Energy Savings through the Automatic Control of Underground Compressed Air Demand

H. Neser

12826294

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Supervisor: Dr. R. Pelzer

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The sole electricity supplier in South Africa, Eskom, currently has an electricity supply crisis. The supplier requires additional available electricity urgently, particularly during the evening peak period between 18:00 and 20:00. This electricity shortage is due to a steady increase in the demand for electricity, which exceeded the increase in supply capacity, and the inefficient utilisation of electricity.

In order to address this problem, Eskom introduced a Demand Side Management (DSM) programme. The aim of DSM projects is to reduce the load of consumers without negatively affecting consumers. Demand Side Management is beneficial for both Eskom and the client. The client benefits from a lower electricity bill and new equipment, while Eskom benefits from a reduced power demand.

Various DSM strategies are implemented in different sectors, such as mining and residential. These projects are managed by Energy Service Companies (ESCo). The ESCo is responsible for the identifying, implementing, and maintaining the DSM project. Any identified DSM project is presented to Eskom, which agrees to fund the project depending on the proposed power saving. The mining industry, which has been selected as a candidate for DSM projects, as it is a major consumer of energy with numerous DSM opportunities, is examined in this dissertation. Because compressors are major consumers of electricity on the mines, significant DSM opportunities exist on compressed air systems.

The purpose of this research project is to investigate and implement sustainable DSM projects on the compressed air systems of the mining industry. The focus is on automatically controlling the underground demand for compressed air. Reducing the demand for compressed air will result in lower power consumption by the compressors.

**Keywords:** Compressed air control, Control valves, DSM, ESCo, REMS3
Die nasionale verskaffer van elektrisiteit in Suid Afrika, Eskom, ondervind tans 'n tekort aan elektrisiteit voorsienings kapasiteit. Eskom benodig dringend addisionele elektrisiteit voorsienings kapasiteit, veral in die namiddag spitstyd tussen 18:00 en 20:00, om aan die huidige vraag na elektrisiteit te voldoen.

Die huidige tekort aan elektrisiteit is weens 'n geleidelike toename in die gebruik daarvan wat groter is as die toename in opwekkingskapasiteit. Die ondoeltreffende gebruik van elektrisiteit het ook bygedra tot die huidige situasie. Die lae elektrisiteitspryse en die energie intensiewe industrie in Suid Afrika het gelei tot die ondoeltreffende gebruik van elektrisiteit.

Eskom het 'n 'Demand Side Management' (DSM) program geloods in Suid Afrika om die probleem aan te spreek. Die doel van DSM projekte is om die elektrisiteitsverbruik van die verbruiker te verlaag sonder om die verbruiker negatief te beïnvloed. Beide Eskom en die verbruiker baat by die projekte. Die verbruiker baat by verlaagde elektrisiteitskostes en nuwe toerusting, terwyl Eskom baat by die addisionele elektrisiteit wat beskikbaar gestel word.

Verskillende DSM strategieë word geïmplementeer op verskillende projekte en verskillende industrieë. Hierdie projekte word bestuur deur 'Energy Service Companies' (ESCo). Die ESCo is verantwoordelik om moontlike DSM projekte te identifiseer, implementeer en in stand te hou. Enige DSM projek word aan Eskom voorgelê, wat die projek dan goedkeur en finansier. Die moontlike elektriteitsbesparing van die projek bepaal dan die finansiering vanaf Eskom.

Die myn industrie is 'n belowende kandidaat vir DSM projekte, aangesien dit 'n groot verbruiker van elektrisiteit is met verskeie moontlikhede vir DSM projekte. Kompressors is 'n groot verbruiker van elektrisiteit op 'n myn met groot potensiaal vir DSM projekte op die kompressors en druklug verspreidingsnetwerk.

Die doel van hierdie studie is om die moontlikheid van DSM projekte op myne se kompressornetwerke te ondersoek en te implementeer. Die fokus is op die automatiese beheer van die ondergrondse aanvraag en gebruik van saamgeperste lug. Deur die behoefte aan saamgeperste lug te verminder sal die elektrisiteit verbruik van die kompressors dienooreenkomstig ook verminder.

**Sleutelwoorde:** Kompressor beheer, Beheer kleppe, DSM, ESCo, REMS3
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<thead>
<tr>
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<th>Description/Definition</th>
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<tbody>
<tr>
<td>Angle of attack</td>
<td>The angle of impact</td>
</tr>
<tr>
<td>Bar</td>
<td>Unit of pressure, 1 bar equals 100 kilopascals</td>
</tr>
<tr>
<td>Density</td>
<td>The mass per unit volume</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>EES</td>
<td>Engineering Equation Solver</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>A measurement of the energy content of a system</td>
</tr>
<tr>
<td>ESCo</td>
<td>Energy Servicing Company</td>
</tr>
<tr>
<td>Eskom</td>
<td>National electricity supplier</td>
</tr>
<tr>
<td>Eskom evening peak</td>
<td>Period from 18:00 to 20:00, when the electricity demand is the highest</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>GDP (PPP) per capita</td>
<td>Gross Domestic Product purchasing power parity per capita</td>
</tr>
<tr>
<td>GWh</td>
<td>gigawatt-hour</td>
</tr>
<tr>
<td>kPa</td>
<td>kilopascal</td>
</tr>
<tr>
<td>kWh</td>
<td>kilowatt-hour</td>
</tr>
<tr>
<td>MW</td>
<td>megawatt</td>
</tr>
<tr>
<td>NERSA</td>
<td>National Electricity Regulator of South Africa</td>
</tr>
<tr>
<td>Net installed capacity</td>
<td>Sum of the net maximum capacity and reserve margin</td>
</tr>
<tr>
<td>Net maximum capacity</td>
<td>Total operational capacity</td>
</tr>
<tr>
<td>OLE</td>
<td>Object Linking and Embedding</td>
</tr>
<tr>
<td>OPC</td>
<td>OLE for Process Control</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>Pneumatic equipment</td>
<td>Air-powered equipment</td>
</tr>
<tr>
<td>Raise bore</td>
<td>Small vertical opening usually used to transport ore to the surface</td>
</tr>
<tr>
<td>REMS3</td>
<td>Real-time Energy Management System version 3</td>
</tr>
<tr>
<td>Reserve margin</td>
<td>The total spare capacity</td>
</tr>
<tr>
<td>SMS</td>
<td>Short Message Service</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisitioning</td>
</tr>
<tr>
<td>Volumetric flow rate</td>
<td>The flow measured in volume per time</td>
</tr>
</tbody>
</table>
A brief introduction to the global electricity situation and the electricity shortage in South Africa
1 Introduction

As a developing country, South Africa has a fast growing economy and expanding population [1]. It is only natural for developing countries to require more electricity as living standards improve and the economy grows. The demand for electricity in South Africa is steadily approaching the maximum installed capacity as evident from a decreasing reserve margin. Predictions previously indicated that the demand for electricity would equal the supply by 2007 [2]. The predictions proved to be correct, and the results were daily electricity load shedding and forced power cuts. One option for increasing the electricity supply capacity and minimising or avoiding an insufficient power supply is to build new power plants. However, this solution would only be immediately feasible had it been undertaken already, as new power plants will only be operational long after the demand has surpassed the supply [3].

The solution for avoiding electrical blackouts and providing sustainable, reliable, and affordable electricity is to manage and control the demand for electricity. This must be accomplished without causing a negative impact on the country’s economic growth. A combination of improved energy conservation, energy awareness, energy efficiency, and additional energy supply sources will contribute to the success of the solution.

This chapter briefly introduces the global electricity situation and the electricity shortage in South Africa. In Section 2, the electricity demand situation both globally and locally, in South Africa, is considered. Next, the Demand Side Management Programme is discussed in Section 3. Thereafter, energy consumption in the South African mining industry is examined in Section 4. Then, the objectives of this research project are delineated in Section 5. Finally, in Section 6, the chapter outline is presented.

2 Electricity Demand Situation

2.1 Worldwide Electricity Status

Worldwide, non-renewable energy sources are becoming depleted. Yet, due to rising population numbers, growing economies, and rising living standards, the global demand for energy continues to increase [4] [5]. The total worldwide energy demand increased from 82.9 billion GWh in 1980 to 131 billion GWh in 2004. It is further predicated that the demand will increase to 205.7 billion GWh by 2030 [4]. This represents an increase of
nearly 60% from 2004 to 2030 in international demand for energy [4] [5]. These past trends and future forecasts of worldwide energy consumption are shown in Figure 1-1.

![Figure 1-1: Actual and predicted worldwide energy consumption trends [6]](image1.png)

The units of the original graph were changed to SI units

Electrical energy supply contributes nearly 30% to the total world energy demand, with fossil fuels providing two fifths of this supply. Figure 1-2 shows the total contribution, per energy source, for the generation of worldwide electricity supply in 2003.

![Figure 1-2: World electricity generation by fuel type [7]](image2.png)
As illustrated by Figure 1-2, the international tendency is to be dependent on non-renewable energy sources for the generation of electricity. This tendency will need to change due to declining availability and the increase in pollution and global warming awareness [8].

2.2 Electricity Situation in South Africa

South Africa is a land rich in valuable minerals. The South Africa economy is largely based on the extraction and processing of these raw materials, which are energy intensive operations. More than two thirds of our national electricity is consumed by the industrial and mining sectors, which are the largest consumers of energy [6] [9].

South Africa’s energy intensive economy is largely dependent on cheaply mined indigenous coal, which provides 68% of South Africa’s energy demand [6] [8]. Figure 1-3 illustrates the primary energy sources in South Africa for 2004 [10]. Hydroelectric power stations contribute insignificantly to the total energy sources.

Eskom has twenty-four power stations, of which thirteen are coal fired [11]. Electricity in South Africa is thus mainly generated by coal-fired power stations, which supply up to 53% of South Africa’s electricity requirements [12]. In 2007, 119.11 megatons of coal were burned to provide the 218 120 GWh of electricity sold [13]. The generation of electricity is largely driven by local and cheaply mined coal, which has lead to relatively low electricity prices in South Africa compared to international tendencies as depicted in
Figure 1-4 for 2007. This is the main reason for the overall inefficient utilisation of electricity in South Africa [9].

![Electricity Prices](image)

**Figure 1-4: Electricity prices**

*indicated in South African currency

This is however set to change drastically, as Eskom has proposed a significant increase of 53% in the electricity price during 2008. The National Energy Regulator of South Africa (NERSA) rejected this proposed increase on the 18th of June 2008, but an increase of 13.3% was granted. This is in addition to the 14.2% increase approved in December 2007, resulting in a total price increase of 27.5%. The National Energy Regulator of South Africa also approved an annual increase of between 20% and 25% for the next three years, should the present situation not improve. This is in a desperate attempt to force consumers to reduce their electricity consumption and implement energy efficient practices, and generate more revenue, to address the electricity shortage in the country [14].

This increase in the electricity price will increase the production cost of metals. The introduction of a penalty system for industries that do not reduce their power consumption by the required amount will also influence the production cost. This will lower the profit margin and negatively influence the economy [15] [16].

In 2001, South Africa had the 26th largest Gross Domestic Product (GDP) in the world and was the 16th largest consumer of energy in the world [17]. In comparison to the rest of the world, South Africa consumes large amounts of energy per GDP as evident from Figure 1-5.
The two main reasons for this are:

- South Africa’s economy is dominated by mining, mineral processing, metal smelting, and synthetic fuel production, which are all energy intensive [18].
- There is a lack of energy efficiency awareness in South Africa, because the low cost of electricity does not encourage its efficient and economical application [17] [19].

The real GDP grew at 4.8% and 5.3% for the third and fourth quarters of 2007, respectively [20]. These figures indicate that South Africa’s economy, and consequently the demand for energy, is growing rapidly. It is expected that approximately 47,252 MW installed capacity will be required by 2010, while existing installed capacity is 40,000 MW [21] [22].

An additional 190 MW and 1360 MW generation capacity was commissioned during 2006 and 2007, respectively [13]. The electricity demand and the net installed capacity (sum of net maximum capacity and reserve capacity) are illustrated in Figure 1-6 for the period December 1997 to March 2007. The decreasing trend in reserve capacity is illustrated by the narrowing difference between net maximum capacity and net installed capacity.
The internationally accepted standard is a reserve capacity margin of 15%. Before 2007, Eskom was able to maintain a reserve margin above this level at between 15% and 20%. With recent increases in demand, generator failures, and generation problems, this margin has been drastically reduced to between 8% and 10%. The lowest reserve margin at peak was recorded at 7.9% in 2007 [22] [24].

From 1994, the government has committed itself to providing affordable electricity to previously disadvantaged urban and rural households [6] [25]. The percentage of electrified households increased from 36% in 1995 to over 70% in 2001 [26]. With this ambitious electrification project by the government and an increased energy demand from the mining industry, the total energy demand has drastically increased with little additional generation capacity commissioned.

In Figure 1-7, the energy demand per sector is illustrated for 2003. The three main consumers are the industrial, mining, and residential sectors. In terms of the last, it is interesting to note that roughly 30% of residential electricity is consumed during peak periods [27].
The recent growth in electricity demand and the predicted shortfall led to research into the daily consumption patterns, in order to determine methods to manage the demand of consumers during the day, rather than just increasing the supply. In order to determine the factors influencing the demand profile, Eskom launched an intensive investigation and found the following [17] [18]:

- **Seasonal changes** have a significant influence on electricity demand. During the winter months, June, July, and August, the consumption of electricity increases significantly. This increase is mostly due to increased use of heating appliances throughout the day. In Figure 1-8, the average increase in demand during a typical winter's day in comparison to a typical summer's day is illustrated, where the higher increase in peak demand for a typical winter's day compared to a summer's day is evident.

- The daily electricity demand is dependent on the **time of the day**. Two peak periods were identified by Eskom, namely, the morning peak (07:00 to 10:00) and the evening peak (18:00 to 20:00). During these periods, a sharp increase in demand is experienced, as shown in Figure 1-8. Although the morning peak lasts longer than the evening peak, the evening peak demand is higher and therefore of greater concern.

- Different **types of days** also influence the demand profile differently. Eskom classifies the days as weekdays, Saturdays, Sundays, and public holidays. The difference in demand between these days is because of the average consumer following a different routine depending on the type of day. During weekdays, the average demand is higher than for the weekends as shown in Figure 1-9.
The daily peaks in electricity demand are mainly due to municipal (residential) use. Industrial and mining sectors have a relatively constant demand, while municipal demand varies depending on the daily activities of its consumers, as illustrated in Figure 1-9. This effect will become more evident and problematic as the population grows and more households are electrified [6].

The problem of insufficient supply capacity and peak demand periods is an interminable problem. As the population grows and industries expand, more electricity is required, increasing the total demand and the peak demand. Eskom is constructing additional power stations: these consist of two open-cycle gas turbine stations, one north of Cape Town and one west of Mossel Bay; a coal-fired power station west of Lephalale; and a pumped
storage scheme near Ladysmith [13] [21]. Three mothballed coal power stations near Ermelo, Belfour, and Middelburg are also being returned to operational status. Eskom is presently also upgrading and expanding its infrastructure and distribution networks [13] [21]. An additional 14 759 MW generation capacity will be installed by 2017 [29].

Although this additional capacity will increase the supply capacity and the reserve margin, it does not address the real problem of controlling the growth in demand and reducing the maximum demand peak in the daily profile. Eskom introduced a variable pricing structure in an attempt to manage the daily demand profile. The price per kWh unit differs according to the three factors outlined above that influence the demand profile, namely, the season of the year, the time of day, and the type of day. In addition to this, Eskom introduced a number of tariff structures, to satisfy the specific needs of each user type. These structures are grouped into three different categories, namely, urban, residential, and rural tariffs [30]. The two types of urban tariffs mostly used in the mining and industrial sector are:

- **NightSave**: Tariff for customers with a Notified Maximum Demand from 25KVA. This tariff consists of two different time-pricing periods, namely, peak and off-peak [30].
- **MegaFlex**: Time-of-use electricity tariff for customers with a Notified Maximum Demand in excess of 1 MVA who are able to shift load. This tariff consists of three different time-pricing periods, namely, peak, standard, and off-peak [30].

The majority of mines and industries are charged based on the MegaFlex tariff structure. This tariff structure is designed for the continual operations commonly associated with the mining and industrial sectors.

![Figure 1-10: Megaflex period structuring [30]](image)
The MegaFlex tariff structure makes provision for peak periods (in red), off-peak periods (in green), and standard periods (in yellow) as denoted in Figure 1-10; these are based on the type of day. The different prices per kWh for each period are stipulated in Table 1.1, which are based on the season in addition to the type of day. Higher prices apply during the high-demand season with a significant increase in the price per kWh (an increase of roughly 350% compared to the low-demand season) during peak periods.

Table 1.1: Megaflex pricing structure as of January 2008 [30]

<table>
<thead>
<tr>
<th>High-demand season (June–August)</th>
<th>Price period</th>
<th>Low-demand season (August–June)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74.21c/kWh</td>
<td>Peak</td>
<td>21.06c/kWh</td>
</tr>
<tr>
<td>19.62c/kWh</td>
<td>Standard</td>
<td>13.07c/kWh</td>
</tr>
<tr>
<td>10.67c/kWh</td>
<td>Off-peak</td>
<td>9.26c/kWh</td>
</tr>
</tbody>
</table>

As illustrated by Figure 1-8 the average demand is higher during winter, particularly during the peak period between 18:00 and 20:00. Therefore, in an attempt to force consumers to change their demand profile, the price for this period was radically increased. This alone was not effective enough, and therefore, Eskom introduced the Demand Side Management (DSM) Programme. This programme is discussed in the next section.

3 Demand Side Management Programme

Demand side or energy demand management was first implemented in the 1970s in the United States by their government. Such programmes were developed because of the fossil fuel scare of the 1970s. During the 1980s, power utilities began to design and implement DSM programmes [31] [32] [33].

Demand side management can be defined as actions that influence the amount of electricity consumed and the consumption pattern of the consumers. This includes the reduction of peak demand when electricity supply capabilities are limited [31]. Demand side management aims to improve the efficiency of electrical equipment, by upgrading the equipment, introducing energy efficient procedures, and manipulating energy usage profiles, while maintaining the same level of service [34].
Although DSM is not a new concept, it was only introduced by Eskom to South Africa in 1992 [18]. Eskom has since invested large amounts of capital and research in the development and implementation of DSM. Demand side management in South Africa is the process by which Eskom induces changes in consumer behaviours, through specific energy-saving programmes. It is predicted that the implementation of DSM could postpone the need for additional installed capacity from 2007 to some time between 2015 and 2025 [33]. It is expected to save an accumulative total of 4,255 MW over its twenty-year planned operation [28].

The key benefit of DSM is energy saving, while other significant benefits include financial savings for both suppliers and consumers and a positive contribution towards limiting climate changes. As energy consumption patterns are changed or energy consumption is reduced, the expansion of installed supply capacity and distribution networks can be postponed, thus decreasing the emission of greenhouse gases [34].

In accordance with the Kyoto Protocol signed by 174 countries, including South Africa, which signed in 2005, South Africa agreed to reduce its greenhouse gas emissions. Demand side management can thus also contribute to achieving the reduction targets as set out in this protocol [8].

The changes induced by DSM can be categorised as energy efficiency (energy conservation) or energy management. Both these initiatives aim at reducing consumers’ demand and improving the efficient usage of electricity. **Energy efficiency** refers to the overall reduction in electricity consumption, while **energy management** refers to influencing the consumer’s daily consumption patterns. Energy management can be accomplished by peak clipping, load shifting, and valley filling.
Peak clipping refers to the method through which the demand during peak periods is reduced. Consumers' demand throughout the remainder of the day is unaffected as illustrated in Figure 1.11 (a) [31] [35]. In addition, there is a financial benefit for consumers, as less electricity is used.

The aim of load shifting is to change the demand profile of the user. The average power demand is not affected, as the load is only shifted to off-peak periods and not reduced. The system is thus energy neutral. This results in a reduced load on power plants and distribution networks during peak periods. The effect of load shifting is illustrated in Figure 1.11(b) [31] [35]. The financial benefit results from more electricity being used in the cheaper off-peak periods and less during the more expensive peak periods.

The goal of valley filling is to increase off-peak loads, in order to smooth out the load and improve the economic efficiency [31], as illustrated in Figure 1.11(c). This method does not necessarily imply any financial savings or reduction in demand but improves the overall efficiency, as the demand is much more uniformly distributed.

The implementation of energy efficient methods results in the overall reduction of energy demand and emission of greenhouse gases, due to reduced demand from power plants and distribution networks. Energy efficient methods also have the desired effect of reducing required maintenance and equipment replacement costs. This is because the equipment is more accurately monitored and controlled within safe operational limits, and because of increased equipment efficiency. Figure 1.11 (d) illustrates the effect of energy efficient methods on the demand profile [31] [35].
The predicted effect and benefit of DSM on national demand is illustrated by Figure 1-12. A total of 72.30 MW was saved through DSM, in 2006, and 169.80 MW, in 2007, [13].

Demand side management implementations can be viewed as the construction of a virtual power station through the saving of electricity. The electricity saving from this virtual power station can be utilised without placing additional strain on the power plants and networks. The projected saving due to DSM projects is indicated by the turquoise area in Figure 1-12. The total installed capacity is the sum of the existing capacity (green) and the reserve margins (blue and yellow).

Thus DSM can be summarised as the implementation of electricity conservation policies that will control, influence, and reduce electricity demand without negatively affecting consumers [34]. By implementing DSM, the electricity supplier will be able to more readily meet consumers’ demand and provide a higher level of service. The national target for energy efficiency is an improvement of 12% by 2015 [37]. In order to achieve DSM benefits, Eskom contracts Energy Servicing Companies (ESCos) to implement DSM projects.

Various parties are involved in a DSM project Figure 1-13 illustrates the relationships between these parties. Potential projects are investigated by the ESCo and a proposal submitted to Eskom. The financing of a project by Eskom is proportional to the proposed power saving potential. This performance-based contracting is the key difference between ESCos and other load management firms [18].
Currently, Eskom is focusing on reducing consumption during the evening peak (18:00 to 20:00), with 100% financing on a load shifting/load reduction project. The focus, in the near future, will be the implementation of energy efficiency projects that currently have only 50% financing by Eskom [36]. The ESCo will sub-contract qualified firms to undertake the required infrastructure upgrades for clients, to enable the ESCo to achieve the contractual power savings. The ESCo will manage the project, in order to ensure the project is completed on schedule and within budget constraints, and realises the required savings.

In summary, ESCos are companies who implement DSM projects. The role of ESCos is to identify DSM projects, develop project proposals, implement and manage the project, and ensure its sustainability [28]. The potential for these projects in relation to energy consumption in the South African mining industry is examined in the next section.

4 Energy Consumption in the South African Mining Industry

There is significant potential for DSM in the mining sector because of its dependence on electricity as a source of energy [3] [23]. The gold mining sector is ranked as the third largest consumer of electricity and ranked first as the sector with the most DSM potential. Platinum mining is rated as the sixth largest consumer of electricity and the fifth largest sector according to DSM potential [38]. In 2005, the South African energy efficiency strategy set a target for the mining industry to reduce its energy demand by 10 to 15% before 2015. This will require a year-on-year reduction rate of between 1% and 1.5% [39]. The South African mining industry consumes 17.6% of the total electricity generated in South Africa [3]. This represents approximately 67% of the total
energy consumed by the mining industry. For 2003, this resulted in an electricity bill in excess of five billion rand [40].

Early in the first quarter of 2008, mines were forced to reduce their electricity demand. Eskom limited the mines to function at 90% of their normal electricity consumption. This had a negative effect on the mining industry, as many mines were unable to operate under this constraint. For some mines, their production dropped to a level where it was no longer financially viable or possible to operate. Many jobs were under threat as some mines were considering closing down or retrenching employees. Such actions, resulting from the enforced consumption reductions, will only contribute negatively to the already high unemployment and crime rates.

Compressors consume the most energy, with an average consumption of up to 21.3% of the total energy consumed by the mine [39] [40]. Other large energy consumers in the mining industry include the pumping systems (17.7%) and the mine hoisting systems (14.2%) [39]. Compressed air is mainly used for drilling, but new methods that use hydropower could drastically lower this. Compressors fulfil an important and invaluable role in the mining industry, as compressed air is required throughout the day, with a higher pressure required during the peak mining period from 6:00 to 14:00. During this period, only certain sections in the mine require the higher pressure, while other sections can operate at a lower pressure.

It is clear that the compressed air requirement of the mine is very diverse. Presently there is little or no control of the demand for compressed air; only the supply of compressed air is managed. There is an opportunity for DSM in the mining sector, to achieve energy savings through the control and management of the compressed air demand. In addition to assisting South Africa in meeting the energy requirements of a developing population and expanding economy, by lowering its energy usage, the mining industry will also make a positive contribution to the environment [40].

In response to the above problem statement, the research objectives of this project are delineated in the following section.
5 Objectives of this Research Project

In light of the preceding discussion, the main objectives of this research project are to examine DSM potential on the demand side of a compressed air network in the South African mining industry and implement an appropriate control strategy. In particular, the objectives are:

- to investigate compressed air system of a mine, in order to determine the potential for energy efficiency;
- to determine optimal infrastructure upgrades, in order to increase the energy efficiency of the compressed air system;
- to design and implement a DSM control system, in order to control and automate the existing equipment and upgraded infrastructure;
- to determine and implement optimised control schedules and parameters, in order to increase energy efficiency, while adhering to the mine’s operational, health, and safety constraints; and
- to optimise the control system, in order to realise maximum cost savings achieved by reducing electricity consumption.

By implementing an effective control procedure, the following benefits can be achieved:

- electricity demand reduction by the mine;
- electricity supply reduction for Eskom;
- financial cost savings for the mine and Eskom;
- increased efficiency of the compressed air networks; and
- reduction of greenhouse gas emissions.

The dissertation, which reports on the results of the research project based on these objectives and projected benefits, is outlined in the next section.
6 Chapter Outline

In Chapter 2, the compressed air system in the mining sector will be examined. This will include the supply methods, control options, and the consumption of compressed air. Next, the types and applications of compressors in the mining industry will be presented. Thereafter, the compressed air distribution network on a typical mine will be considered. Finally, possible control methods for reducing the power consumption of mines based on the reduced power consumption of compressors will be discussed and their effectiveness illustrated.

In Chapter 3, the theory of controlling the pressure or mass flow by means of a valve will be explained. A simulation developed during the research project will be described and the effect of valve opening and airflow rate on the downstream pressure illustrated. In addition, the DSM possibilities associated with the installation and effective utilisation of control valves on underground levels will be illustrated.

In Chapter 4, a description of the control software and interfacing to the compressor network to control the valves and monitor the system will be presented. Thereafter, the control procedures that were implemented in three mines will be discussed and explained.

In Chapter 5, the results of implementing a valve control system on the three mines will be presented and discussed separately for each case study. The effect of controlling the pressure on the various levels according to the specific requirements of each level and the savings achieved will be illustrated.

In Chapter 6, the dissertation will be concluded. The effect of the implemented control procedures on the mining sector and Eskom will be summarised. Recommendations for further studies and investigations into DSM possibilities on compressed air systems in the mining sector will be given.
A discussion of the electricity consumption of mines in relation to compressed air systems.
1 Introduction

Chapter 1 presented the background to large power consumption in the South African mining industry. In particular, it introduced compressors, which are the largest consumers of energy on mines and are a crucial requirement for daily mining activities [38]. The life cycle cost for a typical compressor over a 10-year time span is illustrated in Figure 2-1. As illustrated, the running cost of a compressor, at 73% of the total costs, outweighs all other costs associated with it.

As the compressor’s main cost is associated with its operation and the fact that compressors are invaluable in the mining sector, significant DSM potential is associated with compressors. In order to obtain a better understanding of potential energy savings associated with compressors in the mining industry, it is necessary to understand the compressed air system and the requirements of a typical mine.

This chapter examines the electricity consumption of mines in relation to compressed air systems. In Section 2, types and applications of compressors in the mining industry are presented. Thereafter, the compressed air distribution network on a typical mine is considered in Section 3. Lastly, various possibilities for reducing the power consumption of mines based on the reduced power consumption of compressors are explained in Section 4.
2 Types and Applications of Compressors in the Mining Industry

Different categories of compressors are available, each with its own advantages depending on the application and requirements of the system. The various types of compressors are given in Figure 2-2. The two main categories of compressors are dynamic and positive displacement compressors, which are defined below.

![Figure 2-2: Different types of compressors [41]](image)

**Dynamic Compressors**

"Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers." [42]. An example of a dynamic compressor is shown in Figure 2-3.
Positive Displacement Compressors

"In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge." [42]. An example of a positive displacement compressor is illustrated in Figure 2-4.

The decision regarding which type of compressor is most suited for the intended application is primarily influenced by the following:

- the level of air quality required by the application;
- the flow rate and pressure required;
- the capital available; and
- the associated running costs.

Table 2.1 summarises the average volumetric flow rates required for several types of pneumatic equipment commonly used in the mining industry [44]. Compressed air in the mining industry is mainly used for stope drills, mechanical ore loaders, diamond drills, refuge bays, agitation of dam contents, and loading boxes, which are discussed in the subsequent sections.
Table 2.1: Air consumption of pneumatic equipment [43]

<table>
<thead>
<tr>
<th>Pneumatic Equipment</th>
<th>Use</th>
<th>Average Air Usage (m3/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stope Drills</td>
<td>Used on the stopes to drill holes for the explosives</td>
<td>0.42</td>
</tr>
<tr>
<td>LM250 Ore Loaders</td>
<td>Used to transport the ore on the levels</td>
<td>0.28</td>
</tr>
<tr>
<td>Diamond Drill</td>
<td>Used for development in the mine</td>
<td>0.14</td>
</tr>
<tr>
<td>Refuge Bays</td>
<td>Safe haven for underground personnel</td>
<td>0.01</td>
</tr>
<tr>
<td>Loading Boxes</td>
<td>Used to accumulated and guide the ore to the skips</td>
<td>0.026</td>
</tr>
</tbody>
</table>

- **Rock Drills**
  In South Africa, the tendency in the mining industry is to use pneumatic drills, rather than hydro- or electrically-powered drills. Rock drills are the main consumers of compressed air during mines’ peak production periods. During these periods, the demand for compressed air is at its highest and thus too is the power consumption of the compressors at its highest.

- **Mechanical Ore Loaders**
  A constant supply of compressed air at a predetermined pressure is required for the mechanical ore loaders to function properly. Should the pressure be too low, the ore loaders will not be able load ore into the loading boxes, thereby hampering production.

- **Diamond Drills**
  Diamond drills are used in mines mainly for development work on the levels. Therefore, these drilling operations are not governed by mining operations and are thus generally used throughout the day.
• **Agitation of Dam Contents**

In order to prevent sediment forming in the dams, the dam contents must be agitated continuously. This is achieved with a constant flow of air through the dams, preventing settlement. These agitation systems are usually open-ended pipes located on the bottom of the dams through which air is pumped. The advantage of using compressed air for agitation is that the use of mechanical systems is eliminated, resulting in minimal maintenance.

• **Refuge Bays**

Refuge bays are of immeasurable importance in the mining industry. By law, mines are required to provide a place of safety for personnel working underground. In the event of gas leaks, fire, or any dangerous situation, a refuge bay serves as a safe haven for mining personnel. These bays are pressurised with compressed air, in order to supply a continuous flow of fresh clean air and prevent external gases from entering the bays.

• **Loading Boxes**

The loading boxes are used for accumulating and guiding the ore to the skips. These boxes open and close by means of compressed air. With too low an air pressure, these boxes are unable to operate and ore cannot be transported to the surface. This results in production losses for mines, with an associated reduction in profit margins.

Owing to all the diverse pneumatic equipment on mines, large distribution networks are required. The disadvantage of these networks is the increased risk of air leaks. The amount of air lost compared to the size of the leak at various pressures is illustrated by Figure 2-5 for a few orifice diameters and pressures. As illustrated, the volume of air lost increases exponentially as the orifice diameter increases and increases with an increase in pressure [42].
This is an inevitable problem associated with large compressed air distribution networks. The surface networks are exposed to harsh climatic conditions and deteriorate quickly; therefore, maintaining an airtight network is very difficult. Leaks in these systems waste significant amounts of energy, sometimes up to 30% of a compressor’s output. The most common places for leaks are at couplings, hose connectors, tubes and fittings, pressure regulators, and shut-off valves [42]. By controlling the pressure at the minimum required system pressure, losses through leaks can be minimised. This alone results in significant savings on compressed air systems.

Another problem associated with compressed air in the mining industry is the misuse of compressed air. In the underground sections, the compressed air is misused for cooling, cleaning, and ventilation. A solution would be to force workers to use compressed air efficiently for the purpose for which it is intended. However, it is difficult to control and monitor workers in their use of compressed air.

A typical compressed air pressure and power profile is shown in Figure 2-6 for a gold mine with centralised blasting. Clearly illustrated in the figure is the pressure drop during the peak drilling period, from 06:00 to 14:00, as more compressed airflow is required. During this period, the power consumption of the compressors increases, as illustrated, to compensate for the increase in compressed airflow. Once the drilling period is completed, the demand for compressed air...
decreases and the pressure in the system increases. This will result in a decreased power consumption of the compressors.

Figure 2-6: Typical power and pressure baseline of a mine

The different shifts of a typical mine are shown in Figure 2-7 [45]. The most power is consumed during the drilling period from 6:00 to 14:00 as is evident from Figure 2-6 as well. The mining activities are minimal from 14:00 to 21:00, following the drill shift, during the explosive charge-up shift and the no-entry period when dangerous gases are extracted.

Figure 2-7: Different mine shifts [45]
The different shifts of a mine have to be considered, in order to ensure efficient and effective control of compressed air use and thus power consumption. The ideal method for controlling the compressed air demand, in order to achieve maximum power savings efficiently will be influenced by mining shifts and activities. In the next section, the compressed air distribution network on a typical mine is considered.

3 Compressed Air Distribution Network on a Typical Mine

The function of a compressed air distribution network is to distribute and deliver the compressed air to the point of use with minimal loses. The two distribution networks for compressed air systems are stand-alone systems and ring feed systems, which are detailed in the following sections.

Stand-alone or Single Main Systems

In the mining industry, networks in which all the compressors are located at a single point or the compressors feed a single shaft, as demonstrated in Figure 2-8, are termed stand-alone or single main systems. Maintenance work and leak detection are relatively easy due to the simplicity of the system. This type of system also has a more predictable nature than the more complex ring feed system [41] [44].

![Figure 2-8: Layout of a typical stand-alone distribution network](image-url)
Ring Feed Systems

In a ring feed system, there are numerous take-off points as well as add-in points as illustrated in Figure 2-9. Multiple compressors are located at various points, all interconnected in a ring configuration. Control valves are installed at the take-off points, to control the pressure supplied to the user according to minimum pressure requirements.

Some advantages of a ring feed system are [41] [44]:

- The logistics of maintenance is easier as sections of the ring can be isolated for maintenance without influencing the rest of the ring.
- Air is supplied from more than one point.
- A large array of control options is available.

As with any system, there are also some disadvantages [44]:

- Maintenance can be cumbersome due to the large distribution networks associated with ring feed systems.
- There can be large pressure drops due to the large distribution networks.
- A change in demand at one take-off point influences the supply to other take-off points.

Various possibilities for reducing the power consumption of compressors are explained in the subsequent section.
4 Methods of Controlling Compressed Air Supply and Demand

Optimisation of compressed air networks can improve energy efficiency by between 20% and 50% [56]. Various methods can be used to control the power consumption of compressors, while still delivering the required compressed air. These methods vary from controlling the mass flow of air entering the compressor to controlling the demand for compressed air from the end users. These methods have the desired effect of reducing the compressed air that needs to be generated and thus the power consumption of the compressors. Another method is to store compressed air during off-peak periods. This stored compressed air is then utilised during peak periods, resulting in a lower demand for compressed air from the compressors. Different methods of optimisation are discussed in detail below.

4.1 Use of Inlet Guide Vanes

Inlet guide vanes are used to control the delivery of compressed air from the compressor, by controlling the intake of air. Inlet guide vanes do not control the demand for compressed air and are only utilised for controlling the supply or delivery pressure of the compressor [46].

Inlet guide vanes are mounted on the inlet to the first stage of the compressor and the guide vane angles (angle of attack) are controlled, to vary the delivery pressure. A Moore controller is used to control the guide vanes and compressor valves in such a manner that the correct pressure is delivered and maintained. The guide vane’s angle of attack controls the air velocity and the volume of airflow into the compressor chamber. The angle of attack is dependent on the compressor pressure set point and the demand for compressed air. Should the demand for compressed air decrease, the pressure will build up to a point above the pressure set point and the angle of attack will reduce as shown in Figure 2-10(a). Should the demand increase, the pressure will drop to a point below the pressure set point and the angle of attack will increase, as illustrated in Figure 2-10(b).

The guide vanes are thus implemented to control the delivery pressure of the compressors, by varying the angle of attack. This influences the volume of air that flows into the compressor chamber, as well as the velocity of airflow.
A study conducted by Andrew Garbers on the Vaal River mining operations of AngloGold Ashanti quantified the effectiveness of utilising inlet guide vane control. In Figure 2-11, the result of implementing inlet guide vane control is illustrated [45]. The pressure requirements (yellow line) were closely followed by utilising guide vanes as confirmed by the actual pressure (red line).
Examples of guide vanes are given in Figure 2-12. The inlet guide vanes can influence the delivery pressure by changing the angle and velocity by which the air is drawn in and directed onto the impellers.

![Guide-vane assembly](image)

**Figure 2-12: Guide-vane assembly [50]**

Axial and centrifugal compressors can enter an undesirable state of surge, and it is the function of the Moore controller to prevent the compressor from surging. The Moore controller manipulates the blow-off valve and guide vanes of a compressor, to enable the compressor to deliver the required pressure without entering a stage of surge.

Surge occurs "when the flow in the compressors decreases sufficiently for any speed or guide vane angle, to cause flow reversal in the compressor. Flow reversal occurs when the downstream system pressure exceeds the pressure developed by the compressor. Surge appears as rapid pulsations in the flow and discharge pressure, which invariably causes damage to the compressor, associated piping and upsets to the process" [51].

A unique compressor characteristic curve is associated with every compressor. This curve serves to specify the safe operational characteristics of the compressor. The Moore controller will control the compressor, to operate within the safe limits of this curve, to prevent surging [44].

An example of a compressor surge curve is shown in Figure 2-13. The operating point of the compressor is established at the intersection of the pressure ratio (y-axis) and the volumetric flow rate (x-axis). In order to avoid surging, the operating point should be
below the surge curve. The volumetric flow rate is specified in cfm or m³/h, while the pressure ratio is determined as shown in Equation 2.1.

\[ \Pi = \frac{\text{Downstream pressure}}{\text{Atmospheric pressure}} \]  \hspace{2cm} 2.1

Figure 2-13: Compressor surge curve

The utilisation of guide-vane control is an effective method to achieve power savings. The pressure delivery of the compressors can be controlled to the requirements of the users. An effective guide-vane controller also reduces compressor surge, since the controller controls the compressor to operate within its safe operating limits.
4.2 Selection of Compressors

Regardless of the number of compressors available, the optimum energy usage will be obtained by running the minimal number required and the most efficient. This method of compressor selection does not influence or control the supply or demand but does minimise the power consumption; less power is used to maintain the required air pressure by using the most efficient compressors. By performing regular and comprehensive maintenance on the compressors, compressed air can be generated more efficiently with lower operational costs.

Evaluation of compressor efficiency is based on various kinds of efficiency, which are defined based on several factors. Several types of efficiency are defined below [42] [52]:

- **Adiabatic efficiency**: Adiabatic efficiency is defined as the ratio of adiabatic power to actual power.
- **Mechanical efficiency**: Mechanical efficiency is a measure of losses due to mechanical friction in a system.
- **Overall efficiency**: Overall efficiency is defined as the ratio of adiabatic or isothermal power to shaft power. This ratio is also termed compressor efficiency.
- **System efficiency**: The system efficiency of a compressor system is defined as the product of the compressor’s overall efficiency, overall motor efficiency, overall controller efficiency, and overall efficiency of all auxiliary devices.

By utilising the minimal and most efficient compressors, power savings can be achieved. This method can be implemented quickly, as no additional infrastructure is required.

4.3 Storage of Compressed Air Energy

Compressed air energy storage cells are used to store energy in the form of compressed air. The compressed air is stored during off-peak periods and used during peak periods. The compressed air is stored in large underground cavities or cells as shown in Figure 2-14, on the next page.

The compressed air stored during off-peak periods is then utilised during peak periods to power either pneumatic equipment or turbines connected to generators, in order to generate electricity. This method does not necessarily decrease overall power consumption but
changes the power usage profile of the compressors, as more power is used in the cheaper off-peak periods and less in the more expensive peak periods.

Two types of cavern design concepts are generally used based on constant pressure or constant volume. The storage systems function according to Boyle's Law, which states that the pressure is inversely proportional to the volume in a closed system [55]. In the case of a constant volume cavity, the storage cells do not form a closed system, and therefore drawing air from a cell will result in a pressure decrease over time. In order to overcome this problem and ensure a constant pressure supply from the storage cell, a water system is implemented. As air is consumed from the cell, the cavity is filled with water, which reduces the volume of the cavity and maintains a constant pressure in the cavity. Such a system is more complicated in design and safety than a constant volume cavity. The disadvantage of the constant volume cavity system is the decrease in pressure as air is consumed from the cavity [53].

Air storage systems are not a very practical solution, as large storage cavities are required and there are significant safety issues that render this impractical in the mining environment.
4.4 Valves

The various underground sections may have different air pressure or flow requirements and any excess air supplied will be wasted. Valves can be used to control the supply of compressed air to the different sections of the mine. By installing valves, the pressure or flow of each section can be controlled according to the specific pressure requirements of each section. The installation of valves on the levels will also take advantage of the effect of auto-compression, which results from the pressure on the levels being higher than the supplied pressure due to the variation in depth. This relationship between depth and pressure is illustrated in Equation 2.2 [54].

\[ p = p_0 + \rho gh \]  

where:
- \( p \) = the unknown pressure in Pa;
- \( p_0 \) = the known pressure at the reference height in m;
- \( \rho \) = the density of the air in kg/m\(^3\);
- \( g \) = the gravitational acceleration in m/s\(^2\); and
- \( h \) = the difference in height in m.

Installing valves can have the desired effect of power savings by:
- closing off sections not requiring compressed air;
- regulating the flow and pressure to the different sections; and
- minimising air losses through leaks because pressure and flow is minimised.

The compressed air can be controlled using pressure sustaining valves or control valves (installed on the surface or underground).

**Pressure-Sustaining Valves**

Pressure sustaining valves are specifically designed to maintain a specified upstream or downstream pressure in the line. Different valve types are available to control the downstream pressure or maintain a steady upstream pressure. An example of a pressure sustaining valve is given in Figure 2-15.
The disadvantage of these valves is that the control set point is manually controlled by means of a mechanical adjustment on the valves. The control is also mechanical, as the valve opening is controlled with the line pressure. Pressure sustaining valves are ideal for applications that are constant, where the pressure will be sustained at a specified pressure without change for an indefinite time. This type of valve is unsuitable for use on mines' compressed air systems, where the pressure set point changes throughout the day.

**Control Valves**

Control valves are valves that can be controlled automatically or manually according to a process variable, to control air pressure or flow. These are standard valves fitted with an actuator, as shown in Figure 2-16, and can be connected to a Supervisory Control and Data Acquisitioning (SCADA) system through a Programmable Logic Controller (PLC). This is the main difference between a control valve and pressure-sustaining valve. The control valve can be controlled manually by an operator or automatically by the interconnected SCADA system and PLC.
Control valves control the pressure in accordance with Bernoulli's Theorem, which states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure. This is mathematically represented for non-compressible fluids by Equation 2.3 [47]

\[ \frac{1}{2} \rho v^2 + \rho gh + p = \text{constant} \]  

where:

- \( v \) = the fluid velocity in m/s;
- \( g \) = the gravitational acceleration (9.8 m/s\(^2\));
- \( h \) = the height of the point above a reference in m;
- \( p \) = the pressure at the point in kPa; and
- \( \rho \) = the density of the fluid in kg/m\(^3\).

As Equation 2.3 illustrates, the pressure is dependent on velocity, density, and height. The velocity is dependent on area and volume flow as illustrated by Equation 2.4.

\[ Q = A V \]  

where:

- \( Q \) = the volume flow in m\(^3\)/s;
- \( A \) = the area in m\(^2\); and
- \( V \) = the velocity in m/s.

Velocity is thus influenced by the diameter of the pipe and valve opening. A smaller opening causes velocity to increase, in an attempt to keep the mass flow constant. According to the law of energy conservation, the mass flow (in kg/s) must remain constant throughout the system.

Installing the valve on the surface line or on the different underground levels will result in different results as explained below.

**Surface Installation**

The installation of surface control valves enables the control of the compressed air supplied to each take-off point connected to the ring feed system. The different consumers connected to the ring have different pressure requirements and the ring pressure will be controlled according to the requirement of the consumer with the highest pressure.
requirement. Supplying some consumers with a pressure higher than that required is unnecessary, as the compressed air is wasted. By individually controlling the compressed air supply of each shaft, significant power savings can be achieved.

Underground Installation
Underground installation of control valves enables even greater power savings. The air supplied to each level can be controlled more accurately with underground valves, as the pressure requirements of the levels may also vary. Controlling the air pressure on the levels according to the actual required air pressure reduces the compressed air that needs to be generated and the air wasted through leaks. Closing the valves will cause an upstream pressure build-up, resulting in the compressor inlet guide vanes reducing their angle of attack.

5 Conclusion
This chapter has examined the electricity consumption of mines in terms of compressed air systems in particular. Types and applications of compressors in the mining industry have been presented. It has been shown that the mining industry cannot operate without compressed air because of the various mining equipment that is dependent on compressed air. In addition, it has been noted that the dependency on compressed air for daily operations is costly as compressors are large consumers of energy. Thereafter, the compressed air distribution network on a typical mine has been considered. In this section, it has been demonstrated that significant DSM and financial savings can be achieved by effectively managing the supply and demand for compressed air through compressed air distribution networks. By managing the supply and demand efficiently, the compressed air consumption will be lowered, reducing the power consumption of the compressors. Lastly, various possibilities for reducing the power consumption of mines based on the reduced power consumption of compressors have been explained. The installation of pressure control valves on different underground levels has been indicated as an effective measure of controlling the demand of compressed air according to the specific requirements of each level.
The following results of effective utilisation of pressure control valves and control procedures have been mentioned:

- The pressure delivered to each level will meet the requirements more precisely.
- The control of the underground pressure control valves will cause an upstream pressure build-up, causing the surface control valve to close more or the compressors’ guide vanes to reduce the angle of attack.
- The throttling of the surface control valve in turn causes a build-up of pressure in the compressed air ring, due to the reduction of airflow to the shaft from the ring, causing the compressor guide vanes to reduce the angle of attack.
- The air lost through leaks will be minimised.
- The power consumption of the compressors will be reduced, resulting in financial savings for the mine.

Chapter 3 will illustrate the feasibility of implementing control valves to control the pressure delivered to the mining levels.
Chapter 3: Investigating Energy-Saving Potential Using Underground Valves

An illustration of the feasibility of implementing control valves to control the pressure delivered to the mining levels by means of a simulation.
1 Introduction

Chapter 2 examined the electricity consumption of mines in relation to compressed air systems. In the chapter, the energy saving potential of underground valves was postulated. Controlling the compressed air supplied to mines and the different underground mining levels will influence the upstream pressure. This change in pressure will cause the variable inlet guide vanes of the compressors to change to an optimised angle of attack, resulting in power savings. In some cases, it might even be possible to cease operation of one or more compressors, increasing the potential power savings.

Installing valves on different levels will also assist in controlling the supply of compressed air effectively and efficiently to the levels. Various activities occur on different levels during the different shifts, each level having specific requirements for compressed air pressure and flow. Compressed air supplied beyond the requirements of a specific level is wasted under existing control methods and procedures. Installing valves on the levels will ensure that the requirements of the levels are met more precisely, with minimal air wastage.

The valves can be controlled by a PLC according to the downstream pressure and the pressure set point for the specific level as specified in a SCADA system. By controlling the pressure and following a control strategy specific to the level, the supply to the level and consequently the demand from the compressors can be controlled effectively.

As previously mentioned, the losses through a leak increase with an increase in pressure. Supplying a level with a higher pressure than required will result in unnecessary air losses through the leaks. Installing valves to control the compressed air according to minimum requirements will result in a reduction in air losses.

This chapter illustrates the principle of controlling the compressed air by means of throttling valves, resulting in power saving. In Section 2, the manner in which to identify and quantify DSM potential is presented. Next, the results of inducing a pressure drop using a valve are simulated in Section 3. Finally, the advantages of implementing underground DSM interventions are detailed in Section 4.
2 Predicting Demand Side Management Potential

In order to identify and quantify DSM potential, an initial investigation into the overall system and subsystems is required. This investigation must include:

- the different mining shifts;
- the minimum pressure required;
- the daily pressure profile;
- the installed power and delivery flow capacity;
- the layout of the compressed air system (surface and underground);
- present consumption trends;
- different compressed air users;
- the existing control strategy; and
- the installed infrastructure.

After the data from the investigations has been processed and validated, the viability of a DSM project can be evaluated in terms of installation costs, financial savings, and power savings.

Owing to the variety of applications of compressed air, load shifting will not always be possible or cost effective. With a water-pumping project, load shifting is more easily implemented. During off-peak periods, the dam levels can be optimally controlled so that the pumps on the various levels can be stopped during peak periods, should reserve dam capacity be available, without the dams overflowing due to the inflow of mine water and fissure water.

However, this is not possible with compressed air systems. Supplying more compressed air during off-peak periods will not reduce the compressed air requirements during the peak periods. The only method for implementing load shifting is by utilising a compressed air storage system as described in Chapter 2. Owing to leaks, friction, and restrictions in the compressed air systems, more energy will be required to store the air than can be generated by the stored compressed air.

In the case of a DSM load shifting project, such as a pumping project, the total energy consumption before and after DSM remains the same; in other words, the project is energy neutral. In a DSM compressed air project, energy consumption after the project will be lower than before the project. This type of project is therefore referred to as an energy efficiency or load reduction project.
Load reduction is a more feasible option for compressed air systems. During the Eskom evening peak, mining activities permitted, the load of the compressors will be reduced. This will result in a reduction in the overall power consumption of the compressors rather than shifting the load to a different time period.

With the installation of valves and control procedures on the various levels, the energy efficiency can be controlled, represented the yellow line in Figure 3-1. Significant savings will be realised over a 24-hour period. The results of existing load reduction methods are illustrated in Figure 3-1, with the baseline represented by the red line and the load reduction baseline represented by the blue line. This is achieved by switching compressors off during the Eskom peak period. With the worsening electricity situation, power savings throughout the day are required, which can be achieved effectively, by installing valves and implementing an effective control procedure. The difference in the compressed air consumption on the various levels can now be utilised efficiently for other applications, increasing production without increasing the demand for compressed air from the compressors. Should more compressed air be generated than what is consumed, due to the reduction in requirement through the implementation of control valves, the upstream pressure will increase. The increase will result in the inlet guide vanes reducing the angle of attack, leading to power and financial savings.

Figure 3-1: Load reduction over a 24-hour period
This reduction in electrical load not only reduces the strain on the electricity distribution networks, but also has financial benefits for the mine by reducing electricity costs. There are many other reasons for the mining sector to participate in DSM projects. Because Eskom has a limited electricity generation capacity, load shedding has become a frequent occurrence. Mines are being forced to reduce their consumption by 10% to avoid load shedding. Load shedding on a mine can have catastrophic safety consequences and result in significant production losses. Should mines not comply with the restrictions, penalties will be imposed.

With mining activities and operations, it is not always feasible to reduce the compressed air supplied to the entire shaft. The various activities on the levels have different compressed air requirements. Therefore, the compressed air supply pressure may exceed the requirements of some levels, while meeting the requirements of other levels. Installing valves on the levels with an effective control procedure will minimise situations in which the supply exceeds the requirement, reducing the air consumption of the mine. The results of inducing a pressure drop using a valve are simulated in the following section.

3 Detailed Investigation

In this section, the results of a pressure drop induced by a valve are explained through a simulation. In brief, the valve manipulates the flow of the compressed air through the valve, creating a pressure drop. For this simulation, certain values must be available, which are shown in Table 3.1. These variables served as the initial conditions. A complete list and description of variables used in the simulation is presented in Appendix A. For illustration, the simulation was limited to only one valve.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>Pa</td>
<td>Pressure before the valve</td>
</tr>
<tr>
<td>$D_1$</td>
<td>m</td>
<td>Diameter of the pipe</td>
</tr>
<tr>
<td>$T_1$</td>
<td>K</td>
<td>Temperature of the air before the valve</td>
</tr>
<tr>
<td>$Q^*$</td>
<td>m$^3$/s</td>
<td>The airflow per second in cubic metres</td>
</tr>
<tr>
<td>Valve percentage open</td>
<td></td>
<td>Percentage of valve opening</td>
</tr>
</tbody>
</table>

*In the mining industry, compressed air flow is usually specified in $^3$/minute
The following assumptions were made:

- The vortices in the valve are neglected.
- The pipe friction over the valve section is negligible.
- The properties of an orifice were used to represent a valve.
- Gas properties are ideal.
- Changes in height are negligible.

The simulation and equation solving software program, Engineering Equation Solver (EES) [48], was used to develop the simulation. Internal functions specific to the software are utilised making this software ideal for the simulation.

### 3.1 Controlling the Pressure Using Valves

The theory of controlling the compressed air by the utilisation of a valve is described in this section. A simulation was created to illustrate the pressure drop with changing flow conditions and valve openings.

The general layout of the control valve assembly is shown in Figure 3-2, where an orifice represents the valve for illustration purposes. The calculations are explained with reference to this illustration.

![Graphical illustration of the orifice](image)
The volumetric flow rate of compressed air in the mining sector is usually specified as cubic feet per minute (cfm). For this simulation, cfm was converted to metric units (cubic metres per second) as per Equation 3.1.

\[ Q = \text{cfm} \times 0.0004719474 \quad [\text{m}^3/\text{s}] \quad 3.1 \]

where:

\( cfm = \) volumetric flow rate in ft\(^3\)/minute.

The surface area of the pipe was calculated, normal to the direction of flow by Equation 3.2. The percentage valve opening was used to determine the diameter of the valve opening, Equation 3.3, which was applied in Equation 3.4 to determine the area of the valve opening.

\[ A_i = \frac{\pi \times D_i^2}{4} \quad [\text{m}^2] \quad 3.2 \]

where:

\( D_i = \) Diameter of pipe in m.

\[ A_v = \text{Valve}_{\text{opening}} \times A_i \quad [\text{m}^2] \quad 3.3 \]

where:

\( \text{Valve}_{\text{opening}} = \) Percentage valve opening.

\[ A_v = \frac{\pi \times D_v^2}{4} \quad [\text{m}^2] \quad 3.4 \]

The density (\( \rho \)) and the enthalpy (h) of the air before the valve were calculated as a function of temperature and density by Functions 3.5 and 3.6.

\[ \rho_v = \text{Density}[	ext{Gas}, T_v, P_v] \quad [\text{kg/m}^3] \quad 3.5 \]

\( \text{Gas} \) represents the thermodynamic properties of a specific gas mixture, in this case, air \([48]\)
Mass flow ($m$) is dependent on the density of the air and the volumetric flow rate, while density is related to the pressure of the compressed air. The higher the pressure, the higher the density will be and the higher the mass flow will be for a constant volumetric flow. The mass flow was calculated by Equation 3.7.

$$m = \rho_1 \times Q \quad [\text{kg/s}]$$  

where:

$$\rho_1 = \text{the air density in the pipe in kg/m}^3.$$

The velocity of the compressed air in the pipe was calculated as shown in Equation 3.8.

$$V_1 = \frac{m}{\rho_1 \times A_i} = \frac{Q}{A_i} \quad [\text{m/s}]$$

In order to calculate the head losses due to the narrowing of the pipe, the K-factor was first calculated using Equation 3.9 [57].

$$K_i = \frac{1}{2} \times \left[ 1 - \left( \frac{D_1}{D_2} \right)^2 \right] \left[ \frac{D_2}{D_1} \right]^{1/2}$$

The head losses through the orifice were then calculated using Equation 3.10 [57].

$$\text{head}_i = K_i \times \frac{V_i^2}{2}$$

The temperature in the valve calculated as a function of the enthalpy and pressure as shown in Function 3.11.

$$T_v = \text{Temperature}[\text{Gas, } h, P] \quad [\text{K}]$$
The pressure differential through the valve was calculated using Equation 3.12.

\[ P_v = P_1 - (\rho_1 \times g \times \text{head}_1) \quad [\text{kPa}] \]

where:

\[ g = \text{gravitational acceleration} \ (9.81 \text{m/s}^2). \]

The density of the air through the valve was calculated by Function 3.13.

\[ \rho_v = \text{Density}[\text{Gas}, T, P] \quad [\text{kg/m}^3] \]

The velocity of the air was calculated as shown in Equation 3.14.

\[ V_v = \sqrt{\frac{P_1 \times A_1 - P_v \times A_v + \rho_1 \times V_1^2 \times A_1}{\rho_v \times A_v}} \quad [\text{m/s}] \]

Owing to the expansion of the pipe after the orifice, the head losses needed to be calculated again as shown in Equations 3.15 and 3.16.

\[ K_2 = \left[ \frac{1 - \left( \frac{D_v}{D_1} \right)^2}{\left( \frac{D_v}{D_1} \right)^4} \right] \]

\[ \text{head}_2 = K_2 \times \frac{V_v^2}{2} \]

The temperature and density of the air after the valve was calculated by Functions 3.17 and 3.18.

\[ T_2 = \text{Temperature}[\text{Gas}, h, P] \quad [\text{K}] \]

\[ \rho_2 = \text{Density}[\text{Gas}, T, P] \quad [\text{kg/m}^3] \]
The pressure downstream of the valve was calculated using Equation 3.19.

\[ P_2 = P_v + (\rho_v \times 9.81 \times \text{head}_2) \quad \text{[Pa]} \tag{3.19} \]

The mass flow and volume flow after the valve was calculated as shown in Equations 3.20 and 3.21.

\[ m_2 = \rho_2 \times Q_2 \quad \text{[kg/s]} \tag{3.20} \]

\[ Q_2 = V_2 \times A_1 \quad \text{[m}^3/\text{s]} \tag{3.21} \]

The complete simulation is provided in Appendix B.

### 3.2 Simulation Results

This section discusses the results obtained from the simulation. The expected result is a decrease in pressure relative to the valve opening. The smaller the valve opening, the greater the velocity will be and this increased the pressure drop through the valve.

The law of energy conservation states that energy can only change in form but cannot be created or destroyed. This implies that the energy generated by the compressors in the form of compressed air must equal the sum of the energy delivered to the end users, with energy losses through leaks and friction.

By decreasing the valve opening, the simulated pressure decreased as illustrated in Figure 3-3. The valve opening is limited to 9% in the simulation. The velocity approached supersonic speeds at smaller valve openings, where the properties of the air change.
Figure 3-3: Pressure drop through the valve for different valve openings

Figure 3-4 illustrates the logarithmic change in pressure through the valve with an inverse logarithmic change in velocity.

Figure 3-4: Air pressure and velocity versus valve opening

The volumetric flow rate also had an influence on the velocity and corresponding pressure drop as illustrated in Figure 3-5. The valve opening was set at 65% open and the volumetric...
flow was varied. The velocity increased linearly with a corresponding linear decrease in pressure as the volumetric flow increased. The influence of the volumetric flow on the velocity is illustrated by Equations 3.7 and 3.8.

3.3 Required Infrastructure

The general equipment and network layout required for the automated control of the valves is illustrated by Figure 3-6. In order to enable reliable and effective control and communication, the valves and pressure transmitters on each level need to be connected to the SCADA system through a local PLC. The PLC will control the valve according to the set points in the SCADA system. The valves on each level will be individually controlled through the SCADA system, with a control procedure and profile for each level.

The Real-time Energy Management System version 3 (REMS3) software in automatic mode will manage the set points for each valve in the SCADA system. The function of the REMS3 software is to fulfil the function of a SCADA system operator and manipulate the set point according to a pre-programmed schedule, dependent on the system values at that specific moment.
PLCs are installed with each valve on the levels, to enable manual override of the valve controller in the case of communication failure with the SCADA system. This a safety precaution to minimise the effect a failure will have on production.

The installation of valves alone will not realise power savings, but will assist and increase power savings realised with efficient inlet guide vane control. The valves will modulate to control the pressure, and the inlet guide vanes will adapt to the changes in pressure, realising power savings. Therefore, effective guide-vane control is a prerequisite for achieving power savings.

The SCADA system will also control the compressor's set point according to the set point specified by an operator or the REMS3 software. The REMS3 software will ensure efficient automatic control of the valves and the compressor inlet guide vanes, to realise maximum power savings.

![Diagram of compressed air control system](image)

*Figure 3-6: Complete layout of the compressed air control system*

In the next section, the advantages of implementing underground DSM interventions are detailed.
4 Advantages of Implementing Underground DSM Interventions

4.1 Cost Savings

Eskom
In the short term, no cost savings are involved for Eskom. The electricity supplier finances DSM projects and pays for the power savings. The financial savings for Eskom due to reduced maintenance costs is outweighed by the initial DSM project costs. In the long term, financial savings are achieved by delaying the need for an increased generation capacity.

Client
Reducing electricity consumption reduces monthly electricity costs. In the mining industry, savings could be as high as R300 000 per month. This will decrease expenses and the cost per gram of gold produced. The implemented DSM strategies could also reduce operating costs as equipment is operated more efficiently. The maintenance costs of compressors are also reduced due to new measuring and monitoring equipment, while reduced pressure set points will decrease the power consumption and the strain on compressors. The effective control of the valves and compressors will also reduce maintenance on the compressors and compressed air networks.

4.2 Infrastructure

Eskom
Eskom-funded DSM projects do not make provision for infrastructure upgrades on Eskom infrastructure. DSM projects will however reduce the load on infrastructure networks, reducing the frequency of maintenance and therefore maintenance costs.

Client
New control and measuring equipment will be installed on the compressors and compressed air networks. The new equipment will improve the efficiency and effectiveness of compressor control and compressed air networks.
4.3 Power Savings

Eskom

DSM projects are essentially the construction of a virtual power station. By reducing the electricity consumption of present consumers, electricity supply capacity is made available to be utilised elsewhere without the immediate need for the expansion of the installed supply capacity.

Client

With the present electricity situation, power reduction is of great concern for mines. Penalties will be enforced by Eskom, should mines not reduce their power consumption by the prescribed amount.

Environment

DSM projects also contribute towards meeting the objectives of the Kyoto Protocol. By reducing or suppressing the need for additional generation capacity, the emission of harmful gases is limited, contributing to the reduction of greenhouse gas emission. Minimising the electricity required also reduces the excavation and mining of non-renewable energy sources, reducing pollution from mining activities.

5 Conclusion

This chapter has described, by means of illustration, the effects of installing valves on the compressed air networks. The illustration has shown that levels’ air pressures can be effectively controlled according to the required pressure, resulting in power savings.

By adjusting the valve opening, the pressure downstream of the valve can be controlled. The valve reduces the cross-sectional area of the pipe, resulting in a lower downstream pressure and an upstream pressure build-up. The higher upstream pressure will cause the guide vanes to reduce the angle of attack, resulting in reduced power consumption.

In the simulation, the valve opening was limited to a minimum of 30%. The velocity approached supersonic speeds at smaller openings. At these speeds, the properties of the air changed.
Should the controlling parameter be the compressed airflow rate instead of the pressure, the downstream flow can be measured and used to control the valve in the same manner as controlling according to the downstream pressure. The controller will modulate the valve, in order to meet the downstream requirements as specified by the control parameter.

Implementing an effective underground valve control procedure on a mine compressed air network will have significant advantages for Eskom, mines, and the environment. The next chapter will present the methodology followed in implementing a control system on three mines’ compressed air networks.
Chapter 4: Implementing Underground Valve Control Procedures

A detailed discussion on the implementation of the control strategy on various mines
1 Introduction

Chapter 3 illustrated the effects of installing valves on compressed air networks, resulting power saving. In this illustration, the REMS3 software package was introduced. This software monitors and controls the underground pressure by manipulating the pressure set points in the SCADA system. The relevant control valves will then control the pressure on the level according to the specified pressure.

The information and data obtained, as discussed in the previous chapters, as well as site-specific information was used in the REMS3 compressor controller software. The underground compressed air system of the mines considered in this research project can then be efficiently managed according to the specific set-up and requirements of the mine. The simulation capabilities of REMS3 were utilised to test and verify the specific control strategy before implementation. This should ensure that the underground control strategy can be implemented without any complications, such as the cycling of compressors. Cycling of the compressors implies that a compressor is continuously stopped and started within a short period. This increases power consumption due to high start-up power requirements and maintenance of the compressors because of wear on the mechanical parts.

For this research project, the control strategy was implemented on three mines. The compressed air system, compressed air requirements, restrictions, and limitations of the three case studies are described in this chapter. A complete explanation of the implemented control strategy is also given in the sections that follow.

The implementation of an underground compressed air control system is discussed in this chapter. The REMS3 software package and its implementation and integration into the compressed air system are explained in Section 2. Thereafter, the three case studies of the implementation of the control system are detailed in Section 3.

2 Design of the Control System

2.1 The Real-time Energy Management System Platform

The REMS3 platform is versatile and can be implemented to control various mining systems. REMS3 can be implemented on fridge plants, pumping systems, winder and
hoisting systems, and compressed air systems. For this research project, only the compressed air component of the REMS3 platform was used, which is examined in this section.

REMS3 receives system specific information from the SCADA system using information tags. This information is used to calculate the optimum operation of the compressors and to schedule the set points of the valves. The information REMS3 requires to calculate the scheduling is:

- the compressor status (Running or Stopped);
- the inlet guide vane angles;
- the actual air pressure and flow in the system;
- the desired system air pressure and flow;
- the actual air pressure and flow on each level; and
- the desired air pressure and flow on each level.

A SCADA system is invaluable in the modern mining industry, monitoring and controlling a number of critical operations. Operators can monitor all the operations connected to the SCADA system from a central control room. The operator can manipulate the generation by sending pre-programmed instructions to PLCs through the SCADA system. The SCADA system and PLC communicate through a communication network by means of tag values. The PLCs operate and execute instructions according to these tag values. For example, the delivery pressure set point of the compressor can be changed in the SCADA system and the PLC responsible for adjusting the inlet guide vane control will note the change. The PLC will adjust the guide vane angles of the compressors, to deliver the required pressure as specified by the tag.

The REMS3 software assists the operator by automatically controlling certain processes. The software communicates with the SCADA system, to control and log the tag values. The decision-making is software controlled through the REMS3, reducing the human-factor and error in the control. The great advantage of an automated system is that control will be more precise, reliable, and constant.

The communication between the REMS3 and the SCADA system is by means of the OLE for Process Control protocol (OPC). This
communication protocol is the industry-accepted standard communication protocol for all
process control applications. A set of object functions, interfaces, and application methods
is defined by the specifications. These specifications are used in process control and
manufacturing automation applications. This standardisation has facilitated the inter-
operability between manufacturers [58] [59].

Owing to intellectual property rights and restrictions, a complete discussion of the REMS3
platform cannot be given; instead, a brief explanation is given. The basic REMS3 platform
is shown in Figure 4-1.

![Figure 4-1: The Real-time Energy Management System platform](image)

On this platform, the complete layout of the various mining systems, such as pumping,
winders, or as in this case, the compressed air system, can be modelled. This includes
compressors, valves, pressure indicators, and flow indicators. The basic functions of the
platform are discussed in the following sections.

All the functions of REMS3 are controlled from the toolbar, shown in Figure 4-2 on the
following page. The toolbar consists of the following options, from left to right:

- edit mode;
- idle mode;
- manual control mode;
auto control mode;
run mode settings;
OPC communication settings;
internal programmable tags;
alarms settings;
SMS notification settings;
administrative settings; and
a saving function.

Figure 4-2: Control toolbar

The different components used in constructing the REMS3 compressed air system are summarised in Table 4.1 below. With these components, a complete simulated compressed air system can be assembled and simulated.

Table 4.1: Description of Real-time Energy Management System Compressor Manager components

<table>
<thead>
<tr>
<th>Picture</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Compressor" /></td>
<td>Compressor</td>
<td>The compressor, displaying the operational status, power consumption, guides vane position, and delivery pressure set point</td>
</tr>
<tr>
<td><img src="image" alt="Control Node" /></td>
<td>Control Node</td>
<td>The control node that schedules the pressure for the compressors and/or valves</td>
</tr>
<tr>
<td><img src="image" alt="Valve" /></td>
<td>Valve</td>
<td>A valve usually used in conjunction with a control node</td>
</tr>
<tr>
<td><img src="image" alt="Compressor Controller" /></td>
<td>Compressor Controller</td>
<td>The compressor controller that controls the compressors according to the parameters and values entered into the controller</td>
</tr>
<tr>
<td><img src="image" alt="Generic Data Logger" /></td>
<td>Generic Data Logger</td>
<td>The data logger that can be set up to log all required data</td>
</tr>
</tbody>
</table>
2.2 Simulation Capability

The simulation feature of the REMS3 software was designed to allow the simulation of the proposed control philosophy before implementation. The simulated control philosophy can then be implemented, ensuring that the actual results will closely match the simulated results.

The values used in the simulation were obtained from the three case studies, which are described in Section 3. Information on actual compressor status, air pressure requirements, and other factors are considered in the simulation process. This is done to ensure that the simulation closely represents the actual behaviour of the system.

During the project, different control strategies, within the limitations set by the mine, were simulated. The resulting data outputs were used for comparison with the actual results. An important aspect of the simulation model is that the simulation engine can generate simulated results faster than real time. A day’s worth of simulated results can be generated in minutes. Any possible problems with the control strategy can be recognised and resolved before implementation without any cost or safety implications.

2.3 Control Philosophy

The general control philosophy for a compressed air system is illustrated in Figure 4.3. The REMS3 controller will adjust the set point of the valves according to a schedule configured in the control node. The schedule, as explained previously, is specified over a 24-hour period for weekdays and working or non-working (on or off) Saturdays and Sundays. The pressure downstream of the valves is monitored, and the valves are controlled to deliver the desired downstream pressure or flow specified in the control node. This results in an upstream change in the compressed airflow and pressure. The Moore controller reacts accordingly, to maintain the specified delivery pressure or flow as specified by the pressure or flow set point in REMS3.
Figure 4-3: Control philosophy flow diagram
The control variable monitored and used to control the valve opening can be either the flow rate or the pressure. The control philosophy described based on pressure as the control variable. Should the pressure in the system be at a level above the maximum specified system pressure, the guide vanes would reduce their angle of attack. All the compressors will be controlled simultaneously, implying that all compressor guide vane set points would always be at the same set point.

The guide vane angles for each compressor are calibrated to range between 0% and 100%. This implies, for example, that for one compressor 0% will represent an angle of thirty degrees, while representing thirty-three degrees for another compressor. This depends on the efficiency, limitations, and mechanical set-up of each compressor.

Should the actual system pressure be higher than the pressure specified by the set point and all guide vanes angles be below the specified minimum angle to stop a compressor, one compressor will be stopped. After the compressed air network has stabilised, the decision-making process is repeated. The time required for the system to stabilise after any change, differs for each system depending on the layout of the compressed air system. This stabilisation time is usually ten to fifteen minutes. Once the system has stabilised, another compressor will be stopped, should the guide vane angles have remained below the minimum specified to stop a compressor. The same principle applies should the guide vane angles be greater than the maximum specified value to start a compressor. In this case, a compressor will be brought back online.

The immediate future requirements are also taken into account in the decision-making process. This ensures that a compressor will not be stopped should an increase in pressure be scheduled.

The following example refers to Figure 4-3 on the previous page. A new pressure set point is entered for the valve (1.1 and 1.2), and the valve controller adjusts the valve to deliver the desired pressure (1.2.1 and 1.2.2). The upstream ring pressure is also compared to the compressor pressure set points (1.3). the ring pressure and the specified delivery pressure be equal, within the specified error margin, the conditions will be maintained (1.4).
Should the difference in specified pressure and actual delivery pressure be greater than the allowed error margin (1.5), correctional action will be taken depending on the pressure being higher or lower than required.

The same control applies for both instances (high and low pressure) the only difference is whether a compressor will be stopped or started. Therefore, only one instance is described.

The guide vanes are under the control of the Moore controller. The Moore controller will ensure that the optimal guide vane angles are maintained, to deliver the specified pressure. The Moore control also ensures the compressor operates within its safe operational limits.

Should the pressure in the system be too high but the guide vanes have not reached the minimum percentage specified for a compressor to be stopped (1.5.1), REMS3 will continue to monitor the system. Should the guide vanes be at the minimum percentage (1.5.1), the appropriate compressor to be stopped will be determined (1.5.1.1). The compressor selection is based on the following criteria:

- **Number of compressors**: The minimum number of compressors should be operational.
- **Compressor efficiency**: The least efficient compressor will be stopped.
- **Compressor availability**: REMS3 is allowed to control the compressor when work is not being conducted.

Once the appropriate compressor is selected and stopped, the valves will adjust accordingly, to maintain the required pressure. This is to accommodate the lower delivery pressure, while maintaining the specified downstream pressure.
An example of a REMS3 compressed air system is illustrated in Figure 4-4. The system consists of two surface compressors, a surface pressure control node, underground valve and an underground pressure control node. The control nodes are used in conjunction with a pressure or flow instrument, to monitor and control the pressure or flow at that point in the system.

![Figure 4-4: Example of the Real-time Energy Management System platform set-up](image)

In accordance with the implemented control strategy, the REMS3 software will change the appropriate tag values in the SCADA system. The PLCs will then adjust the valve opening to deliver the pressure as scheduled in the control node—in this example, 400kPa. The PLCs and Moore controller will also change the compressor inlet guide vane angles, to deliver the pressure as set in the compressor set points. The compressor set points will always be the highest pressure scheduled for the system—in this case, 550kPa.
3 Implementation of the Control System

3.1 Case Study: Kopanang

The Kopanang Gold mine is situated in the North-West Province. The mine is approximately 10 kilometres North East of Orkney on the R502 between Orkney and Potchefstroom. It is owned and operated by AngloGold Ashanti. The mine is part of Vaal River Operations, which include Great Noligwa and Moab Khotsong. The mine is part of a compressed air ring as shown in Figure 4-5. The compressors at 1 shaft, 2 shaft, 4 shaft, and 7 shaft are owned by AngloGold Ashanti, although the mines are owned and operated by Pamodzi Gold. The Vaal River compressed air ring covers a total length of approximately 40 kilometres.

![Figure 4-5: Layout of the compressed air network at Vaal River Operations](image-url)
Site Details

An aerial photo of Kopanang Gold mine is shown in Figure 4-6.

![Aerial photo of Kopanang mine](image)

**Figure 4-6: Aerial photo of Kopanang mine**

The air consumption of all the shafts connected to the ring is monitored and each shaft is billed accordingly. Equation 4.1 was used to calculate the power equivalent of the compressed air consumption of each shaft.

\[
Shaft_{\text{Power Consumption}} = \frac{Shaft_{\text{Air Consumption}}}{Air_{\text{Generated Total}}} \times Compressor_{\text{Power Consumption}} \quad [\text{kW}] \quad 4.1
\]

where:

- \(Shaft_{\text{Air Consumption}}\) = the total air consumed by the shaft in kg/s;
- \(Air_{\text{Generated Total}}\) = the total air generated by the compressors in kg/s; and
- \(Compressor_{\text{Power Consumption}}\) = the total power consumption of the compressors in kW.

Equation 4.1 takes into account the individual reduction in compressed air consumption for each shaft in calculating the individual power consumption. Therefore, the compressed air savings realised by the shaft will reflect in the calculated power consumption for the specific shaft. The individual shafts will thus benefit only from their own compressed air saving initiatives. This is illustrated in Table 4.2 with Kopanang as an example.
Table 4.2: Calculation of individual power consumption attributed to the compressed air*

<table>
<thead>
<tr>
<th>Shaft</th>
<th>Before DSM strategy</th>
<th>After DSM strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average mass flow</td>
<td>Average power usage</td>
</tr>
<tr>
<td></td>
<td>(kg/s)</td>
<td>(kg/s)</td>
</tr>
<tr>
<td>No. 1</td>
<td>7.00</td>
<td>3.32</td>
</tr>
<tr>
<td>No. 2</td>
<td>14.00</td>
<td>6.64</td>
</tr>
<tr>
<td>No. 4</td>
<td>4.00</td>
<td>1.90</td>
</tr>
<tr>
<td>No. 5</td>
<td>17.00</td>
<td>8.06</td>
</tr>
<tr>
<td>No. 6</td>
<td>15.00</td>
<td>7.11</td>
</tr>
<tr>
<td>No. 7</td>
<td>19.00</td>
<td>9.01</td>
</tr>
<tr>
<td>Great Noligwa</td>
<td>11.00</td>
<td>5.22</td>
</tr>
<tr>
<td>Moab</td>
<td>16.00</td>
<td>7.59</td>
</tr>
<tr>
<td>Kopanang</td>
<td>13.00</td>
<td>6.16</td>
</tr>
<tr>
<td></td>
<td>10.00</td>
<td>4.74</td>
</tr>
<tr>
<td>Total</td>
<td>116.00</td>
<td>55.00</td>
</tr>
</tbody>
</table>

*Figures stated are only for illustration purposes

In Table 4.2, it is shown that Kopanang reduced its average compressed air mass flow rate by 3 kg/s, namely from 13 kg/s to 10 kg/s. As illustrated, this reduction in compressed air flow rate from Kopanang, only influenced the average power usage of Kopanang. However, the overall total power usage was reduced from 55MW to 53.57MW, due to the compressed air reduction of Kopanang. As the shafts are billed individually according to their power consumption, only Kopanang will benefit from its compressed air reduction initiatives.

**System Details**

The compressed air network of Vaal River Operations consists of fourteen compressors with the two base-load compressors (located at Kopanang) each rated at 15 MW. The rated installed power of the compressed air network is 83.5MW, with an average of 40.6MW reserve capacity available in the case of an emergency.

The compressed air power consumption baseline of the compressors for Vaal River Operations is shown in Figure 4-7 on the next page. The increase in the power consumption during the drill shift is because of an increase in compressed air consumption. This correlates to the increase in the compressed air consumption during the same period, as shown in Figure 4-8 on the following page.
The power baseline was calculated over a period of three months (March to April 2008). The power consumption of each compressor was logged every thirty minutes. From this data, the average power baseline was calculated over a 24-hour period.

The increase in compressed air consumption is mainly due to the pneumatic equipment utilised in the mine during this period. As was indicated in Figure 2-7, the drill shift is from 6:00 to 14:00.
Stope drills require large amounts of compressed air (as was shown in Table 2.1) and are mainly used during the drill shift. Outside of this period, less pneumatic equipment is in use and thus less compressed air is required.

**Implementation**

Before implementation of this load reduction project, the appropriate hardware must be installed. This includes flow and pressure transmitters, PLCs, communication networks, and control valves where required. The compressed air consumption on the levels will be automatically reduced by the REMS3 compressed air controller. During the drill shift period, the valves will be completely open, to allow maximum unrestricted airflow to the levels. The REMS3 layout is shown in Figure 4-9.

The power-saving control philosophy is implemented on the main surface delivery line and on 11 underground levels. The bypass valves, installed on some levels, are only controlled either fully open or fully closed, to control the airflow through the bypass line. The different levels to be controlled were identified by the mine. These levels will realise the maximum compressed air savings.

![Figure 4-9: REMS3 layout for Kopanang](image)

An example of the weekday control schedule for the valve on 70 level is shown in Figure 4-10. Air pressure on this level, during weekdays, is reduced between 16:00 and 20:30, due
to reduced mining activities. The pressure profile can be specified in increments of one minute. The pressure value is specified for each change in pressure. This pressure is maintained until the next change specified in the schedule. This pressure profile was specified by the mine and differs for each level. The pressure is also specified for the different day types (weekdays, Saturdays, Off-Saturdays, and Sundays).

The PLC controller on each valve continually monitors and compares the actual pressure on the line with the pressure scheduled in the REMS3 valve controller.

The surface valve is modulated to ensure a pressure of between 450 and 600 kPa, depending on the day and time of the day. During the periods between 06:00 to 16:00 and 20:30 to 06:00, the valve on 70 level is controlled at a pressure set point of 600kPa. This pressure set point is equal to or higher than the surface pressure, ensuring that the underground valve will be completely open during this period. This in turn ensures that the maximum compressed airflow and pressure is delivered to the level during these periods.
The set point on the surface valve may be lower than the set points on the various levels. This is to allow for the effect of auto-compression. Auto-compression implies a systematic increase in the pressure due to an increase in depth.

The data logger, as previously discussed, is configured to log the total mass flow in the shaft. The logged data can be retrieved from a remote off-site computer. This requires the appropriate software and access permission.

3.2 Case Study: Beatrix

The Beatrix gold mining complex is situated in the Free State Province. The mine is located approximately 40 kilometres south of Welkom on the R30 road between Welkom and Theunissen. The complex is owned and operated by Goldfields.

Site Details

The Beatrix mining complex consists of two shafts and a gold plant. The compressed air system is comprised of surface compressors, a compressed air pipe network, valves, drills, agitators, loading boxes, loaders, and other pneumatic equipment.

An aerial photo of the Beatrix mining complex is shown in Figure 4-11.
System Details

The compressed air network of Beatrix consists of eight compressors, shown in Table 4.3. The total installed capacity is 19,500 kW.

<table>
<thead>
<tr>
<th>Compressor Type</th>
<th>Power per compressor [MW]</th>
<th>Total power per compressor type [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK32</td>
<td>2.90</td>
<td>17.4</td>
</tr>
<tr>
<td>VK10</td>
<td>1.05</td>
<td>2.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>19.50</td>
</tr>
</tbody>
</table>

The layout of the compressed air network is illustrated in Figure 4-12. The compressors are all located at Beatrix 1 shaft. The supply of compressed air and the pressure on the underground levels at Beatrix 1 shaft, 2 shaft, and 3 shaft are controlled from the central control room at Beatrix 1 shaft.

The power baseline for the Beatrix compressed air network is shown in Figure 4-13. The required compressed air increases during the drilling period, with a corresponding increase in power consumption of the compressors. Presently no significant increase is evident in the compressor power consumption during the drill period. This implies that the air consumption throughout the day is relatively constant. As less pneumatic equipment is active outside of the drilling period, the required compressed air is lower. Therefore, the
constant power baseline indicates that compressed air is unnecessarily wasted outside of
the drill shift and there are power saving opportunities.

Presently the compressors are operating close to their maximum rated limits, because no
DSM project has been implemented on the compressors. By reducing the power
consumption and air wastage, spare operating capacity is made available. As all the
compressors are already operating close to their maximum capacity, the compressors will
not be able to provide any additional compressed air. No reserve capacity is available on
the compressed air network, in the event of compressor failure or compressor maintenance.

![Figure 4-13: Power baseline of Beatrix compressors](image)

**Implementation**

The implementation commenced on the 15\textsuperscript{th} of August 2007. For this load reduction
project, the load was only reduced automatically by the REMS3 software during the Eskom
evening peak (18:00 to 20:00). This was one of the restrictions imposed by the mine, as this
period is outside of production and is financially the most beneficial to the mine. The
electricity network is also under the highest load during this period, as shown in Figure 1-8.

Another restriction imposed by the mine was that the compressors could not be
automatically controlled (switched on and off). The on and off switching of the
compressors was done manually by an operator.
The inlet guide vanes on the compressors were therefore the only means of automatically controlling the delivery pressure and flow as specified by the compressor set point. This set point was not to be changed by the REMS3 controller.

The compressed airflow rate was used as the control variable with a proposed power reduction during the evening peak of 6.7MW. The proposed saving was based on tests conducted and simulations.

The mining activities during the Eskom evening peak is more dependent on airflow than pressure, and therefore the flow rate was the control parameter on this project. The existing communication infrastructure and PLCs were utilised where possible and expanded where they were found to be insufficient. This is indicated in Figure 4-14, with installed infrastructure represented by red. Items that were installed as part of this project are represented by green.

As previously explained, the PLCs were connected to the SCADA system, which is under REMS3 control. A modem was installed on the REMS3 server to allow system access from a remote control and monitoring room. The REMS3 platform could thus easily be updated and data collected from an off-site computer with the required access permission. This
allowed multiple projects to be monitored from a central point. As an example, Beatrix mine is located in Welkom, while the REMS3 control and monitoring room is located in Pretoria, some 400 kilometres away. From the same control and monitoring room, Amandelbult mine, which is 350 kilometres from Pretoria, could also be monitored and controlled.

As indicated in Figure 4-14, a total of 17 valves were controlled, and relevant information was acquired by the SCADA system from the compressors. The REMS3 software connects to the SCADA system through OPC and retrieves the required information for control purposes (and future improvements).

Fibre optic communication to the surface SCADA system and between the PLCs and valves on the levels was installed. Six PLCs were installed as part of the infrastructure upgrade, to control the valves at 3 shaft. The PLCs at 1 shaft and 2 shafts were utilised to control the valves at the respective shafts.

The REMS3 layout for Beatrix mine is shown in Figure 4-15. The total delivery flow of the compressors and the flow at each of the shafts were monitored. The Moore controller adjusted the inlet guide vanes to the correct angle, to deliver the required flow. In this project, the flow on each level was the controlling variable. The valves were controlled, to deliver the volumetric flow rate specified in the flow schedule.
Figure 4-15: REMS3 layout for Beatrix

The schedule for the valve at 2 shaft on 23 level is shown in Figure 4-16. The flow was limited to a maximum of 500 m$^3$/h between 17h40 and 20:00. During the rest of the day, the flow rate was controlled to a maximum of 550 m$^3$/h. The flow rate was also specified for all different day types.

Figure 4-16: Flow rate schedule
3.3 Case Study: Amandelbult

The Amandelbult mining complex is situated in the Limpopo Province. The mine is located approximately 40 kilometres south-west of Thabazimbi on the R510 road between Northam and Thabazimbi. Amandelbult is owned and operated by Anglo Platinum.

Site Details

The Amandelbult mining complex consists of two large vertical shafts, as well as an incline shaft and numerous raise bores. It uses a complex compressed air system comprised of surface compressors, a compressed air pipe network, valves, drills, agitators, loading boxes, loaders, and other pneumatic equipment. The major commodity is platinum and the minor commodities are nickel and copper.

An aerial photo of the Amandelbult 2 shaft is shown in Figure 4-17.

![Aerial photo of Amandelbult 2 shaft](image)

Figure 4-17: Aerial photo of Amandelbult 2 shaft
System Details

The compressed air network of Amandelbult consists of 8 compressors, as shown in Table 4.4, with a total installed capacity of 46 600kW.

<table>
<thead>
<tr>
<th>Compressor</th>
<th>Type</th>
<th>Power per compressor [MW]</th>
<th>Total power per compressor type [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 7</td>
<td>BB</td>
<td>4.80</td>
<td>14.4</td>
</tr>
<tr>
<td>3, 4</td>
<td>Centac</td>
<td>4.80</td>
<td>9.6</td>
</tr>
<tr>
<td>5</td>
<td>No. 5</td>
<td>2.80</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>GHH</td>
<td>4.80</td>
<td>4.8</td>
</tr>
<tr>
<td>8</td>
<td>BB</td>
<td>15.00</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>46.60</td>
</tr>
</tbody>
</table>

The layout of the compressed air network is illustrated in Figure 4-18.
The compressor power baseline for the Amandelbult compressed air network is shown in Figure 4-19. As was shown in Figure 2-7, maximum air is required during the drill period from 06:00 to 14:00. Presently, the air consumption before and after the drill shift is approximately the same as derived from the relative equal power consumption. Therefore, there is the potential to reduce air consumption at the end of the drilling shift. This will result in a reduction in power consumption, in particular, during the Eskom evening peak.

The sudden increase in power consumption is due to increased mining activities during the drilling period. This is the daily power profile expected for compressors in the mining environment. The profile indicates that the power consumption of compressors is controlled, manually or automatically, outside of the drilling period.

### Implementation

In this load reduction project, the REMS3 program only reduced the load automatically during the Eskom evening peak, from 18:00 to 20:00. This period was the focus for power savings in an attempt to reduce the Eskom evening peak. The control philosophy and infrastructure can be adapted at a later stage, to reduce the load throughout the day automatically. For this DSM project, the control parameter was pressure. The main restriction imposed by the mine was that the system pressure could not be lowered beyond 450kPa.

### Table 4-1

<table>
<thead>
<tr>
<th>Time</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>25.26</td>
</tr>
<tr>
<td>01:00</td>
<td>25.44</td>
</tr>
<tr>
<td>02:00</td>
<td>25.90</td>
</tr>
<tr>
<td>03:00</td>
<td>26.01</td>
</tr>
<tr>
<td>04:00</td>
<td>26.00</td>
</tr>
<tr>
<td>05:00</td>
<td>26.00</td>
</tr>
<tr>
<td>06:00</td>
<td>25.31</td>
</tr>
<tr>
<td>07:00</td>
<td>24.62</td>
</tr>
<tr>
<td>08:00</td>
<td>25.05</td>
</tr>
<tr>
<td>09:00</td>
<td>26.44</td>
</tr>
<tr>
<td>10:00</td>
<td>30.92</td>
</tr>
<tr>
<td>11:00</td>
<td>32.90</td>
</tr>
<tr>
<td>12:00</td>
<td>34.54</td>
</tr>
<tr>
<td>13:00</td>
<td>33.69</td>
</tr>
<tr>
<td>14:00</td>
<td>32.24</td>
</tr>
<tr>
<td>15:00</td>
<td>27.71</td>
</tr>
<tr>
<td>16:00</td>
<td>24.90</td>
</tr>
<tr>
<td>17:00</td>
<td>24.32</td>
</tr>
<tr>
<td>18:00</td>
<td>24.16</td>
</tr>
<tr>
<td>19:00</td>
<td>22.26</td>
</tr>
<tr>
<td>20:00</td>
<td>21.98</td>
</tr>
<tr>
<td>21:00</td>
<td>24.36</td>
</tr>
<tr>
<td>22:00</td>
<td>24.52</td>
</tr>
<tr>
<td>23:00</td>
<td>24.63</td>
</tr>
<tr>
<td>00:00</td>
<td>25.26</td>
</tr>
</tbody>
</table>

**Figure 4-19: Power baseline for Amandelbult compressors**
The results of tests conducted on the Amandelbult compressed air system are illustrated in Table 4.5. A green block indicates the specific compressor that was operational during the tests, whereas a red block indicates an offline or stopped compressor. These results were obtained, without any valve control strategy. This shows that savings are possible with the implementation of an underground compressed air control strategy. The proposed saving during the evening peak is 9.4MW. The proposed power saving is based on tests conducted on the compressed air network.

Table 4.5: Compressors operational during the test scenario through the evening peak

<table>
<thead>
<tr>
<th>Shaft</th>
<th>1# West</th>
<th>15E</th>
<th>2# East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>No. 1</td>
<td>No. 2</td>
<td>No. 3</td>
</tr>
<tr>
<td>18:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19:15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19:30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19:45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20:00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The infrastructure upgrade and installation can be separated into two parts, the surface installation and underground installation. The surface installation includes flow and pressure transmitters, communication infrastructure, PLCs, compressor upgrades, SCADA system upgrades, and REMS3 installation. The underground installations were conducted on 20 levels at 1# West and 2# East. The installation includes flow and pressure transmitters, PLCs, communication networks, and control valves. The valve assembly, illustrated in Figure 4-20, consists of the control valve with two isolation valves in the main column, as well as a bypass column with a bypass isolation valve. The bypass valves on each level used only for maintenance purposes and were thus not controlled by REMS3.
The REMS3 layout for the surface control system is illustrated in Figure 4-21 and the underground control system in Figure 4-22. The two systems are shown separately but are controlled collectively from a single controller. The pressure on each level was the control inputs for the REMS3 system.

The compressor delivery pressure set point is equal to the maximum pressure set point specified for the levels. This implies that the control valve on the level with the highest requirement was fully open and the control valves on the remaining levels were throttled.

The volumetric flow and pressure were monitored at various points in the surface compressed air network. This information was required to enable the compressor controller to control the compressors efficiently. The volumetric flow and pressure on each level were monitored and utilised by the valve controller, to control the valve on the level and thereby deliver the desired flow or pressure.

The power consumption, guide vane angles, compressor set points, pressure, and flow in the compressed air network were logged electronically. This logged data was then retrieved through a modem connection from a remote location. The data was analysed and processed to calculate the power consumption. The information was also used to verify system performance, by comparing the daily power profile to the power baseline.
Figure 4-21: REMS3 surface layout for Amandelbult

Figure 4-22: REMS3 underground layout for Amandelbult
4 Conclusion

In this chapter, an overview has been given of the REMS3 platform and the compressor controller. The implementation of an underground compressed air control system has been presented, showing the manner in which this was done, using the REMS3 software package. The implementation and configuration of the REMS3 software was also been explained.

A valve control strategy was designed and implemented in three different mines, which have been reviewed in this chapter in the form of case studies. In addition, the implementations of the valve control philosophy on the three different sites have been explained. It was shown that the implementation of an underground valve control strategy in conjunction with compressor control realises significant savings.

In order to determine whether the different projects were successful, a thorough analysis and verification of the results are required. In Chapter 5, the results achieved on the three different sites will be presented and discussed.
Chapter 5: Results

Presentation and discussion of the results achieved on the different mines where the control strategy was implemented.
1 Introduction

In the previous chapter, the implementation of the infrastructure, the REMS3 controller and valve control philosophy on the compressed air network for each site were explained. The aim of the implementations was to lower the power consumption of the compressors on the different sites. The implementation is regarded as successful should the proposed load reduction have been achieved.

An independent team, the Measurement and Verification (M & V) team, was used to verify the baseline and the load reduction achieved on the sites. During the performance assessment period, the three months following the completion of the project, monthly reports will be presented stating the load reductions as measured and calculated by the M & V team.

The load reduction and financial savings achieved with the implementation of the REMS3 software at the sites are discussed in this chapter. The results are presented for each case study separately. The results for Kopanang are presented in Section 2. Thereafter, the results for Beatrix are presented in Section 3. Lastly, the results for Amandelbult are presented in Section 4.

2 Case Study: Kopanang

This was the first project where the REMS3 valve controller was implemented to control the underground valves automatically. The project was completed in October 2005 but was updated in June 2008. In this compressed air load reduction project, the load was controlled and managed throughout the day. The successful implementation of this project and the lessons learnt, resulted in the successful implementation of other similar load reduction projects which are discussed in the subsequent sections.

In June 2008, the REMS3 valve controller was upgraded and the control philosophy adapted, in order to accommodate any changes in the compressed air demand. Data acquired during the three months following the upgrade (June 2008 to August 2008) was used in the calculation of the results. The data collected during the same months for 2007 (June 2007 to August 2007) was used to assess the improvement with the newly implemented controller and philosophy.
2.1 Load Reduction

As was previously explained, the compressed air was controlled on various levels and the mass flow in the shaft measured. This air mass flow was used to calculate the power consumption attributed to the compressed air consumption of Kopanang using Equation 4.1.

![Power Profile Graph](image)

Figure 5-1: Average calculated compressor power profile for Kopanang (2007)

The average power profile for the period of June 2007 to August 2007 is shown in Figure 5-1. The average load reduction throughout the day was 2.08MW. The average air mass flow for the same period is illustrated in Figure 5-2 on the next page.
The profiles in Figure 5-1 and Figure 5-2 are similar because the power consumption is proportional to the mass airflow, assuming changes in height are negligible.

Figure 5-3 illustrates the average daily power saving for the three-month period. The reduced average saving on day 16 and 17 was due to an increase in the compressed air consumption during July. This increase reduced the average financial saving over the three months.

Figure 5-2: Average compressed air mass flow profile for Kopanang (2007)

Figure 5-3: Average daily power savings for Kopanang (2007)
The new power profile and air mass flow profile for the period of June to August 2008, following the implementation of the new control philosophy, is illustrated in Figure 5-4 and Figure 5-5, respectively.

Figure 5-4: Average calculated compressor power profile for Kopanang (2008)

Figure 5-5: Compressed air mass flow profile for Kopanang (2008)
Figure 5-6 illustrates the average daily load reduction. This figure shows the significant increase in the average daily power savings compared to 2007 in Figure 5-3.

![Figure 5-6: Average daily power savings for Kopanang (2008)](image)

With the implementation of the new valve controller and a new control philosophy, the average power saving was increased from 2.08MW to 3.4MW. This is an improvement of 63%.

### 2.2 Financial Benefit

The daily saving for the period of June to August 2007 is shown in Figure 5-7 on the next page. The reduced financial saving for day 16 and 17 is due to reduced power savings as illustrated in the figure.
Figure 5-7: Daily financial savings for Kopanang (2007)

The savings increased by an average of R198 000 per month over the corresponding period in 2007. This increase in financial savings is not only due to the decrease in power consumption, but also the large increase in electricity tariffs, which increased financial savings per MW reduction. The average daily financial savings for the period of June to August 2008 is shown in Figure 5-8.

Figure 5-8: Average daily financial savings for Kopanang (2008)
2.3 Kopanang Conclusion

The air mass flow was reduced from 82.5kg/s for the 2007 period to 67.8kg/s for the 2008 period. This represents a 14.7kg/s, or 17.8%, reduction in air mass flow. The load reduction was improved by 60%, or 1.32MW, with the implementation of the new controller and control philosophy. The average load reduction achieved for the 2008 period was 3.4MW. This resulted in an average financial saving of R340 000 per month.

The reduction in CO₂ emission was calculated at 0.958 ton/MWh. [13] For this project, with an energy reduction of 81.6MWh per day, the reduction was 78 tons of CO₂ per day.

3 Case Study: Beatrix

The project was completed on the 10th of September 2008. The load reduction philosophy was implemented and commissioned, and load reduction was achieved from the 12th of September 2008.

The compressed air network consists of three shafts and the demand on all three shafts is controlled automatically. The load reduction and financial savings realised are the total savings for all three shafts. A period of 38 days (12 September to 19 October 2008) was used in calculating the savings. The proposed load reduction for this project was 6.5MW.

3.1 Load Reduction

The average power profile for the period is shown in Figure 5-9 on the following page. The load reduction for the period 02:00 to 06:00 was achieved manually through the mine’s initiative. Load reduction is already being achieved from 15:00.
The pressure profile is shown in Figure 5-10 on the following page; note that the pressure baseline and actual pressure demand remained approximately the same, with a maximum variation of 5%. This is because the compressors controlled the delivery pressure to the specified pressure set point. With the throttling of the valves in the delivery pipes, the pressure upstream of the valves changed. The Moore controller registered the changes and adapted the guide vane angles, in order to maintain the specified delivery pressure.

In this load reduction project, the compressor set points were not altered and the compressors controlled the pressure in the system to the same level as before the project. This restriction reduced the maximum savings that could be achieved. By controlling the pressure, additional savings could have been achieved.
The daily power savings over the 38-day period are shown in Figure 5-11. The average saving was 4.7MW, which is 1.8MW, or 28%, less than the proposed reduction.

The daily fluctuation in achieved daily savings was due to the irregular control of the compressors associated with the manual control.
The underperformance by 1.8MW may be contributed to the following factors:

- This was a new system and not all mine personnel were acquainted with the system.
- The compressors were controlled manually and not always switched off and on as recommended by the REMS3 software, to achieve the savings. This is evident from Figure 5-9, in which it can be seen that the power consumption of the compressors increased midway through the evening peak.

3.2 Financial Benefit

The daily financial savings are illustrated in Figure 5-12. The accumulative savings for this period were R85 000.

3.3 Beatrix Conclusion

The load reduction achieved over the 38-day period was 4.7MW, and the project is presently underperforming by 1.8MW. This is due to the human factor in the control philosophy. By improving the management of the responsible personnel or by implementing full system automation, the savings would be increased and the proposed 6.5MW reduction could be achieved.
The financial saving for this period was R85 000. The estimated annual saving, based on the existing tariff structures, is R1,600,000.

The project also contributes to a reduction in CO2 emission associated with the generation of electricity. The 9.4MWh of energy saved per day during the evening peak, resulted in a reduction of 9 tons of CO2 per day.

4 Case Study: Amandelbult

The project was completed in October 2008. The load reduction philosophy was implemented and commissioned and load reduction was achieved from the 13th of October 2008.

The underground compressed air supply at 1 shaft and 2 shaft was controlled automatically during the evening peak. The surface compressors were also controlled during the evening peak, to deliver the minimum required pressure. The load reduction and financial savings indicated are the totals for the compressed air ring and not per shaft. A period of 31 days (14 October to 13 November 2008) was used to calculate the savings. The proposed load reduction for this project was 9.4 MW.

4.1 Load Reduction

The average load reduction achieved for the period was 5.57MW as illustrated in Figure 5-13. The profile was manually controlled by the mine during the day, to meet the restrictions imposed by Eskom and avoid possible penalties. During the evening peak, REMS3 automatically controlled the compressed air system.
Presently the project is underperforming by 38.8% or 3.65MW. This maybe attributed to the following factors:

- This is a new system and not all mine personnel are acquainted with the system.
- Changes have been made in the compressed air system since the control philosophy was developed.

The surface pressure profile is shown in Figure 5-14. Although the underground pressure on the levels was lower, the surface pressure was controlled according to the same set points used prior to the project implementation. The pressure profile closely matched the pressure baseline with an average variance of 2% and a maximum variance of 5%.
The daily power savings achieved are shown in Figure 5-15. The days not shown were considered condonable days. The six condonable days, resulting from mining activities not permitting load reduction or work on the compressed air system, were not used in calculating the savings.
4.2 Financial Benefit

The financial benefit is shown in Figure 5-16. The accumulative saving for this period was R72 000.

![Figure 5-16: Daily financial savings for Amandelbult](image)

4.3 Amandelbult Conclusion

The load reduction of 5.75MW was achieved over the 31-day period, which was an underperformance of 3.65MW. The reason for the underperformance of the project is that it is a newly implemented project and system changes occurred during the implementation. Once the system changes have been incorporated into the REMS3 controller, the proposed savings will be realised.

The financial saving for this period was R72 000. The estimated annual saving, based on existing tariff structures, is R2,000,000. The reduction in CO$_2$ emission due to the reduced power consumption was calculated at 11 tons per day.
5 Conclusion

This chapter has discussed the results achieved on the three different projects, with the implementation of an appropriate underground valve control philosophy. Table 5.1 summarises the results achieved on the three projects.

For the Kopanang project, the control was extended to a 24-hour period instead of the two-hour evening periods for Beatrix and Amandelbult. This demonstrates that the REMS3 valve controller can be utilised over a 24-hour period. The results obtained from Kopanang clearly show that automation of the valve control realised significant savings over the manually controlled valves.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Power savings (MWh)</th>
<th>Proposed Financial savings (R/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kopanang</td>
<td>81.6</td>
<td>4 080 000.00</td>
</tr>
<tr>
<td>Beatrix</td>
<td>9.4</td>
<td>1 600 000.00</td>
</tr>
<tr>
<td>Amandelbult</td>
<td>11.5</td>
<td>2 000 000.00</td>
</tr>
</tbody>
</table>

The projects, together with the results achieved, demonstrated the feasibility of underground compressed air control as viable DSM projects.

The final chapter will review the dissertation and present recommendations for future research.
Conclusion to the research project, with recommendations for future studies
1 Introduction

Chapter 5 presented and discussed the results of the implementation of an underground compressed air control system in three mines. This chapter reviews these results and concludes the dissertation. In Section 2, an overview of the dissertation and the results of the implementations are given. Thereafter, recommendations for future research are made.

2 Overview

South Africa presently has an electricity crisis, because Eskom is no longer capable of ensuring a continuous and reliable supply of electricity to the consumer, while maintaining a sufficient reserve capacity. Demand side management projects, which are able to assist in the reduction of the electricity demand, are being implemented to address the problem of insufficient supply capacity. Demand side management promotes the efficient utilisation of electricity, to reduce the electricity consumption.

This research project focused on compressed air networks of South African mines. Compressors were identified as the largest consumers of energy on a mine, while forming a crucial part of the daily mining operations. The underground sections of compressed air networks on three mines were investigated, to identify potential DSM projects on the underground sections. Each of the various underground mining levels has different air pressure requirements. Existing control methods do not consider this, and all the levels are supplied with compressed air at the same pressure, neglecting any losses or gains in pressure through the system. No provision is made for the individual requirements of each level. This results in levels being supplied with compressed air at a higher pressure than required.

A simulation model was developed to demonstrate that valves could indeed be implemented to reduce the pressure at which compressed air is supplied to a level. This reduction causes an increase in the pressure upstream from the valve. The increase in the pressure enables the compressor to reduce delivery by means of guide-vane control, resulting in reduced power consumption of the compressors.

An underground valve control strategy was implemented on three different mines. The control philosophy and the hardware requirements for each mine were unique to the specific mine, to
enable maximum efficiency and power savings. The REMS3 software was implemented at each mine to control the valves on the various levels. The valves were modulated as the supply and demand for compressed air varied to meet the requirements of the individual levels.

Crucial to the success of the underground valve control is the efficient control of the compressors. The compressor was fitted with an effective inlet guide vane system and controller. The guide vane angles control the flow of air into the compressor. The power consumption of the compressors is proportional to the flow of air entering the compressor. The compressed air delivery set point, which determines the guide vane angle, of the compressor was controlled according to the maximum compressed air requirement on the levels.

The control was implemented on three different mines. On all three mines, power consumption of the compressors was successfully reduced, either over a 24-hour period, or during the Eskom evening peak (18:00 to 20:00). The control strategy was implemented without negatively influencing the production of the mines.

Eskom benefits from reduced power consumption, while the mines benefit from new infrastructure and a reduction in electricity consumed. The electricity supplier enforces penalties on the mines should they not reduce their electricity consumption by the prescribed percentage. The possibility of penalties has been reduced with the implementation of these projects. Eskom benefits from these projects further, as the load on the electricity distribution network and power plants is reduced. In addition, the need for expanding the present infrastructure will also be delayed. The environment also benefits from the consumption reduction, as the emission of harmful gases associated with the generation of electricity is reduced. Reduced power demand means that less coal is consumed, which is beneficial to the environment and landscape.

The combined average energy reduction realised through the three projects is 102.5MWh per day. With the present CO₂ emission factor of 0.958kg/kWh, this results in a reduction of 98 tons of CO₂ emission. The consumption rate of coal is 550kg/MWh. The reduction in coal consumption is calculated at 56 tons, while water consumption is 1.35kl/MWh, which realises a reduction of 138kl.
Following evaluation, it can be concluded that DSM projects in general are in the best interests of the environment, the country, and the economy. DSM holds significant advantages for both the consumer and the supplier.

Based on the results of this research project, recommendations for future research are made in the next section.

### 3 Recommendations for Future Work

The successful implementation of a valve control philosophy proved the feasibility of such a control. The feasibility of a valve controller should be investigated in other sectors and industries as well. It is also proposed that the control, where possible, should be extended to a 24-hour period instead of only during the evening peak period.

It is further recommended that alternatives for compressed air be investigated. The conversion of pneumatic equipment, such as loading boxes, to hydraulically operated systems, will further lower the pressure requirements of the levels. This is due to less pneumatic equipment being utilised on the various levels.

In addition, investigating and implementing effective methods of detecting and repairing leaks on the compressed air network will contribute significantly towards reducing the power consumption of the compressed air network.

### 4 Conclusion

This chapter has presented an overview of the dissertation and the results of the project. It has also made recommendations for future research, based on these results. Implementing an underground compressed air control strategy is an effective method of achieving significant power savings on compressed air systems. Control valves with the required hardware for automatic control were installed on the underground mining levels of three mines. The supply of compressed air to the levels was controlled according to the different requirements for compressed air on each level. The implemented valve control strategy together with the guide vane control of the compressors ensured that the requirements of each level were met with minimal losses and minimal power consumption of the compressors.
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REFERENCES


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APPENDIX A: Description of Variables Used in the Simulation Model

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Volumetric flow rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>cfm</td>
<td>Volumetric flow rate</td>
<td>ft³/minute</td>
</tr>
<tr>
<td>A₁</td>
<td>Inside area of the pipe</td>
<td>m²</td>
</tr>
<tr>
<td>Π</td>
<td>constant</td>
<td></td>
</tr>
<tr>
<td>D₁</td>
<td>Inside diameter of the pipe</td>
<td>m</td>
</tr>
<tr>
<td>Dᵥ</td>
<td>Inside diameter of the valve opening</td>
<td>m</td>
</tr>
<tr>
<td>Valve percentage_open</td>
<td>Percentage of the valve opening</td>
<td></td>
</tr>
<tr>
<td>Aᵥ</td>
<td>Inside area of the valve</td>
<td>m²</td>
</tr>
<tr>
<td>ρ₁</td>
<td>Density of air in the pipe</td>
<td>kg/m³</td>
</tr>
<tr>
<td>P₁</td>
<td>Air pressure in the pipe before the valve</td>
<td>kPa</td>
</tr>
<tr>
<td>T₁</td>
<td>Temperature of air in the pipe before the valve</td>
<td>K</td>
</tr>
<tr>
<td>h₁</td>
<td>Enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow</td>
<td>Kg/s</td>
</tr>
<tr>
<td>V₁</td>
<td>Velocity of air in the pipe</td>
<td>m/s</td>
</tr>
<tr>
<td>K</td>
<td>K-factor</td>
<td></td>
</tr>
<tr>
<td>Tᵥ</td>
<td>Temperature of the air through the valve</td>
<td>K</td>
</tr>
<tr>
<td>ρᵥ</td>
<td>Density of the air through the valve</td>
<td>kg/m³</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>Vᵥ</td>
<td>Velocity of air through the valve</td>
<td>m/s</td>
</tr>
<tr>
<td>T₂</td>
<td>Temperature of the air after the valve</td>
<td>K</td>
</tr>
<tr>
<td>ρ₂</td>
<td>Density of the air after the valve</td>
<td>kg/m³</td>
</tr>
<tr>
<td>P₂</td>
<td>Air pressure after the valve</td>
<td>kPa</td>
</tr>
<tr>
<td>m₂</td>
<td>Mass flow after the valve</td>
<td>kg/s</td>
</tr>
<tr>
<td>Q₂</td>
<td>Volumetric flow rate</td>
<td>m³/s</td>
</tr>
</tbody>
</table>
APPENDIX B: Graphical and Mathematical Illustration of Simulation Model

Figure B.1: User interface of the simulation

\[ T_{pipe} = 30 \text{ [°C]} \]
\[ P_{pipe} = 480 \text{ [kPa]} \]
\[ V_{el_{pipe}} = 48.07 \]
\[ Q_{before, valve} = 9.439 \]
\[ D_{pipe} = 0.5 \text{ [m]} \]
\[ \dot{m}_{pipe} = 52.12 \]
\[ cf_{m} = 20000 \text{ [ft}^3/\text{min}] \]
\[ P_{after, valve} = 471.3 \text{ [kPa]} \]
\[ V_{el_{after, valve}} = 48.56 \]
\[ Q_{after, valve} = 9.534 \]
\[ \dot{m}_{after, valve} = 51.64 \]
$g = 9.81$ [Gravitational acceleration]

$Q = \text{cfm} \times 0.0004719474$ [Convert cfm to m$^3$/s]

$A_i = \frac{\pi \times D_i^2}{4}$ [Inner surface area of pipe]

$D_v = \frac{\text{Valve}_{\text{percentage_open}} \times D_i}{100}$ [Diameter of valve opening]

$A_v = \frac{\pi \times D_v^2}{4}$ [Inner surface area of valve opening]

$\rho_i = \text{Density}[^{\text{Air}}_T, h = h_i, P = P_i]$ [Air density in the pipe]

$h_i = \text{Enthalpy}[^{\text{Air}}_T, h = h_i, P = P_i]$ [Enthalpy in the pipe]

$m = \rho_i \times Q$ [Mass flow in the pipe]

$V_i = \frac{m}{\rho_i \times A_i}$ [Velocity of air in the pipe]

$K_1 = \frac{0.5 \times \left[1 - \left(\frac{D_v}{D_i}\right)^2\right]}{\left[\frac{D_v}{D_i}\right]}$ [K-factor]

$\text{head}_i = K_1 \times \frac{V_i^2}{2}$ [Head losses due to narrowing of pipe]

$T_v = \text{Temperature}[^{\text{Air}}_T, h = h_v, P = P_v]$ [Air temperature through the valve]

$P_v = P_i - \frac{\rho_i \times g \times \text{head}_i}{1000}$ [Air pressure through the valve]

$\rho_{\text{valve}} = \text{Density}[^{\text{Air}}_T, h = h_v, P = P_v]$ [Air density through the valve]

$V_v = \sqrt{\frac{P_i \times A_i - P_v \times A_v + \rho_v \times V_i^2 \times A_i}{\rho_v \times A_v}}$ [Air velocity through the valve]

$K_2 = \frac{\left[1 - \left(\frac{D_v}{D_i}\right)^2\right]^2}{\left[\frac{D_v^2}{D_i}\right]^4}$ [K-factor]

$\text{head}_2 = K_2 \times \frac{V_v^2}{2}$ [Head losses due to widening of pipe]
\[ T_2 = \text{Temperature}['Air', h = h, P = P] \]  
[Air temperature after the valve]

\[ \rho_2 = \text{Density}['Air', T = T_2, P = P_2] \]  
[Air density after the valve]

\[ P_2 = P_1 + \frac{\rho_2 \times 9.81 \times \text{head}_2}{1000} \]  
[Air pressure after the valve]

\[ m_2 = \rho_2 \times Q_2 \]  
[Mass flow after the valve]

\[ Q_2 = V_2 \times \text{\(\nu\)}_1 \]  
[Volumetric flow after the valve]