to reduce the high electricity demand of the country [16]. During the implementation of these types of projects, there are various challenges that need to be addressed.

The Project Management Institute (PMI) developed a set of standard terminology and guidelines called the Project Management Body of Knowledge (PMBOK). The PMBOK identifies knowledge and practices that are applicable to most projects and that can be used to enhance the chances of success of a project. These guidelines are specifically based on project management principles. According to PMBOK, specific aspects need to be taken into account when implementing projects [17]. Thus, attention needs to be given to the following aspects when implementing a compressed air energy savings project:

- scope management;
- time management;
- cost management;
- human resource management;
- risk management; and
- stakeholder management.

Scope management

The project scope defines what the project is supposed to accomplish, and defines the budget of both time and money of the project. The scope of a compressed air energy savings project will typically include the cost, size, and position of control valves. The scope will also include the installation period of the valves. It is important to fully understand what the project needs to accomplish before starting. A change in scope will most likely also induce a change in project time and budget [17].

Time management

Every delivery during a project is time-bound. When a delivery is late, it not only delays other deliverables, but it can also prolong the completion date of the entire project. Time wasting will not only affect the project manager and the project itself, but it will also affect other parties such as contractors that are involved [17]. Equipment installations on a mine's compressed air network, for example, need to be carefully planned. Certain critical parts of the network can only be isolated over weekends for installations to take place. Compressed air is continuously used throughout the network during weekdays.

Cost management

The costs of a project need to be thoroughly determined and controlled. It would essentially determine whether an organisation makes a profit or loss. [17]. In the case of an energy savings project on a mine, it can prolong the payback period of a project.

Human resource management

One of the key features of human resource management is hiring the right people for the job. Contractors are not only expected to do high quality work, but they also need to remain on schedule [17]. Contractors have a significant impact on the costs of a project since they determine the infrastructure and installation costs. Choosing the correct contractor for a project is, therefore, of utmost importance.

Risk management

It is important to identify and monitor various risks that could possibly occur during the implementation of a project. Minimising the impact of project threats can allow a project to be delivered on time, on budget and with quality results. [17]. Minimising project risks are not only

done to meet project deadlines and budgets; it is also done to prevent equipment damage and injuries to personnel. For a compressed air energy savings project, project risks can include control limitations and insufficient valve sizes due to constantly changing mine operational conditions.

Stakeholder management

Project stakeholder management focuses on ensuring that the right stakeholders are identified and that the appropriate stakeholders participate in the relevant project activities. It also focuses on ensuring that the stakeholder requirements are captured and incorporated into the scope of the project [17].

When challenges such as industrial action (also known as strikes) arise, relevant stakeholders need to address the problem as soon as possible. Furthermore, DSM projects have specific power saving targets to achieve. When the targets are not met, penalties have to be paid to Eskom. Stakeholders responsible for project penalties have to ensure that projects are successfully implemented.

Although management is concerned with these various aspects, project management has a unique focus shaped by the goals, schedule and resources of projects [18].

1.5) Goals of the study

In light of the preceding discussion, it is evident that Eskom has an electricity shortage on hand. Not only is the company unable to increase its generation capacity fast enough during this time of shortage, but maintenance on its power plants is also becoming a great concern.

The implementation of DSM initiatives will assist Eskom to meet the growing electricity demand. Large electricity consumers such as mines will also benefit from the initiatives when continuously increasing electricity prices are taken into account.

Practical challenges, however, arise during the implementation of DSM projects on gold mines. This dissertation identifies and addresses various practical challenges associated with the implementation of a compressed air energy savings project on a gold mine.

The main objectives of this dissertation are to:

- investigate a compressed air system on a gold mine in order to establish the feasibility of a DSM initiative;
- design and implement a DSM control system to improve the operations of the infrastructure;
- address practical problems encountered during the implementation of the energy savings project; and
- verify the various advantages of such an energy savings opportunity to both the client and Eskom.

1.6) Overview of the dissertation

Chapter 1 provided an overview of the electricity situation in South Africa. Large electricity consumers on mines were identified and compressed air systems was found to be the third largest electricity consumer. DSM initiatives as well as challenges associated with the implementation of energy savings projects were discussed.

Chapter 2 provides an overview of compressed air systems on gold mines. Various types and applications of compressors, as well as different compressed air networks are discussed. Problems associated with the implementation of mine compressed air projects are investigated. Existing energy savings strategies are also discussed.

Chapter 3 provides a method that was used to identify and implement a compressed air energy savings project on a gold mine. Various challenges identified during the implementation of the project are discussed.

Chapter 4 discusses the savings achieved with the optimisation of the mine compressed air system. Various baseline adjustment models are identified to determine accurate savings on a daily basis.

Chapter 5 discusses the conclusion of the study. Recommendations are made for further studies.

Chapter 2: Overview of compressed air systems on gold mines



2

The chapter provides background information regarding compressors in the gold-mining industry. Problems associated with mine compressed air systems are reviewed and existing energy savings measures on compressed air systems are researched.

² Photo courtesy of HVAC International personnel

2.1) Introduction

Chapter 1 focused on the demand and shortage of electricity in South Africa. It also discussed the power usage of mines in South Africa. It presented compressors as one of the main electricity consumers on mines, using 17% of the total electricity consumed on mines [10]. Compressed air, however, remains a key component for daily mining activities.

When combining these aspects, the prospect of an energy savings project is investigated that would benefit both the mine and Eskom. Reducing the energy usage of compressors on mines will not only decrease mining expenses, but will also reduce the strain on the national electrical grid.

Compressed air is often considered a ‘fourth utility’ alongside gas, oil and electricity as it is widely used throughout industries due to its cleanness, availability and ease of use [19], [20]. However, it is also considered one of the most expensive utilities used on a mine [21]. Studies have shown that only 19% of the power used by a compressor can be converted into useable work. The majority of the power is lost as waste heat [22].

Figure 5 show that 73% of the cost of a compressor over a 10-year cycle is due to its electricity usage. The capital investment for a new compressor only accounts for 18% of the total cost, while installation accounts for 2% of the total cost. The remaining 7% of the total cost is for maintenance on the machine [23].

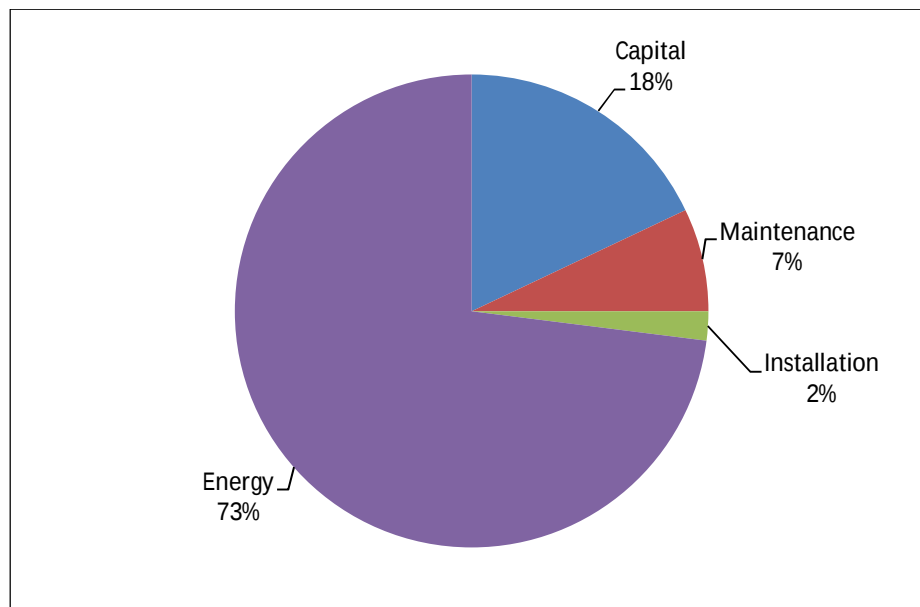


Figure 5: Compressor costs over a ten-year cycle [23]

With such a large portion of the total life cycle cost of a compressor due to energy usage, significant cost savings can be achieved by improving the efficiency of compressors and by using compressed air effectively. Other improvements will include enhancing the system performance and reducing the ‘carbon footprint’. Energy efficiency will, furthermore, increase the portion of compressed air that can be used for production and minimise unnecessary waste [23].

This chapter focuses on the electricity usage of gold mines, especially the electricity usage of compressors. Section 2.2 discusses various types and applications of compressors on mines. Section 2.3 focuses on different types of compressed air networks. Problems associated with compressed air systems on mines are discussed in Section 2.4, and finally, the possibility of DSM opportunities is investigated in Section 2.5.

2.2) Types and applications of compressors in the gold-mining industry

2.2.1) Compressor types

Although there are various different compressor types, all of them can be divided into mainly two basic compressor types, namely, positive displacement and dynamic compressors [24]. The two main compressor types can be described as follows:

Positive displacement: A given quantity of air or gas is trapped inside the compressor chamber of a positive displacement-type compressor. As the volume of the chamber is mechanically reduced, a corresponding rise in pressure takes place prior to the discharge. The airflow remains essentially the same at constant speed with a variation in discharge pressure taking place [24].

Dynamic: Dynamic compressors use rotating impellers to impart velocity energy to continuously flowing air or gas [24]. Since mines need a constant supply of airflow, dynamic compressors would be the preferred option of the two.

Figure 6 illustrates the different types of compressor.

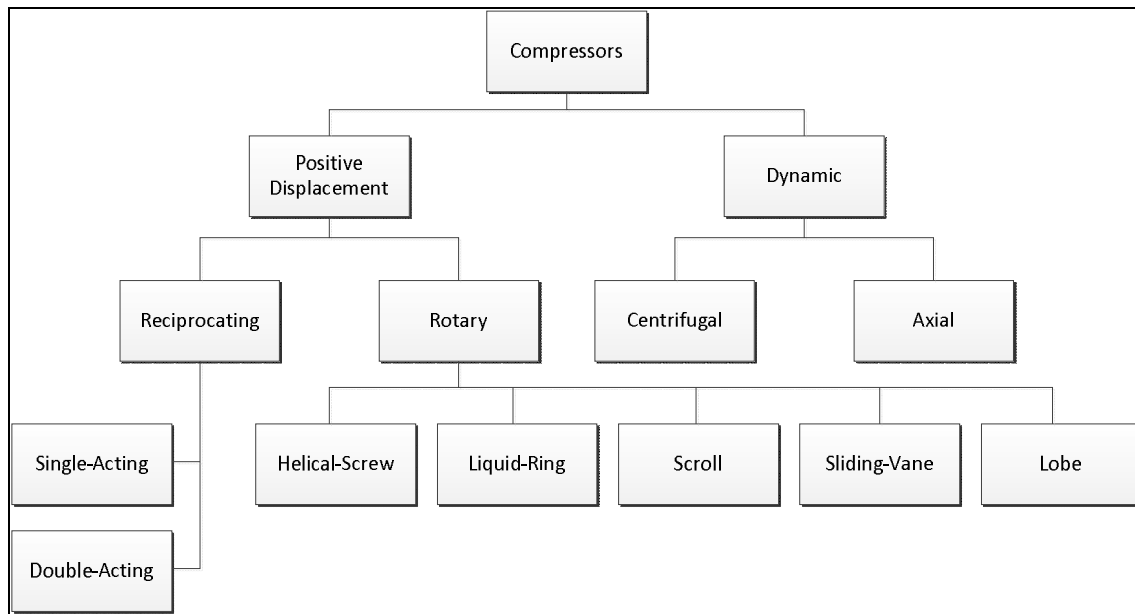


Figure 6: Types of compressor [24]

One of the two compressor types that are categorised under dynamic compressor types is the centrifugal compressor. The United Nations Environmental Programme states, “*The centrifugal air compressor is a dynamic compressor, which depends on transfer of energy from a rotating impeller to the air.*” This is accomplished by the rotor by changing the momentum and pressure of the air. Momentum converts to useful pressure by reducing the air speed in a stationary diffuser [25].

The most common centrifugal air compressor is one with two or four stages, increasing the air pressure during each stage. This is known as a multistage compressor and is used to either improve efficiency at a constant pressure or to achieve higher pressures [26]. Through personal experience, it was found that motors used with centrifugal compressors on gold mines range from 1 MW to 15 MW. Figure 7 shows an example of a typical centrifugal compressor.

The essential characteristic of a centrifugal air compressor is that as the system pressure decreases, the compressor’s flow capacity increases. The mass flow of a centrifugal compressor increases as the temperature decreases, assuming a constant discharge pressure is maintained [26].

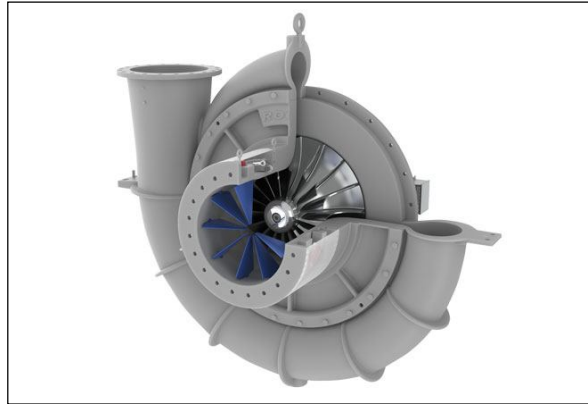


Figure 7: Centrifugal compressor³

Centrifugal compressors are best suited for applications where the demand is relatively constant [26]. This, and because centrifugal compressors only have a few moving parts, make them particularly suited to high volume applications such as those used on mines [25].

Large, sudden changes in demand can cause the pressure of a compressor to drop below the minimum requirements, leading to improper function or even damage to the equipment. Caution thus needs to be taken when lowering the average system pressure [27]. Centrifugal compressors are efficient to about 60% of their design output; below that they have little turndown in energy consumption [23]. Table 2 shows the advantages and disadvantages of centrifugal compressors.

Table 2: Advantages and disadvantages of centrifugal compressors [23], [26]

Centrifugal compressors	
Advantages	Disadvantages
Energy efficient	Limited control range
Large capacity	Specialised maintenance required
High air quality – lubricant free air	High initial cost
Relative capital and installation costs improve as size increases	High rotational speed requires special bearings, sophisticated monitoring of vibrations and clearances
Complete package solution – easy to install	Only water-cooled models

³ Picture courtesy of <http://www.ge-energy.com>

2.2.2) Electric motors

As previously mentioned, motors used with centrifugal compressors on gold mines range between 1 MW and 15 MW and, therefore, require large motors to drive the compressors.

The two most common types of alternating current (AC) electric motor for compressor drives are synchronous motors and asynchronous motors (also known as induction motors). Both of these types of motor consist of two electric circuits. The stator, the stationary part on the outside of the motor, is connected to the three-phase AC input voltage. On the inside of the motor is the rotating circuit, known as the rotor, which is used to drive applications [28]. Figure 8 illustrates the two parts of the motor, namely, the stator and rotor.

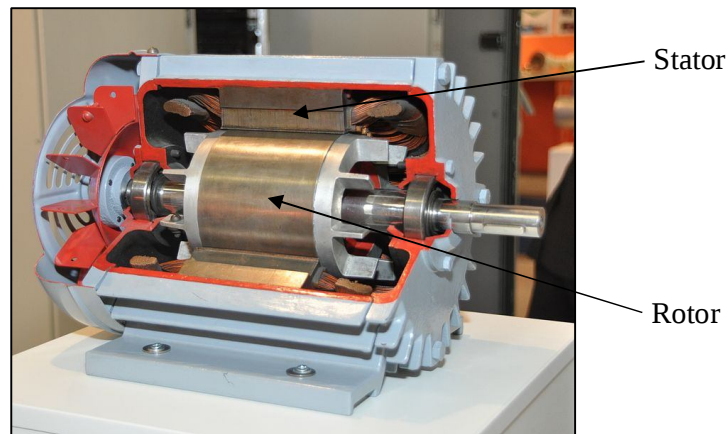


Figure 8: Cutaway view through the stator of an induction motor⁴

Induction motor

Nored et al. state, “An induction motor works by inducing current in the rotor through the small air gap between the stator and motor.” The interaction between the induced rotor current and the rotating magnetic field generates a torque on the rotor, forcing the shaft to turn [28].

Induction motors have the advantage of being self-regulated and have high starting torque. Under no-load conditions, the rotor speed will slightly lag the synchronous speed, which defines the slip of the motor. As the motor is loaded, the difference between the rotor and synchronous speed will increase, which also increases the percentage of slip, decreasing the efficiency of the motor [28].

⁴ Picture courtesy of http://en.wikipedia.org/wiki/File:Rotterdam_Ahoy_Europort_2011_%2814%29.JPG

An induction motor draws five to eight times the normal current during start-up. Repeated starts within a small time span will cause the winding temperature to increase rapidly. It also causes weakening effects of expansion and contraction of the insulation system. When the insulation system loses physical integrity, it fails to resist other dielectric, mechanical and environmental stresses [29].

The force on the coils of an induction motor (due to the stator winding current) is at maximum during the starting cycle. The force causes the coils to vibrate at twice the line frequency with movement in both the radial and tangential directions. The movement can cause damage to the coil insulation and copper conductors [29]. It is, therefore, evident that induction motors should not be stopped and started frequently.

Synchronous motor

A synchronous motor's rotor is primarily a single winding with the same number of magnetic poles as the stator. The rotor rotates in synchronism with the stator's magnetic field. Due to the synchronism between the rotor and stator, the motor has no slip.

Synchronous motors have the ability to control the power factor actively and has less in-rush current than inductive motors, but they have limited starting torque [28]. Synchronous motors are the preferred choice for large applications due to their high inherent efficiency and their simple and robust construction [30]. However, a synchronous motor cannot start directly from the AC power line. Thus, a separate starter winding is used to start the motor. This is essentially the same as starting an inductive motor [28].

An across-the-line starter is usually used to start the motor, applying the full line voltage (also known as full load voltage) to the motor terminals [31]. Smaller size across-the-line starters can be operated manually while larger starters use electromechanical contactors, also known as relays [32].

Starting a motor across the line will cause an increase of up to 500–700% of full load current drawn [28], as can be seen in Figure 9. Not only does this put strain on the starter itself, but energy is also converted into heat in the rotor [30]. Therefore, large compressors that use large synchronous motors (such as those on gold mines) cannot be stopped and started on a frequent basis. Both synchronous motors and inductive motors need time to cool down and to return to their original starting conditions before they can be started again.

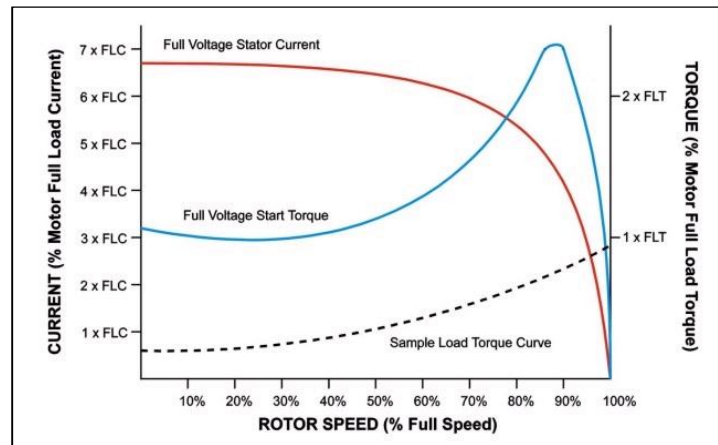


Figure 9: Starting current versus torque of a motor [33]

2.2.3) Compressed air requirements

Technical and complex start-up conditions are not the only reasons why compressors are used throughout the day without being stopped frequently. Compressed air is used throughout the day for various applications on a mine.

The highest volume of compressed air is used between 06:00 and 14:00, which is called the drilling shift. The different shifts on a mine are displayed in Figure 10. Explosives are inserted into the mine after the drilling shift and blasted at around 16:30. No mine personnel are allowed underground after blasting has taken place until approximately 21:00 when miners re-enter the mine.

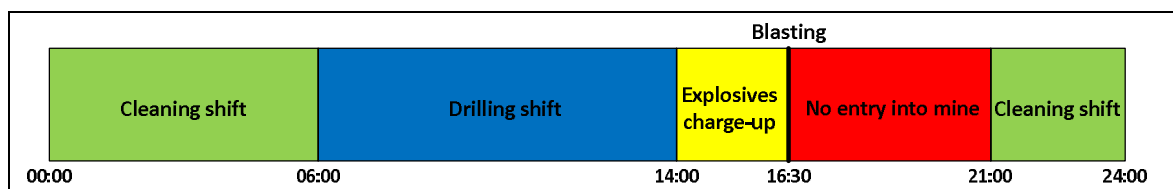


Figure 10: Mine schedule [34]

This no-entry period aligns with Eskom's peak time energy period when electricity is most expensive for customers who use the Eskom Megaflex tariff structure. This phenomenon makes it possible to implement DSM peak clipping projects during this period, which not only reduces Eskom's electricity load, but also brings the highest amount of financial savings for the mine.

Various high compressed air consuming applications are used during the different shifts [35]. These are discussed in the sections that follow.

Rock drills

Rock drills are the primary air users during the drilling shift in mines. Although rock drills can be hydraulic, electric or pneumatic, pneumatic rock drill are mostly preferred in the mining industry. Rock drills typically require an air pressure of 600 kPa [36]. Figure 11 shows an example of a pneumatic rock drill.



Figure 11: Example of a pneumatic rock drill⁵

Loading boxes

Loading boxes are used to unload ore into carts by means of a latch. The latch uses pneumatic cylinders to open and close. In case of a pressure drop, the latch will open and the load will be dropped. Compressed air is needed to close the latch and to keep it in the closed position [35]. Figure 12 shows how a pneumatic cylinder is used to keep a loading box closed.

Loading boxes are used during the cleaning and drilling shifts. This should be taken into consideration during the design of a compressed air energy savings project where the compressed air pressure will be reduced.

⁵ Picture courtesy of <http://www.tradekorea.com>



Figure 12: Example of a pneumatic cylinder used to open and close a loading box[37]

Agitation

In order to prevent sediment from forming in water dams, compressed air is used to agitate the dam continuously. Agitation systems usually consist of open-ended tubes in the bottom of the dam through which compressed air flows to prevent the sediment from forming [38]. Since this process is done throughout the day, it requires sufficient compressed air continuously.

Mechanical ore loaders

Mechanical ore loaders are used to load ore into the loading boxes or onto conveyors. They require a constant supply of approximately 350 m³/h of compressed air to operate sufficiently. These machines are designed to operate at an air pressure range of 483–860 kPa [39]. Figure 13 illustrates a typical mechanical ore loader. These machines are used during the cleaning and drilling shifts.



Figure 13: Example of a mechanical ore loader⁶

Diamond drills

Diamond drills are mainly used for development drilling. A diamond drill consumes approximately 500 m³/h of compressed air and is used throughout the day [38]. This should be taken into consideration when reducing a mine's compressed air pressure during certain periods. Figure 14 shows an example of a miner using a diamond drill.



Figure 14: Miner using a diamond drill⁷

⁶ Picture courtesy of <http://www.tridentsa.co.za>

⁷ Picture courtesy of <http://financialpress.com>

Refuge bays

Refuge bays typically require compressed air at 200–300 kPa. Since flow always occurs from a high-pressure to a low-pressure area, harmful gases with lower pressures will not be able to enter the pressurised bay. The required volume flow is estimated at 85 ℓ/min for every person occupying the refuge bay [40]. Figure 15 shows an example of an underground refuge bay.



Figure 15: Underground refuge bay [37]

2.3) Compressed air networks on deep-level mines

A compressed air network can be defined as a network that provides and delivers compressed air to either one shaft or to multiple interconnected shafts. There are two types of compressed air network [35]:

- stand-alone system; and
- ring-feed system.

2.3.1) Stand-alone system

A stand-alone system comprises one or more compressors that are connected together and supply compressed air to a single delivery point. In the mining industry, compressors are typically situated in a compressor house and supply compressed air either to a single shaft or to a shaft and a gold plant. Figure 16 shows the layout of a typical stand-alone compressor system.

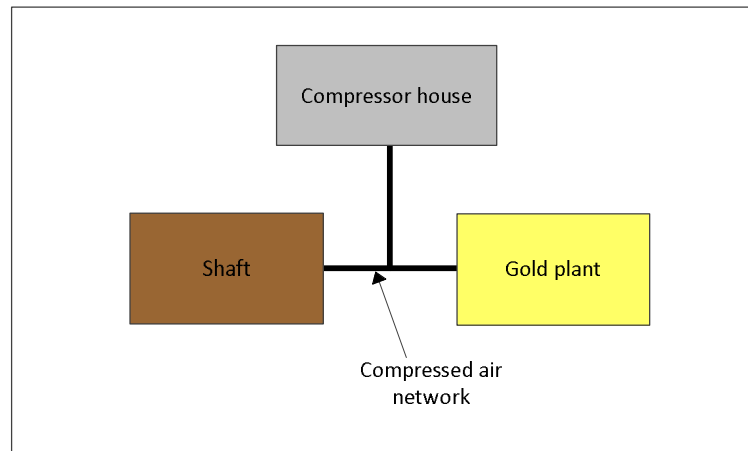


Figure 16: Typical layout of a stand-alone compressor system

This system has a fairly predictable nature and changes occur more rapidly due to the smaller volume of the system compared with a ring-feed system. Due to the simplicity of a stand-alone system, maintenance and leak detection are easier than on a ring-feed system [35].

2.3.2) *Ring-feed system*

In a ring-feed system, various compressors situated on different sites are all interconnected and supply compressed air to various shafts connected to the network. Various compressor houses contribute to delivering compressed air to the grid, providing sufficient air to all of the connected shafts. Figure 17 shows a typical ring-feed compressor system.

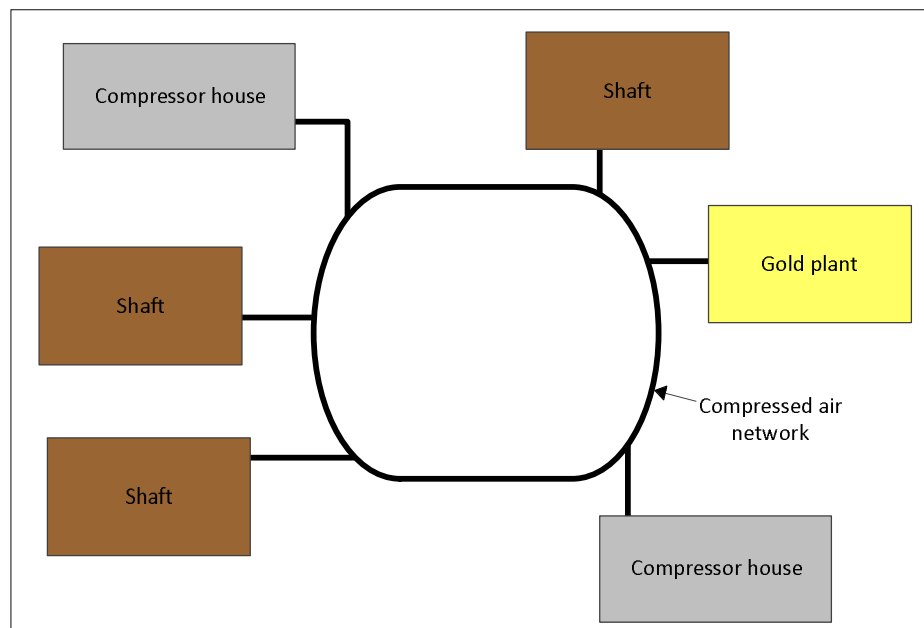


Figure 17: Typical layout of a ring-feed compressor system

Changes in the system are experienced with a delay in time due to the higher volume of compressed air circulating through the system. Maintenance and leak detection on the system are more difficult due to the time delay in the system [35].

The advantages of a ring-feed system are as follows [35]:

- A shaft is able to draw extra compressed air from other shafts if its own compressors are unable to supply sufficient air.
- Compressors are not needed on all shafts if the compressed air ring has enough capacity to supply all of the shafts.
- When maintenance needs to be done on a specific shaft's compressors, other compressors can provide compressed air to that specific shaft.

The disadvantages of the system are as follows [35]:

- High flow resistance in such a system will possibly cause pressure drops, depending on the status of the pipes and the flow velocity through the pipes.
- Due to the complexity and size of a ring-feed system, many leaks can occur and can be difficult to detect and fix.
- Large air leaks and ineffective air usage on a single shaft can reduce the overall pressure of the system, thus impacting other shafts.

2.4) Problems associated with mine compressed air systems

One of the largest sources of wasted energy in a compressed air system is leaks. Up to 20–30% of a compressor's output can be wasted on air leaks. A typical plant, where the compressed air is not well maintained, will likely have a leak rate equal to 20% of the total compressed air production capacity. Proactive leak detection and repair can reduce the number of leaks to less than 10% [41]. The most common areas where leaks occur are [42]:

- Damaged hoses, couplings, tubes and fittings;
- Open ends and shut-off valves; and
- Pipe joints and thread sealants.

Compressed air is also used for other non-productive purposes such as ventilation and cooling. Mine personnel tend to improvise when bulk air coolers, which are used to cool air in a mine, are broken or are switched off. Through personal experience, it was found that mine personnel use

compressed air to cool underground workstations during such times. Due to the size and complexity of a mine, it is not always possible to monitor this kind of compressed air wasting.

Not only does compressed air leaks and waste account for energy losses, they also contribute to other operating losses. They cause a pressure drop in the system, which means that pneumatic equipment will lose efficiency. Equipment with a lower efficiency will reduce production [42].

Operating at an elevated system pressure also increases the air consumption of end users, the rate of leaks and the overall energy consumption. By stopping and starting equipment more frequently, leaks will indirectly also decrease the lifespan of machinery [42]. Frequent starting and stopping is commonly known as cycling within the mining industry.

Compressed air leaks and waste can also contribute to problems with systems operations (including fluctuating system pressures) as well as the need for additional compressor capacity. Additional compressor capacity will lead to higher capital costs [43]. An increase in running time will also increase scheduled maintenance and unscheduled downtime.

Proper maintenance control can be implemented by constantly tracking power, pressure, flow and temperature readings. Compressor efficiency is degrading when power increases at constant pressure and flow rates [44]. In recent years, attempts have been made to reduce compressor costs by minimising the cost of installation at the expense of increased operating costs. In many cases, the operating cost of a compressor can exceed the initial equipment cost five times over its lifetime [19].

Industrial compressed air systems require periodic scheduled maintenance. This is needed to maintain peak efficiency and to minimise unscheduled downtime. Maintenance has a great impact on energy consumption through lower compressor efficiency and air leaks. Inadequate maintenance leads to high system temperatures, poor moisture control and excessive contamination if equipment is exposed to wet compressed air [44].

Figure 18 shows the cross section of a blade of a single-stage centrifugal compressor that was installed on the front section of an aircraft. This is the same type of compressor typically used on mines. The compressor failed during operation. Multiple fatigue cracks were generated during service. When they grew to a critical size under high cycle fatigue, the blade detached and collided with other rotating parts of the engine. The cracks can be seen in Figure 18(a) and Figure 18(b). It was found that the cracks followed the grain of the material. A chain of cavities is also shown in Figure 18(c) and Figure 18(d) [45].

During macro examination, it was found that damage was caused on the blades as well as on the shaft bearings. Further damage such as rubbing of the inductor and rotor, misalignment of the bearings and consequent jamming of the engine ensued [45].

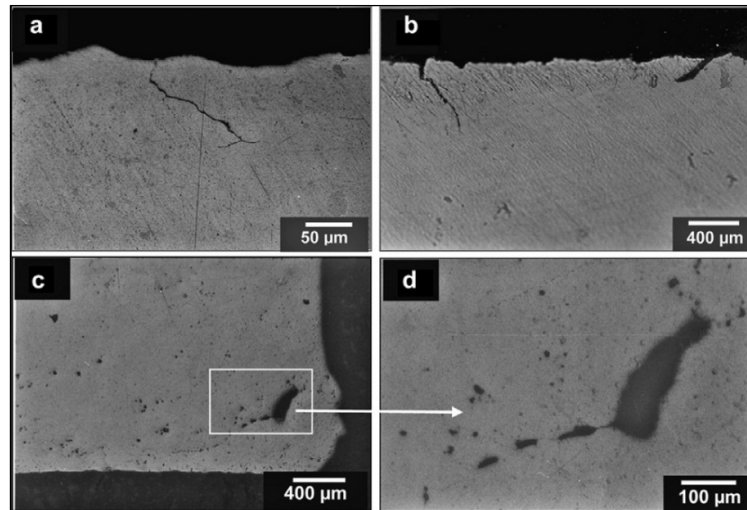


Figure 18: Example of a damaged blade of a single-stage centrifugal compressor
(a, b) Cracks in cross section of compressor blade, (c) chain of cavities in root of blade, (d) boxed region in (c) at high magnification [45]

Figure 19 shows an example of a damaged centrifugal compressor. Damage reduces the efficiency of the machine, causing it to consume more energy to produce the same amount of compressed air.

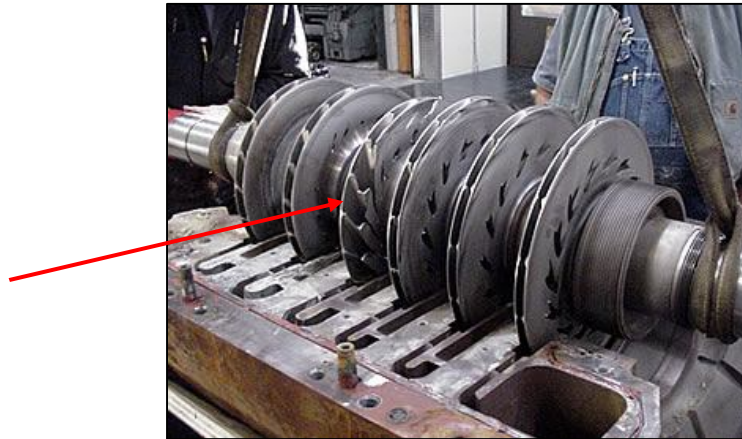


Figure 19: Example of a damaged centrifugal compressor⁸

Not only should individual components be addressed, but the supply and demand sides of a system should also be analysed when maintaining and improving a system. This is referred to as taking a system approach, since the total system performance is more important than the individual components. Analysing should be done especially during peak demand periods [43].

⁸ Picture courtesy of http://www.glmcorp.com/compressors_repair.html

Although mines aim to follow a constant daily schedule, it is not always that simple when there are production targets that have to be achieved. Mines aim to reach a target amount of gold produced for each day. This can lead to prolonged shifts if the target is not met.

Production time can also be lost due to unforeseen circumstances. Although mining companies strive to deliver 'safe gold', accidents still regularly occur underground. Such incidents force production to be halted while an investigation is done to determine the cause of the accident [46]. By establishing the cause, mining companies can implement new measures or change current measures to try to minimise future accidents.

Another factor that can cause a loss in production time is industrial action. Mines cannot always foresee when industrial action will take place, nor do they know how long it will last. Not only does industrial action affect the mine itself, but it also affects the economy of the country [47]. When production time is lost, extra daily shifts have to be implemented to try to recover production targets.

Although it would not be possible to consider all varying conditions when implementing an energy savings project, consideration needs to be given to the fact that mine schedule changes could possibly occur.

2.5) Existing energy savings measures

This section provides information regarding the various control strategies for energy savings projects on compressed air systems. Many of these strategies have already been implemented on numerous projects. The optimised control of compressed air systems can be divided into two groups, namely, supply side control and demand side control.

2.5.1) Supply side control

Supply side control focuses on optimising the amount of compressed air generated and delivered. Although there are various control strategies that can be used to perform supply side control, this paper will focus on the three most commonly used strategies, namely [48]:

- compressor selection;
- load sharing; and
- guide vane control.

Compressor selection

Compressor selection focuses on running the most efficient compressors more frequently. Since compressors that are more efficient use less electricity than compressors that are less efficient, energy savings can be achieved in this manner.

From personal experience, it was noted that less efficient compressors should also be operated from time-to-time. If the most efficient compressors are used all of the time, their efficiencies would decrease up to a point where all of the compressors would become equally inefficient.

Load sharing

Due to the complexity of large mining systems, the size and number of compressors will differ. The layout and the number of end users will also change frequently. All of these factors and constant changes will cause the compressors to operate ineffectively. A method called load sharing can be used to prevent this ineffectiveness. Load sharing focuses on sharing the load equally between all of the compressors.

Different methods to load share are [48]:

- using variable speed drives (VSDs); and
- managing intake volume of compressors by using a suction valve and guide vane control.

Variable speed drives

Centrifugal compressors operate at the discharge pressure that the system imposes on it. Basic regulation uses constant speed while regulating the discharge pressure to meet the demand. A reduction in power usage is induced by a reduction in flow. This is due to the fact that less compressed air need to be supplied at a lower flow [49].

Speed reduction, as in the case with a VSD, will reduce the compressor's capability to generate a pressure increase. A centrifugal compressor's operational range through speed variation is therefore limited. However, savings are still achievable since the need for power increases with the cube of the speed of the compressor. A small increase in speed requires a great deal more power. On the contrary, a modest speed reduction can produce significant energy savings [50].

VSD control on compressors is, however, a relatively new application. Many users favour traditional control methods since they are easy to implement and straightforward to understand.

VSD technology is also very expensive when compared with traditional control methods such as inlet guide vane control [50].

Inlet guide vane control

Inlet guide vanes are used to control the mass flow of air through a compressor. They are usually mounted on the compressor's first-stage inlet, but they can also be installed on each of the other stages in the case of a larger unit. When using inlet guide vanes to throttle the flow, the vanes shift from being parallel to the air to being fully perpendicular. This reduces the work required to produce the same air discharge condition. This results in lower airflow and a reduction in input power [49].

A control system is typically used with inlet guide vane control to maintain the flow capacity and to operate within the power limits. One such an inlet guide vane controller is a Moore controller. Generally, a controller enables an operator to construct a 24-hour pressure profile. A Moore controller controls the inlet guide vanes to deliver the required compressed air profile [51].

The amount of reduction in flow rate is limited by the minimum point flow reversal, also known as surge. Compressors are either unloaded or they blow off excess air into the atmosphere to avoid surge. Surge results in excessive vibration that can cause damage to a compressor. Since the mines use high-speed rotating machines, vibrations should be closely monitored to not only ensure the safety of the equipment, but also the safety of the personnel nearby [26], [52].

2.5.2) Demand side control

Demand side control is based on reducing the air demand in a network. By reducing the air demand, less compressed air needs to be generated. Inlet guide vanes can then be used to reduce the amount of compressed air generated, thus reducing the amount of electricity consumed by the compressors.

Demand side control can be divided into two main categories [48]:

- surface control; and
- underground control.

Surface control

Surface control valves are most commonly used on ring-feed networks. These networks consist of various shafts with different compressed air demands. The pressure of the ring-feed system is determined by the shaft with the highest pressure demand [53].

Surface valves are used to provide each of the shafts with the desired pressure, thus minimising compressed air losses. Figure 20 shows a surface control valve being used on a deep-level mine. As previously mentioned, an excess of compressed air in shafts will only lead to more compressed air being wasted.



Figure 20: Example of a surface control valve⁹

Underground control

While surface valves are used to control the demand of a shaft's total compressed air usage, underground valves are used to control the pressures of the various mining levels independently. Therefore, underground valves are used more commonly on shafts in stand-alone compressor systems.

By controlling each level individually, different levels can have different compressed air pressures. If needed, control at a specific levels can be fully disabled to provide maximum air on those levels while still reducing the demand on the other levels.

⁹ Photo courtesy of HVAC International personnel

Autocompression arises in mines due to the variation in depth. The compressed air pressure on the underground mining levels will be higher than the supplied pressure on surface. The relationship between pressure and depth is calculated as follows [54]:

$$p = p_0 + \rho gh \quad (1)$$

Where:

p	–	unknown pressure	kPa
p_0	–	known pressure at a specific height	kPa
ρ	–	density of the air	kg/m ³
g	–	gravitational acceleration	m/s ²
h	–	difference in height	m

Autocompression will increase the pressure of an air column in a mineshaft by approximately 11% for each 1 000 m of depth [38]. However, the diameter of the air column in the mineshaft is also critical to autocompression. If the diameter is too small for the mass flow required, the beneficial effect of autocompression will be lost because of the extra friction losses that occur at the higher velocity [55].

The effective loss of autocompression can be reduced by increasing the inside diameter of the main air pipeline. A larger pipe will allow for a larger mass airflow at a lower velocity. The drawback of this solution is the greater costs involved – a larger pipe would be more expensive to install and maintain [55].

Control valves

A control valve is a normal valve that is fitted with an actuator. The actuator can be controlled using a supervisory control and data acquisition (SCADA) system that is connected through a programmable logic controller (PLC) [53].

When the valve in the main line is closed, an actuator with a positioner is used to control the bypass valve to deliver the desired amount of compressed air. Two pressure transmitters, the upstream and downstream pressure transmitters, are used to monitor the compressed air pressure on both sides of the control valve. Figure 21 shows an example of this configuration.



A	Downstream pressure transmitter
B	Main line butterfly valve
C	Main line actuator
D	Bypass globe valve
E	Bypass actuator with positioner

Figure 21: Example of an underground control valve

Butterfly valves are usually used as main isolation valves since they are cheaper than most other valves. A smaller globe valve is used as the control valve. Globe valves are used for control since the flow curves of globe valves tend to be more linear, thus making control easier and more accurate. Since a smaller globe valve is used as a bypass valve, a smaller actuator is also used thus reducing the cost of infrastructure.

It is, however, important to establish the correct size of the reduced bypass valve to ensure it will deliver the required amount of compressed air. The pressure of the control valve is controlled according to Bernoulli's theorem. The theorem states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure [56]. Bernoulli's theorem, at any arbitrary point along a streamline, is mathematically shown as follows:

$$\frac{1}{2}\rho v^2 + \rho gh + p = \text{constant} \quad (2)$$

Where:

ρ	–	density of the fluid	kg/m ³
v	–	fluid velocity	m/s
g	–	gravitational acceleration	m/s ²
h	–	height above a reference point	m
p	–	pressure at the point	kPa

The pressure is thus dependent on the velocity, density and height of the fluid. Equation (3) illustrates that velocity is dependent on area and volume flow.

$$Q = Av \quad (3)$$

Where:

Q	–	volume flow	m ³ /s
A	–	area	m ²
v	–	fluid velocity	m/s

It is, therefore, evident that the diameter of the pipe and the opening of the valve will have an effect on the airflow velocity. A smaller valve opening will cause an increase in velocity in an attempt to keep the mass flow constant. According to the law of energy conservation, the mass flow of a system must remain constant [57].

2.6) Conclusion

This chapter examined the importance of compressed air on gold mines. It focused on different types of compressor, especially centrifugal compressors, which are commonly used on gold mines. Attention was given to the various motors used to drive compressors. It was noted that compressors are unable to stop and start frequently due to the starting current of a synchronous motor being five to seven times greater than the operating current. The starting current produces a significant amount of heat during the start-up of a motor. Different applications for compressed air on mines were also examined.

Thereafter, different compressed air networks were discussed. The importance of maintenance and the managing and repair of compressed air leaks were also discussed. It was found that compressed air is not only wasted through leaks, but that it is also wasted by mine personnel who uses compressed air for alternative purposes such as ventilation.

It was found that energy savings could be produced by reducing the demand and supply of compressed air on mines. Various methods have been identified to reduce the compressed air supply. Special attention was given to inlet guide vane control. It was found that the demand side could also be reduced by using surface and underground control valves. Globe control valves were found to be better control valves than butterfly valves. This is due to globe valves having a more linear flow curve, thus they can be controlled more accurately.

Chapter 3 will focus on the design and implementation of a compressed air savings project. Practical problems associated with the implementation of the project will be discussed.

Chapter 3: Addressing practical challenges during the implementation of a compressed air project



10

The chapter focuses on the investigation and simulation of a potential compressed air energy savings project. Challenges associated with the implementation of such a project are also discussed.

¹⁰ Picture courtesy of <http://digiday.com/publishers/bloomberg-justin-smith-modern-media/>

3.1) Introduction

The previous chapter discussed various types and applications of compressors on gold mines. It was found that compressed air is a necessity on gold mines. This chapter focuses on the investigation and implementation of a compressed air energy savings project on a gold mine.

Inlet guide vane control is used to lower the volume of compressed air delivered by the compressors. Control valves are implemented to reduce the amount of compressed air used on the mining levels, thus reducing the demand on the compressed air network. A reduction in compressed air on both the supply and demand sides of the network leads to a reduction in power usage of the compressors.

A reduction in power consumption does not only induce financial savings for the mine itself, but it also reduces the high electricity demand on the national electricity grid. While electricity reserve capacity is kept at 15% internationally, Eskom's reserve capacity has been reduced to 8%. This is insufficient for reliable supply [58].

Background on the mine that is used as the case study is discussed in Section 3.2. This includes the layout of the mine and installed equipment. Equipment communication is also discussed along with the existing compressed air control strategy.

In Section 3.3, an investigation is done to determine the potential of optimising a compressed air network. An improved control strategy is identified. Simulations are done to determine the feasibility of the savings project. A baseline is also established. The baseline is used for simulations and for determining the actual savings after the implementation of the project.

Finally, various constraints identified during the investigation and implementation of the project are discussed in Section 3.4. These constraints include, among others, installation delays and control limitations.

3.2) Background information

The South African gold mine on which the case study is done will be referred to as Mine A due to a confidentiality agreement.

The compressed air of Mine A is obtained from a stand-alone compressed air system. Five Sulzer compressors are situated within a compressor house. The five compressors supply compressed air to both the shaft and the gold plant. Moore controllers are used to control the

discharge pressure of the compressors. This is done with proportional-integral-derivative (PID) control within the PLC. All of the compressors are connected by means of a common manifold from where the compressed air flows to the gold plant and shaft. The discharge pressure set points of the compressors are generally maintained at 450 kPa with minimal change taking place. The compressors are manually stopped and started by mine personnel. Minimum monitoring equipment is installed on the compressors. Table 3 shows the installed capacity and flow rates of the compressors.

Table 3: Installed capacity and flow rates of compressors on Mine A

Compressor	Installed capacity [kW]	Flow rate [m³/h]
1	4 800	50 970
2	4 800	50 970
3	2 000	21 237
4	4 800	50 970
5	4 800	50 970
Total	21 200	225 117

Mine A consists of a main shaft and a subshaft. The subshaft starts at Level 76. The underground compressed air network consists of a 700 mm pipeline situated vertically within both the main- and subshafts. Figure 22 displays the compressed air layout of the mine along with the existing infrastructure. The mine has eight active production levels from where ore is extracted. These levels are as follows:

- Level 88;
- Level 92;
- Level 95;
- Level 98;
- Level 102;
- Level 105;
- Level 109; and
- Level 113.

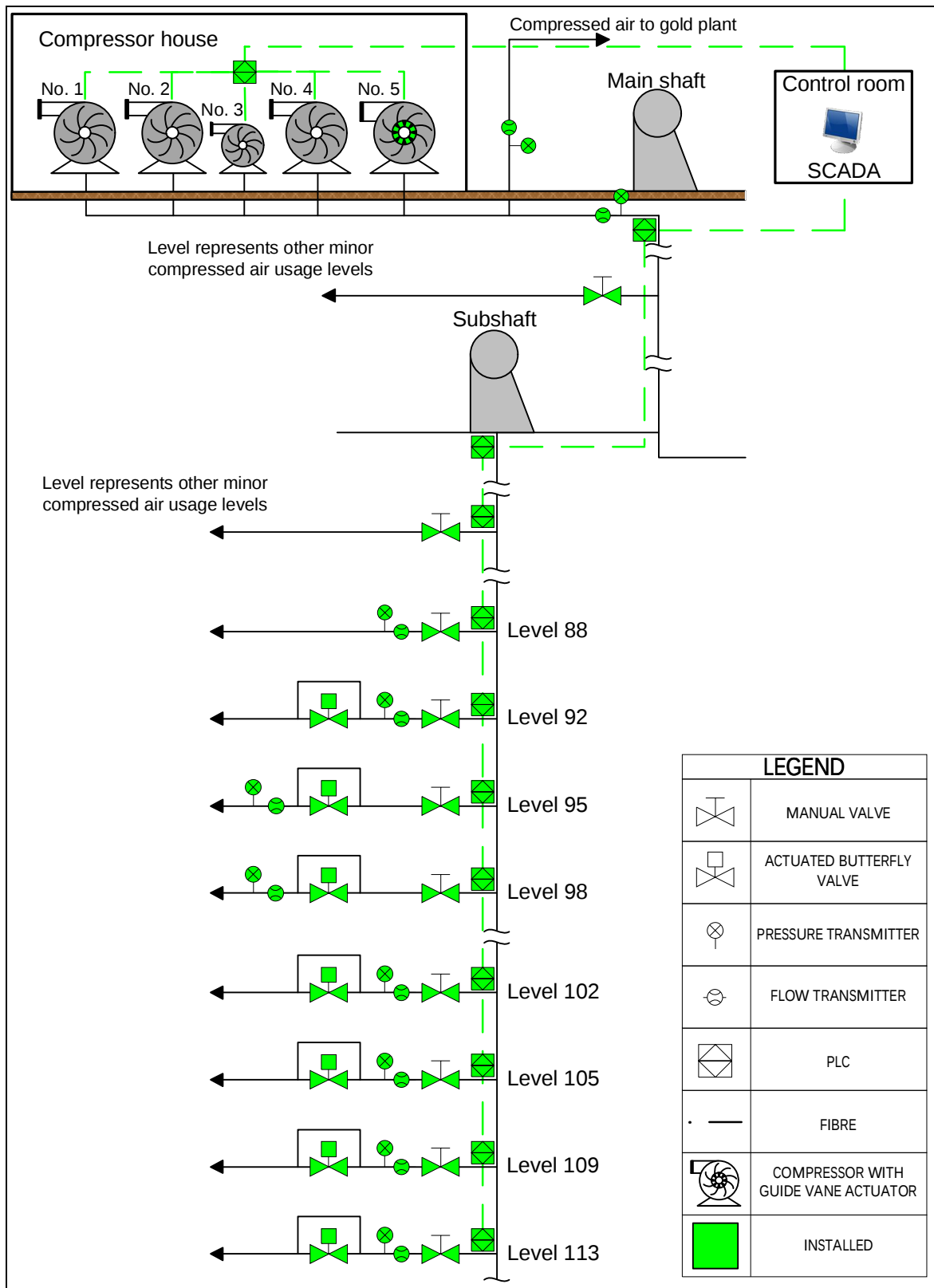


Figure 22: Compressed air layout and existing infrastructure

Level 88 has a 450 mm compressed air pipeline, whereas the remaining seven levels all have 350 mm compressed air pipelines. Manual shut-off valves are installed on all mining levels. These valves are mainly used when maintenance is needed on the compressed air pipelines.

Actuated butterfly valves are installed downstream of the manual valves on seven of the eight active production levels – Level 88 do not have a butterfly valve. The butterfly valves are operated from the SCADA on surface using the PLCs on the levels. Bypass pipelines are also installed in parallel with the actuated butterfly valves, as can be seen in Figure 23. This was previously implemented by the mine as part of an energy savings initiative.



Figure 23: Bypass pipeline in parallel with the main line valve¹¹

During periods when minimal compressed air was used, the butterfly valves were closed while only a limited amount of compressed air was delivered to the levels through the narrow bypass pipelines. The control was very limited since the amount of compressed air going into the levels could not be controlled accurately. Due to constant operational changes in the mine and limited flexibility of the control strategy, the initiative was deemed unsuccessful.

All eight of the active production levels are equipped with fibre optic cables. PLCs are also installed on all of these levels. Flow- and pressure transmitters are installed on the eight production levels to monitor the flow rates and pressures on the levels.

¹¹ Photo courtesy of HVAC International personnel

3.3) Project investigation

3.3.1) Existing operations

Blasting in the mine takes place at about 17:30 (Section 2.2). Mine personnel are only allowed to re-enter the mine at about 21:00. Due to the size and complexity of the mine, these times are just estimates. However, during this time compressed air is only used to pressurise refuge bays. Refuge bays require a pressure of 200–300 kPa at all times (Section 2.2).

The ‘no-entry’ period after blasting overlaps with Eskom’s peak period during which electricity prices and costs are at its highest. By controlling the amount of compressed air delivered to the various levels more accurately, the potential for an energy savings project arises. Therefore, an investigation was done to determine the feasibility of a DSM peak-clipping project.

The feasibility of a project is mainly determined by the payback period of a project. Figure 24 is used as an example to illustrate a typical payback period. For example, in Figure 24 payments were made in the first seven months for, amongst others, equipment and installation costs. When the project was completed, the project reduced the electricity cost of the mine on a monthly basis. This increased the cash flow of the mine (from August 2013 onwards as shown in Figure 24). The payback period is defined as the time required to recover the cost of the investment (installations and equipment), which is the breakeven point. Lengths of acceptable payback periods would vary as determined by the financial criteria used by the company.

Apart from the financial aspects of the project, the following need to be taken into account during the investigation of a compressed air energy savings project:

- layout and infrastructure of the mine;
- installed compressed air capacity;
- compressed air usage;
- mining shifts; and
- existing control strategy.

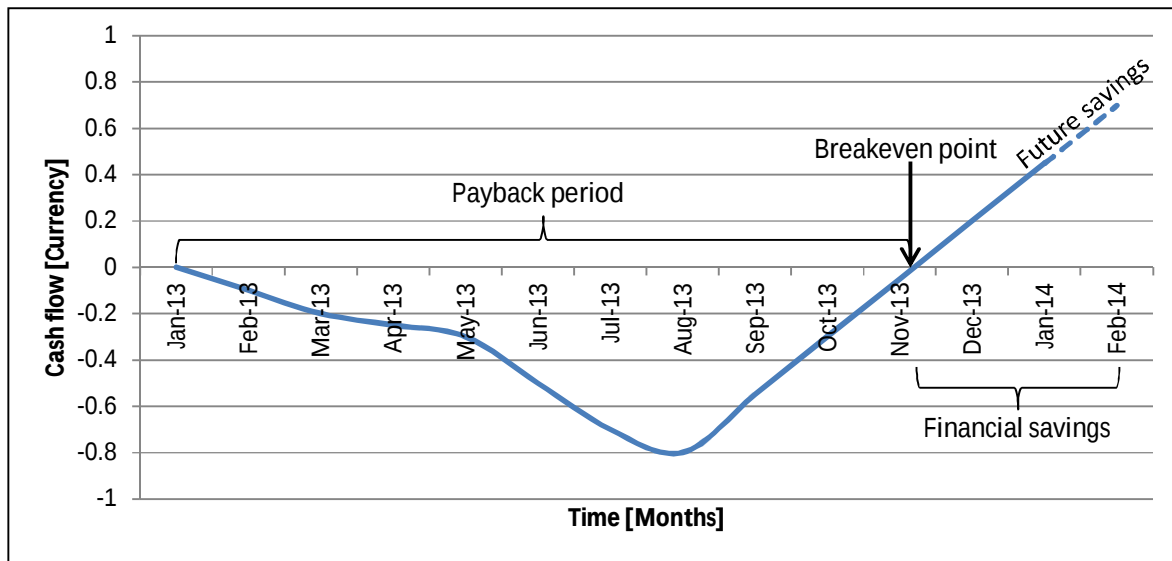


Figure 24: An illustration of a typical project payback period and cash flow

The layout, infrastructure and the installed compressed air capacity have already been discussed in the previous section.

When considering compressed air usage and existing control strategy, the gold plant required a minimum compressed air pressure of 400 kPa throughout the day. Although the gold plant had a stand-alone compressor, which was mainly used to power pneumatic equipment, compressed air received from the shaft was used for agitation purposes at the gold plant. As previously stated, the set points of the compressors were generally maintained at 450 kPa with minimal set point changes taking place.

During the project investigation, which was done by an independent investigation team, it was found that the compressed air consumption on all of the main shaft levels were minimal with no major air consumers. Level 76 to Level 85 on the subshaft also used minimal compressed air. It was found that Level 88 to Level 113 were, and still are, the major air-consuming levels. Level 100 and Level 115 were mining services levels where no production took place. Consequently, minimum compressed air was used on those two levels.

Only the major air-consuming levels were used for the investigation and implementation of the project. Since it was impossible to reduce the flow rate on levels that already use an insignificant amount of compressed air, energy savings was not be feasible on those levels.

3.3.2) *Proposed control*

As previously stated, the mine installed bypass pipelines in parallel with the existing actuated butterfly valves on seven of the eight mining levels. Since control was not possible using only bypass pipelines, it was proposed that control valves were to be installed on the bypass pipelines to control the compressed air more accurately on the various levels (Section 2.5).

Although butterfly valves were used in the main line on the levels, they would not be ideal control valves for the bypass pipelines. Significant pressure drops are likely to occur with a butterfly valve in a nearly closed position. This could cause erosion damage to the seat and disc of the valve (as can be seen in Figure 25) causing unwanted leaks when the valve is closed [59]. Butterfly valves are, therefore, more applicable to on/off applications.

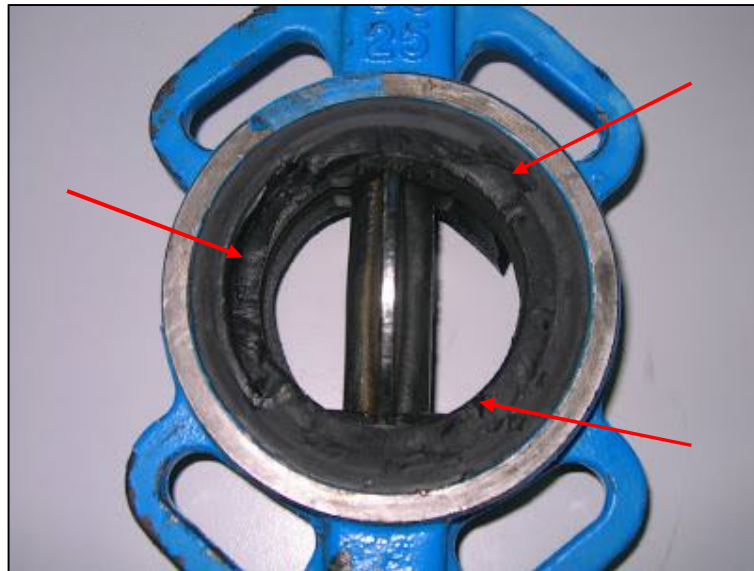


Figure 25: Example of butterfly valve with a damaged seat due to erosion¹²

Globe control valves are more applicable to applications that need accurate control. However, one of the major disadvantages of globe control valves is that they are very expensive. Quotations from various suppliers were received and analysed. Trends show that the estimated cost of a globe valve is R1 000 per 1 mm of inside diameter of pipeline where the valve needs to be installed.

A 350 mm globe control valve typically costs approximately R350 000 compared with a butterfly valve that costs about R30 000¹³.

¹² Picture courtesy of <http://chem-eng.blogspot.com/2007/02/butterfly-valve.html>

¹³ Based on prices obtained in December 2012

Since a reduced flow rate is required during the control period, a smaller bypass control valve can be used. The client requested that 50 mm control valves be used on all of the control levels. If all of the valves were the same size, the mine could stock a limited number of spare valves.

The mine had already installed an inlet guide vane actuator on Compressor 5. Two more were ordered, one for Compressor 1 and another one for Compressor 4. Inlet guide vanes are used to reduce the flow rate through a compressor, which in turn reduces the electricity usage of the compressor (Section 2.5). As part of the energy savings project, an inlet guide vane actuator had to be ordered for Compressor 2. Since Compressor 3 was only used to complement the four large compressors during the drilling shift, the installation of an actuator on Compressor 3 did not form part of the project scope.

Actuators, along with updates to the Moore controllers and PLC control were proposed for the optimisation of the compressors. Similar updates were also due for the SCADA system. Figure 26 shows the layout of the mine, along with the new infrastructure that was proposed to optimise the compressed air system.

3.3.3) Project simulation

To determine the feasibility of a project, a simulation model needs to be constructed to determine the mass flow of the compressors at the optimised pressure set point. This reduction in flow is used to determine the theoretical potential savings. However, a baseline needs to be established in order to create a simulation and do a comparison. The baseline is needed to determine the potential savings during the investigation of the project. It is also compared with the actual profile after the implementation of the project to determine the actual energy and financial savings of the project.

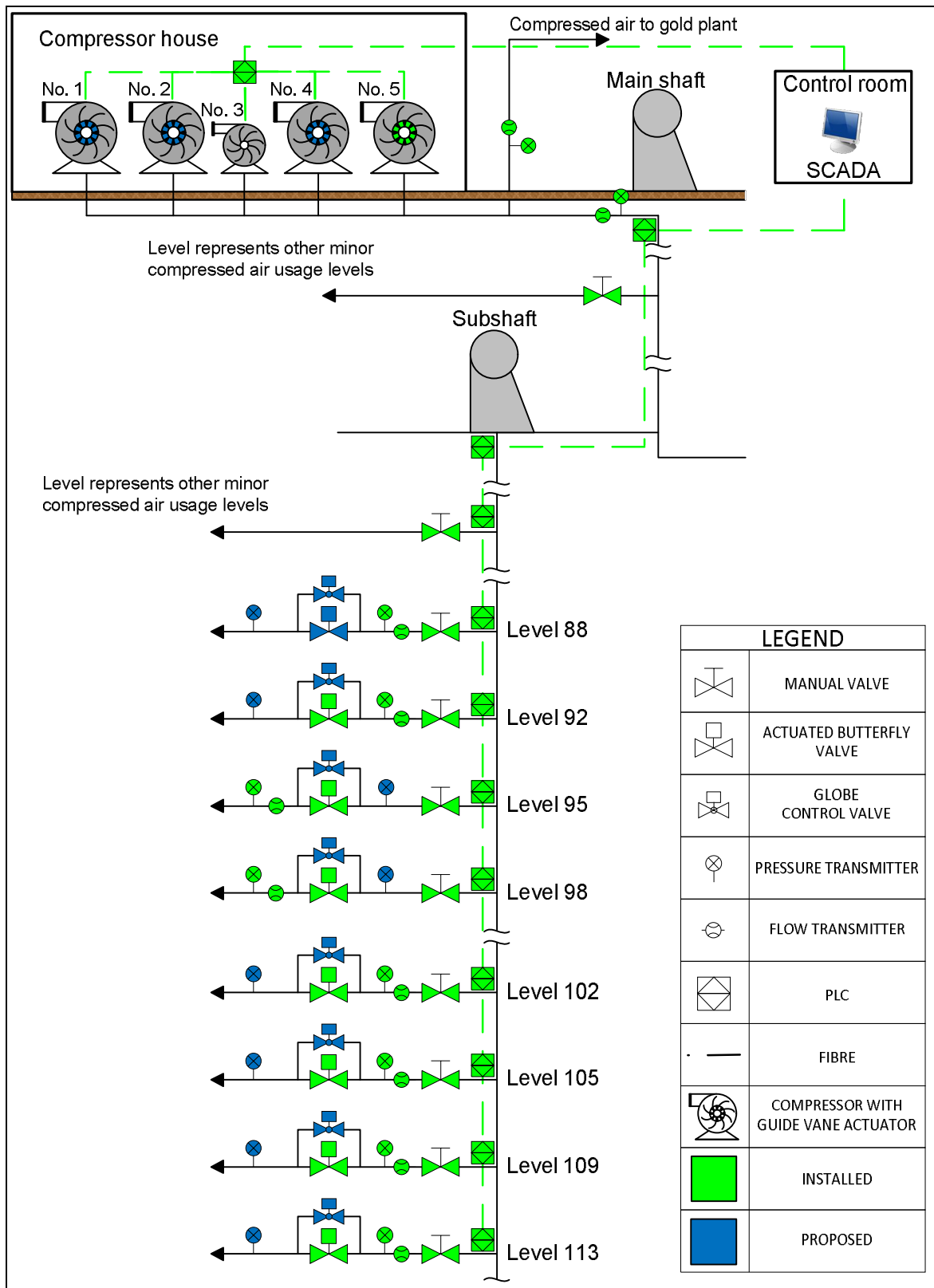


Figure 26: Compressed air layout with proposed infrastructure

The power usage of the five compressors is used to establish the baseline. The corresponding pressure and flow needs to be logged along with the power usage during the baseline period. The pressure and flow data are used when baseline adjustment needs to be implemented on a later stage of a project. Baseline adjustment needs to be implemented when any of the pre-implementation conditions are to change. Baseline adjustment is used to bring the two time periods, namely before and after implementation, under the same set of operational conditions [60].

The following assumptions were made when the baseline was established before the implementation of the compressed air energy savings project [61]:

- there would be no other energy interventions by the client;
- there would be no new compressors that could affect the current compressed air load; and
- all of the compressors would be working.

Baseline adjustment needed to be implemented when any of these assumptions were breached.

The baseline for the energy savings project was established by an independent investigation team. Figure 27 shows the combined power usage profile of the compressors, which was used as the baseline for the project. The power usage, pressure and flow data can be seen in Appendix A. It should be noted that Compressor 5 was out for maintenance during the time when the baseline was established.

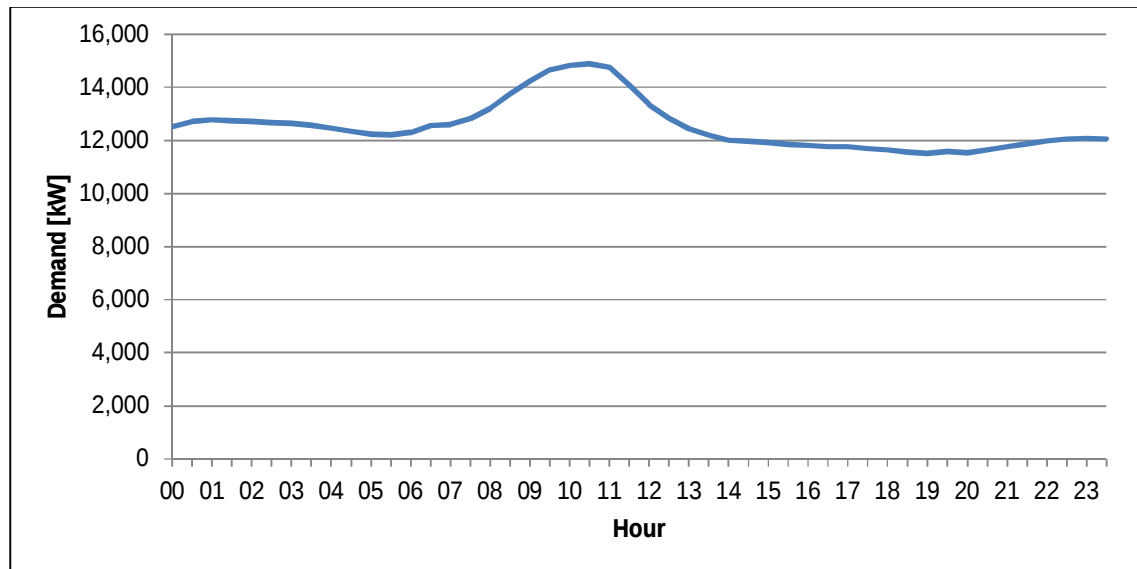


Figure 27: Project baseline

According to mine personnel, Compressor 5 was the baseload compressor which consumed an average of 3 300 kW power. The investigation team established a baseline by using the logged data of the four compressors, along with an extra 3 300 kW to compensate for Compressor 5.

It should be noted that the x-axis of Figure 27 ranges from 00 to 23 hours, instead of 1 to 24. Hour '00' represents the data between 00:00 and 00:59, hour '01' the data between 01:00 and 01:59 and so forth. This numbering will be used throughout the dissertation.

After the project baseline is established, a simulation has to be done. The simulation model determines the reduction in flow rate of the compressed air being delivered, which is used to calculate energy and financial savings.

One such a simulation package, which is used in industry to simulate various real-life operations, is KYPipe® [62]. KYPipe® can be used to simulate a variety of compressed air scenarios. However, before a simulation package can be used to determine the potential savings of a project, its accuracy needs to be verified. This was done using data from a previous project.

The project used a control valve to reduce the pressure on a mining level from approximately 500 kPa to 400 kPa. For the verification process, six random control periods were selected. KYPipe® was configured at the level's actual pressure with its corresponding flow for each scenario. The supply pressure of the simulation model was then reduced in accordance with the actual reduction that took place on that day. The actual flow during the control period was compared with the simulated flow.

An image of the simulation model can be seen in Appendix B. The results in Table 4 show an average difference of 2.6% between the actual and simulated reduced flow rate data. The accuracy of KYPipe® was, therefore, sufficient for the purpose of this study.

Table 4: KYPipe® verification data

Scenario	Actual flow [m³/h]	Simulated flow [m³/h]	Difference [%]
1	5 999	5 968	0.5%
2	5 690	5 725	-0.6%
3	6 213	6 058	2.6%
4	6 624	6 264	5.7%
5	5 709	5 602	1.9%
6	6 492	6 160	5.4%
		Average	2.6%

After verifying the accuracy of the simulation package, it was used to determine the mass flow rates of the compressors. The data and an image of the simulation model can be seen in Appendix B. The model comprised a compressor house, a gold plant, eight major air-consuming levels and a level representing all of the minor compressed air consuming levels. The model determined the total flow rate that had to be generated by the compressors at a specific pressure set point.

Using the simulation, it was found that the compressors had to deliver a combined volumetric flow rate of 80 137 m³/h when the combined discharge pressure was 400 kPa and the downstream pressures on the eight levels were reduced to 250 kPa. This was a reduction of 44 113 m³/h compared with the flow rate during normal operations. The detailed inputs and outputs of the simulation can be seen in Appendix B.

The reduced volumetric flow rate, which was converted to mass flow, was then used to calculate the electrical energy required by the compressors at those conditions. This was calculated using the following equation [63]:

$$W_e = \left[\dot{m} C_p T_{in} \left(\frac{P_{out}^{\left(\frac{k-1}{k}\right)}}{P_{in}} - 1 \right) \right] \frac{1}{\eta_c \eta_m} \quad (4)$$

Where:

W_e	–	electric power	kW
$\dot{m}$	–	mass flow of the air being compressed	kg/s
C_p	–	specific heat constant	kJ/kg·K
T_{in}	–	absolute inlet air temperature	K
P_{out}	–	absolute air pressure	kPa
k	–	polytrophic exponent	–
P_{in}	–	absolute inlet pressure	kPa
η_c	–	efficiency of the compressor	%
η_m	–	efficiency of the electric motor	%

The following assumptions were made during the electricity consumption simulation:

- The inlet pressure (P_{in}) of the compressor was atmospheric pressure (87 kPa absolute pressure);
- The outlet pressure (P_{out}) was the pressure supplied to the network;
- The mass flow ($\dot{m}$) that had to be supplied by the compressors was the sum of the mass flows required by all of the consumers;
- The total electricity consumed by the compressors were distributed proportionally between the compressors;
- The compressors were seen as a single compressor for simulation purposes; and
- The compressor and motor efficiencies were taken as 80% combined.

Figure 28 shows a comparison between the actual baseline and a calculated baseline that was constructed using Equation (4) at half-hour intervals. The calculated baseline was established using the pressure and flow data from the baseline period.

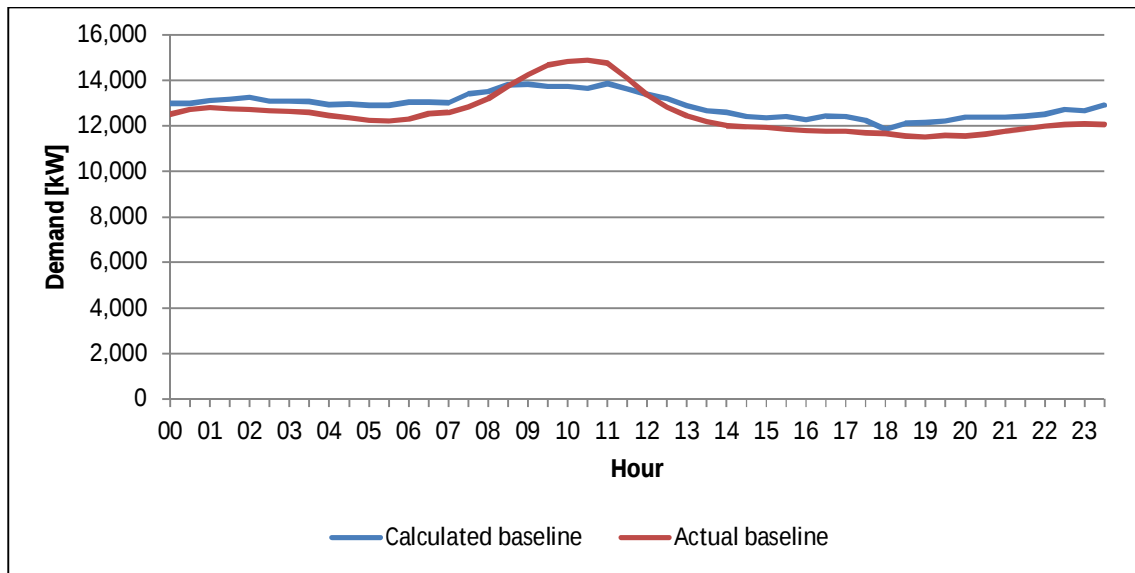


Figure 28: Comparison between actual baseline and theoretical baseline

An average difference of 2.97% between the two profiles showed that Equation (4) was sufficiently accurate. Using the equation, it was found that the compressed air energy savings project had the potential of achieving a peak clip of 3.5 MW between 18:00 and 20:00. Due to the size, complexity and unforeseen conditions of a mine's compressed air system, a safety factor of 20% was used for this project. This ultimately produced a peak clip target of 2.8 MW. Figure 29 shows the proposed savings profile along with the baseline profile.

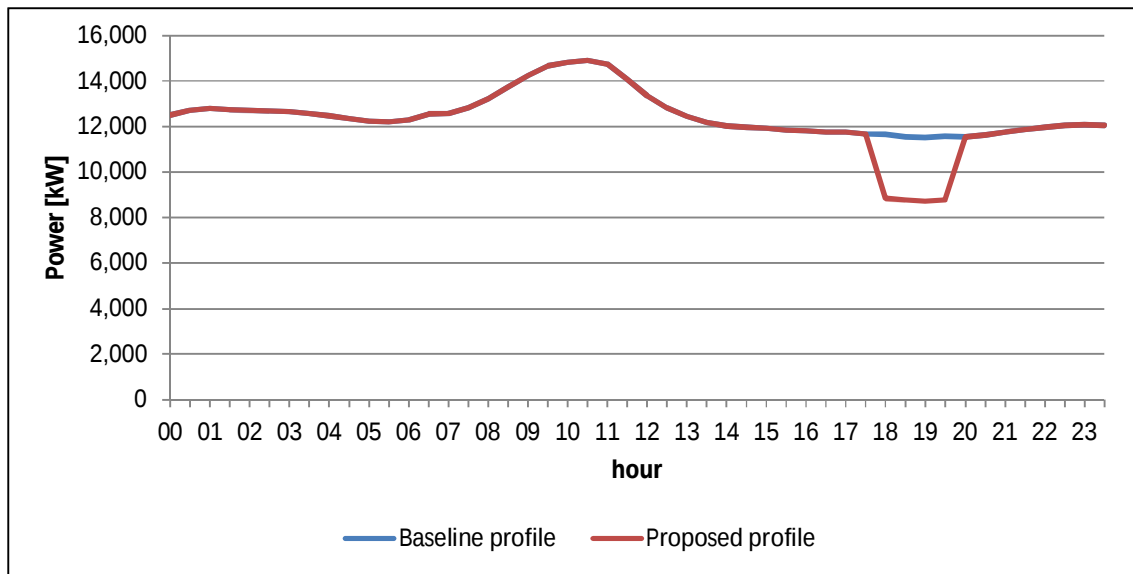


Figure 29: Project baseline versus proposed savings profile

3.4) Practical challenges

According to the PMBOK (as discussed in Section 1.4), one of the key aspects of implementing a project is risk management. Minimising project threats increases the chances of a project being delivered on time, on budget and with quality results. Practical challenges that had an effect on the compressed air energy savings project are now identified and discussed. Figure 30 illustrates the timeline of the various incidents that took place during the course of the project.

3.4.1) Installation delays

South African mines have faced numerous industrial actions during the last couple of years [64], [65]. Industrial action took place during the implementation of this compressed air energy savings project as well. Not only does industrial action account for financial losses, but it also affects basic mining operations.

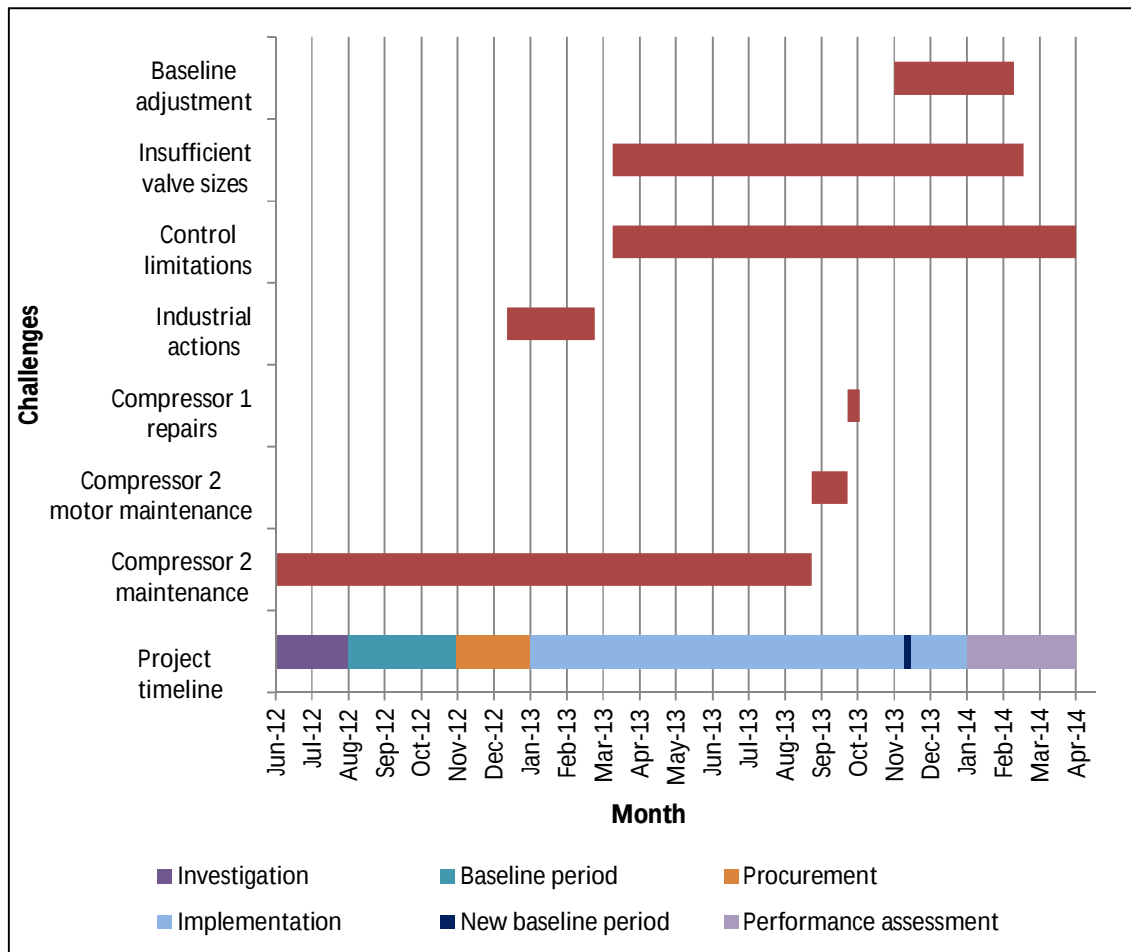


Figure 30: Project challenges timeline

When the mine reopened after the industrial action took place, personnel needed to go through health and safety induction while inspections were done on underground areas to ensure safety and operability. Employees were instructed to return to the mine in phases and over a period of time. The process from reopening a mine to returning to full production can take up to four and a half months [66].

Since people were not allowed to enter the mine premises during industrial action, the contractors' equipment installation schedule was changed forcefully. This was a concern for the project. Since contractors have projects at multiple sites, a change in schedule on one of the projects could possibly affect the contractor's schedule on other sites as well. Contractors with specialised skills, such as software specialists who are responsible for wiring PLC panels and coding PLCs, are only able to work at a single site at a time. Figure 31 shows the complexity of a PLC panel.

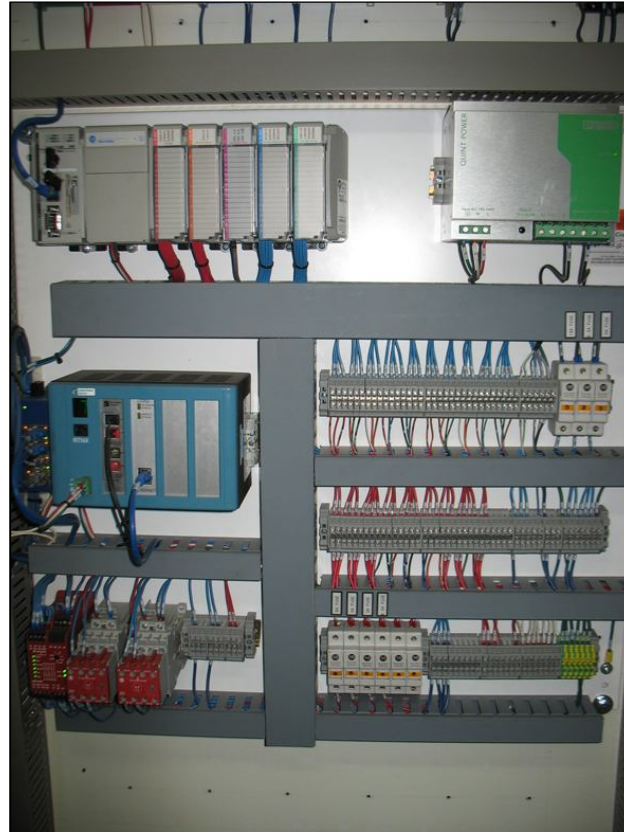


Figure 31: Example of a PLC panel¹⁴

The industrial action that took place, therefore, delayed the equipment installations of the compressed air energy savings project. As a result, the completion date of the project was delayed.

3.4.2) Control limitations

After discussions with mine personnel, it was found that mines tend to implement extra shifts after industrial action. This is done to compensate for production losses. Extra shifts include, among others, additional blasting and drilling shifts. This means that the normal daily schedule (as discussed in Section 2.2) is not followed, as it happened during the course of this project.

Thus, the problem arose that mine personnel needed to use drills and other types of pneumatic equipment during the evenings as well. Reducing the mine's compressed air pressure on all of the controllable levels was, therefore, not possible during the evenings.

¹⁴ Picture courtesy of <http://www.automation-drive.com>

Energy savings were mainly achieved on the demand side of the mine compressed air system. Since control valves operate independently on various mining levels, it was possible to reduce the compressed air pressure on some of the levels while disabling the control on the other levels.

Industrial action is not the only cause of additional mining shifts. Emergencies such as personnel injuries or fires within the mine also halt production. A decrease in equipment and mine personnel performance can cause production targets to be missed. When this happens, extra mining shifts are implemented that limit the extent to which the compressed air network can be controlled. Due to industrial action and emergencies, additional mining shifts were implemented on Mine A for several months.

Additional mining shifts were not the only problem that minimised savings on the demand side of the project. As part of the original project scope, bypass control valves were installed on all eight of the high compressed air usage levels, as already mentioned. During the commissioning of the control valves, it was found that the valves on Level 88 and Level 98 were unable to deliver the required amount of compressed air.

According to Bernoulli's theorem, which is stated in Equation (2) in Section 2.5, an increase in the speed of a fluid occurs simultaneously with a decrease in pressure. Due to the high compressed air flow rates on these levels, large pressure drops were induced over the small valves. This caused the downstream pressure after the valve to drop below the minimum pressure set point of 250 kPa. Improvements on these valve sizes will be discussed in Chapter 4.

3.4.3) Compressor operation and fatigue

During the original project investigation that was done by an independent investigation team, it was found that one of the four large compressors could be shut down during the control period. A combination of three large compressors and one small compressor would be able to supply sufficient compressed air while continuing to provide the required flow rate demand during the control period. This was due to the reduction in flow rate caused by the compressor discharge pressure reduction and by using control valves on the underground levels.

According to the simulations, the total flow rate demand would be reduced to 80 137 m³/h during the control period. Given the ratings of the compressors, which can be seen in Table 3 (Section 3.2), the combined flow rate achievable from three large and one small compressor was 174 147 m³/h. This was more than double the flow rate demanded during the control period.

As part of the energy savings project, a non-return valve had to be installed on one of the large compressors. The purpose of the non-return valve would have been to maintain the compression inside the compressor when it was stopped. Compression was needed inside the machine to ease the start-up process. However, as found in Section 2.4, scheduled maintenance is very important for all mining equipment to increase the lifespan and to ensure that equipment operate at their highest efficiencies.

Mine A sends one compressor away for maintenance each year. Due to the delayed installations caused by industrial action, the project installations and the maintenance of one compressor overlapped. Because the compressed air supplied by the remaining four compressors was barely sufficient, the mine was forced to use all four of the compressors continuously. It was found that the compressors were not able to deliver their rated flows. Therefore, another large compressor could not be shut down so that the non-return valve could be installed. This forced the project's completion date to be extended once again.

Only once the compressor was returned from maintenance after several months, was the motor also sent in for scheduled maintenance. Maintenance on the machine, therefore, took even longer than anticipated. The machine was only recommissioned after the return of both the compressor and the motor. During recommissioning, one of the other large compressors was damaged and had to be sent for repairs. This prolonged the completion date of the project even further.

As the compressor was damaged, the scope of the project concerning the compressors had to be re-evaluated. It was found that the flow demand was not the main concern regarding the old compressors. Due to the extensive period of operation, damage to the compressor was likely to occur when the machine was started and stopped on a daily basis.

The main concern regarding compressors is the motors. As discussed in Section 2.2, high electric currents are induced during the start-up of compressor motors. Although the machine would only be started once a day, it would still be a risk due to the condition of the compressors.

If mining equipment were damaged as a result of the energy savings project, the purpose of the project would be to no avail. Financial savings would have to be used to replace damaged equipment. It was, therefore, decided that none of the large compressors would be stopped and started on a daily basis.

The smaller compressor, which was mainly used to complement the four larger compressors during the drilling shift, was already being stopped and started on a daily basis. However, effort

had to be made to stop it daily before the commencement of the control period, which was the period when electricity costs were at its highest.

Since the compressors were manually operated, the best way to make the operation as sustainable as possible was to explain the purpose of the project thoroughly to the operators. By doing this, the operators grasped the goal of the project, thereby feeling part of the energy savings initiative.

The operators were trained, which ensured that the small compressor was switched off on a daily basis before the commencement of the control periods. Savings were maximised as far as possible without a large compressor being shut down on a daily basis.

Due to the project being delayed several times, special approval had to be obtained from one of the main stakeholders, namely Eskom, to extend the project completion date.

3.5) Conclusion

In this chapter, it was found that Mine A had the potential to achieve significant savings by optimising its compressed air network. According to the simulation a peak-clip energy saving of 2.8 MW was achievable by reducing both the amount of compressed air supplied by the compressors and the demand delivered to the active production levels.

The power usage, pressure and flow data were used to determine the baseline of the project. As mentioned previously, the baseline would also be used to determine the impact of the project after implementation.

Various constraints were identified in this chapter. It was found that not only does industrial action delay equipment installations, but it also alters a mine's mining schedule. Industrial action and other incidents such as personnel injuries can cause a mine's optimised compressed air control strategy to be temporarily disabled.

During project implementation, it was found that insufficient control valve sizes would reduce the impact of the project since control on particular levels needed to be disabled. This, together with the maintenance on the fragile compressors, reduced the impact of the project on the mine's compressed air system.

The project investigation and simulation showed that significant savings could be achieved by installing and controlling guide vane actuators and underground control valves. It was found that

various unforeseen events, such as changes in operating conditions, had a significant effect on a project. These incidents delayed the project several times for which approval had to be obtained from Eskom. It also had an effect on the performance of the project, as will be discussed in Chapter 4.

Chapter 4: Verification and validation of project results



15

Supply and demand side control initiatives are verified in this chapter. Various baseline adjustment models are also developed to identify a model that will produce accurate project savings.

¹⁵ Picture courtesy of <http://ircamera.as.arizona.edu/NatSci102/NatSci102/images/stonehengeghr.jpg>

4.1) Introduction

The previous chapter investigated the potential of an energy savings project on a mine's compressed air system. A simulation was done to determine the feasibility, the potential energy savings and the potential financial savings of the project.

Practical constraints that occurred during the reinvestigation and implementation of the project were also discussed. Improvements on these constraints are addressed in this chapter. The performance results due to the installed equipment are also discussed in this chapter.

Various baseline adjustment models are investigated to determine which model reflects a true indication of the actual saving obtained. Lastly, a scaling model is used to determine the actual project savings achieved, which is the deciding factor of the success of a project.

4.2) Valve sizing

It was found in Section 3.4 that 50 mm bypass valves were inadequate to deliver sufficient compressed air on Level 88 and Level 98. Figure 32 shows the actual upstream and downstream pressures on Level 98 when an inadequate control valve was used. It also shows the desired downstream pressure trend when an appropriate bypass valve is used.

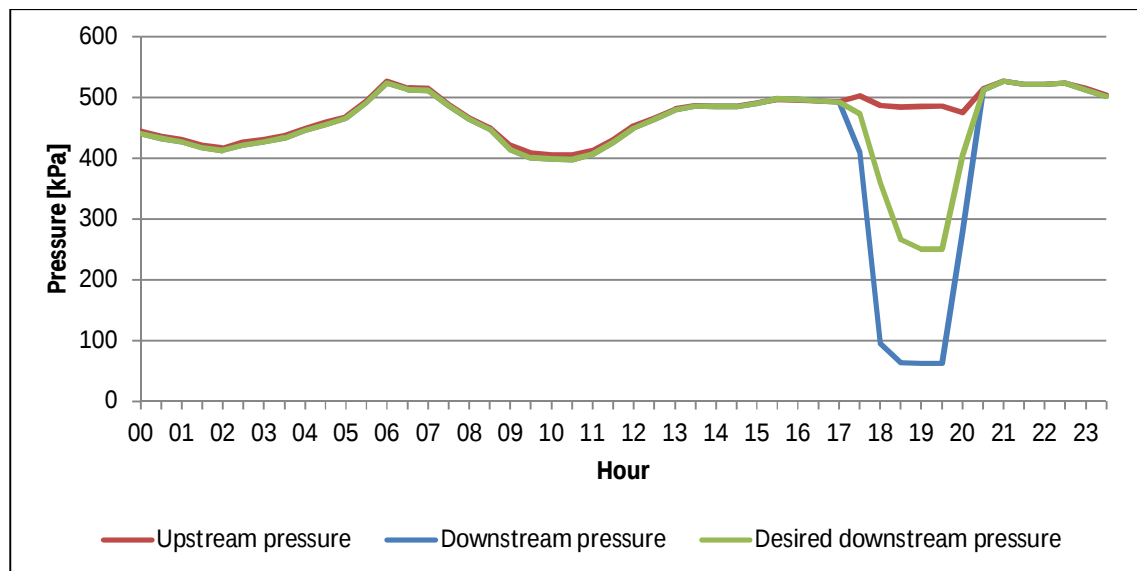


Figure 32: Upstream and downstream pressures of an insufficient control valve

Another phenomenon noticeable in Figure 32 is the pressure drop between 07:00 and 13:00. This is because one of the compressors was out for maintenance during this period. Maximum compressed air is used during this time of the day, which is the drilling shift (Section 2.2). Since the remaining four compressors were unable to meet the demand, a reduction in pressure consequently took place. It was clear that four compressors were unable to fully meet the mine's compressed air demand during the drilling shift.

A simulation was done to determine sufficient valve sizes for the two levels. KYPipe® was once again used for the simulation. During the time when new valve sizes had to be established, the flow rates on both levels were 9 200 m³/h on average. Therefore, one simulation model was used to represent both levels.

The following parameters were used for the valve sizing simulation:

- inlet absolute pressure of 480 kPa;
- outlet pressure of 87 kPa; and
- flow rate of 9 200 m³/h.

A simulation was used to determine the correct flow coefficient for the bypass valve. The bypass valve flow coefficient would define the size of the valve that would be sufficient for the application. An image of the simulation can be seen in Appendix C. According to the simulation, a valve with a flow coefficient of 91 would produce a downstream pressure of approximately 250 kPa. At those conditions, the flow rate through the valve would decrease to approximately 4 900 m³/h according to the simulation model. According to Table 9 in Appendix C, an equal-percentage 100 mm globe valve would deliver a downstream pressure of 250 kPa when opened just less than 70%.

It is found that 100 mm valves would be sufficient on both levels to meet the compressed air demand. However, after consulting with the mine, it was found that mining expansions were bound to take place on Level 98. Therefore, it was decided that a 150 mm bypass control valve had to be used instead of a 100 mm valve on Level 98. This was done to accommodate any compressed air flow rate increase on this level. A 100 mm valve was still used on Level 88.

Based on specification sheets obtained from manufacturers, a 150 mm globe control valve would deliver the required pressure set point with the valve open at approximately 30%. Therefore, it would be able to maintain the desired set point while making provision for any expansions on the level.

After it was found that 50 mm bypass control valves were insufficient, an investigation was done to determine why excessive pressure drops did not take place on the other levels as well. It would be understandable if Level 88 and Level 98 were the two highest compressed air consuming levels, but this was not the case.

During the investigation, it was found that there were compressed air leaks through the butterfly valves on the other levels. Since a large amount of compressed air leaked through the main-line valves, less compressed air needed to travel through the small control valves, enabling it to maintain a sufficient downstream pressure.

It should be noted that the bypass valves on the other levels will also have to be replaced eventually. When the butterfly valves are replaced, most of the 50 mm bypass control valves would be insufficient to accommodate the high compressed air flow rates without leaks in the main-line valves.

4.3) Automation and control

The impact of the control valves on the underground levels and the impact of the inlet guide vane controllers on the compressors are now discussed. For consistency, data from a single day will be used to illustrate the results of all the various aspects of the project.

4.3.1) Underground control valves

Figure 33 shows the difference between the upstream and downstream pressures on one of the controllable levels. It is clear that the upstream pressure remained above 400 kPa while the downstream pressure reduced to the desired pressure set point of 250 kPa during the control period. The upstream pressure was higher than the compressor set-point pressure of 400 kPa due to autocompression (Section 2.5).

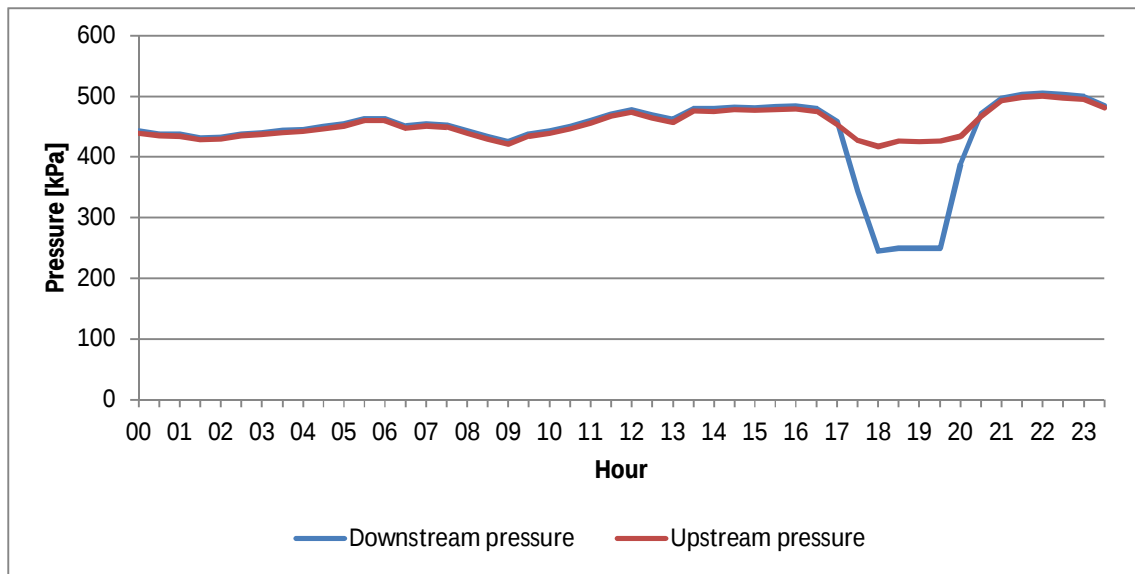


Figure 33: Comparison between measured upstream and downstream pressure profiles

The corresponding decrease in flow rate on the same level during the control period can be seen in Figure 34. Due to the lower flow rate, less compressed air was wasted on open ends, leaks, and so forth. According to the simulation, this specific level's flow rate would have dropped from 7 400 m³/h to 3 812 m³/h. According to the measured data, the flow rate dropped to approximately 5 500 m³/h. The actual drop in flow rate was, therefore, much lower than expected.

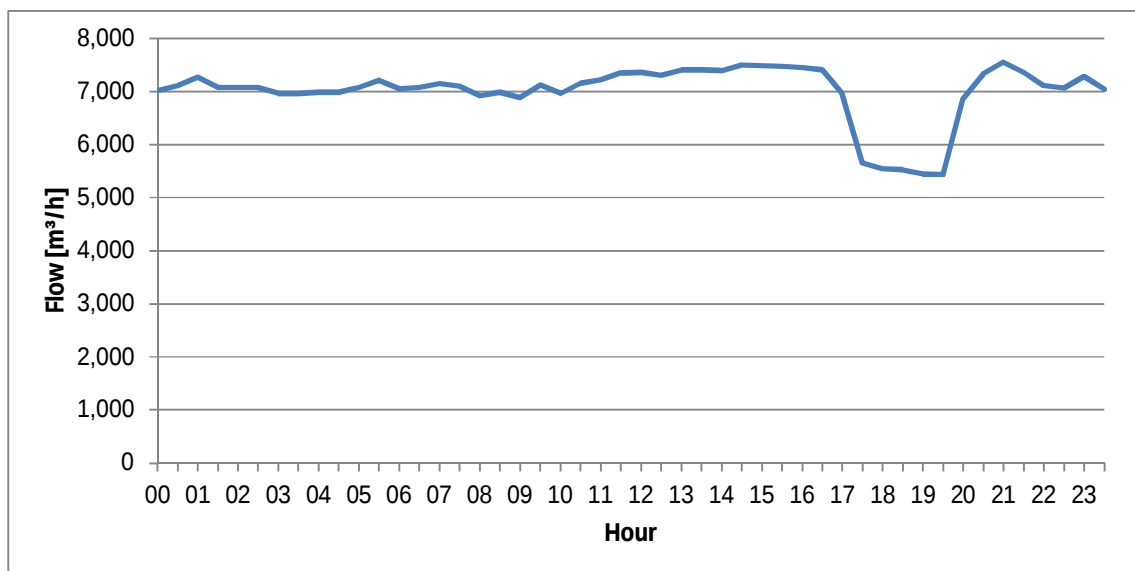


Figure 34: Measured flow rate decrease during control period

According to Table 9 in Appendix C, a 50 mm globe valve will have a flow coefficient of 53.80 when fully opened. However, according to the KYPipe® simulation, a flow coefficient of 72 was needed to produce a flow rate of 3 812 m³/h at a pressure of 250 kPa. It was clear that the valve was also too small to provide sufficient compressed air while maintaining the flow rate. It was, therefore, assumed that the main-line butterfly valve on this level was leaking compressed air as well. Due to safety reasons, a test could not be conducted to determine the flow rate when both valves were closed simultaneously.

4.3.2) Inlet guide vane control

Inlet guide vanes were used on all five compressors to reduce the discharge pressure of the compressors during the control period. Figure 35 shows the ratios between the various compressor power usages and the inlet guide vane positions. The figures show that the smaller compressor, Compressor 3, was started after 08:00 to complement the other compressors during the drilling shift. When Compressor 2, Compressor 4 and Compressor 5 started closing their guide vanes, Compressor 3 was switched off and the four large compressors were operating at maximum efficiency once again. Compressor 3 was switched off just before 14:00, which was when the drilling shift typically ended.

It should be noted that the positions of the various compressor guide vanes were not reduced to the same extent during the control period. This was done to ensure that the compressors operated at their highest efficiencies. Higher compressor efficiencies result in cost and energy savings that benefit the mine as well as Eskom.

Due to the size of the compressors, sudden changes in power and flow rates could be very harmful to the machines. Pressure and flow rate reductions, therefore, needed to take place gradually. As can be seen in Figure 35, the control started before 18:00 so the compressors already used minimum power at the start of Eskom's peak period. Maximum savings could, therefore, be achieved during the two hours when electricity cost was at its highest. The pressure and flow rate also only started to return to normal after 20:00. Therefore, normal conditions were only reached after about 21:00.

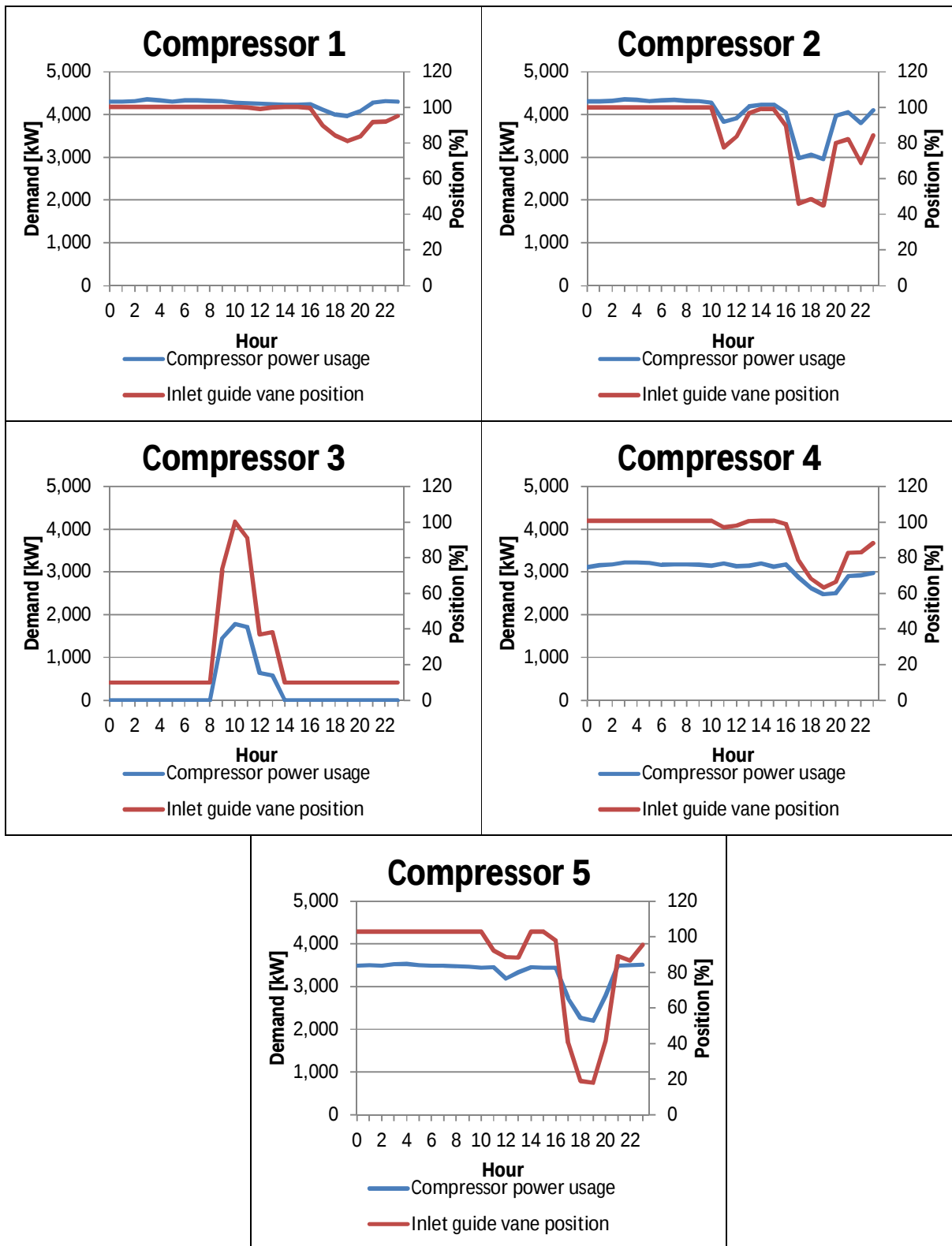


Figure 35: Compressor power usages versus inlet guide vane positions

Figure 36 shows how the guide vanes of the compressors were used to control the common discharge pressure of the compressors. The extent to which the compressed air pressure may have been reduced was determined by the gold plant, which required 400 kPa at all time (Section 3.3). During the performance assessment period when the results were obtained, a pressure difference of approximately 35 kPa was experienced between the shaft and gold plant pressures. The cause of this phenomenon could not be determined.

After it was confirmed that both pressure transmitters were fully functional, the compressors' common discharge pressure set point was reduced to 370 kPa. A required pressure of 400 kPa was still supplied to the gold plant, therefore, not violating any mining requirements, while generating additional energy savings.

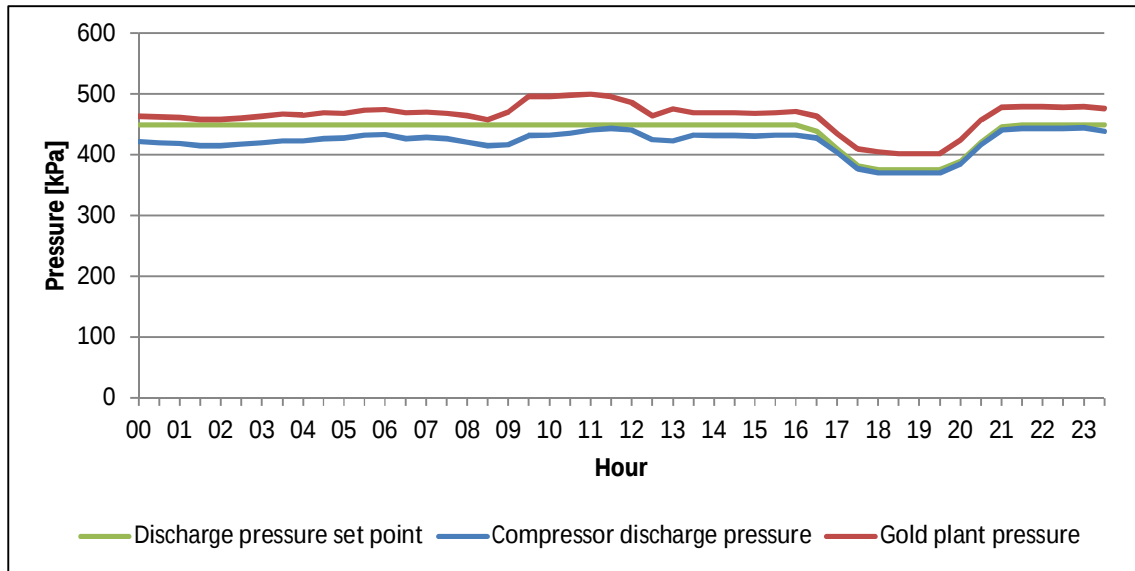


Figure 36: Compressors discharge pressure control

Figure 37 shows the flow rate of compressed air delivered by the compressors. A distinct reduction can be seen during the control period. On this particular day, the flow rate reduced from an average of 137 000 m³/h before the control period, to an average of 112 400 m³/h during the control period.

A decrease of 24 600 m³/h was, therefore, induced during the two hours. This was lower than the simulated flow rate decrease of 44 113 m³/h. This shortcoming could be attributed to various levels not being controllable during the assessment period due to various constraints. This includes, among others, control being disabled on some levels due to extra production shifts, as well as insufficient control valves on other levels (Section 3.4).

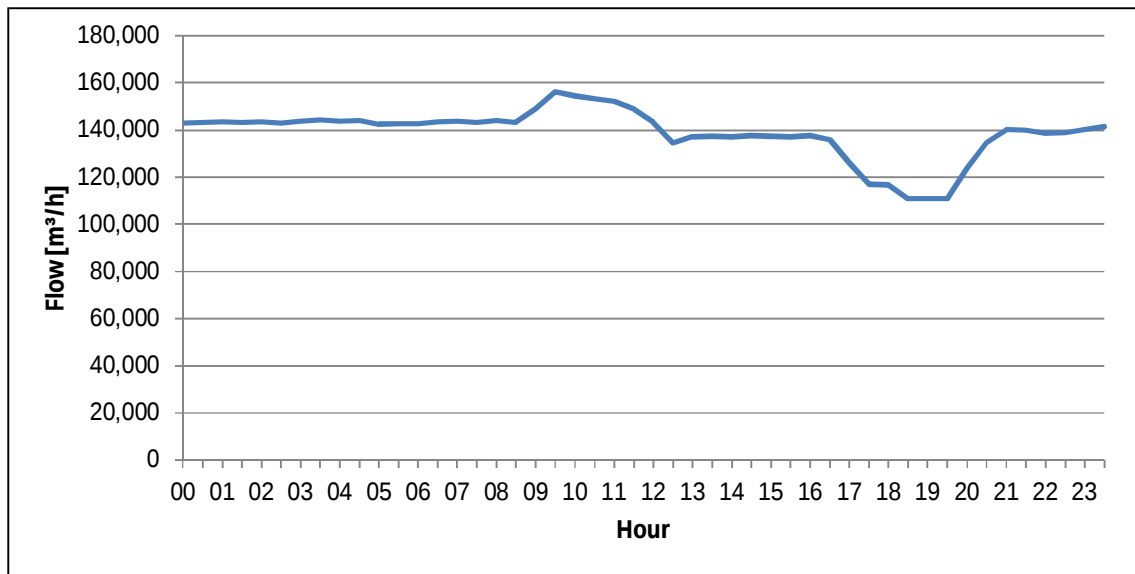


Figure 37: Compressors delivered flow rate

Figure 38 shows the total power usage of the compressors throughout the day compared to the project baseline. A distinct peak clip is noticeable during the control period. There are, however, various differences between the two profiles. The baseline was significantly lower overall than the actual profile. The relationship between the peak part of the drilling shift (09:00–12:00) and the control period (18:00–20:00) was not the same. It was, therefore, clear that the baseline, even with baseline adjustment, was not sufficient to determine the actual savings achieved on the particular day. Therefore, a new baseline had to be constructed.

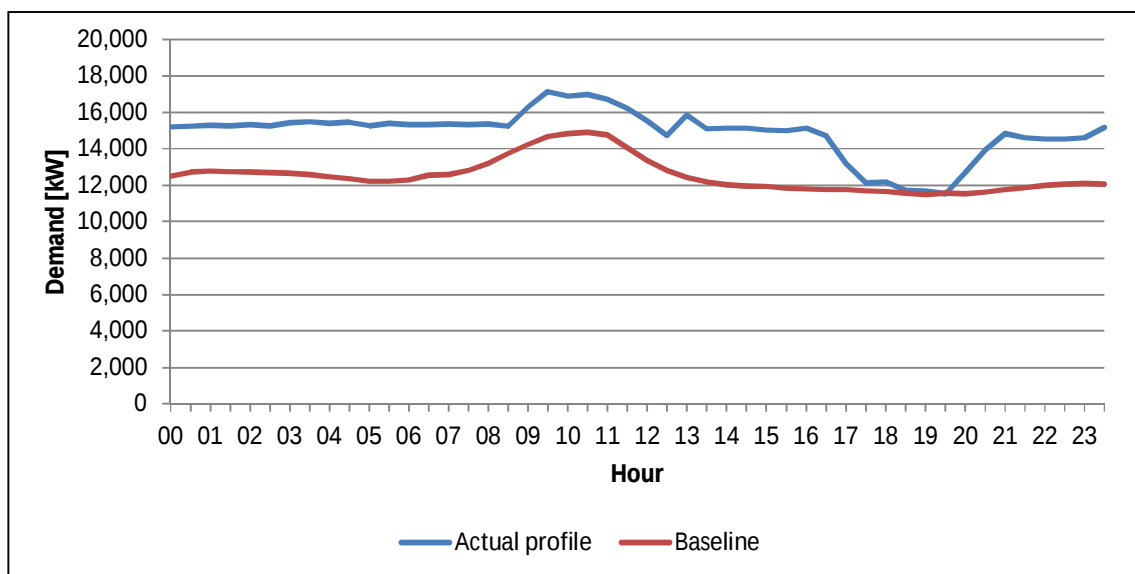


Figure 38: Comparison between a typical demand profile and the project baseline

4.4) Baseline adjustment through measurement and verification

At the end of a project, the baseline is compared with the optimised profile after project implementation to determine the savings of the project. This is ultimately the deciding factor whether a project is successful or not. The results of the project were sent to an independent team for measurement and verification (M&V). The M&V team uses data from the first three months after implementation, known as the performance assessment period, to determine the performance of the project [67].

Due to the complexity and constant changing of mining systems, it could happen that a baseline becomes outdated and is not applicable anymore, as is the case in Figure 38. This is due to mining schedule changes that could not be accommodated. Baseline adjustment would typically be used to bring the two time periods under the same set of operational conditions.

However, in a case such as this project, baseline adjustment on its own would not be sufficient to determine the true savings of the project. In this case, a new baseline needs to be established. This is done by switching off all control and recording data during normal operations without any control taking place.

The M&V team required data for three months to establish a baseline [60]. Three months of ‘no-control’ data, however, would not be possible for the energy savings project. The project was already achieving financial savings of more than a R100 000 each month and thus already reducing the energy demand of South Africa.

Due to the special circumstances, the M&V team decided that one-week’s data would be sufficient to establish a new baseline. The control was switched off for seven days while mining operations went on as normal. The weekday average power usage data was recorded and the profile is shown in Figure 39. The data for the new baseline can be seen in Appendix D.

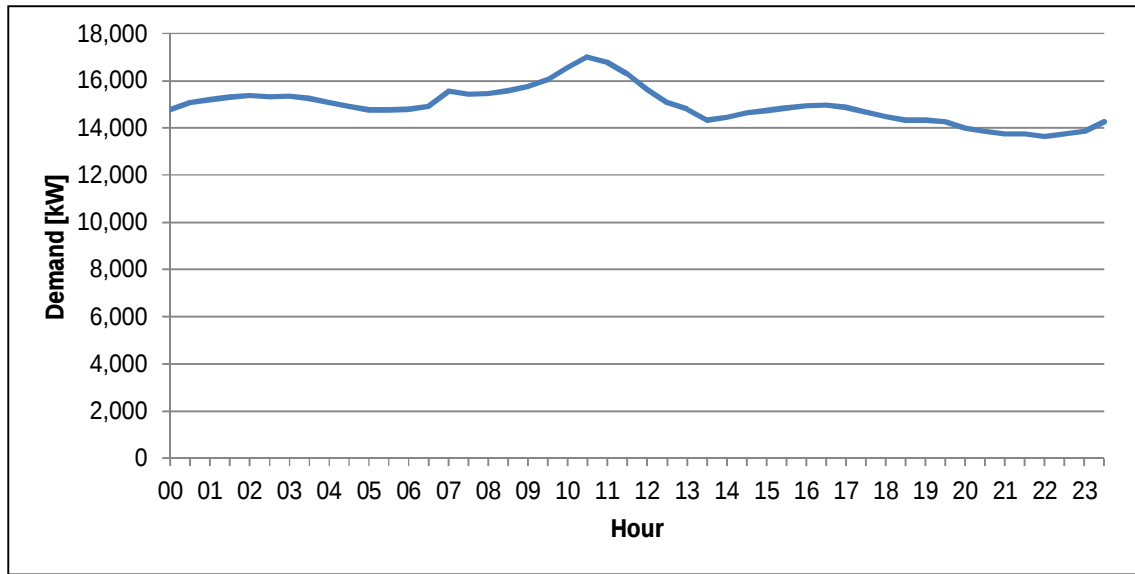


Figure 39: New project baseline

Although the new baseline was a more accurate representation of the mine's compressed air power usage, daily scaling was still needed to ensure energy savings were calculated accurately on a daily basis. A scaling model had to be identified which would produce accurate savings for the project. The M&V team designed and tested three different baseline adjustment models after which the most accurate one was chosen to determine the actual savings of the project.

Scaling Model 1

The M&V team designed Scaling Model 1 based on the principle of scaling the baseline using the power usage, flow and discharge pressure of the compressors. A regression model was created from the power, flow and pressure data obtained during the seven-day no-control period. The relationship between these three variables was determined by the M&V team to be as follows:

$$P_m = f(Q_m, p_m) = aQ_m + bp_m + c \quad (5)$$

Where:

P_m	–	power usage at the m -th sampling point	kW
Q_m	–	flow rate at the m -th sampling point	m ³ /s
p_m	–	air pressure at the m -th sampling point	kPa

Coefficients a and b of function f were calculated using regression analysis of the power usage, flow and discharge pressure of the compressors. Using the data from the adjusted baseline, the coefficients were found to be as follows:

$$\begin{aligned}a &= 451.473244 \\b &= -9.269673 \\c &= 1\,267.195680\end{aligned}$$

A scaling factor between the regression baseline and the actual power usage was then calculated. The data that was used to calculate the scaling factor was in half-hour intervals between 09:00 and 12:00. This period was explicitly used since it was the only period where the power, pressure and flow rate could be derived. The baseline was then adjusted according to the scaling factor calculated. The scaled baseline was compared with the actual profile of the day to determine the day's energy savings.

The model was dependent on the number of compressors used between 09:00 and 12:00 (peak part of drilling period) and between 18:00 and 20:00 (the control period). During the week when the control was disabled to establish a new baseline, the mine used five compressors during the drilling period and four compressors during the control period.

Therefore, the scaling model would only be accurate on days when five compressors were used during the drilling period and four compressors were used during the control period. However, this was not the case. Occasionally, the mine would use five compressors throughout the day, sometimes only four. The scaling model would not be able to calculate the true savings during such days.

The scaling model was not able to determine accurate savings constantly on a daily basis and was, therefore, deemed unsuccessful by the M&V team.

Scaling Model 2

Due to the constantly changing characteristics of the daily power usage profiles, the M&V team developed a model to accommodate each daily profile independently. The model focused only on the controllable time rather than on the complete 24-hour profile. The model also only used no-control data points closest to the control period and calculated what the profile would have been if control did not take place.

As explained in the previous section, pressure set points of compressors need to change in small intervals since large sudden changes could potentially damage the compressors. The compressor set-point controllers, therefore, reduced the discharge pressures gradually from 16:45 to 18:00. After the control period, the discharge pressures were once again gradually increased. This took place from 20:00 to 21:15. Scaling Model 2, therefore, focused on the period between 16:30 and 21:30.

This scaling model consisted of independent linear functions for each half-hour interval between 16:30 and 21:30. Using the seven-day baseline data, the M&V team created linear functions for each half-hour interval. The gradient and constant were obtained and was used as constants in the scaling function. The function is as follows:

$$P_m = f(P_{m-1}) = aP_{m-1} + b \quad (6)$$

Where:

P_m – power usage at the m -th sampling point kW

An error, however, would be induced during each interval. Since the power usage of each sampling point was dependent on the power usage of the previous sampling point, the error would increase during each interval. To minimise this phenomenon, the model was constructed from both ends, namely, from 16:30 onwards until 19:00; and from 21:30 backwards, also until 19:00. An average of the two values was used at 19:00, thereby minimising the error of the profile.

Coefficients a and b of function f were calculated for each interval from the seven-day baseline and was found to be as follows:

Table 5: Seven-day baseline intervals

Interval	a	b	Interval	a	b
16:30 to 17:00	0.9066	1 295.60	21:30 to 21:00	0.9022	1 341.50
17:00 to 17:30	0.7675	3 233.50	21:00 to 20:30	0.9149	1 247.10
17:30 to 18:00	0.9544	500.11	20:30 to 20:00	1.0117	–46.29
18:00 to 18:30	0.8838	1 543.20	20:00 to 19:30	0.8873	1 773.20
18:30 to 19:00	0.9427	802.56	19:30 to 19:00	0.9446	852.09

Scaling Model 2 was, however, not sufficient for all scenarios. Figure 40 shows a scenario where the model was insufficient. Since the profile throughout the day was fairly linear except for the control period and from 22:00 onwards, a linear function was created. Data from before and after the control period were used to establish a linear function that represented how the profile would have looked if control did not take place. A distinct difference can be seen between the calculated baseline and the linear function.

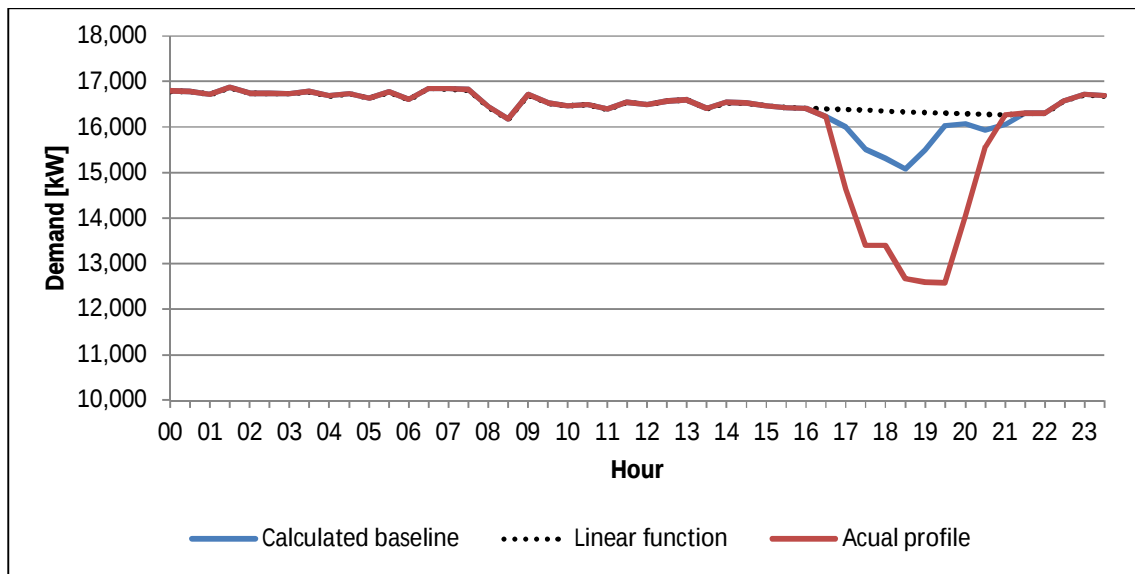


Figure 40: Example of Scaling Model 2

According to the calculated baseline, an average peak-clip energy saving of 2 667 kW was achieved during the specific day illustrated in Figure 40. When the linear function was used in comparison with the actual profile, it shows that a peak-clip energy saving of 3 563 kW was achieved. The scaling model, therefore, only accounted for 75% of the savings achieved during that day.

Scaling Model 2 was, therefore, found to be insufficient by the M&V team and could not be used to determine the project's actual savings on a daily basis.

Scaling Model 3

Unlike Scaling Model 2, which used half-hour intervals and as a result induced accumulative errors, the M&V team developed Scaling Model 3 to consist of only two large intervals.

This model used the periods from 16:30 to 19:00 and from 21:30 to 19:00 as two large intervals. The average was once again taken at 19:00 to compensate for any error. The error would be smaller since the errors would not accumulate.

The gradients of the two lines were calculated from the seven-day baseline data. Lines with the calculated gradients were scaled to fit onto each daily profile's 16:30 and 21:30 points. As mentioned, the average was taken at 19:00. The scaling model was constructed using the following equations determined by the M&V team:

$$P_m = f(P_{m-1}) = P_{m-1} + a \quad (7)$$

$$P_n = f(P_{n+1}) = P_{n+1} + b \quad (8)$$

$$P_{19:00} = f(P_{m-1}, P_{n+1}) = \frac{(P_{m-1} + a) + (P_{n+1} + b)}{2} \quad (9)$$

Where:

P_m	–	power usage at the m -th sampling point	kW
P_n	–	power usage at the n -th sampling point	kW
$P_{19:00}$	–	power usage at 19:00	kW

The M&V team calculated the coefficients by regression analysis of the power consumption of the compressors. They found the coefficients to be as follows:

$$a = -102.3167$$

$$b = 109.7400$$

For consistency, the profile from Scaling Model 2 was once again used to determine the accuracy of the model. Figure 41 shows the actual profile, the linear function and the scaled baseline from Scaling Model 3.

As previously stated, when the linear function was compared with the actual power usage, an energy saving of 3 563 kW was achieved during the specific day. When the calculated baseline was compared with the actual power usage, it was found that an energy saving of 3 433 kW was achieved. The baseline adjustment model was, therefore, 96% accurate on the given day.

Scaling Model 3 was deemed sufficiently accurate and was used to determine the actual savings of the project. However, it was believed that a simplified baseline adjustment model could be used to determine the accuracy just as effectively.

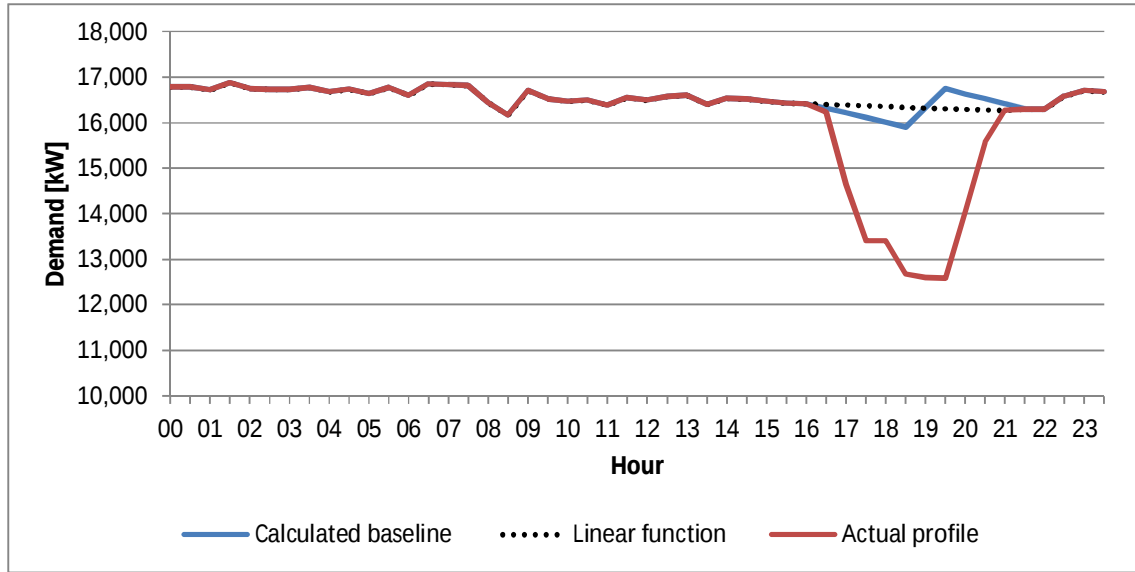


Figure 41: Example of Scaling Model 3

Simplified version of Scaling Model 3

As was seen in Figure 40 and Figure 41, a linear function could be used to determine the actual savings on a daily basis. The linear function was determined using the following equation:

$$P_m = f(X_m) = aX_m + b \quad (10)$$

Where:

- P_m – power usage at the m -th sampling point kW
- X_m – variable position at the m -th sampling point kW

Coefficients a (gradient) and b (Y intercept) of function f were calculated on a daily basis using regression analysis of the power usage of the compressors.

To verify the model, six random days during the performance assessment period were used to determine the savings of Scaling Model 3 compared to the linear function. The data is illustrated in Table 6.

Table 6: Comparison in savings achieved according to Scaling Model 3 and the linear function

Day	Scaling model 3 [kW]	Linear function [kW]
2014-01-14	2 979	2 999
2014-01-30	2 294	2 467
2014-02-05	2 918	2 832
2014-02-20	3 500	3 299
2014-03-10	3 139	3 159
2014-03-13	3 325	3 220
Average	3 026	2 996

An average daily saving of 3 026 kW was achieved when using Scaling Model 3. An average daily saving of 2 996 kW was achieved when the linear function was used. The linear function, therefore, reflected 99% of the savings achieved compared with savings achieved with Scaling Model 3. It was, therefore, evident that a basic linear function would also be sufficient to determine the actual power savings on a daily basis.

4.5) Performance and financial results

After implementing a DSM project, the project is subject to a five-year performance agreement. The performance agreement is based on the savings obtained within the performance assessment period. The M&V team determines the final savings obtained by the project.

During the three-month assessment period for this project, the project obtained an average peak-clip energy saving of 2 611 kW during weekdays. This was according to the M&V team who used Scaling Model 3. This saving equalled an annual electricity saving of 1.91 GWh if the savings were maintained throughout a year. This figure was based on the total weekdays in a year, excluding public holidays which were seen as weekend days. Not only was this a significant energy saving, but it also induced other benefits such as reducing carbon dioxide emissions.

Figure 42 shows the daily power savings achieved during the second month of the performance assessment period, which was February 2014. Weekday profiles are displayed in blue, whereas Saturdays and Sundays are displayed in red. The daily power and financial savings for the three-month performance assessment period can be seen in Appendix E.

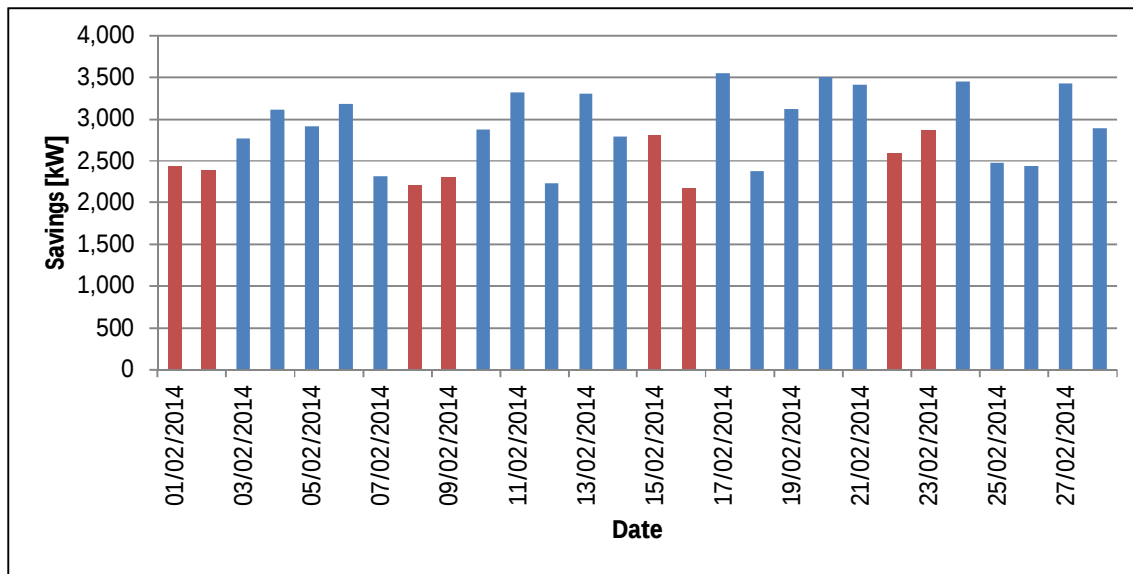


Figure 42: Daily energy savings during February 2014

A daily weekday saving of 2 611 kW would produce an annual financial saving of R1.46 million (2014/2015 Eskom tariffs). As previously stated, the control on the compressors' inlet guide vanes already started at 16:45 and only ended at 21:15. Although the focus of the project was on electricity savings between 18:00 and 20:00, additional savings were also achieved outside of the two-hour period. By including the time intervals just before and directly after the peak period, the total annual financial savings were R1.91 million (2014/2015 Eskom tariffs).

On 28 February 2013, NERSA approved an 8% average electricity increase per annum between 2013 and 2018 [9]. The optimisation of the compressed air system would, therefore, produce an annual financial saving of R2.81 million during 2018.

4.6) Conclusion

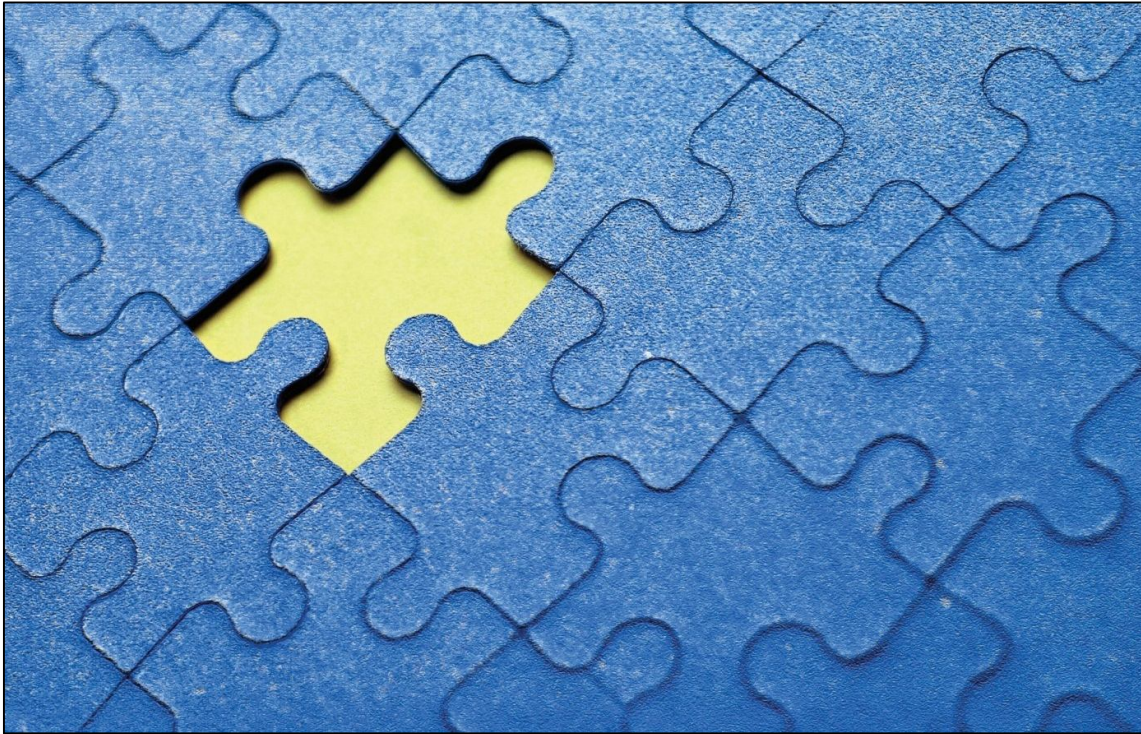
This chapter focused on determining sufficient control valve sizes for levels where the original valves were insufficient. It was noted that the problem was likely to arise on the other levels once the main-line valves were refurbished or replaced.

The effects of control valves on the active production levels were also analysed. The control valves were able to reduce the compressed air flow rate on the levels while maintaining the specified pressure. Inlet guide vanes were used to reduce the compressed air flow rate through the compressors. This caused the compressors to consume less energy, which ultimately produced financial savings.

A new baseline was established since the original baseline was insufficient to determine the actual energy savings of the project. Various scaling methods identified by the M&V team were discussed. It was found that a linear function would also be sufficiently accurate to determine the savings on a daily basis.

The optimisation of the mine compressed air system produced an average daily saving of 2 611 kW during Eskom's peak period. The project ultimately produced a financial saving of R1.46 million per year (2014/2015 Eskom tariffs) during the peak periods on weekdays.

Chapter 5: Conclusion and recommendations



16

Objectives are reviewed in this chapter. The research study is concluded and recommendations for further studies are made.

¹⁶ Picture courtesy of http://images.flatworldknowledge.com/wrench/wrench-fig11_x002.jpg

5.1) Conclusion

It is clear that South Africa currently has an electricity shortage at hand. This can be improved by identifying and optimising various large energy consumers. One such a demanding energy consumer is compressed air systems on gold mines.

Optimising the compressed air system of a gold mine will benefit both the mine and the country. The mine will achieve financial savings while the electrical load of the country will be reduced. This study focused on the optimisation of a gold mine's compressed air system.

The power usage of the mine's compressed air system was reduced by implementing strategies on both the supply and demand sides of the network. Control valves were used to reduce the amount of compressed air being consumed by the various underground mining levels. Inlet guide vanes were used to reduce the airflow through the compressors. Both strategies enabled the compressors to deliver less compressed air, thus reducing the energy usage of the machines.

However, during the implementation of a compressed air energy savings project on a gold mine, various challenges can occur. The challenges can occur either during the investigation or during the implementation of such a project. The challenges can lead to a project not being delivered on time, within budget or with quality results.

Various challenges that had an impact on the performance of the project have been discussed in this study. Industrial action forced the installation of equipment to be delayed. Industrial action and other unforeseen events forced the mine to implement extra operating shifts. Due to a change in the mining schedule, only certain underground control valves could be used since some of the levels required maximum compressed air pressure throughout the day. This reduced the impact of the savings project on the demand side of the compressed air system.

Maintenance on compressors and the condition of the compressors forced the supply side control of the project to be re-evaluated. It was found that the large compressors could not be shut down on a daily basis. This reduced the impact of the project on the supply side of the mine's compressed air system as well.

After the implementation of the project, the performance of the project needed to be evaluated by comparing the optimised power usage profile with the project baseline. It was found that a new baseline had to be established to determine the impact of the project accurately. Baseline

adjustment was also needed along with a new baseline, since the number of compressors used varied from day to day.

Various baseline adjustment models were identified by the M&V team. The most accurate model was verified by them as being sufficiently accurate and was used to calculate the actual daily savings of the project. A simplified model was developed which could be used to calculate the daily savings as well.

According to the results obtained during the performance assessment period, the project produced an average daily peak-clip saving of 2.61 MW during Eskom's peak period. This would ultimately produce a yearly financial saving of R1.46 million (2014/2015 Eskom tariffs) during Eskom's peak periods. When all periods are taken into account, the project will produce an annual financial saving of R1.91 million (2014/2015 Eskom tariffs).

5.2) Recommendations

During the implementation of the project, it was found that most of the levels had large air leaks in the main-line valves. A decrease in flow on those levels can, however, still be accomplished with control valves. Future investigations can be done to determine the extra savings achievable by refurbishing the main-line valves. The refurbishing costs and the cost of larger bypass control valves will have to be compared to the extra savings achievable to determine the feasibility of the initiative.

Due to a constantly changing mining schedule, various underground control valves had to be disabled. By actively monitoring the minimum compressed air pressure required on each of the levels, the various pressure set points can be changed as needed to accommodate all underground equipment. Although a higher pressure set point on a level will produce less savings, any significant savings will benefit the mine and Eskom.

Mine personnel responsible for the sustainability of the project savings should constantly monitor the mining schedule to utilise the control valves on all of the levels as effectively as possible.

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Appendix A: Project baseline data

Table 7 shows the half-hourly averages of the power, pressure and flow data obtained during the project baseline period.

Table 7: Baseline data

Time	Power [kW]	Pressure [kPa]	Flow [m ³ /h]
00:00	12 505	397	139 172
00:30	12 723	396	139 524
01:00	12 790	396	140 998
01:30	12 750	398	141 338
02:00	12 712	401	141 619
02:30	12 680	399	139 887
03:00	12 649	401	139 467
03:30	12 580	403	138 531
04:00	12 468	403	136 689
04:30	12 345	404	136 652
05:00	12 235	404	135 958
05:30	12 212	404	136 137
06:00	12 302	406	137 189
06:30	12 549	408	136 914
07:00	12 593	409	136 313
07:30	12 821	412	140 735
08:00	13 204	410	143 118
08:30	13 751	410	147 136
09:00	14 241	407	148 381
09:30	14 664	401	148 410
10:00	14 835	401	148 652
10:30	14 898	398	148 379
11:00	14 758	407	148 563
11:30	14 084	409	144 465
12:00	13 344	411	140 970
12:30	12 829	410	138 510
13:00	12 440	410	134 271

Time	Power [kW]	Pressure [kPa]	Flow [m ³ /h]
13:30	12 194	407	132 005
14:00	12 016	407	130 609
14:30	11 963	406	128 447
15:00	11 930	404	128 182
15:30	11 846	404	129 047
16:00	11 804	399	128 487
16:30	11 764	401	129 992
17:00	11 758	404	128 704
17:30	11 686	404	126 815
18:00	11 660	393	123 743
18:30	11 565	398	126 218
19:00	11 517	401	126 165
19:30	11 578	402	126 764
20:00	11 546	406	128 245
20:30	11 641	404	128 478
21:00	11 768	399	129 972
21:30	11 870	398	131 091
22:00	11 985	398	132 189
22:30	12 066	401	134 348
23:00	12 083	398	134 289
23:30	12 065	396	138 077

Appendix B: KYPipe®

KYPipe® verification

The accuracy of KYPipe® is verified in Section 3.3 by comparing simulated flow with actual flow at a reduced pressure supply. Figure 43 shows a scenario where the supply pressure was reduced to 387 kPa, which was equivalent to the actual pressure on that specific day.

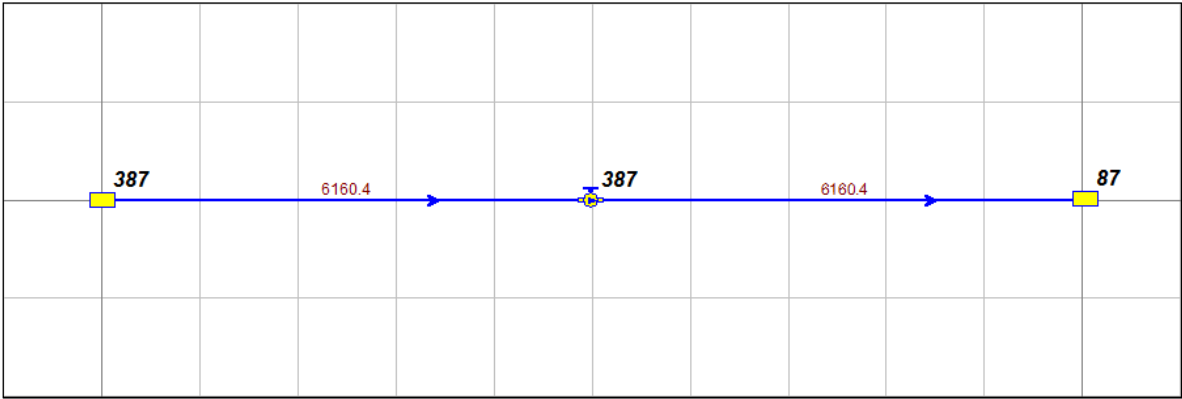


Figure 43: KYPipe® simulation verification: pressure and flow at controlled pressure set point

Project simulation

After verifying the data using KYPipe®, the data was used to simulate the reduction in flow that had to be delivered by the compressors. This data, along with Equation (4), was used to determine the electrical savings viable for the project. Figure 44 shows the layout of the simulation model that was used to determine the reduction in compressed air flow.

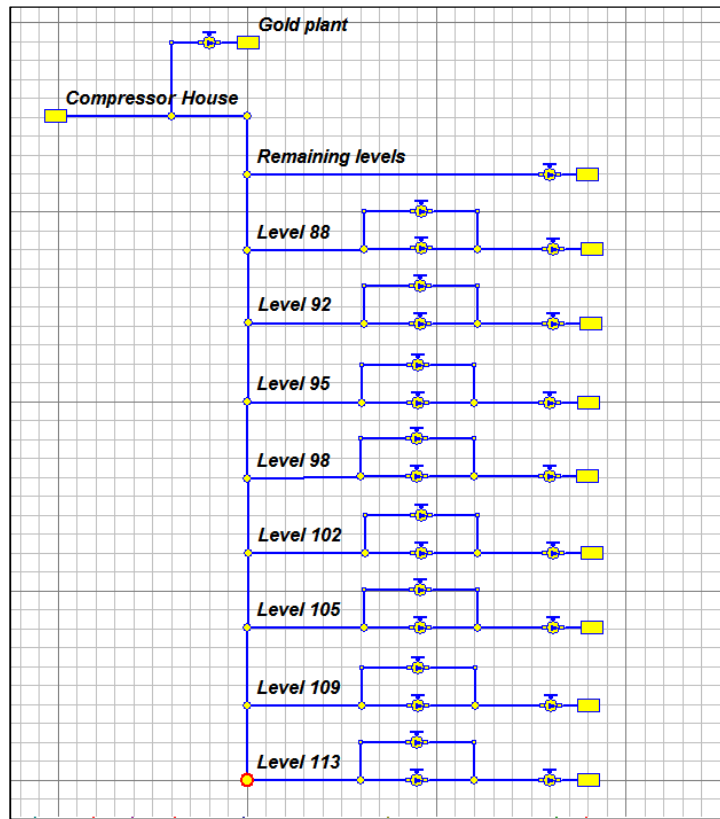


Figure 44: KYPipe® project simulation layout

Table 8 shows the various input and output flows of the simulation model. It should be noted that only four compressors were available during the baseline period as already mentioned in Section 3.3. Therefore, although the compressor discharge pressure set points were maintained at 450 kPa, the four compressors were only able to deliver approximately 400 kPa. The compressor discharge pressures before and during control were, therefore, kept at 400 kPa for the simulation.

Table 8: Input and output flow of the project simulation model

Description	Flow rate [m ³ /h]	Flow rate @ 250 kPa [m ³ /h]
Level 88	6 387	3 335
Level 92	7 349	3 812
Level 95	9 267	4 737
Level 98	18 425	9 435
Level 102	15 485	7 840
Level 105	16 376	8 100
Level 109	14 055	6 907
Level 113	4 297	2 068
Remaining levels	13 889	14 994
Gold plant	18 720	18 908
Total	124 250	80 137

Appendix C: Level 88 and Level 98 valve sizing

After it was found that the bypass control valve on Levels 88 and Level 98 were insufficient, alternative valves sizes had to be determined (Section 4.2). Figure 45 shows the KYPipe® simulation used to determine the flow coefficient needed for sufficient valves.

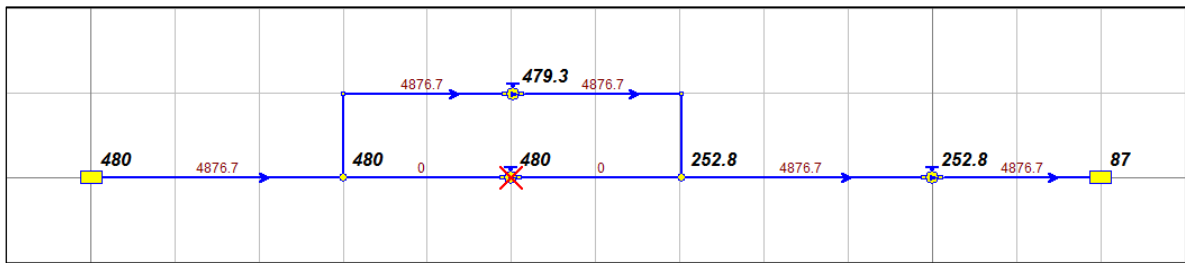


Figure 45: KYPipe® simulation for Level 88 and Level 98 valve sizing

Table 9 shows the various openings of different valve sizes for a typical equal-percentage globe control valve. The valve opening size was based on the flow coefficient of the valve.

Table 9: Globe valve sizing table (adapted from [68])

Valve size		Equal-percentage valve opening [%]			
		10	30	70	100
Diameter nominal (DN)	Nominal pipe size (inch)	Flow coefficient			
DN 25	1	0.79	1.80	7.59	13.20
DN 40	1½	0.80	1.91	9.84	28.10
DN 50	2	1.65	4.30	32.80	53.80
DN 80	3	3.11	9.12	60.40	114.00
DN 100	4	4.90	13.50	96.70	190.00

Appendix D: New baseline data

Table 10 shows the average half-hourly data of the new baseline. The baseline was established during the seven-day no-control period (Section 4.4).

Table 10: New baseline data

Time	Power [kW]	Pressure [kPa]	Flow [m³/h]
00:00	14 758	442	142 101
00:30	15 061	433	144 624
01:00	15 205	430	145 307
01:30	15 299	427	145 787
02:00	15 386	427	146 029
02:30	15 324	428	145 716
03:00	15 352	425	145 528
03:30	15 240	429	144 812
04:00	15 079	430	143 761
04:30	14 927	432	142 744
05:00	14 770	433	141 419
05:30	14 762	434	140 896
06:00	14 781	434	141 126
06:30	14 929	431	142 338
07:00	15 552	436	146 268
07:30	15 434	436	145 022
08:00	15 465	430	145 185
08:30	15 577	425	145 804
09:00	15 763	420	146 429
09:30	16 053	419	148 516
10:00	16 554	421	150 838
10:30	17 020	435	153 507
11:00	16 789	441	151 991
11:30	16 307	442	149 090
12:00	15 636	444	143 796
12:30	15 076	443	139 565
13:00	14 802	444	137 483
13:30	14 328	445	136 559
14:00	14 468	445	137 304

Time	Power [kW]	Pressure [kPa]	Flow [m³/h]
14:30	14 642	444	138 789
15:00	14 736	444	139 655
15:30	14 844	443	140 508
16:00	14 934	443	140 179
16:30	14 981	443	140 053
17:00	14 867	444	139 014
17:30	14 654	445	137 403
18:00	14 478	445	135 953
18:30	14 330	445	134 938
19:00	14 321	445	134 907
19:30	14 243	444	135 044
20:00	13 990	445	134 271
20:30	13 840	445	133 675
21:00	13 734	445	133 055
21:30	13 734	445	134 039
22:00	13 656	445	134 432
22:30	13 736	445	134 910
23:00	13 855	445	135 241
23:30	14 265	444	138 704

Appendix E: Performance assessment savings

Table 11 displays the financial and energy savings achieved during the performance assessment period of the project. The data was verified by an independent M&V team. Since the project mainly focused on weekdays, the weekends are highlighted in grey. It should be noted that the mine was still on Christmas break until 3 January 2014, hence the negative savings during the first three days. All control was disabled by the mine during 20–23 March 2014. This also affected the savings significantly during those four days.

Table 11: Daily savings achieved during performance assessment period

Date	Power saving [kW]	Financial saving [R]
2014-01-01	–68	–101
2014-01-02	–166	–246
2014-01-03	–211	–313
2014-01-04	2 377	3 522
2014-01-05	2 359	3 496
2014-01-06	2 702	4 005
2014-01-07	2 950	4 372
2014-01-08	2 921	4 329
2014-01-09	2 961	4 388
2014-01-10	3 130	4 638
2014-01-11	1 765	2 616
2014-01-12	2 193	3 250
2014-01-13	481	713
2014-01-14	2 979	4 415
2014-01-15	2 789	4 133
2014-01-16	443	656
2014-01-17	3 016	4 470
2014-01-18	2 740	4 060
2014-01-19	2 503	3 710
2014-01-20	2 637	3 909
2014-01-21	2 516	3 729
2014-01-22	2 587	3 833

Date	Power saving [kW]	Financial saving [R]
2014-01-23	2 120	3 142
2014-01-24	2 568	3 805
2014-01-25	2 338	3 465
2014-01-26	2 139	3 169
2014-01-27	2 433	3 605
2014-01-28	2 404	3 563
2014-01-29	2 473	3 666
2014-01-30	2 294	3 400
2014-01-31	2 407	3 567
2014-02-01	2 438	3 613
2014-02-02	2 388	3 539
2014-02-03	2 764	4 096
2014-02-04	3 111	4 610
2014-02-05	2 919	4 325
2014-02-06	3 181	4 715
2014-02-07	2 319	3 437
2014-02-08	2 209	3 273
2014-02-09	2 306	3 418
2014-02-10	2 874	4 259
2014-02-11	3 320	4 921
2014-02-12	2 232	3 308
2014-02-13	3 305	4 898
2014-02-14	2 785	4 127
2014-02-15	2 807	4 160
2014-02-16	2 169	3 214
2014-02-17	3 553	5 265
2014-02-18	2 375	3 519
2014-02-19	3 120	4 624
2014-02-20	3 500	5 187
2014-02-21	3 417	5 063
2014-02-22	2 598	3 851
2014-02-23	2 876	4 262
2014-02-24	3 452	5 116
2014-02-25	2 481	3 676
2014-02-26	2 434	3 608
2014-02-27	3 427	5 079
2014-02-28	2 887	4 279

Date	Power saving [kW]	Financial saving [R]
2014-03-01	3 046	4 514
2014-03-02	2 434	3 607
2014-03-03	2 582	3 826
2014-03-04	3 432	5 087
2014-03-05	2 697	3 997
2014-03-06	3 333	4 940
2014-03-07	3 280	4 861
2014-03-08	2 066	3 062
2014-03-09	3 063	4 539
2014-03-10	3 139	4 652
2014-03-11	3 399	5 037
2014-03-12	3 273	4 850
2014-03-13	3 326	4 929
2014-03-14	3 327	4 930
2014-03-15	2 675	3 964
2014-03-16	2 187	3 241
2014-03-17	2 727	4 041
2014-03-18	2 626	3 892
2014-03-19	3 160	4 683
2014-03-20	-442	-654
2014-03-21	-379	-561
2014-03-22	-642	-952
2014-03-23	-287	-425
2014-03-24	1 935	2 868
2014-03-25	1 876	2 780
2014-03-26	2 302	3 412
2014-03-27	2 575	3 816
2014-03-28	2 271	3 365
2014-03-29	2 301	3 410
2014-03-30	1 593	2 361
2014-03-31	2 514	3 726