# Optimising deep-level mine refrigeration control for sustainable cost savings
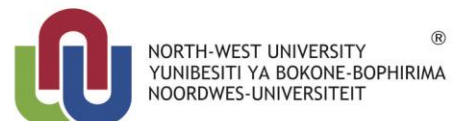
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## 22815600

Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering* in Mechanical Engineering at the Potchefstroom Campus of the North-West University

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# ABSTRACT

Title:          Optimising deep-level mine refrigeration control for sustainable cost savings

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Degree:      Master of Engineering (Mechanical)

Keywords:   gold mine, sustainability, demand side management, load management, control optimisation, refrigeration, cost savings

Declined productivity and increased operational costs have seen South African deep-level gold mines become marginal operations during the past few years. The price of electricity is one of the major contributors to an increase in the operational costs. This is mainly due to gold mining depending heavily on electricity for its operations and the price of electricity increasing at higher-than-inflation rates.

The past few years also saw South Africa's power utility, Eskom, struggling to keep up with its economy and to adequately supply the electricity demand. Ageing infrastructure and mismanagement led to power outages being experienced throughout the country. Since gold mining is such an electricity-intensive operation, it is very sensitive to Eskom's ability to meet the demand. During peak periods, Eskom regularly operates without adequate reserve margins, subsequently reverting to load curtailment of large users in order to ensure grid stability. This directly influences the productivity of industries such as gold mines.

The problems experienced by Eskom led to the establishment of Demand Side Management (DSM). Energy Services Companies (ESCos) are employed by Eskom to implement DSM initiatives on large electricity consumers such as gold mines. However, research proves that implemented load management initiatives (part of DSM) were not sustainable in the past. This is mainly due to the structure of the old DSM model, which only required ESCos to maintain targeted savings for a period of three months after implementation.

The DSM model was revised in recent years to ensure that the performances of implemented load management initiatives are more sustainable. The revised DSM model, however, brought new challenges for ESCos as they are forced to sustain the performances of implemented projects for a period of 36 months. Project funding for infrastructure and implementation time were also drastically reduced with the new model. This presented the need for ESCos to develop creative and sustainable load management techniques that will be cost effective and easy to implement.

One of these techniques is developing optimised control strategies for the electricity consuming systems of deep-level mines. Due to their large electricity consumption patterns, two deep-level gold mine refrigeration systems were identified for optimised control. The development commenced by determining the theoretical impact of the developed optimised control strategies through verified simulation models. The simulation results were then validated in the form of practical tests on the respective refrigeration systems. Validation proved the accuracy of the optimised strategies with a correlation error of 2% for Mine D and 3% for Mine R, measured against the average summer evening peak period load reduction.

The optimised control strategies were implemented on the refrigeration systems of Mine D and Mine R. By the time of this study, load management proved to be sustainable for a consecutive period of eight months at Mine D and nine months at Mine R. An average evening peak period load reduction of 7.28 MW (Mine D) and 2.00 MW (Mine R) was measured at the respective mines. This accumulates to financial cost savings of R 1.17 million (Mine D) and R 143 000 (Mine R) over the respective measuring periods. Assuming sustainability over a period of 36 months, a total financial saving of approximately R 6 million is expected.

The study proved that sustainable cost savings on deep-level gold mine refrigeration systems are possible through the implementation of optimised control strategies. It is, however, important to note that the sustainability is not solely measured on cost savings, but also determined by the effect of load management on system operational parameters such as temperatures, dam levels and safety regulations.

# ACKNOWLEDGEMENTS

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# LIST OF SYMBOLS

| | |
|---|---|
| # | Denotes a mining shaft |
| $ | United States Dollar |
| % | Percentage |
| $\alpha$ | Absorption coefficient |
| $Cp_w$ | Specific heat capacity of water |
| $\Delta R$ | Unit of thermal resistance |
| D | Pump rotor diameter |
| dP | Differential pressure |
| $\varepsilon$ | Emittance |
| $\eta$ | Efficiency |
| G | Irradiation |
| h | Enthalpy |
| $h_0$ | Convection heat transfer coefficient |
| m | Mass flow |
| n | Rotational speed |
| P | Electrical power |
| Q | Heat |
| R | South African Rand |
| $\rho$ | Density |
| t | Temperature |
| U | Overall heat transfer coefficient |
| v | Volume |
| $W_{in}$ | Electrical power input |

# LIST OF UNITS

| | |
|---|---|
| °C | Degrees centigrade |
| g/t | Grams per tonne |
| K | Kelvin |
| kg/m$^3$ | Kilogram per cubic meter |
| kg/s | Kilogram per second |
| kJ/kg | Kilojoule per kilogram |
| kJ/kg·K | Kilojoule per kilogram Kelvin |
| km | Kilometer |
| kW | Kilowatt |
| l/s | Liters per second |
| m | Meters |
| m$^2$·K/W | Square meter Kelvin per Watt |
| m$^3$ | Cubic meters |
| MW | Megawatt |
| oz | Ounce |
| Pa | Pascal |
| W/m$^2$ | Watt per square meter |
| W/m$^2$·K | Watt per square meter Kelvin |

# LIST OF ABBREVIATIONS

BAC       Bulk air cooler

CCT       Condenser cooling tower

DSM       Demand side management

EE        Energy efficiency

ESCo       Energy services company

Eskom      Electricity Supply Commission of South Africa

GDP       Gross domestic product

HVAC      Heating ventilation and air Conditioning

KPI        Key performance indicator

LM        Load management

PA        Performance assessment

PCT       Pre-cooling tower

PTB       Process Toolbox by TEMM International

SCADA     Supervisory control and data acquisition

SLA       Service level adjustments

TES       Thermal energy storage

TOU       Time-of-use

VFD       Variable frequency drive

# Chapter 1

# 1 Introduction

## 1.1 South African gold mining and the economy

### 1.1.1 Background

During the 19th century the first South African gold reef was discovered in the Witwatersrand area [1]. The basin stretches in an elliptical arc crossing approximately 400 km through three provinces (Gauteng, Free State and North West) [1]. Since its discovery, the Witwatersrand Basin contributed  approximately 33% of global gold production (over two billion ounces), and remains one of the world's largest gold resources [2]. Figure 1 shows the geological location of various South African gold mining operations within the Witwatersrand Basin.
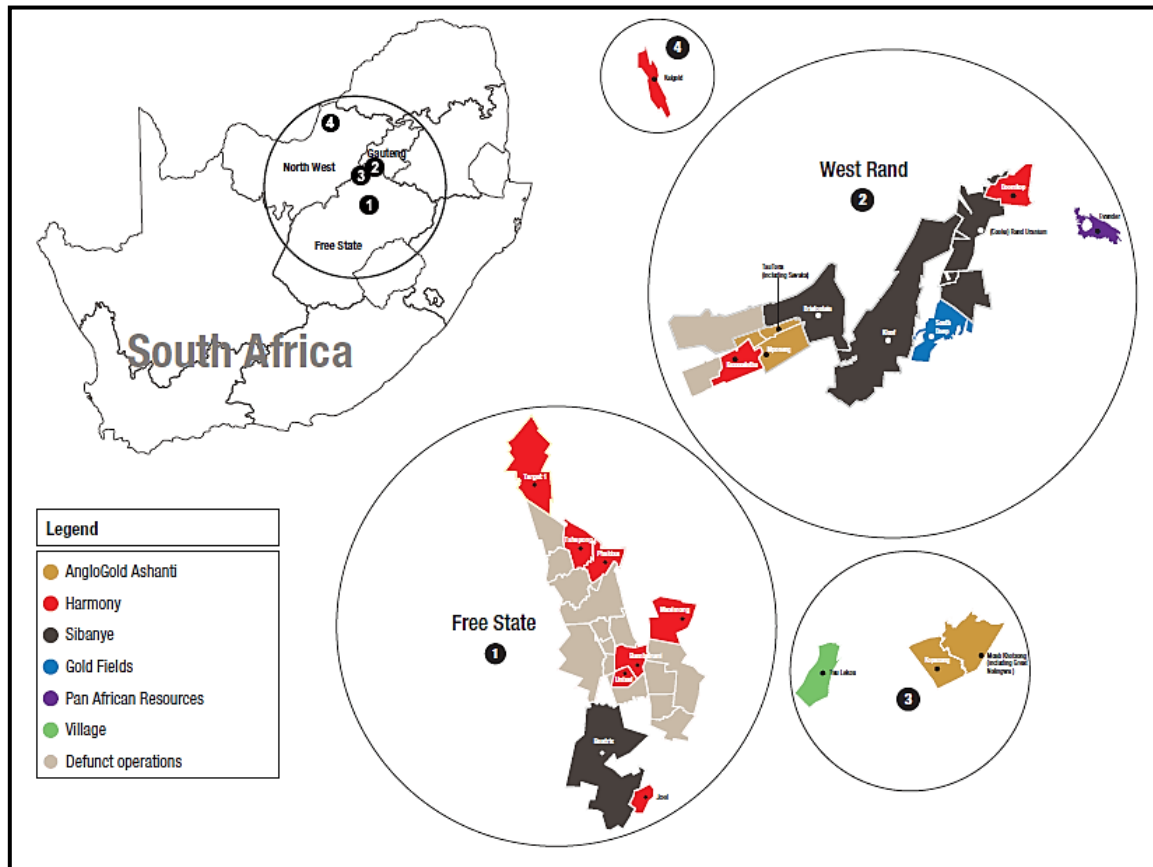


**Figure 1: Geological location of mining operations within the Witwatersrand Basin** [1]

During 1980, South Africa was the largest gold producer in the world with 675 000 kg of gold produced [3]. South African gold production, however, declined with a significant 87% from the mid 1980s [3]. Figure 2 shows the decline in gold production during this period.
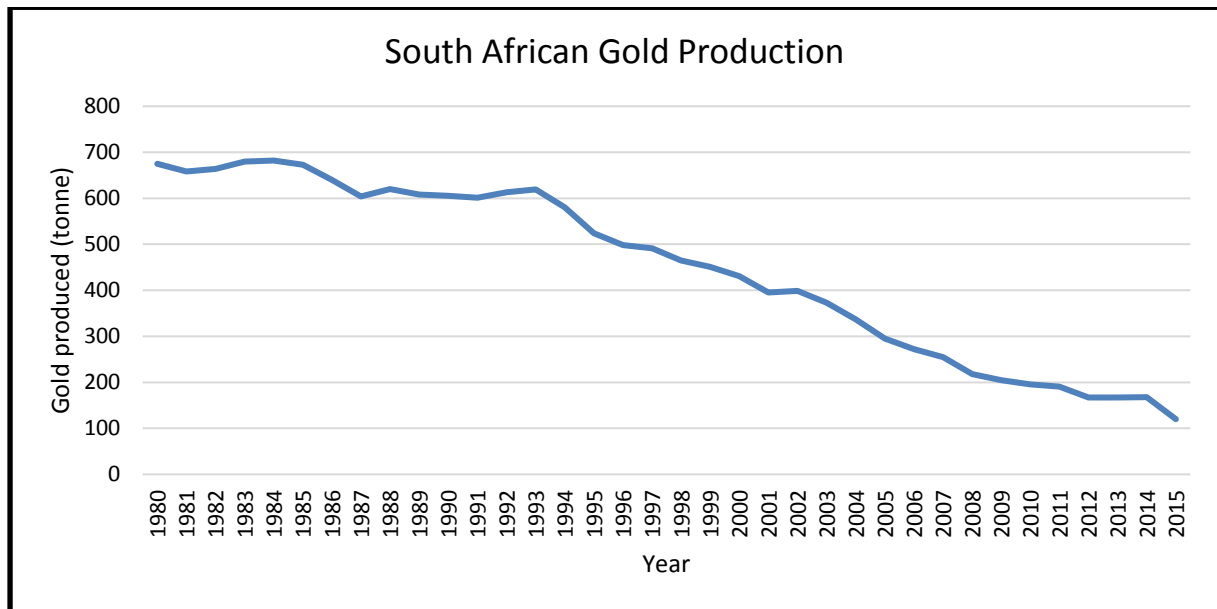


**Figure 2: South African gold production, 1980-2015** [3]**,** [4]

Since 2002, South Africa's gold output declined faster than any other of the top gold producing countries in the world. Figure 3 compares the gold production growth among the top gold producing countries in the world from 2002 to 2013. South Africa is currently the sixth largest gold producer in the world, down from first place in less than a decade [2]. South Africa has, however, the world's largest gold ore deposits, while contributing only 5.3% to global production (2013 statistics) [5].
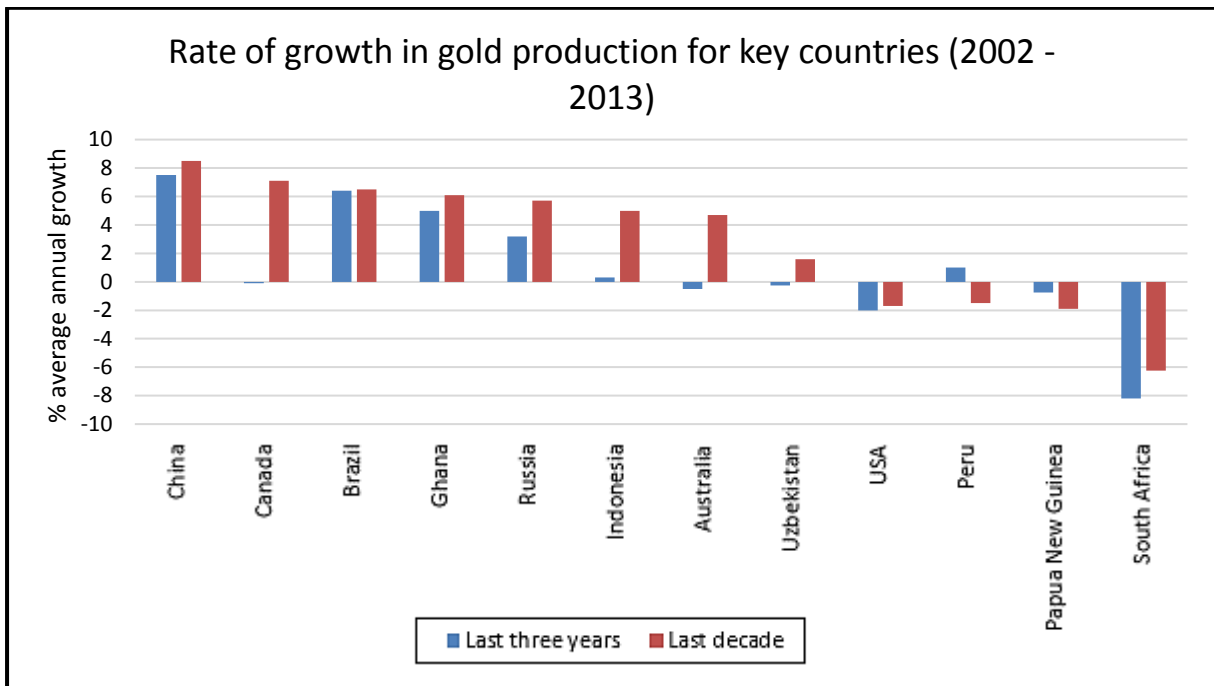
**Figure 3: Gold production growth rate of top producers (2002 – 2013)** [5]

Gold's contribution to South Africa's Gross Domestic Product (GDP) declined from 3.8% in 1993 to 1.7% in 2013 [3]. The reduction is aligned with the production decrease (50% decline) experienced over the same period [1]. Gold accounted for 12.5% of all mineral sales in 2014, down from 67% in 1980 [3]. These mineral sales have decreased with 40% between 2012 and 2016. It is evident from these figures that the gold mining industry is experiencing challenges to remain productive in modern day mining. The challenges are discussed in the following section.

### 1.1.2   Challenges in the gold mining industry

The decline in production can be mainly attributed to factors such as falling gold prices, declining ore grades, industrial action (strikes) and reduced productivity [4].

Productivity per gold mine employee has also declined over the years. This can be attributed to factors such as increased operating depth and travelling time to operating areas. As travelling time increases, productive mining time decreases [6]. South African gold mines are estimated to be productive for 274 days of the year (75%). Of those 274 days, workers are only active for two-thirds of each day [5].

Despite the decline in productivity, labour costs have increased substantially during the last decade. Figure 4 depicts the increased labour cost and reduced production per employee since 1990 [5].
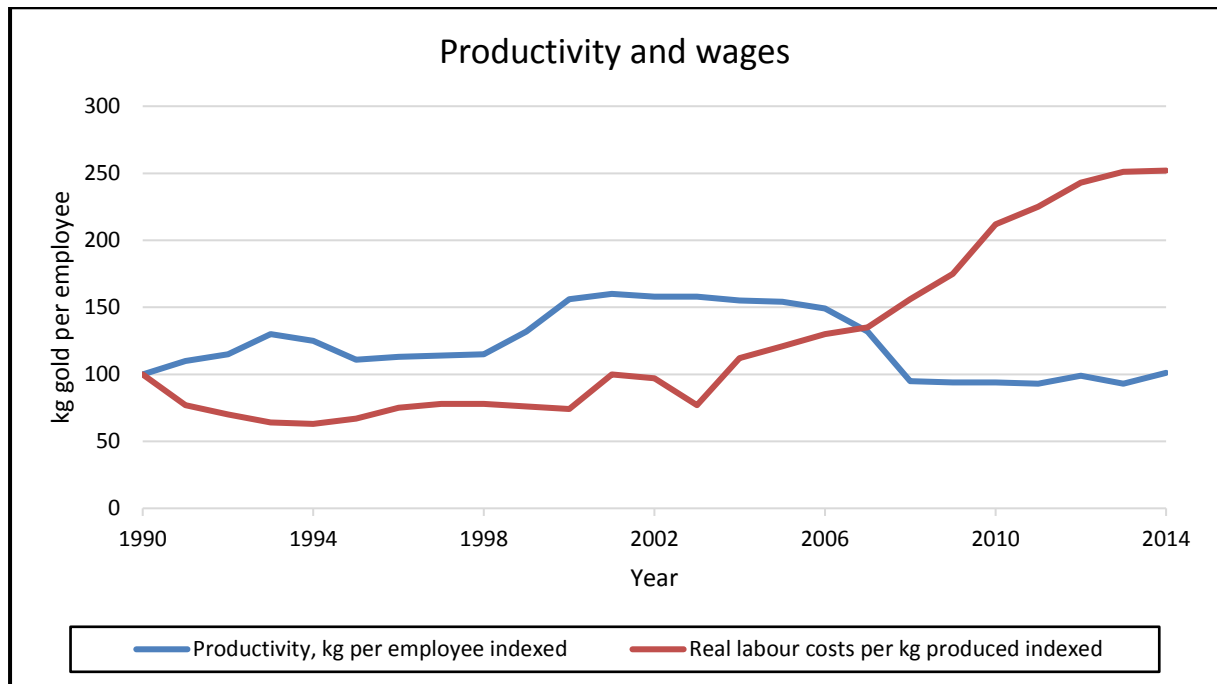


**Figure 4: Productivity and labour cost per employee (1990 – 2014)** [5]

The weak financial performance of gold mines is worsened with the increases in operating costs [4]. Large contributors to increased operating costs are labour and electricity [4]. This is mainly due to the substantial annual increases in these portions of a deep-level mine's operating costs in recent years. Figure 5 illustrates the breakdown of a typical gold mining group's operating costs (2014 data) [4]. As indicated, labour and electricity comprise just over half of the total expenditure.

## Typical Gold Mine Group Expenditure
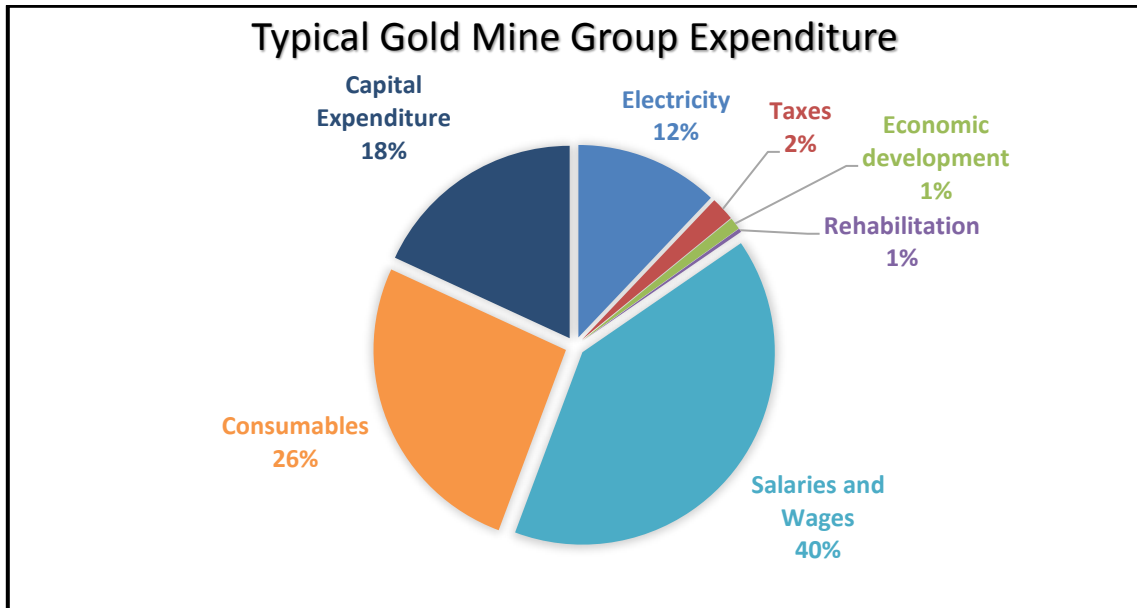
**Figure 5: Typical gold mine group expenditure (2014 data)** [4]

Figure 6 shows the cost inflation affecting various sectors within the gold mining sector for the period 2008 – 2014. It is evident that electricity shows some of the highest cost inflation. Further it is noticed that the majority of mining's operating costs increases at a higher-than-inflation rate. Increased production costs, especially at the current rate, can eventually force weaker-performing mines to close down [5].

## Cost inflation affecting the mining sector (annual average 2008 - 2014)
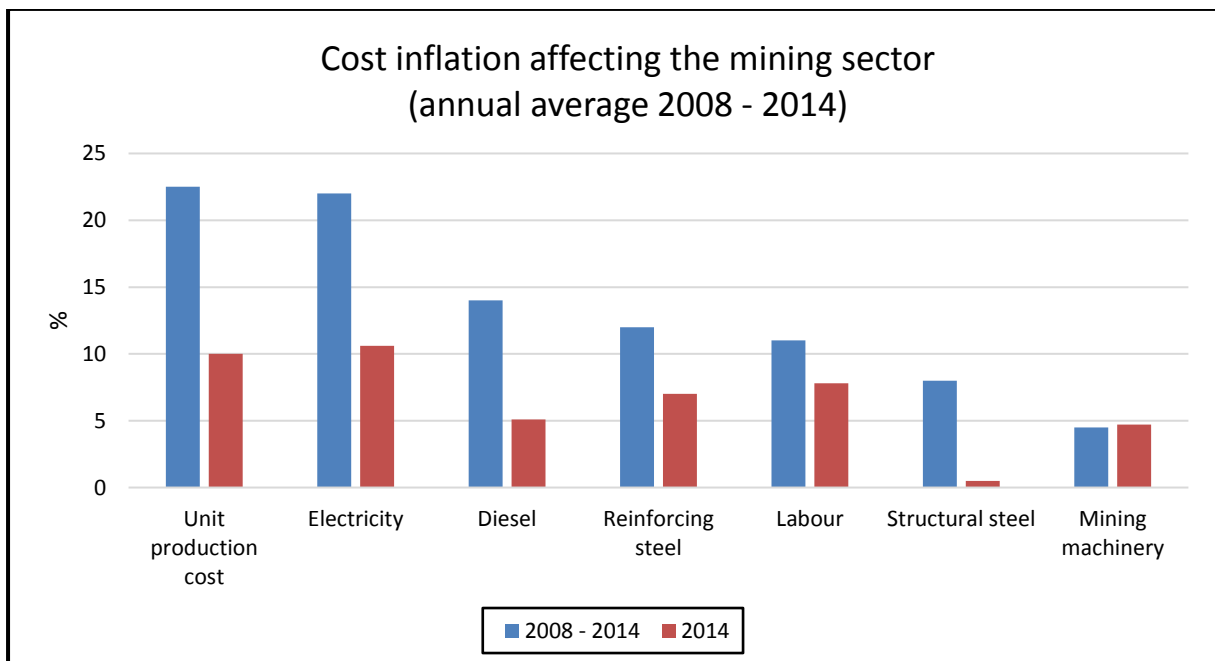
**Figure 6: Cost inflation affecting gold mining** [5]

The above-mentioned factors all contribute to the decline in productivity of gold mining in South Africa. Increases in major expenses along with declining production has reached the point where the majority of South African gold mines are marginal operations [2]. The financial performance of various South African gold mines can be seen in Figure 7 – indicating operating cost per ounce of gold mined for multiple South African gold mines. Profitable mines are indicated by green bars and non-profitable indicated by red. The gold price per ounce of gold is indicated by the gold bar.
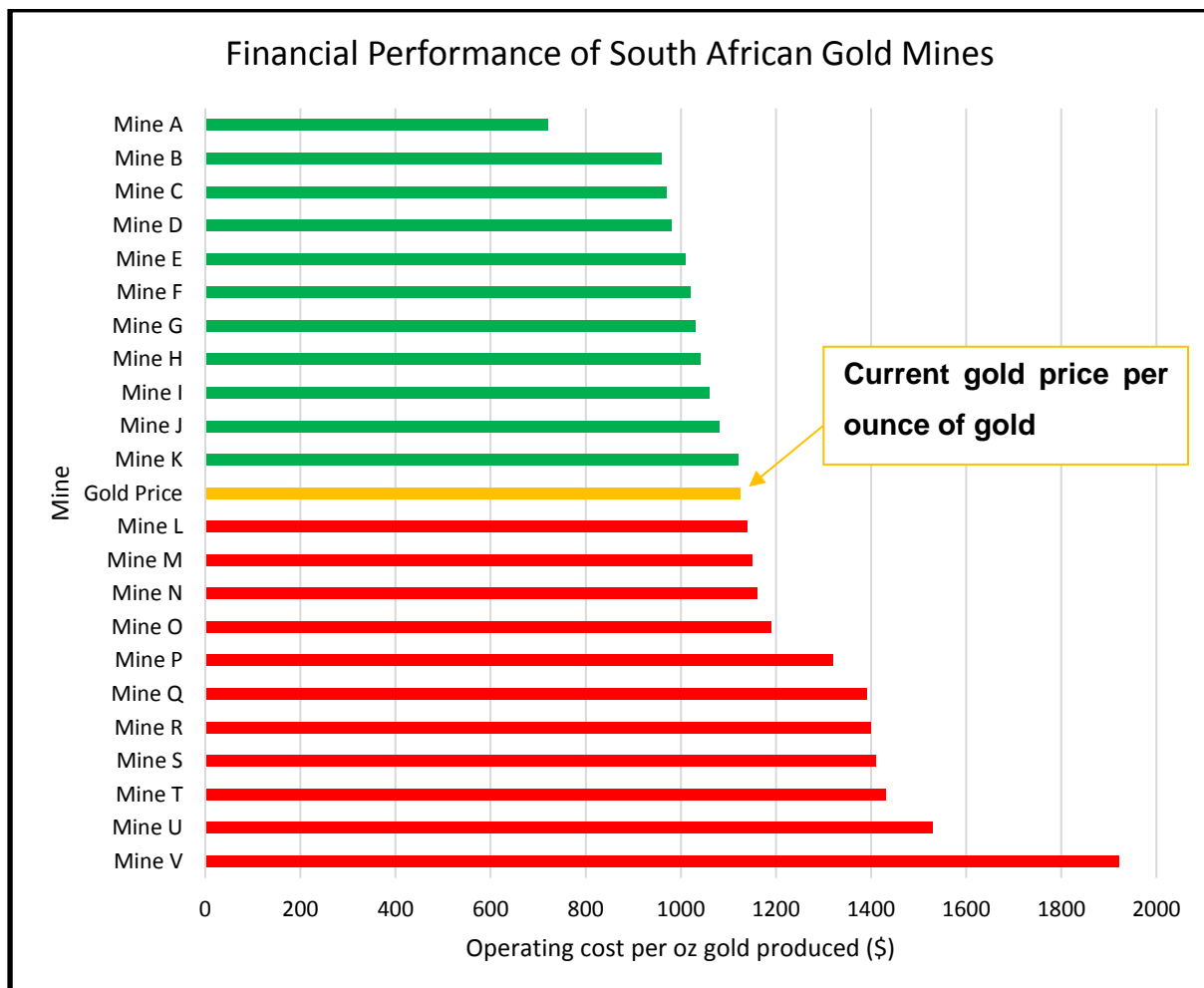


**Figure 7: Financial performance of South African gold mines (2015 2nd Quarter)** [2]

Despite the concerning statistics presented in this section, gold mining still plays an important part in the South African economy [4]. Gold mining employs thousands of people and supports millions of dependants in the form of employee families [5]. Gold mines therefore need to find creative measures to offset increasing operating costs and increase profitability. Due to the

aggressive nature in which operating costs are increasing, especially that of electricity, one initiative that can be employed to reduce the impact of operating costs on profitability, is to reduce gold mining's electricity demand.

## 1.2 Electricity supply and deep-level gold-mining demand

### 1.2.1 South Africa's electricity generating capacity

The electricity supply commission of South Africa (Eskom) supplies roughly 95% of the country's electricity needs [7], [8], [9]. Eskom's total nominal generating capacity for 2015 was 42 090 MW, the majority contributed by coal-fired power stations [7]. Since the gold-mining sector depends heavily on electricity for its operations, it is dependent on Eskom for its electricity.

### 1.2.2 Gold mining electricity demand

The mining sector in South Africa consumes 14.7% of the country's total electricity demand (based on 2014/2015 electricity sales data from Eskom) [10]. From this, gold mines consume almost half of the mining industry's total electricity demand [11]. Gold mining's electricity usage equates to almost 7% of the country's total electricity consumption. Figure 8 shows the breakdown of electricity consumers within South Africa and its mining sector.
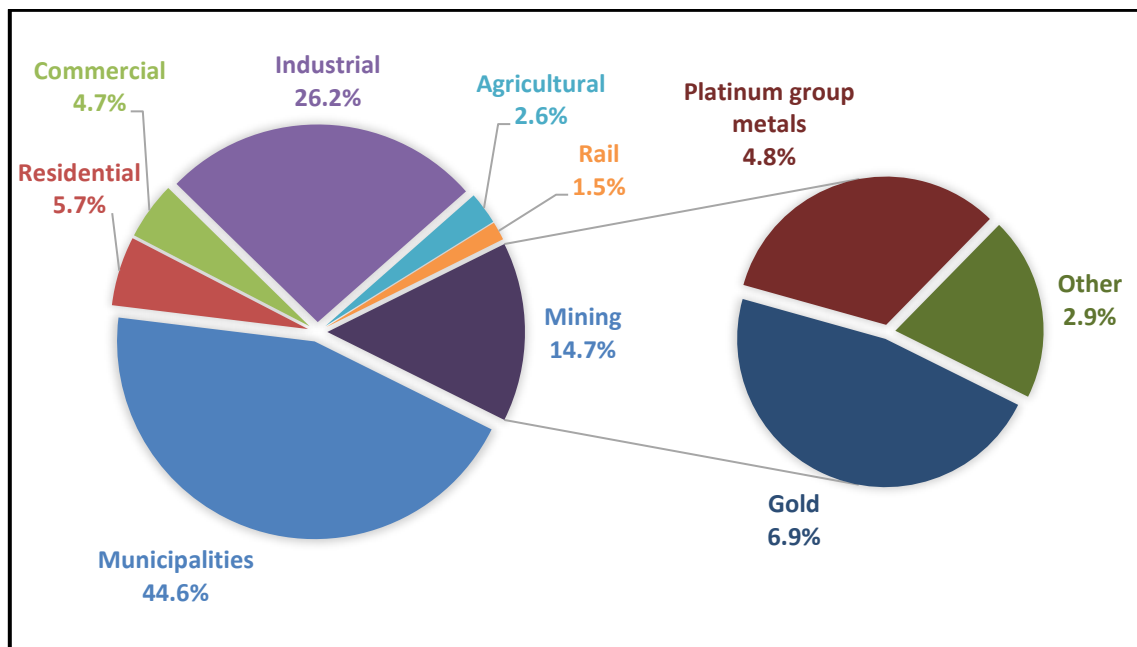


**Figure 8: South African electricity usage breakdown**

As the mining industry is such a large consumer of electricity in South Africa, proved by Figure 8, it becomes evident that an uninterrupted supply of electricity is required for full productivity. This is not always the case as Eskom experiences challenges from time to time to meet South Africa's electricity demand.

### 1.2.3 Challenges faced by Eskom

Eskom's ability to supply the country's electricity demand has come under scrutiny in 2008, 2014 and more recently in 2015 when scheduled load shedding had to be implemented. Eskom failed to add any generating capacity to the electricity grid from the early 1990s due to having a reserve margin of almost 40% [12]. Mismanagement and a lack of maintenance also contributed to these problems [13]. Steady growth in electricity demand of 3.5% per annum meant that, in 2003, the reserve margin degraded to the point where unplanned outages could severely compromise the system's integrity. In 2005 this eventuality arrived and load had to be shed in the Western Cape, followed by country-wide load shedding in 2008 [12].

Eskom is currently constructing two large coal-fired power stations (Medupi and Kusile) with a combined electrical generating capacity of 9 600MW [14]. These power stations are due to be commissioned in 2019 [14]. Despite the construction of new power plants, there are still concerns in terms of Eskom's supply capacity. This is mainly due to the fact that Eskom will start decommissioning several of its older plants from 2020 onwards. Eskom CEO Brian Dames stated in 2012: *"By 2020 we will start decommissioning at least 10 000MW of power plants because they will have reached the end of their lifespan."* There still looms an enormous risk for large electricity consumers in South Africa in regards to reliable electricity supply [14].

It is apparent that South Africa's electricity grid remains unstable in light of the discussions above. Eskom frequently struggles to maintain an adequate reserve margin of 15%, leaving the system vulnerable to unplanned outages [8]. When the demand needs to be reduced, large consumers are usually the first to be curtailed [8]. This is a major concern for the mining industry, and gold mines in particular, as they rely heavily on electricity for its operations, and subsequently its productivity.

To achieve a large impact with load management, large consumers need to be targeted for best results. Seeing that gold mines are one of the largest single users of electricity in South Africa, they are ideal targets to implement such initiatives. By implementing load management on large electricity users, Eskom's reserve margin can be increased during peak periods. The following section will break down a typical gold mine's electricity usage to determine where load management will have the maximum impact.

## 1.3 Electricity usage and load management on deep-level gold mines

### 1.3.1 Electricity usage breakdown

Figure 9 depicts the electricity usage breakdown of a typical gold mine into its various systems. According to Figure 9, one of the largest electricity consuming systems on South African gold mines is refrigeration and ventilation, consuming up to 28% of the total electricity demand. This is mainly due to the extreme depths of some of the deep-level gold mines [5]. Virgin rock temperatures can reach over 50°C in some of these mines [5]. Large refrigeration machines and ventilation fans are therefore required to regulate the underground environmental temperatures. This is to ensure a safe working environment for mine employees as regulated by law [15].
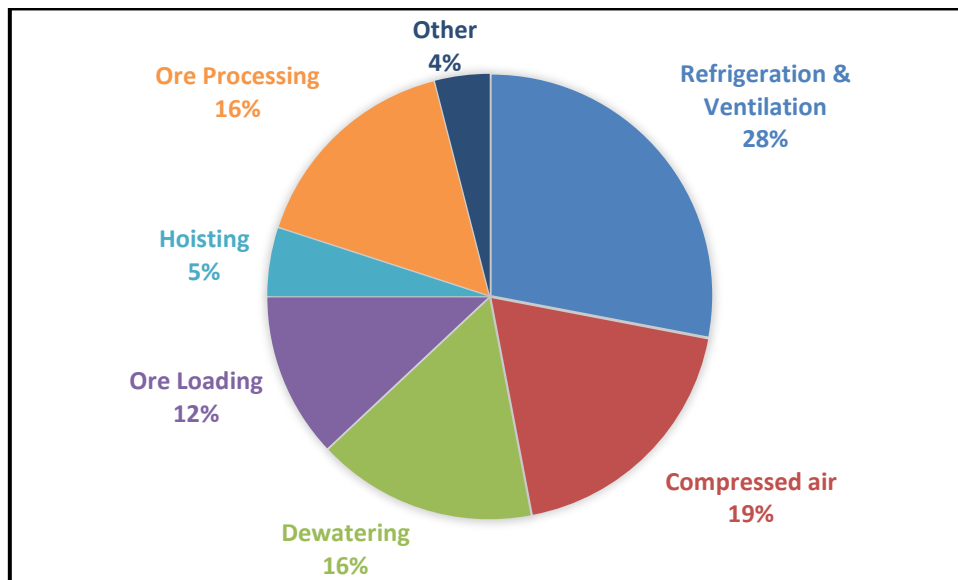


**Figure 9: Gold mine electricity usage breakdown** [16]

### 1.3.2 Load management on gold mine systems

In order to maximise the impact of load managing initiatives, large electricity consumers such as refrigeration and ventilation are usually targeted. This load management focuses on shifting electrical load out of the "peak" periods when Eskom struggles to meet the demand with an inadequate reserve margin. Peak periods are when the electricity demand for the country is at its maximum, indicated by Figure 10.
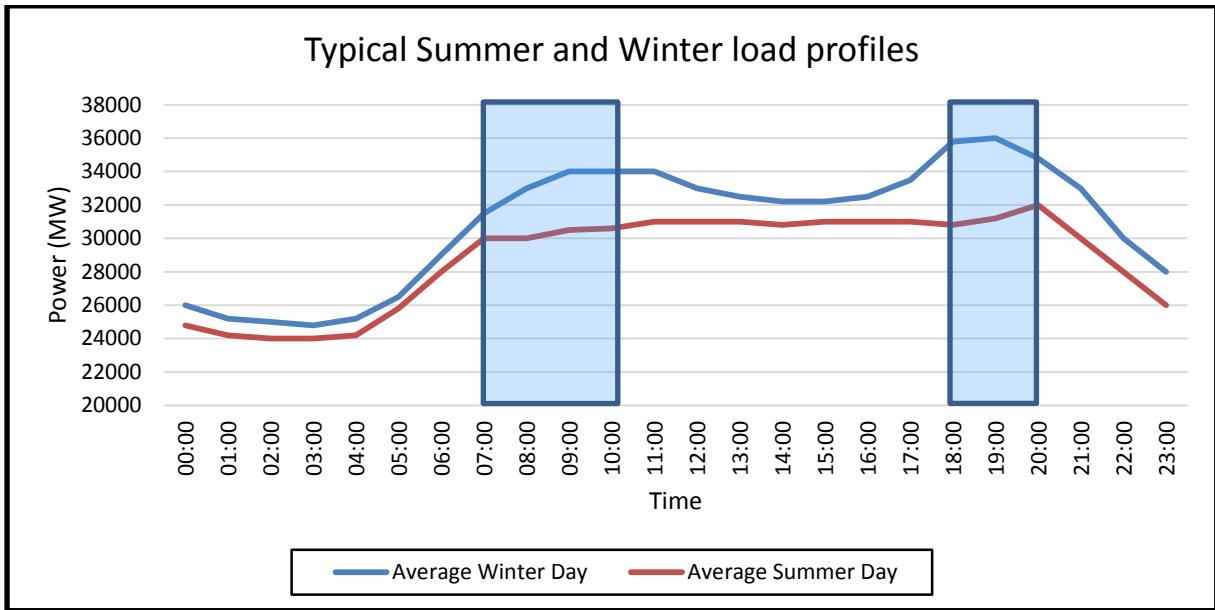
**Figure 10: Eskom average daily demand profile** [17]

When viewing the average daily winter and summer demand in Figure 10, two "peaks" become visible. Eskom defines these "peaks" as high demand periods and subsequently charge large consumers more during these times [18]. Figure 11 shows how the Time-of-Use (TOU) tariff is structured in both summer and winter (denoted as low demand season and high demand season, respectively). Eskom implements this TOU tariff structure to force large consumers to reduce their demand during these peak periods, in turn stabilising the national power grid.
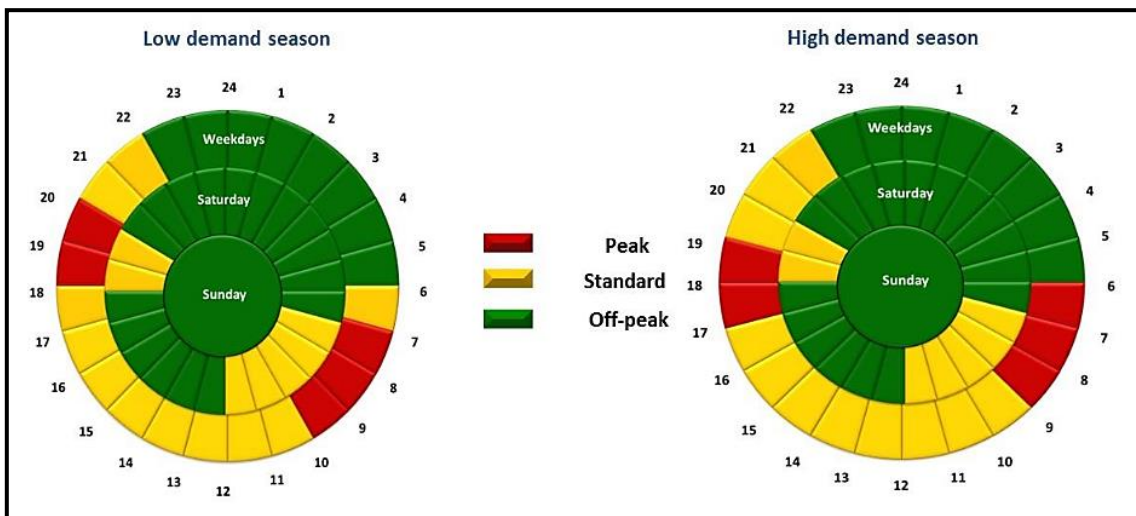


**Figure 11: Eskom TOU tariff structure** [18]

Since the electricity cost is higher during these peak periods, large consumers try to reduce their usage as far as possible during these times. This is where the Eskom DSM model originated, contracting a third party to ensure reduced load during peak periods. The next section will discuss these third parties (ESCos) and the DSM model to which they need to comply during the implementation of load reduction projects.

## 1.4 Demand side management model

### 1.4.1 ESCos background

ESCos use their expertise to reduce the electricity consumption of large consumers, such as gold mines, during certain periods of the day. By providing funding for ESCos, Eskom encourages the implementation of load management initiatives. Figure 12 indicates the relationship between Eskom, gold mines and the ESCo.
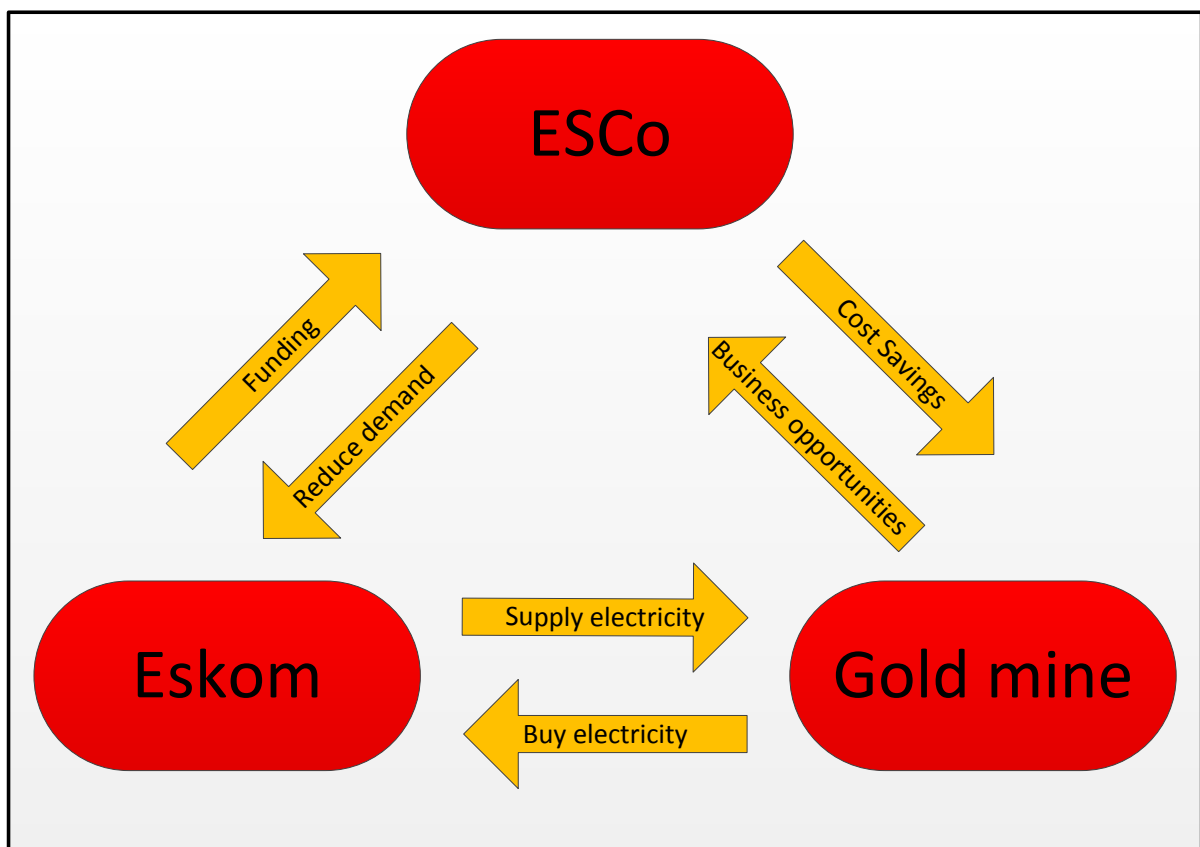


**Figure 12: ESCo relationship triangle**

By identifying large electricity consumers on gold mines, such as refrigeration, a strategy can be developed to ensure lower overall electricity demand during peak periods. Considering large electricity consumers on gold mines for DSM projects can therefore alleviate the pressure on the already strained power grid. Due to refrigeration being one of the largest single consumers of a gold mine's electricity, it is expected to see the maximum impact when considering these systems for DSM.

### 1.4.2 Revised DSM model

DSM projects usually require large amounts of capital to upgrade or install infrastructure to realise the electricity cost-saving potential. Eskom awards DSM initiatives and associated funding to ESCos based on their DSM model. This model was, however, revised in 2015, specifically with sustainability and ESCo liability in mind. The changes from the old model to the revised model are indicated in Table 1 [19], [20].

**Table 1: Changes to DSM model** [19]**,** [20]

|  | **Old model** | **Revised model (2015 onwards)** |
|---|---|---|
| Project types | >100 kW energy efficiency and load management | >500 kW load management |
| Pre-implementation funding | Up to R5 million/MW | None |
| Performance assessment (PA) [ESCo liability] | 3 months | 36 months |
| Client contractual period | 5 years after PA | None |
| ESCo payment finalisation | Payment processed after PA period | • Processed quarterly<br>• Payments processed after each PA period (12 in total) based on performance |

The lack of pre-implementation funding and an extended performance assessment period challenged ESCos to develop creative techniques to implement successful and sustainable DSM initiatives.

## 1.5 Problem statement

The South African gold mining industry faces multiple challenges, which influences their productivity and profit margins. One of the challenges is increasing operating costs, of which electricity is a concern due to the gold mining industry's intensive use and higher-than-inflation increases. Gold-mining groups have reached the point where most of their operations are marginal.

In addition to high electricity costs, gold mines also face problems on their electricity demand side. This is mainly due to Eskom, the main supplier of electricity to South African gold mines, struggling to adequately supply the demand. Since gold mining is such an electricity intensive operation, it is very sensitive to Eskom's ability to meet the demand. During peak periods Eskom regularly operates without adequate reserve margins, subsequently reverting to load curtailment of large users in order to ensure grid stability. This directly influences the productivity of the gold mines.

These challenges highlight the importance of load management initiatives on gold mines, especially on electricity-intensive systems such as refrigeration and ventilation. Load management initiatives would ensure a reduction in gold mine operating costs and in turn increase profit margins. Eskom will also benefit from these initiatives as a reduced demand during peak periods will ensure a stable reserve margin for the country.

ESCos play an important role between the gold mining industry and Eskom, as they complement both parties through DSM initiatives and load management. The revised DSM model has, however, challenged ESCos to optimise the implementation of these initiatives. There is therefore a need for ESCos to develop creative load management techniques that will be cost effective, easy to implement and sustainable over a minimum period of 36 months. In this way gold mines will benefit from the cost savings and Eskom will be able to improve the supply reserve margin. From an ESCo's point of view, by sustainably implementing these initiatives, continued involvement in DSM can be secured.

## 1.6 Objectives of study

The main objective of the study is to investigate the implementation of sustainable load-management initiatives on the electricity-intensive systems of deep-level gold mines. The implementation of the projects is under the regulations of the new Eskom DSM model. This complicates the sustainability of the projects' performance over a period of 36 months as there is limited funding available for sufficient infrastructure and upgrades. This study will, therefore,

focus on low-cost techniques such as optimising the control on deep-level mine systems for sustainable cost savings.

As refrigeration and ventilation are the largest electricity consumers on typical deep-level gold mines, control optimisation will be implemented on these particular systems. Load management projects on the refrigeration and ventilation systems of two separate gold mines will be identified. To validate the feasibility of the study, these projects must be implemented under the new Eskom DSM model.

To prove the feasibility of optimising deep-level gold mine refrigeration control for sustainable cost savings, the following criteria need to be adhered to:

- **Low-cost** – As limited funding is available these projects need to be implemented with little to no capital expenditure.
- **Complexity** – Design of optimised control strategies need to be simple to eliminate complex implementation.
- **Sustainability** – Optimised control needs to ensure that implemented projects remain sustainable over long periods of time.

## 1.7   Document overview

*Chapter 1*

Background is given on the South African gold-mining industry and its role in the economy. Electricity intensity of gold mines is highlighted and refrigeration as one of the largest electricity consumers is discussed. Challenges with the revised Eskom DSM model are highlighted and formulated to develop the problem statement. Finally, the objectives of the study are stated.

*Chapter 2*

The chapter commences with a background on the concept of refrigeration in deep-level gold mines. The operation of deep-level mine refrigeration systems is discussed, including the different components and configurations. Previously implemented load management initiatives on deep-level mine refrigeration systems are investigated with the focus on their sustainability. Finally, the importance of mathematical modelling and simulations are discussed as it forms an integral part in the development of the methodology.

*Chapter 3*

Information gathered in Chapter 2 is used to develop the methodology for optimised control strategies on deep-level gold mine refrigeration systems. The methodology includes identifying load-reduction potential, developing baselines and adjustment models, developing control strategies and optimising the strategies through simulations and testing.

*Chapter 4*

In Chapter 4, optimised control strategies are implemented on the refrigeration systems of two South African deep-level gold mines, Mine D and Mine R. The results presented in Chapter 4 serve as the motivation for the successful implementation of optimised control strategies in terms of sustainability, which is the main objective of the study.

*Chapter 5*

Chapter 5 provides an executive summary on the feasibility of implementing optimised control strategies on deep-level gold mine refrigeration systems. Finally, the recommendations for future work on this topic are provided.

# Chapter 2

# 2 Refrigeration in the deep-level mining environment

## 2.1 Introduction

As highlighted in Chapter 1, refrigeration and ventilation is one of the largest electricity consumers of a deep-level mine. The study therefore focuses on the sustainable implementation of load management initiatives on these systems of deep-level mines. This is to ensure sustainable and maximised electricity demand impact, especially under the new Eskom DSM model [16].

In order to develop a sustainable cost-saving strategy on deep-level mine refrigeration systems, it is important to understand and interpret the concept, operation and configuration of such systems. It is also important to understand the implementation of different load management strategies. Previously implemented strategies will therefore be investigated to determine the shortcomings in terms of sustainability. Finally, the importance of thermal hydraulic modelling and its contribution to developing effective and sustainable strategies with low cost and short implementation periods will be highlighted in this chapter.

## 2.2 Refrigeration concept in deep-level gold mines

### 2.2.1 Preamble

As set out in the Mine Health and Safety Act No. 967 of 1996, underground temperatures need to remain under 27.5°C wet-bulb in the working areas and under 32.5°C wet-bulb in the stopes[1] [15]. Virgin rock temperatures in deep-level mines can reach up to 50°C [21]. This highlights the importance of refrigeration and ventilation systems on deep-level mines to keep operational temperatures within health and safety regulations [22]. The following sections investigate the fundamentals, operation, components and configurations of deep-level mine refrigeration systems.

### 2.2.2 Vapour-compression refrigeration cycle fundamentals

Figure 13 shows a simplified schematic of a refrigeration compression cycle. Superheated, low pressure refrigerant vapour enters the compressor at point 1. At point 2 the vapour leaves the compressor and enters the condenser as a high pressure vapour. The condenser exchanges heat ($Q_H$) with cooling water or the environment. At point 3 the refrigerant is a condensed high pressure liquid. As the refrigerant flows to point 4 over an expansion valve, the high pressure liquid flashes to cold vapour. Any remaining low pressure and temperature

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[1] Inclined areas where the ore containing the valuable minerals is extracted for processing.

liquid is vaporised in the evaporator as heat ($Q_L$) is absorbed from the refrigerated water or environment [23].
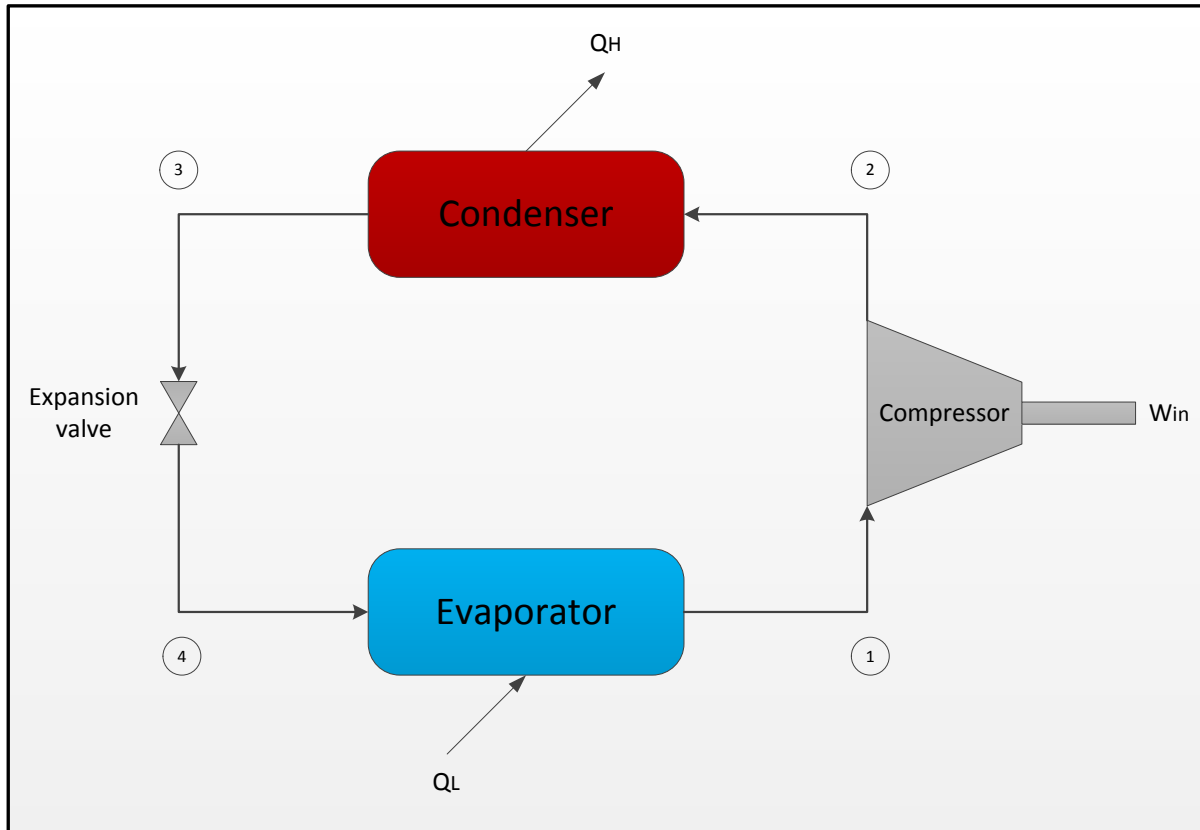


**Figure 13: Simplified layout of a vapour-compression refrigeration cycle** [23]

Figure 14 illustrates the P-h (pressure versus enthalpy) diagram for the ideal vapour-compression refrigeration cycle. The amount of cooling ($Q_L$) for any specific system is determined by the amount of heat (enthalpy) that can be absorbed by the system between points 4 and 1 (indicated by $Q_L$ on Figure 13) [23].
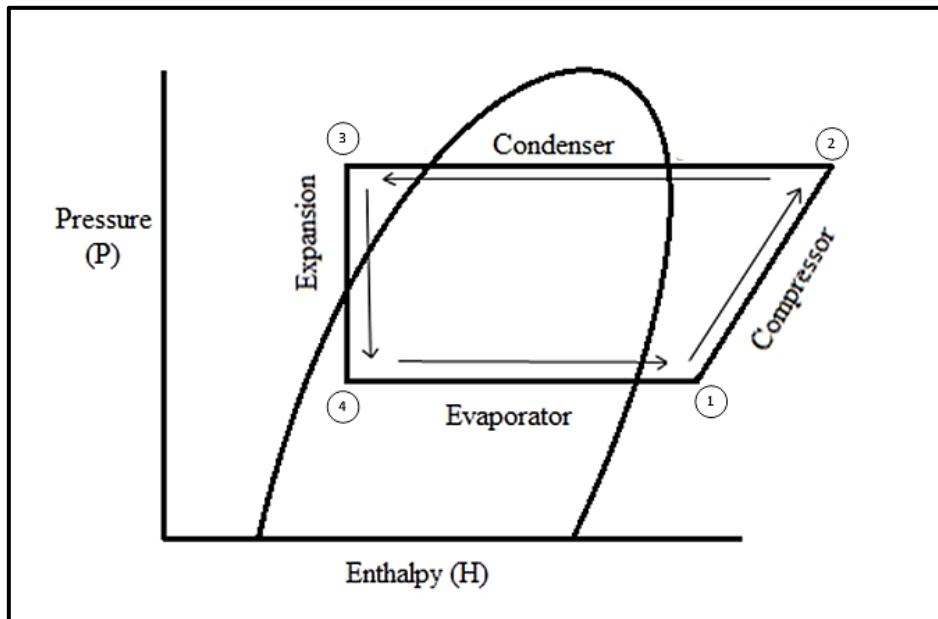
**Figure 14: Vapour compression refrigeration cycle P-h diagram** [24]

From small household appliances to large industrial cooling systems, the basic principle of cooling is based on the vapour-compression cycle. The different components and their configurations need to be examined to better understand deep-level mine refrigeration systems. The following section focuses on incorporating this cycle within deep-level mine refrigeration systems for practical use.

## 2.3 Deep-level mine refrigeration operation

### 2.3.1 Gold mine refrigeration and ventilation systems

Figure 15 depicts a basic layout of a typical deep-level gold mine refrigeration system. The major components (indicated by circled numbers) will be discussed in more detail in this section. An overview on the different refrigeration system configurations in the deep-level mining industry is also provided.
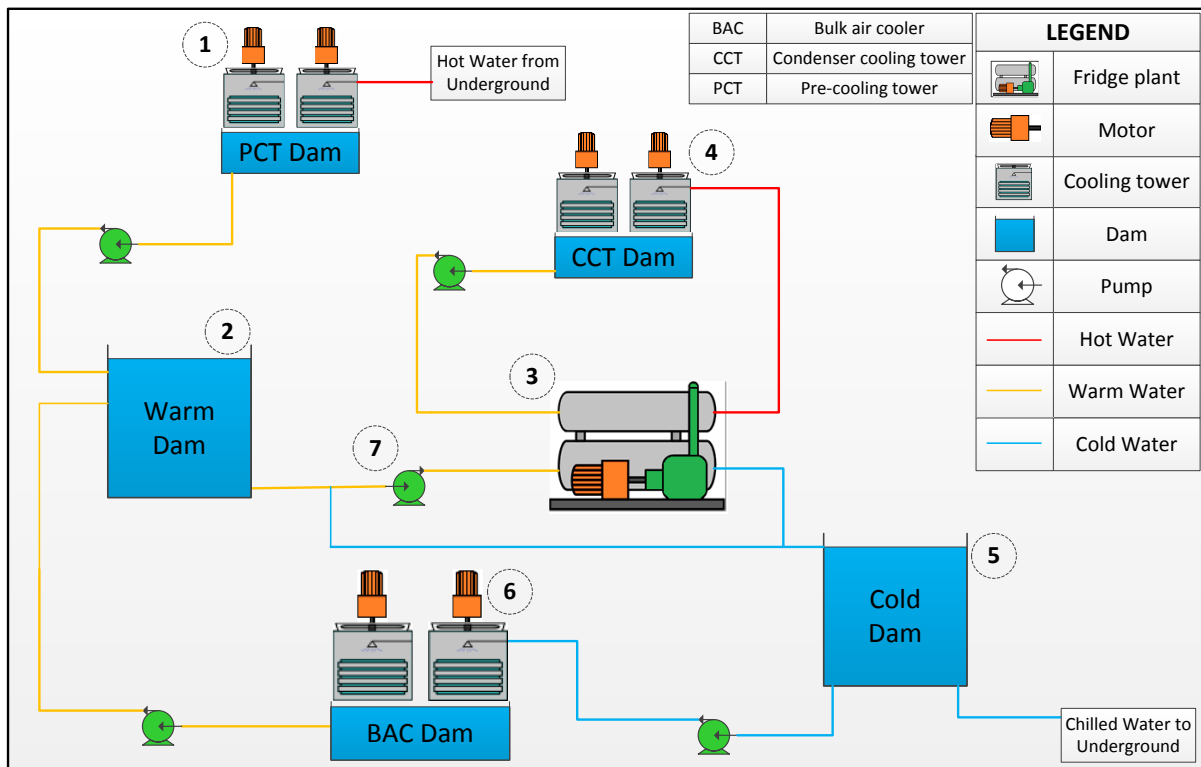
**Figure 15: Simplified layout of a gold mine refrigeration system**

**Pre-cooling tower (PCT) (1)**

The pre-cooling towers are used to cool down the hot water pumped from underground. It is usually designed to cool down the water to a minimum of 2°C above the ambient wet-bulb temperature [25]. The temperature decrease is due to sensible and latent heat transfer [26]. These towers use motor driven mechanical fans (usually mounted at the top of the tower) to facilitate heat transfer between warm water and cooler ambient air. The warm water is sprayed into the tower as a fine mist over a corrugated fill. The corrugated fill increases the surface contact area and heat transfer time between the water and ambient air [26]. Figure 16 shows a typical cooling tower setup.

**Figure 16: Mechanical draft cooling towers**

**Warm dam (2)**

The water from the PCTs is transferred to the warm dam. The main purpose of the warm dam is to provide water storage capacity. This provides a safety barrier to ensure uninterrupted supply of water to the chillers and consequently to the underground operations [27]. Figure 17 shows surface storage dams on a gold mine.

**Figure 17: Warm and cold dams**

**Chiller (3)**

The chillers use the vapour-compression cycle, discussed in section 2.2.2, to supply cooling to the mine in the form of chilled water. These chillers make up the largest portion of the refrigeration system, comprising up to 66% of the entire system's electrical load [26]. The water from the warm dam is drawn through the evaporator side of the refrigeration plant (chiller). This water exits at a lower temperature due to heat exchange between the water and refrigerant gas.

Most chillers used on deep-level gold mines use tube-in-shell heat exchangers [28]. The tubes are contained within a pressure vessel, which acts as the shell. The water flows through the tubes while refrigerant gas is passed over them within the pressure vessel [29]. Figure 18 shows a typical chiller with its insulated evaporator vessel.

**Figure 18: Vapour-compression chiller** [30]

As warm water enters the chiller's evaporator, heat is rejected to the refrigerant gas, in turn cooling the water. As the gas is compressed to a high pressure vapour by the chiller's compressor, heat is rejected from the high pressure liquid to the water in the chiller's condenser [23].

**Condenser cooling tower (CCT) (4)[2]**

Condenser cooling towers operate on the same principal as pre-cooling towers. The warm condenser outlet water from the chiller is cooled in a condenser cooling tower. The condenser cooling towers have sump dams where the cooled water is collected and returned to the condenser vessel of the chiller (semi-closed loop) [26]. Basically the condenser cooling towers are used to reject the heat absorbed from the refrigerant in the condenser vessel of the chiller [31].

**Cold dam (Thermal storage) (5)**

As with the warm dam, the cold dam is used as a storage mechanism. The difference is the cold dam stores the electrical energy, consumed by the chillers, thermally in the form of chilled

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[2] Photo not provided due to towers operating on same principle as pre-cooling towers.

water [27]. This storage ensures a constant supply of cold water to mining operations even when the refrigeration system is offline. These dams act as "electrical capacitors" within the refrigeration system [32]. Figure 19 depicts typical gold mine refrigeration storage dams.



**Figure 19: Surface cold storage dams**

Thermal storage is vital during the implementation of load management initiatives on refrigeration systems [27]. Load management requires the refrigeration system to operate at a reduced capacity or be entirely switched off during certain periods. When this happens, the flow of cold water stops. During these periods water is supplied from the cold storage dams, resulting in their levels decreasing.

**Bulk Air Cooler (BAC) (6)**

The operation of a BAC is very similar to that of a cooling tower, except in a BAC the chilled water is used to cool down the ambient air. The BAC not only cools the ambient air, but also serves as a dehumidifier [28]. This cooled and dehumidified air is sent underground to cool

and supply adequate ventilation to the mine. The warm BAC outlet water is pumped back to the warm dam from where the refrigeration cycle repeats itself [33]. Figure 20 shows a typical BAC, with the mechanical fans and cooling tower visible.
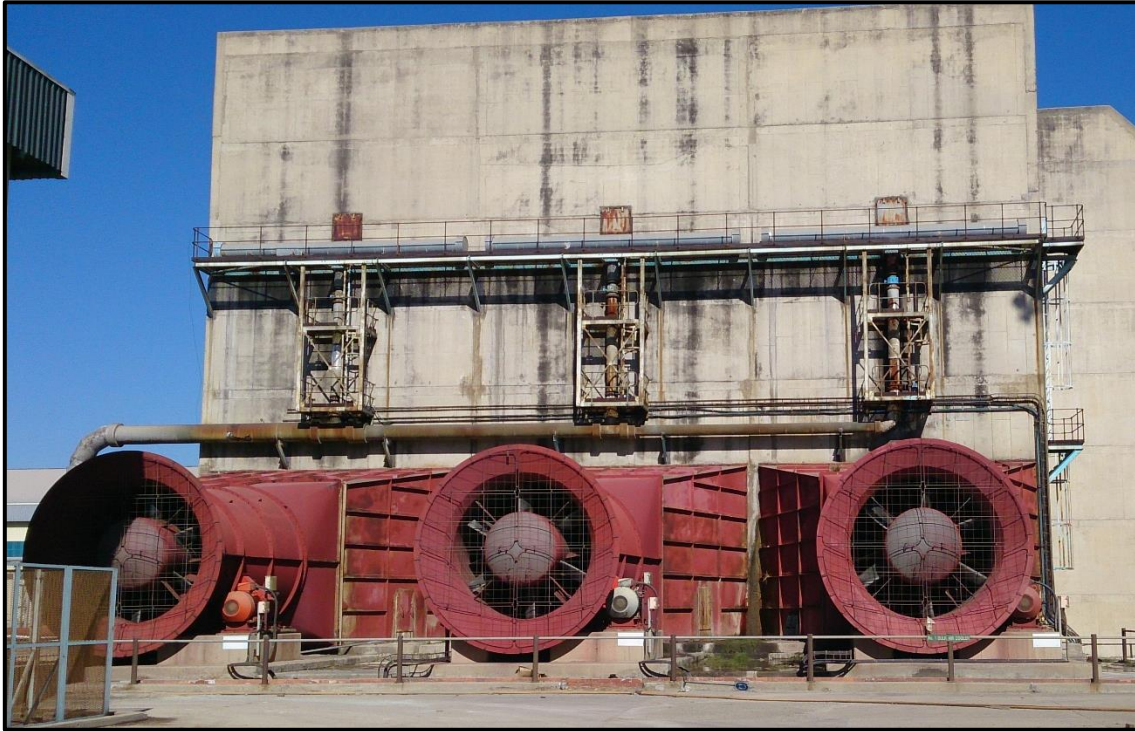


**Figure 20: BAC fans and tower**

In addition to BAC fans transferring cool and dehumidified air underground, large ventilation fans (not present in layout) are also used to create a negative air pressure draft through the mine [34]. This draft ensures that the cold air from the BACs is transferred through the mine [34].

**Pumps (7)**

Centrifugal pumps are generally used throughout a mine's refrigeration system to transfer water between the different components [28]. These can either be conventional pumps with a fixed operating speed, supplying a constant flow of water, or pumps fitted with Variable Frequency Drives (VFDs) to vary the flow output [35]. Figure 21 illustrates a typical transfer pump and electrical motor set used on deep-level mine refrigeration systems.
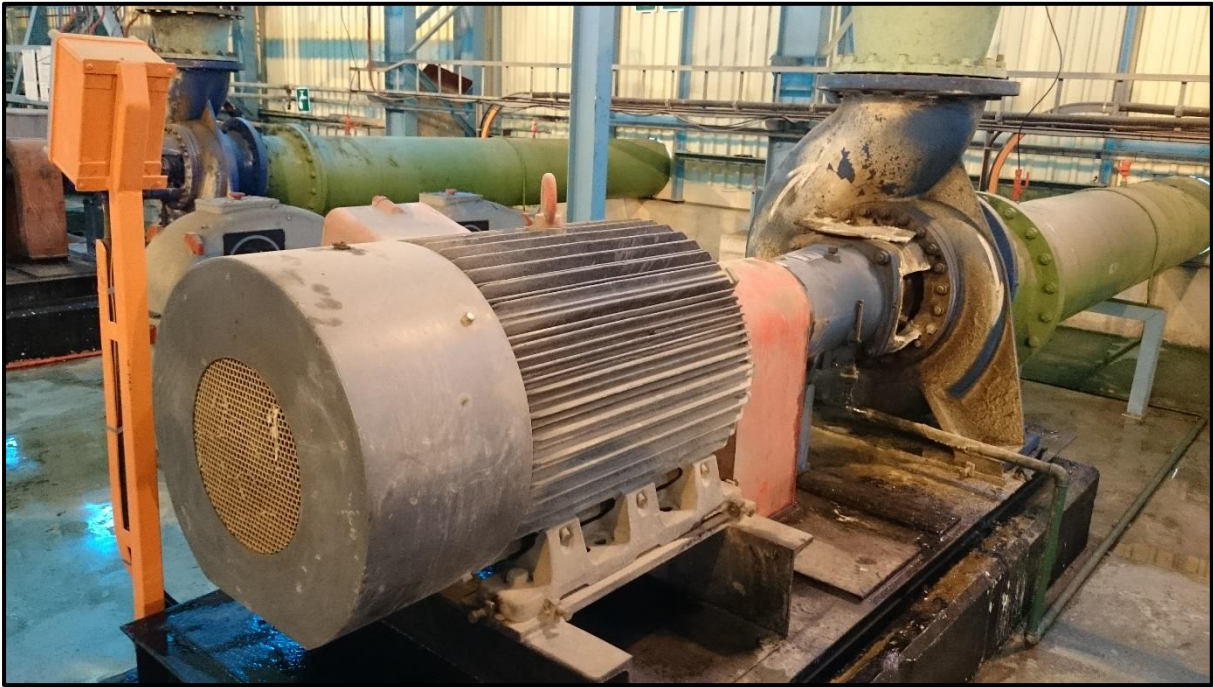
**Figure 21: Centrifugal pump and electrical motor set**

All the components within a deep-level mine's refrigeration system have been identified and discussed. Depending on the mine's specific cold water requirements, these components can be arranged in different combinations. The following section will discuss the different refrigeration configurations present on deep-level mines.

### 2.3.2 Refrigeration system configurations

Due to their importance within the refrigeration system, the configuration of the chillers is an important factor. The chiller configuration determines the amount of water that can be chilled, as well as the minimum evaporator outlet temperature. There are three different configurations for chillers in a deep-level mine's refrigeration system, namely:

- Series configuration
- Parallel configuration
- Parallel-series configuration

The different configurations are determined by the magnitude of the mine and its cooling requirements [28]. Each of the three configurations is discussed in more detail below:

### Series configuration

Figure 22 illustrates series configured chillers in a refrigeration system. The water outlet temperature can be controlled by means of running one or both chillers. This configuration is mainly used when a constant flow of water is supplied to the chillers. As ambient conditions vary between summer and winter, one of the chillers can be switched off when less or more cooling capacity is required [36].
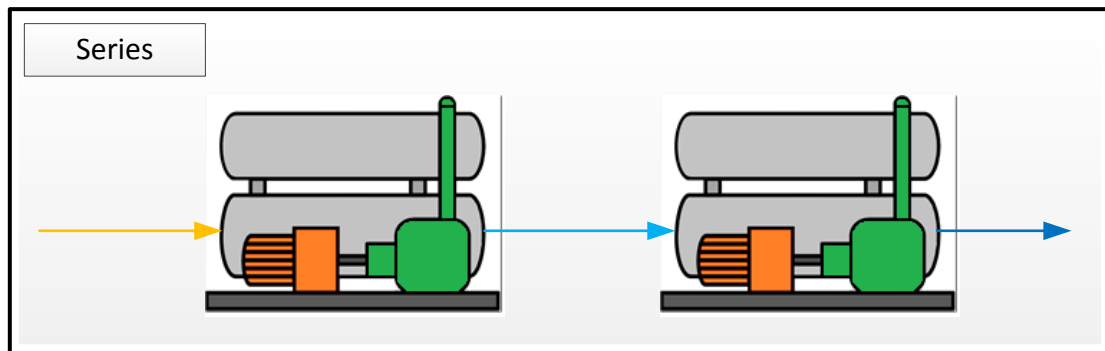


**Figure 22: Series configured chillers**

### Parallel configuration

Figure 23 illustrates parallel configured chillers. When increased cooling is required, the water flow through parallel chillers can be reduced by means of VFD pumps. This configuration is mainly used when the water flow rate is varied to determine the outlet temperature. When chilled water demand is low, one of the chillers and its auxiliary pumps can be switched off and isolated, thus reducing the amount of water that is supplied to the system at the same temperature [36].
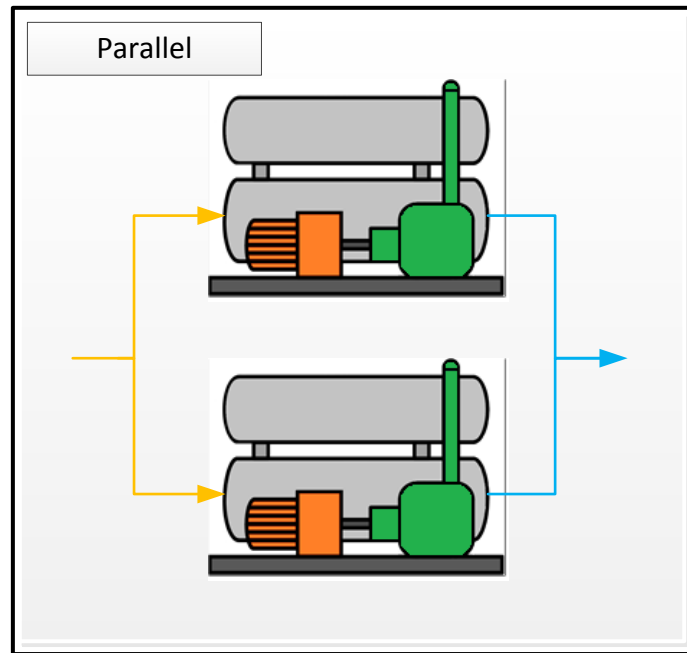
**Figure 23: Parallel configured chillers**

### *Parallel-series configuration*

As illustrated by Figure 24, the final configuration is a combination of both parallel and series configured chillers. Varying the cooling can be achieved by running only one, or both chillers in each parallel leg. This configuration allows more water to be chilled to a lower temperature than either the series or parallel configurations. Parallel-series configurations are used when very low temperatures need to be supplied at high flow outputs [28]. If the cooling requirement is reduced, one of the chillers can be switched off. Both chillers in one of the parallel legs can also be switched off if the chilled water or cooling demand drastically reduces [36].
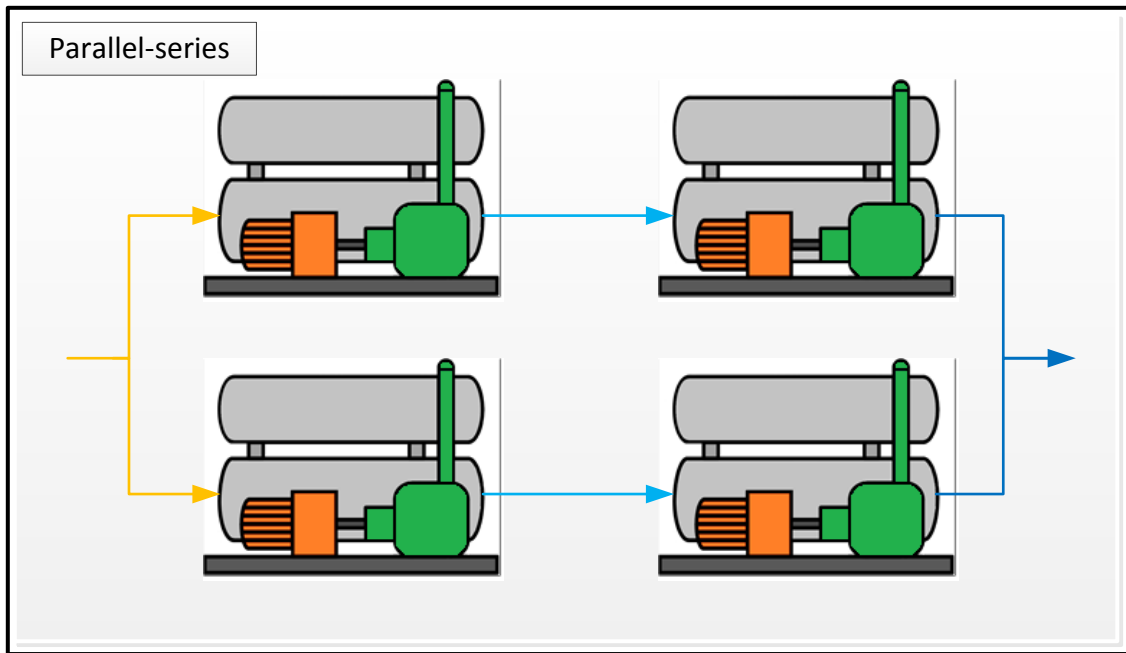
**Figure 24: Parallel-series configured chillers**

This section discussed the basic components and operation of deep-level mine refrigeration systems. The different refrigeration configurations were also discussed. The next section focuses on the implementation of load management initiatives on deep-level mine refrigeration systems.

## 2.4  Load management on deep-level mine refrigeration systems

By understanding the operation of deep-level mine refrigeration systems and its components, load management potential can be determined. It was found in literature that load management can be implemented on deep-level mine refrigeration systems if the following criteria is adhered to [37]:

- Adequate thermal storage, in particular for the chilled water
- Adequate chilled water supply to consumers, while switching off chillers
- Adequate comeback load and flow capacity to recover operational parameters

Multiple load management studies and initiatives implemented on deep-level mine refrigeration systems were investigated. The sustainability of these initiatives is of concern as the majority were implemented under the old Eskom DSM model. The identified initiatives are evaluated on the following criteria:

- Implementation cost

- Implementation time
- Load management impact (MW)
- Sustainability

**Study 1 (2007)**

Schutte identified thermal storage as a key component to enable load management on refrigeration systems. The critical prerequisites required to implement load management on mine refrigeration systems were also identified. Findings were used to implement load management on a case study. A mathematical model of a deep-level mine refrigeration system was developed to aid with further research in the field [37].

Schutte recommended including the BACs into the load shift control strategy and monitoring the effects thereof. Facilitating water flow control by means of underground control to reduce chilled water consumption was also recommended [37].

**Study 2 (2007)**

Van der Bijl used integrated simulation models to investigate the potential for load management initiatives on deep-level gold mine refrigeration systems. The importance of mathematical and simulation models in the fast and effective identification of load management potential on refrigeration systems were highlighted [32].

Further testing of the "generic" control strategy on more refrigeration systems was recommended along with the need to optimise these strategies for improved cost savings [32].

**Study 3 (2015)**

Engels focused on the cost savings achievable by combining energy efficiency and load management initiatives. Although the overall cost savings achieved deemed the project feasible, the load shift was routinely interrupted due to underground chilled water demand. The load shift part of the project was unsustainable from inception [31].

Engels highlighted the need to include the underground chilled water demand in the control strategy to maximise load management potential [31].

**Study 4 (2015)**

Vermeulen investigated the implementation of a load management project without implementation costs and achieved load shifting manually. A simulation model was used to

determine the load management scope, which enhanced the implementation period of the project. Vermeulen mentioned that sustainability could become an issue due to manual load shifting instead of automated control [38].

Recommendations from the study included adding the BACs to the load management strategy. Implementing real-time monitoring of underground temperatures was also suggested to monitor the impact of load management over longer periods of time [38].

**Project results matrix**

A variety of load management projects implemented on deep-level mine refrigeration system were also investigated. Table 2 summarises various aspects of these projects, as highlighted by the criteria discussed earlier in this section.

**Table 2: Previously implemented load management projects matrix** [31]**,** [32], [37], [38]

| Project | ESCo model | Project type | Implementation duration (Months) | Implementation cost (R million) | Load Shift achieved (MW) | Implementation cost/load shift achieved (R/MW) | Sustainability (Months) |
|---|---|---|---|---|---|---|---|
| Mine 1 [32] | Old | Load shift | 12+ | 3.08 | 3.86 | 798 000 | 18 |
| Mine 2 [37] | Old | Load shift | 12+ | 4.18 | 4.5 | 929 000 | 12 |
| Mine 3 [32] | Old | Load shift | 12+ | 1.17 | 4.0 | 292 500 | 12 |
| Mine 4 [31] | Old | Load shift & Energy efficiency | 8 | 4.37 | 3.5 | 1 248 500 | 0[3] |
| Mine 5 [38] | Revised | Load shift | 0 | 0 | 3.7 | 0 | 6[4] |
| Mine 6 [28] | Old | Load shift | 8 | 3.9 | 4.0 | 975 000 | 0[5] |

[3] Project active for eight months at the time of this study
[4] Project active for six months at the time of this study
[5] Project active for 23 months at the time of this study

From Table 2 it becomes evident that the implementation cost against the achieved load shift for projects under the old DSM model was very high (on average R 848 000 per MW). In addition to the high implementation cost, load management cost savings under the previous DSM model were not sustainable.

Under the old DSM model, the clients were responsible to maintain the project savings after the three-month performance assessment period conducted by the ESCo. This resulted in the deterioration of the project's performance [19]. Although this is mainly due to a lack of project maintenance, it severely affects the sustainability of load management on refrigeration systems.

The project implemented on the refrigeration system of Mine 5 proved to have low implementation costs and time. Vermeulen proved that this is ascribed to the value of a simulated control strategy [38]. This simulated strategy was implemented manually on the refrigeration system at Mine 5.

As indicated by Table 2, the implementation of load management projects under the old DSM model required a lot of time and effort. Adequate simulation models proved to have a significant impact on addressing these issues during project implementation, but sustainability remains an issue.  By incorporating some of the recommendations made in the investigated studies within a simulation model, an effective and sustainable control strategy can be developed. The next section will therefore focus on modelling and simulating thermal hydraulic systems and how effective their use is in practical applications.

## 2.5   Thermal hydraulic system modelling

### 2.5.1   Preamble

Determining the potential impact of a control strategy on a mine's refrigeration system prior to implementation is important. Control strategies on mine refrigeration systems can be evaluated by using mathematical modelling within simulation software. By predicting the outcome of a control strategy by means of simulation would help mine personnel to make an informed decision when implementing load management initiatives.

Under the new Eskom DSM model where funding for projects are limited, low cost, accurate and time-efficient implementation of sustainable load management initiatives became crucial. Accurate simulations and modelling are therefore very important to accomplish this. This section highlights the mathematical equations used to model thermal hydraulic equipment

found on mine refrigeration systems. This information will be used to determine which simulation software package is most suitable for the purpose of this study.

### 2.5.2 Mathematical equation modelling

To be able to select an appropriate simulation software package, the mathematical equations used to model major components within an industrial refrigeration system needs to be investigated. This will also aid in understanding the mathematics behind refrigeration and cooling components. The mathematical modelling of four major refrigeration components will be discussed. These components are listed as follows:

- Chillers
- Pumps
- Cooling towers
- Dams (thermal storage)

**Chillers**

The schematic illustrated by Figure 25 represents the operation of a chiller. The schematic explains how to determine the outlet evaporator and condenser water temperature of a chiller [32], [39], [40].
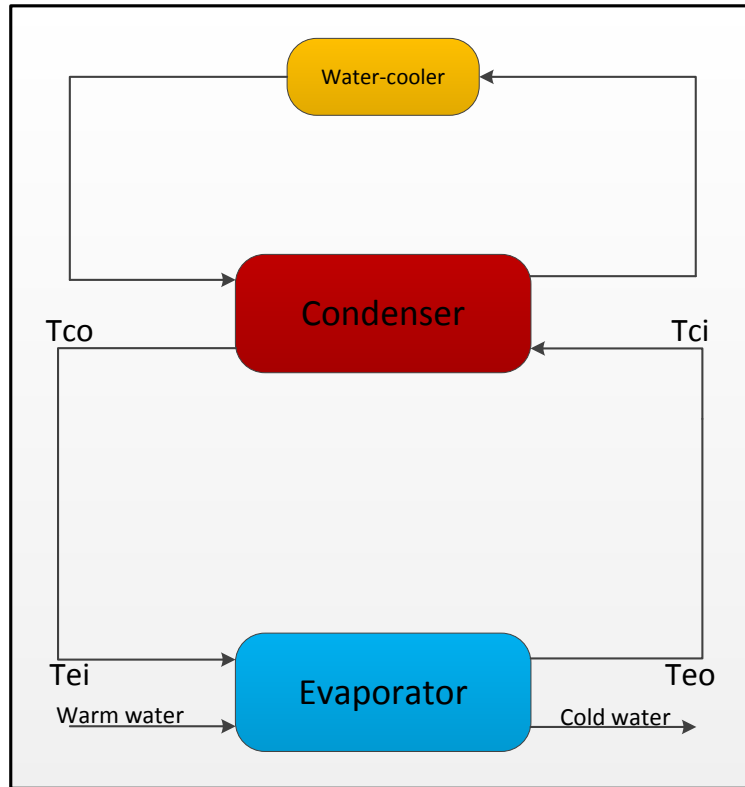


**Figure 25: Water-cooled chiller schematic**

The specific equation for cooling capacity of a chiller yields [32]:

**Equation 1: Explicit chiller cooling capacity (C$_c$)**

$$Q_e = f(a_0 + a_1 t_{ci} + a_2 t_{ei})$$

With

$$a_0 = C_c - (a_1 t_{ci} + a_2 t_{ei})$$

$$a_1 = -0.01 C_c + 0.2289$$

$$a_2 = -0.0266 C_c + 2.8714$$

And

$t_{ci}$       =       Condenser water inlet temperature [K]

$t_{ei}$       =       Evaporator water inlet temperature [K]

$C_C$       =       Cooling capacity [kJ/kg]

The coefficient $a_0$ is calculated at a specific operating point obtained from measurements. The remaining coefficients $a_1$ and $a_2$ were found to be linear over a range of chillers in regards to cooling capacity. This results in only one operating point being required to determine the model of a specific chiller [32]. The power consumption of a chiller is calculated as follows:

**Equation 2: Explicit chiller power consumption**

$$P = f(b_0 + b_1 t_{ci} + b_2 t_{ei})$$

With

$$b_0 = P - (b_1 t_{ci} + b_2 t_{ei})$$

$$b_1 = 0.0124P + 0.4207$$

$$b_2 = 0.007P + 0.3549$$

And

$t_{ci}$       =       Condenser water inlet temperature [K]

$t_{ei}$       =       Evaporator water inlet temperature [K]

$P$       =       Compressor power [kW]

The coefficient $b_0$ is calculated at a specific operating point obtained from measurements. The remaining coefficients $b_1$ and $b_2$ were found to be linear over a range of chillers in regards to compressor power. This results in only one operating point being required to determine the model of a specific chiller [32].

By combining the equations above, the outlet temperature of the evaporator and condenser water can be determined with the help of the following equations:

**Equation 3: Evaporator water outlet temperature**

$$t_{we(evap)} = t_{wi(evap)} - \frac{Q_e}{m_{w(evap)} c_{pw}}$$

**Equation 4: Condenser water outlet temperature**

$$t_{we(cond)} = t_{wi(cond)} - \frac{Q_e + P}{m_{w(cond)} c_{pw}}$$

With

| | | |
|---|---|---|
| $t_{we}$ | = | Water outlet temperature [K] |
| $t_{wi}$ | = | Water inlet temperature [K] |
| $Q_e$ | = | Cooling capacity [kJ/kg] |
| $P$ | = | Compressor power [kW] |
| $m$ | = | Water mass flow [kg/s] |
| $c_{pw}$ | = | Specific heat of water taken as 4.186 [kJ/kg·K] |

**Pumps**

Figure 26 shows a basic schematic of a centrifugal pump. The following model describes how to obtain the heat rise over a centrifugal pump as well as the pump's electrical power consumption [32], [41].
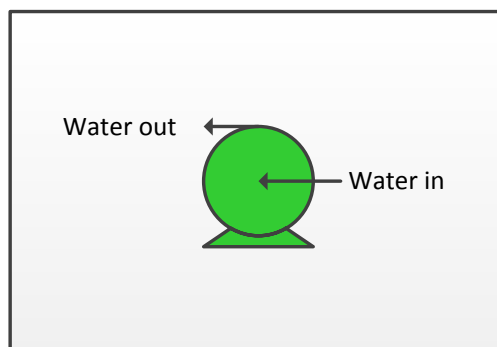


**Figure 26: Pump schematic**

This model is based on the two non-dimensional variables below, derived from using the Buckingham-Pi theorem [42], [43].

**Equation 5: Flow coefficient**

$$K_f = \frac{\dot{m}}{\rho n D^3}$$

**Equation 6: Pressure head coefficient**

$$K_h = \frac{dP}{\rho n^2 D^3}$$

With

| | | |
|---|---|---|
| $\dot{m}$ | = | Water mass flow [kg/s] |
| $dP$ | = | Static pressure increase [Pa] |
| $\rho$ | = | Water density taken as 1000 [kg/m³] |
| $n$ | = | Pump rotational speed [rev/s] |
| $D$ | = | Pump rotor diameter [m] |

These two equations are used to specify the characteristics of any centrifugal pump [32], [42], [43]. By using polynomial regression the following equations are derived:

**Equation 7: Pressure head polynomial regression**

$$K_h = a_0 + a_1 K_f + a_2 K_f{}^2 + .. + a_k K_f{}^k$$

With $a_k$ the k+1 correlation coefficient, determined from data tables. Depending on the relation between $K_f$ and $K_h$, the order of the polynomial equation will vary between models. Similarly the efficiency can be calculated as:

**Equation 8: Pump efficiency**

$$\eta_P = b_0 + b_1 K_f + b_2 K_f{}^2 + .. + b_k K_f{}^k$$

Subsequently the temperature rise over the pump can be calculated with the following equations:

**Equation 9: Heat transfer to water due to compression in pump**

$$Q = \frac{(1 - \eta_P)\dot{m}dP}{\rho\,\eta_P}$$

With

$\eta_P$ $=$ Pump efficiency [%]

$\dot{m}$ $=$ Water mass flow [kg/s]

$dP$ $=$ Static pressure rise [Pa]

$\rho$ $=$ Water density taken as 1000 [kg/m³]

**Equation 10: Water temperature rise over pump**

$$t_e = t_i + \frac{Q}{\dot{m}C_{pw}}$$

With

$t_e$ $=$ Water outlet temperature [K]

$t_i$ $=$ Water inlet temperature [K]

$\dot{m}$ $=$ Water mass flow [kg/s]

$C_{pw}$ $=$ Specific heat of water taken as 4.186 [kJ/kg·K]

The required electrical power can also be calculated as:

**Equation 11: Pump electrical power**

$$P = \frac{k\dot{m}dP}{\rho\eta_P\eta_M}$$

With

$k$ $=$ Pump stages [-]

$\dot{m}$ $=$ Water mass flow [kg/s]

$dP$ $=$ Static pressure rise [Pa]

$\rho$ $=$ Water density taken as 1000 [kg/m³]

$\eta_P$         =         Pump efficiency [%]

$\eta_M$        =         Motor efficiency [%]

**Cooling towers**

Cooling towers are used on heat rejection devices, most commonly on the chiller's condenser side [37]. The same process can be used in a BAC, in which cold water cools down hot air [28]. Figure 27 illustrates a schematic of a basic cooling tower.
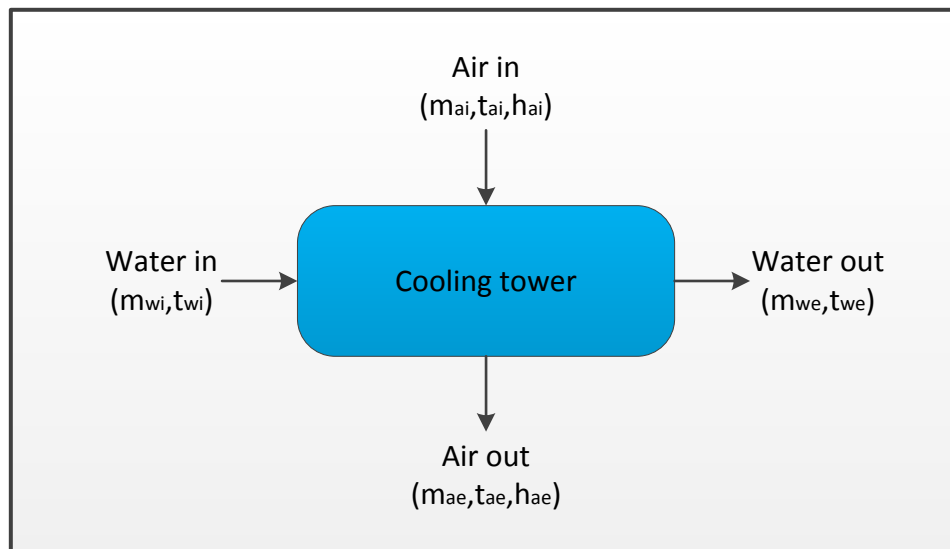


**Figure 27: Cooling tower schematic**

Manufacturing catalogues can be used to predict the explicit equation for a cooling tower model's cooling capacity [44]. The relationship between water mass flow and cooling capacity is illustrated by the equation below:

**Equation 12: Water mass flow and cooling capacity relation**

$$Q_c = A(t_{wb}) m_{wi}{}^B$$

$A$         =         Described by Equation 13

$B$         =         Constant over range of cooling towers

| $t_{wb}$ | = | Ambient wet-bulb temperature |
|---|---|---|
| $m_{wi}$ | = | Water mass flow through tower |

The constant A is a function of the ambient wet-bulb temperature of the air in the cooling tower and given by the following equation:

**Equation 13: Constant A**

$$A = C(t_{wi})t_{wb} + D(t_{wi})$$

The gradient and constant (C and D) are dependent on the water inlet temperature and given by the following equations:

**Equation 14: Gradient C**

$$C = a_0 t_{wi} + a_1$$

**Equation 15: Constant D**

$$D = a_2 t_{wi} + a_3$$

The cooling capacity of the tower can be calculated empirically by substituting variables A, B and C into Equation 12 as indicated below, where $a_0$ to $a_3$ are empirical curve fit coefficients.

**Equation 16: Cooling capacity of cooling tower**

$$Q_c = [(a_0 + a_1 t_{wi})t_{wb} + a_2 t_{wi} + a_3]\, m_{wi}{}^B$$

When the cooling capacity is calculated, it can be used to determine the outlet water temperature and air enthalpy with the following equations:

**Equation 17: Outlet water temperature – cooling tower**

$$t_{we} = t_{wi} - \frac{Q_c}{m_w C_{pw}}$$

With

| $t_{wi}$ | = | Water inlet temperature [K] |
|---|---|---|
| $Q_c$ | = | Cooling capacity [kJ/kg] |
| $m_w$ | = | Water mass flow [kg/s] |
| $C_{pw}$ | = | Specific heat of water taken as 4.186 [kJ/kg·K] |

**Equation 18: Outlet air enthalpy – cooling tower**

$$h_{ae} = h_{ai} + \frac{Q_c}{m_a}$$

With

$h_{ai}$      =      Air inlet enthalpy [kJ/kg]

$Q_c$      =      Cooling capacity [kJ/kg]

$m_a$      =      Air mass flow [kg/s]

The temperature of the outlet air ($t_{ae}$) can now be determined by using psychrometric charts, assuming the outlet air is fully saturated [44].

**Dams (thermal storage)**

The final major component to be modelled is the storage dams. Figure 28 shows the schematic of a thermal storage dam [32], [44]. For the purposes of this model, the assumption is made that the thermal storage dam reacts in the same way as an electrical capacitor [45].
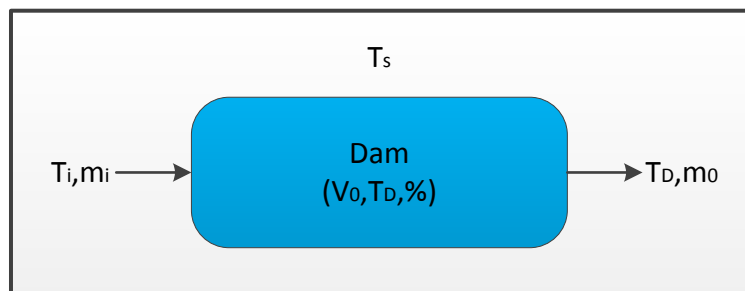


**Figure 28: Dam (thermal storage) schematic**

Multiple variables affect the temperature within a storage dam. This includes initial volume, initial temperature and solar air temperature [44]. The solar air temperature ($T_s$) includes absorption and emittance of air in contact with the dam wall. The convection coefficient of the dam wall is also part of the solar air temperature [44]. By taking the heat transfer mentioned above into account (including the heat transfer of the dam's exposed areas), the following equation can be derived:

**Equation 19: Basic thermal storage dam equation**

$$C\frac{dT}{dt} = m_i C_{pw}(T_i - T_D) + UA(T_s - T_D)$$

With the solar temperature given by the following equation [45]:

**Equation 20: Solar air temperature**

$$T_s = T_A + \alpha\frac{G_t}{h_0} - \frac{\varepsilon\Delta R}{h_0}$$

With

| | | |
|---|---|---|
| $T_A$ | = | Ambient dry-bulb temperature [K] |
| $\alpha\frac{G_t}{h_0}$ | = | Absorption heat transfer of air [-] |
| $\frac{\varepsilon\Delta R}{h_0}$ | = | Emittance heat transfer of air [-] |

By factorising Equation 19 and separating the results, the following equation can be obtained [32]:

**Equation 21: Basic thermal storage dam equation – Step 2**

$$C\frac{dT}{dt} = -T_D \cdot a + b$$

With

$$a = m_i C_{pw} + UA$$

$$b = m_i C_{pw} T_i + UAT_s$$

$$C = C_0 + (m_i - m_0)C_{pw}\Delta t$$

$$C_0 = V_0 \cdot C_{pw}$$

By rearranging the equations above, the following equation can be obtained:

**Equation 22: Basic thermal storage dam equation – Step 3**

$$\int_{T_{D_0}}^{T_D} \frac{1}{T_D \cdot a - b}\, dT = \int_0^1 \frac{-1}{C}\, dt$$

When integration is complete, the exponential rules can be used to obtain the following equation:

**Equation 23: Thermal storage dam temperature**

$$T_D = \frac{1}{a}\left(\left(T_{D_0} \cdot a - b\right)e^{\frac{-a\Delta t}{C}} + b\right)$$

With

$C = max, if\ C \geq max$

$m_0 = 0, if\ C \leq 0$

The dam volume is another important factor to consider in the thermal storage system. As inlet and outlet flow varies over time, the volume (dam level) dynamically changes. The following equation models the dam volume [44]:

**Equation 24: Thermal storage dam volume**

$$V_t = V_{t-1} + \frac{(m_i - m_o)\Delta t}{1000}$$

With

$m_0 = 0, if\ V_{t-1} = 0$

$m_i = 0, V_t = V_T, if\ V_{t-1} \geq V_T$

This model requires the user to input information such as initial conditions, total volume and basic design of the dam.

The mathematical models explained in this section have become more accessible through simulation packages. These simulation packages incorporate the described models into optimised software that reduces the time spent on modelling a refrigeration system. The different commercially available simulation packages are evaluated in the next section as it forms an integral part of this study.

### 2.5.3   Simulation software for deep-level mine refrigeration systems

In the past, simulation software packages were not commonly available for mine refrigeration systems, forcing researchers to use commercial HVAC (Heating, Ventilation and Air Conditioning) packages [46]. In recent years, more and more simulation software packages are specifically designed to simplify and simulate mine refrigeration systems. One particular

study identified over forty-five such packages [30]. The most commonly available simulation packages developed for mine refrigeration systems are discussed as follows:

**ENVIRON**

ENVIRON is commonly used throughout the mining industry. It simulates the airflow underground and aids in the design of mine ventilation. Hourly profiles required to simulate Eskom's TOU tariff structure is, however, not available with this package. The main use of ENVIRON is to specify the cooling capacity required for adequate cooling of the underground environment [32].

**VUMA (Ventilation of Underground Mine Atmospheres)**

This software package can be used to simulate ventilation and water-cooling applications in large mines. VUMA is one of the few software packages that can fully analyse thermodynamic effects in underground mining environments. It also aids in analysing the heat and gas distribution throughout a mine.

This software is mainly used to optimise the refrigeration and ventilation systems of mines. It requires a large amount of input data to deliver accurate results. Trained and qualified personnel are required to operate the software and obtain accurate results [32], [28], [47].

**Process Toolbox (PTB)**

Process Toolbox (PTB) is a thermal hydraulic simulation software package. It is used to simulate a mine's refrigeration, dewatering and compressed air system. The software has the capability to determine optimal operation of equipment and to calculate potential cost savings from proposed load management initiatives. PTB also enables the design, analysis and optimisation of a system's performance [48].

PTB features a Graphical User Interface that enables the drag and drop of system components [48]. Each system comprises pipes and nodes to calculate the flow and thermal hydraulic properties, respectively [48]. In addition to this, the four major components described in section 2.5.2 are all available in PTB [48]. Figure 29 below illustrates a simplified layout of a thermal hydraulic system simulated with PTB.
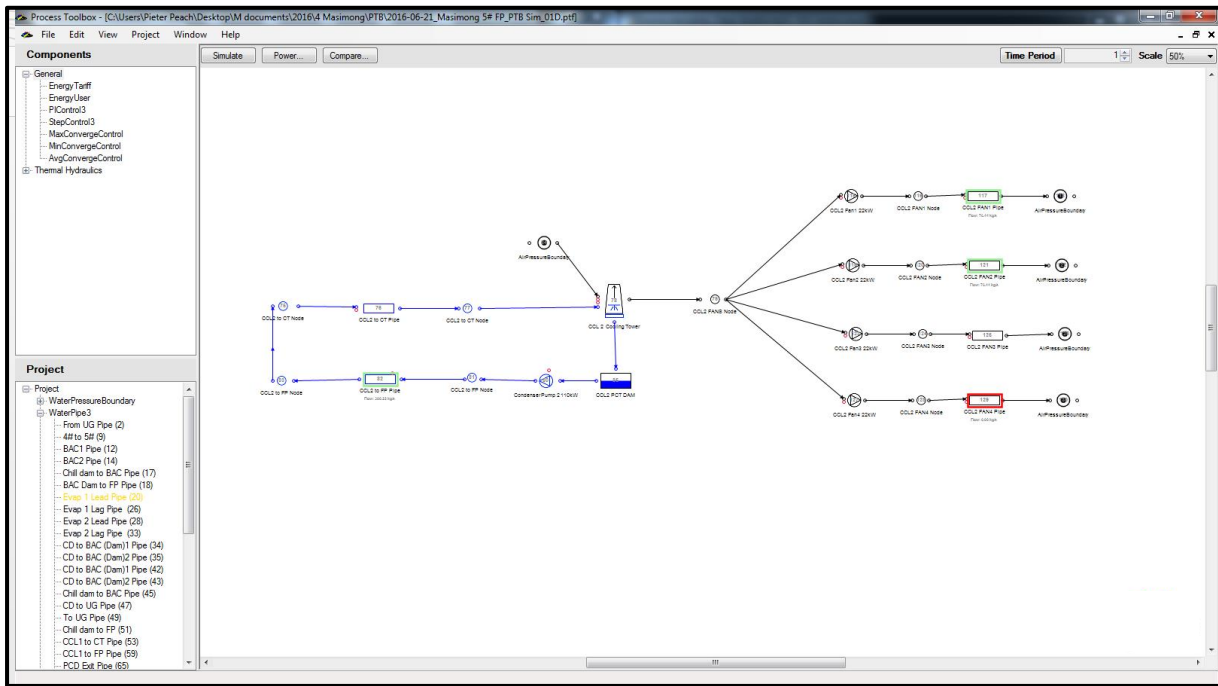
**Figure 29: Simplified illustration of a thermal hydraulic system simulated in PTB**

Previous studies by **Oberholzer** [28], **Vermeulen** [38] and **Mare** [49] on mine refrigeration systems proved the accuracy of the PTB simulation software. A summary of the three studies are provided as follows:

- **Oberholzer** simulated the successful reconfiguration of a deep-level gold mine refrigeration system for improved operation. The simulated and actual results corresponded.

- **Vermeulen** simulated cost-effective management techniques to realise cost savings on mine refrigeration systems. The simulated and actual results corresponded.

- **Mare** simulated the optimised control for improved energy savings on mine refrigeration systems. The simulated and actual results corresponded.

The simulation software packages were evaluated according to each one's advantages and disadvantages. The evaluation assists in identifying the most suitable package for the purposes of this study. Table 3 shows the evaluation of the simulation packages.

**Table 3: Simulation software package evaluation**

| Software package | Advantages | Disadvantages |
|---|---|---|
| ENVIRON | • Can specify cooling required by mine | • Dynamic control of components not possible<br>• TOU tariff structure cannot be incorporated |
| VUMA | • Can fully analyse underground thermodynamic properties<br>• Can optimise refrigeration and ventilation systems | • Requires large amounts of input data<br>• Requires experienced and trained personnel to achieve successful results |
| PTB | • Specific refrigeration components available<br>• User friendly<br>• Can incorporate Eskom's TOU tariff structure<br>• Proven results with DSM project implementations | • Requires input data for every component |

The commercially available simulation software packages discussed in this section are all capable of simulating deep-level mine refrigeration systems. ENVIRON, however, cannot incorporate Eskom's TOU tariffs, eliminating it for the use in this study. VUMA requires large amounts of input data and trained operators. PTB is user friendly with all the components required to accurately simulate deep-level gold mine refrigeration systems within short time periods. It has also been proven to accurately simulate load management initiatives through actual case studies. PTB will therefore be the appropriate software for the purposes of this study.

## 2.6  Conclusion

To be able to accurately simulate a control strategy on mine refrigeration systems for sustainable performance, it was required to thoroughly understand the basic concept of mine refrigeration. The general operation, components and configurations were also discussed to provide an overview on mine refrigeration systems.

Previously implemented load management initiatives were also investigated to highlight the differences between the old and new Eskom DSM model. The initiatives were critically analysed in terms of implementation cost, time and sustainability of delivered cost savings. Finally, modelling and simulation of refrigeration systems were studied to enable informed decisions on software packages during the development of sustainable control strategies.

The information gathered in Chapter 2 will be used to develop and optimise a control strategy to realise sustainable cost savings on deep-level gold mine refrigeration systems. The strategy will be aligned with the criteria set by the new Eskom DSM model, which are limited funding, short implementation periods and sustainable cost savings over long periods of time.

# **Chapter 3**

# 3 Optimising refrigeration control for sustainable cost savings

## 3.1 Introduction

The information gathered in Chapter 2 will be used to develop a methodology for an optimised control strategy to ensure sustainable cost savings on mine refrigeration systems. Figure 30 depicts a visual representation of the methodology that will be discussed in this chapter.
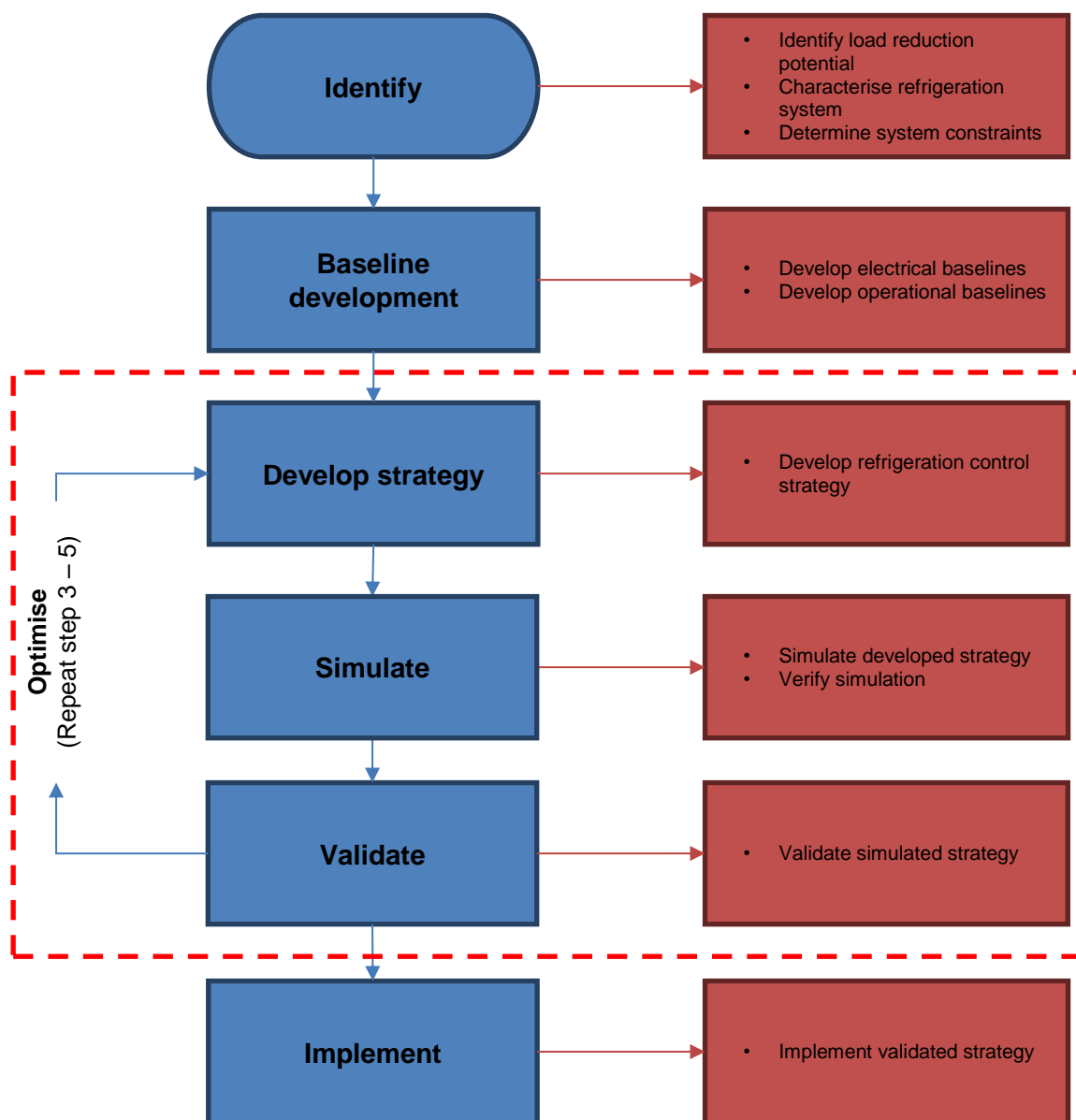


**Figure 30: Control optimisation methodology**

The first step is to identify load management potential on a deep-level mine refrigeration system. Suitable electrical and operational baselines then need to be developed to measure cost savings and operational changes after implementation of optimised control strategies. The next step is to develop, simulate, verify and validate a control strategy to determine the theoretical impact on the practical system.

To improve cost savings and overall system operation, steps 3 to 5 must be repeated, which is also defined as optimisation of the control strategy. Finally, the optimised control strategy can be implemented on the refrigeration system. These steps of the methodology will be discussed in detail in the following sections.

## 3.2 Identifying load reduction potential

### 3.2.1 Electrical power usage

Due to gold mines operating on Eskom's Megaflex TOU tariff structure, cost savings are realised by shifting the load out of Eskom's peak periods. Potential scope will therefore be determined by estimating the potential of reducing a refrigeration system's electricity demand during this time.

The first step is to consult with mine personnel to determine the scope for load management on the particular system. Electrical power data must be collected and analysed to verify the potential. It will become apparent from the power data whether scope is present as illustrated by the following examples.

An hourly average daily power profile is used to determine potential load management scope. The theoretical load shift is the average power usage during the Eskom evening peak hours of 18:00 and 19:00 (17:00 and 18:00 in winter). Figure 31 indicates two profiles where potential load management scope is present. Although one profile (indicated by the dotted line) indicates an existing load shift, further scope exists due to electrical power still being used during the peak period. This indicates the need to optimise the control to maximise the cost savings.
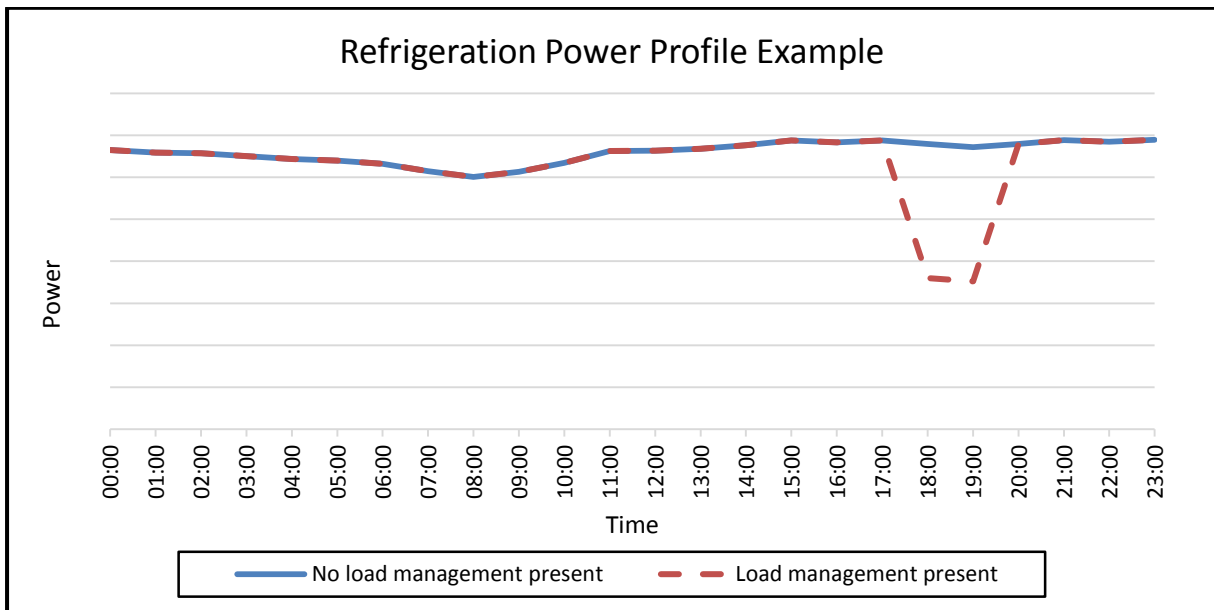
**Figure 31: Potential load management identification**

Calculating an evening peak to average power usage ratio can support the power profiles in determining potential scope for load shifting. Equation 25 illustrates the calculation in determining the evening peak to average ratio. A ratio of one indicates a "flat" profile, as illustrated by the blue line in Figure 31. Ratios between 0.1 and 0.9 can indicate existing load shifts. A ratio of 0 indicates no potential scope as it means all the load is shifted from the evening peak period.

**Equation 25: Evening peak to average ratio**

$$Ratio = \frac{\frac{\sum Evening\ Peak\ \ Energy\ Usage}{2}}{\frac{\sum Total\ Energy\ Usage}{24}}\ [-]$$

The potential cost savings through load management are determined from the amount of load (kWh) that can be shifted from the evening peak period. Once the cost-saving potential has been determined, the next step is to characterise the refrigeration system. This includes the following:

- listing major components and their installed capacities;
- examining the layout and operation of the system; and
- identifying the system constraints

Once the system has been characterised, the feasibility of a potential load management project can be determined. The inner detail of the characterisation procedure is discussed as follows:

### 3.2.2 Listing major components and data collection

A site visit can be arranged to verify all the components and their installed capacities. Mine personnel may be ideal to assist with the task. SCADA layouts can also be obtained to assist in characterising the refrigeration system. Table 4 lists the major components present in a general deep-level gold mine refrigeration system and the data that should be collected for each component.

**Table 4: Major components of a gold mine refrigeration system**

| Component | Required Data |
|---|---|
| Fridge Plants (Chillers) | • Compressor motor installed capacity [kW] <br> • Evaporator inlet and outlet temperature [°C] <br> • Condenser inlet and outlet temperature [°C] <br> • Evaporator and condenser flow rate [l/s] |
| Pumps | • Pump motor installed capacity [kW] <br> • Pump flow rate [l/s] <br> • Pumping elevation [m] |
| Cooling towers and BACs | • Water inlet and outlet temperatures [°C] <br> • Air inlet and outlet temperature [°C] <br> • Water flow rate [l/s] <br> • Air flow rate [kg/s] |
| Cooling tower and BAC Fans | • Fan motor installed capacity [kW] <br> • Air flow rate [kg/s] |
| Dams | • Water temperature [°C] <br> • Volume [m³] <br> • Operating levels [%] <br> • Configuration |

| Valves | • Valve positions<br>• Automated capabilities |
|--------|-----------------------------------------------|

In addition to the information mentioned in Table 4, ambient temperature data at the location of the specific refrigeration system are also required. Ambient conditions are required as it determines the performance of cooling towers (and therefore the chillers) and the temperature of the air being sent underground by the BACs.

The information described in this section is required to accurately simulate and verify the refrigeration system's operation and potential impact of load shift control strategies. Accurate simulations will also engender credibility of proposed control strategies to optimise the system. Once all the information has been collected, the next step is to interpret all the components into a system layout to simplify and understand the operation.

### 3.2.3 Refrigeration system layout and operation

Figure 32 shows an example of a simplified deep-level gold mine refrigeration system layout (for reference purposes, the same layout as presented in chapter 2 is used). Once all the components have been included into the layout, the potential scope for load management can be verified by evaluating the current operation of the system. It is important to note that refrigeration system operations and layouts may vary between different mines.
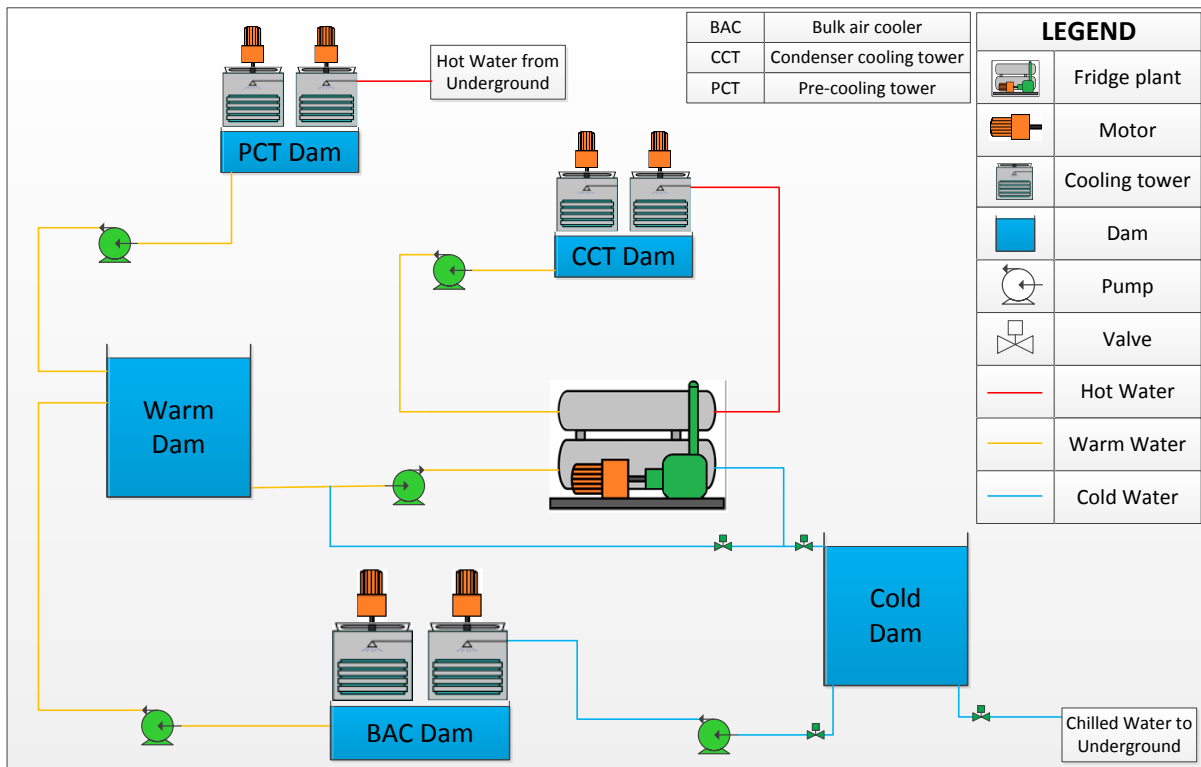
**Figure 32: Simplified refrigeration system layout**

It is crucial to compile an accurate layout of the components, pipe reticulation and water storage configuration. This will aid in determining whether the current operation can be adapted to incorporate a load shift during Eskom's evening peak periods. The next step is to determine whether any constraints within the system will prohibit the implementation of a load management strategy.

### 3.2.4  System constraints

Switching off components in large refrigeration systems affects operational conditions within the system. It is, therefore, important to identify and understand the constraints as it influences implementation of load management initiatives. Table 5 summarises the most common constraints and related risks when determining the load shift potential on deep-level gold mine refrigeration systems. A brief description of each constraint is provided after Table 5.

**Table 5: Possible constraints during implementation of load shift initiatives on gold mines**

| Constraint | Risk |
|---|---|
| Cold water storage capacity | Moderate |
| Cold water storage condition | Low |
| Maximum operating flow for comeback load | Moderate |
| Lack of isolation valves | Moderate |
| Safe underground environmental conditions | High |
| Machine mechanical issues | Moderate |
| Mine personnel cooperation | Moderate |

*Cold water storage capacity (Moderate Risk)*

By switching off some of the components in the refrigeration system, the continuous flow of cold water to storage dams is interrupted. If there is any cold water demand during these periods, water needs to be supplied from the storage dams. It is vital to ensure that there is enough cold water storage capacity to ensure the required water demand is met during the evening load shift period. As soon as components need to be started during peak periods due to a cold water supply shortage, the load management initiative becomes unsustainable.

*Cold water storage condition (Low Risk)*

The physical condition of the storage dam indicates how well the cold water inside is insulated. If it is, for example, a closed dam, the water will retain temperatures much better than an open dam. When cold water storage temperatures rise to an unacceptable level, the refrigeration system will have to be started, irrespective of how much storage capacity is available. When this happens the initiative becomes unsustainable. Adequate insulation is therefore important to ensure that the temperatures of the stored water remain acceptable.

*Maximum operating flow for comeback load (Moderate Risk)*

The cold water storage levels need to be recovered after load shifting periods. The refrigeration system's output therefore needs to be increased after the load shift to recover

cold water storage levels and temperatures. If the maximum capacity of the refrigeration system is not sufficient to achieve this, load shift sustainability will be negatively affected.

### *Lack of isolation valves (Moderate Risk)*

Depending on the configuration of the refrigeration system, cold water storage dams need to be isolated from warmer water in the system. If there are no isolation valves installed to accomplish this task, warmer water will mix with chilled water and the system temperatures will increase. If these temperatures rise to unacceptable levels, the refrigeration system will need to be started to reduce system temperatures. This directly influences load shift sustainability.

When the temperature in the storage dams significantly increases after a load shift, it becomes necessary to continuously run the refrigeration system until the temperature decreases. In some cases it affects the following days' load shifts as temperatures may take a couple of days to recover. This in turn influences the sustainability.

### *Safe underground environmental conditions (High Risk)*

Due to the cold water demand of Bulk Air Coolers (BACs), switching off the refrigeration system and BACs' cold water supply may result in an increase in underground temperatures. If the underground temperatures increase beyond unsafe levels, the refrigeration system will be started, as a safe working environment is of utmost importance for deep-level gold mines. In some instances, mine personnel request tests to be conducted to verify that the temperatures are not negatively affected by switching off refrigeration components for short periods of time (two hours).

### *Machine mechanical issues (Moderate Risk)*

Due to the age of most refrigeration systems on South African gold mines, some components may experience issues when regularly stopped or started. Regular maintenance should, however, prevent start-up problems on these components. In some cases certain components will have to be excluded from the load shift due to high repair or replacement costs. Although this will result in reduced cost savings, ensuring all the refrigeration equipment is operational at all times will increase the sustainability.

### *Mine personnel cooperation (Moderate Risk)*

Refrigeration and adequate ventilation remain one of the most important aspects when it comes to safe deep-level mining. Mine personnel are not always willing to switch of

refrigeration components due to the extreme underground environmental conditions. The cooperation of mine personnel therefore plays a crucial role in sustainable load management initiatives.

Once all of the constraints have been identified and the associated risks mitigated, scope for a load shift initiative can be confirmed. If scope is confirmed to be present, the next step will be to develop baselines from historical data. The baselines will serve as benchmarks which future performance and sustainably of the load management initiative are measured to. The next section provides the detail of developing baselines and the associated baseline adjustment techniques.

## 3.3 Developing baselines and adjustment models

### 3.3.1 Preamble

Two types of baselines will be developed, namely: an electrical power baseline and system operational baselines. The electrical power baseline will be used to determine the cost savings achieved after implementation of load management initiatives. The operational baselines will be used to determine the project's sustainability in terms of operational indicators such as dam levels and system temperatures. Due to the seasonal variances, a suitable baseline adjustment method will also be required for the electrical power baseline.

### *3.3.2 Electrical power baseline*

The electrical power baseline consists of a half-hourly average daily profile of the entire refrigeration system's power consumption. A summer (September to May) baseline is compiled for the purposes of this study. Figure 33 shows an example of an electrical power baseline for a deep-level mine refrigeration system.
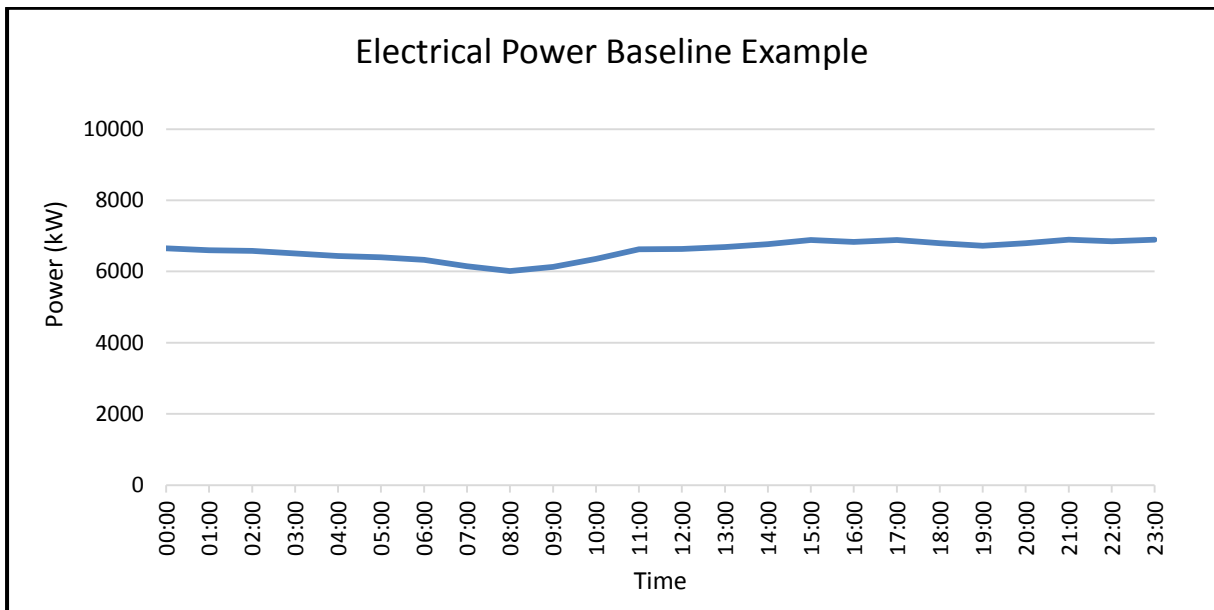
**Figure 33: Electrical power baseline example**

The baselines will be used to determine the impact of load management on the operating cost of the refrigeration system. Due to operational changes and dynamic power consumption profiles of mine refrigeration systems, a Service Level Adjustment (SLA) method is required. The details behind SLA are discussed in the following section.

### 3.3.3  Service level adjustments

SLA for the electrical power baselines is required to ensure credible cost savings are calculated and reported. Since load management initiatives do not necessarily result in net energy savings, energy neutral scaling will be used for service level adjustments[6] [50]. The adjustments are based on daily kilowatt hour neutrality as indicated by the following equations.

**Equation 26: Service level adjustment factor**

$$SLA_f = \sum_{i=0}^{47} \frac{kWh_{Actual_i}}{kWh_{Baseline_i}} \ [-]$$

Where:

$kWh_{Actual_i}$ $\quad=\quad$ Half-hourly actual energy consumption

$kWh_{Baseline_i}$ $\quad=\quad$ Half-hourly baseline energy consumption

---

[6] Standard M&V procedure for load management initiatives

**Equation 27: Scaled baseline calculation**

$$Scaled\ Baseline_i = SLA_f \times Original\ Baseline_i\ [kW]$$

Where:

$i$          =          Half-hourly intervals for each day

By using Equation 26 and Equation 27, a suitably scaled baseline can be determined for the baseline example illustrated by Figure 33. Figure 34 illustrates the concept of SLA for this particular baseline.
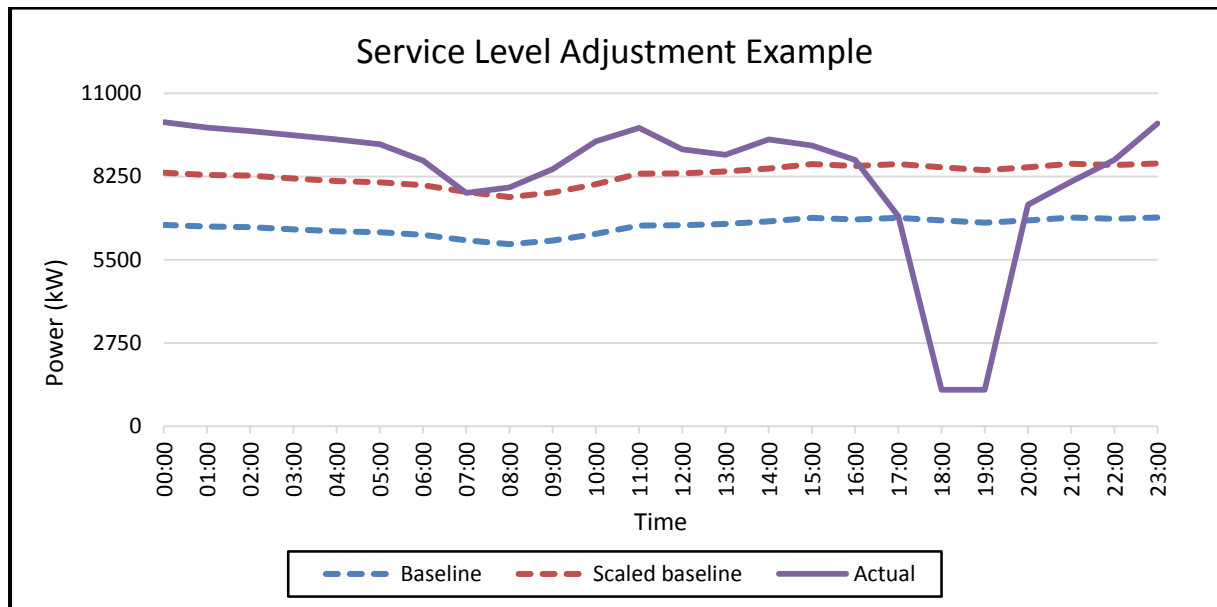


**Figure 34: Service level adjustment illustration**

The electrical power baseline is finalised with the establishment of a suitable SLA method. The next step will involve determining operational baselines for the refrigeration system.

### 3.3.4 Operational baselines

Operational baselines must be developed to determine the effect of load management on the operational parameters of the refrigeration system. Key Performance Indicators (KPI) must be identified and set limits must be determined. To ensure sustainability of a daily load shift, KPIs need to be monitored to ensure they remain within the daily prescribed limits.

The KPIs that need to be identified are:

- Cold water storage level
- Cold water storage temperature
- BAC outlet air temperature
- Underground ambient temperature

The next step is to develop, simulate and implement a sustainable control strategy to reduce the refrigeration system's electricity demand during Eskom's evening peak periods.

## 3.4 Developing a load shift control strategy

### 3.4.1 Preamble

The information gathered and mentioned in the preceding sections is used to develop a sustainable load shift control strategy for the refrigeration system. The developed strategy must be simulated, verified and optimised prior to implementation.

### 3.4.2 Developing the control strategy

The development of the control strategy will mainly focus on the sequence in which the refrigeration components are switched off during Eskom's evening peak period. An important factor to consider while developing the control strategy is low costs. Only existing infrastructure should be considered in the development, as any additional infrastructure will attract unwanted implementation costs. Figure 35 illustrates the typical shutdown sequence (indicated by circled numbers) for a load management initiative on deep-level mine refrigeration systems.
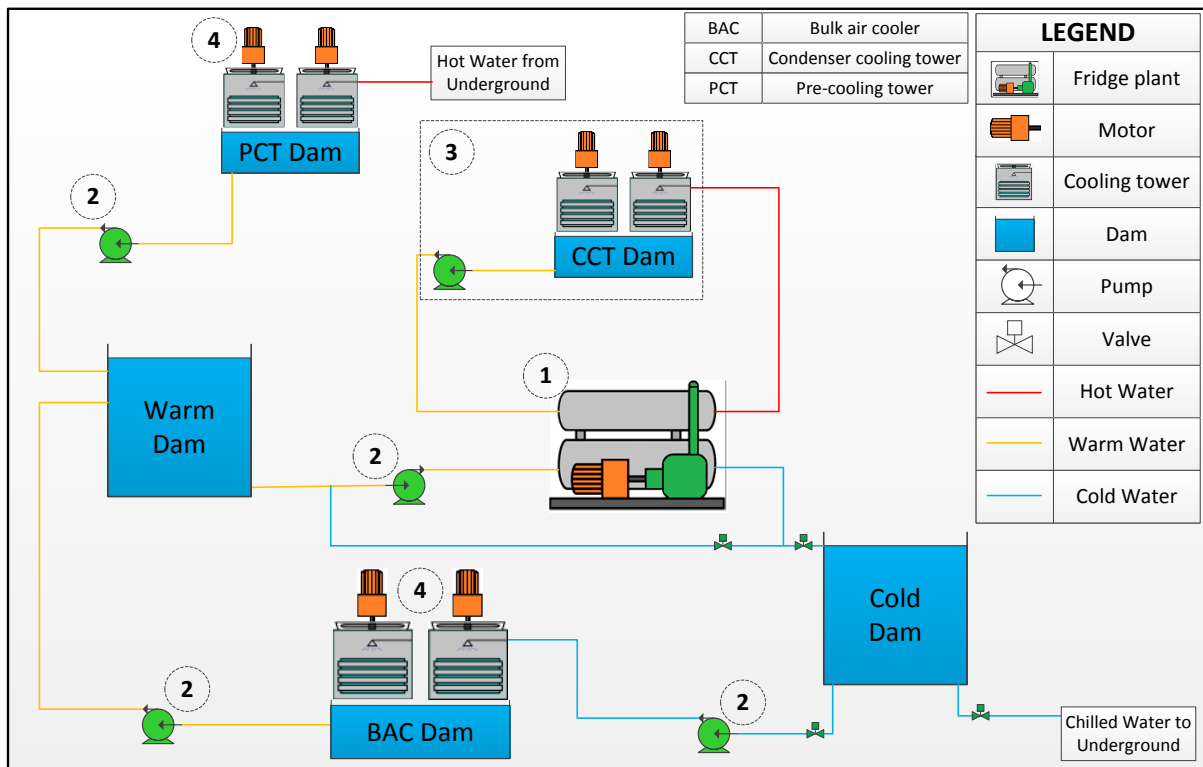
**Figure 35: Refrigeration components shutdown sequence**

Figure 35 indicates the sequence in which the refrigeration system components need to be switched off before Eskom's evening peak period. Firstly the chillers should be switched off, followed by any auxiliary pumps that are not required. Finally, the fans in the cooling towers and BACs should be switched off. The constraints associated with this example are listed in Table 6.

**Table 6: Refrigeration system component shutdown sequence example**

| Shutdown sequence | Component | Power consumption [kW] | Possible constraints |
|---|---|---|---|
| 1 | Chillers | 500 – 8000 | <ul><li>Start-up issues</li><li>Cold water temperature</li><li>Cold water dam level</li></ul> |

| 2 | Auxiliary pumps | 30 – 800 | <ul><li>Start-up issues</li><li>Minimum dam level requirements</li><li>Maximum dam capacity</li></ul> |
|---|---|---|---|
| 3 | Condenser pumps and tower fans | 20 – 800 | <ul><li>Start-up issues</li><li>Minimum dam level requirements</li><li>Maximum flow rate</li></ul> |
| 4 | BAC tower fans | 20 – 500 | <ul><li>Start-up issues</li><li>Reduced airflow to underground</li><li>Underground air temperature</li></ul> |

The chillers are switched off first due to being the largest electricity consumer within the refrigeration system. To ensure warm water does not mix with the cold water in the storage dams, any auxiliary pumps not required are switched off. When the chillers are offline, there is no need to run the condenser pumps and cooling tower fans, as no heat exchange is required in the chillers. Finally, the BAC fans can be switched off in order to reduce the amount of uncooled air being sent underground. After Eskom's evening peak period, the components are started-up in reverse order.

It is important to remember that a deep-level mine refrigeration system is very large and complex. Switching off any of the components may result in negative effects within the system. Simulations must, therefore, be developed to determine the theoretical impact of the proposed control strategy on a practical system.

### 3.4.3   Simulating the control strategy

The next step is to simulate the developed control strategy to determine the feasibility of cost savings and operational impact on the practical system. To achieve this, the simulation package Process Toolbox (PTB) will be used, as motivated by literature in Chapter 2 [28], [38], [49]. The data collected in Section 3.2.2 are used to replicate the existing refrigeration system in PTB. The Eskom TOU tariff structure is incorporated by simulating the system in hourly intervals for a period of 24 hours.

To verify the accuracy of the simulation, actual historical data can be used and compared to the simulated results. Verification will require the simulation to match the actual electrical

power data and KPIs. Once the simulation has been verified, the proposed load shift control strategy can be simulated.

Simulating the KPIs and ensuring that they remain below the prescribed limits within the simulation will confirm the sustainability of the control strategy. The simulated values also need to adhere to all the constraints identified and described in Section 3.2.4. This will ensure that the load management strategy remains sustainable over long periods of time.

The following section discusses the validation of the developed strategy on a practical refrigeration system.

### 3.4.4   Validating the control strategy

After the new control strategy has been simulated, the next step is to physically test the strategy. This will validate the results obtained through simulation and ensure credibility of the developed solution. The following parameters need to be monitored during the test:

- refrigeration system power consumption
- ambient air temperature
- BAC outlet air temperature
- water storage temperature
- water storage level
- underground environmental temperature (various underground levels if possible)

After the tests for the new control strategy have been completed, the relevant test data can be compared to the results obtained from the simulation. This will serve as an indication of the simulation's accuracy and ensure credibility in the developed solution for sustainable cost savings. Once validation is completed, the proposed strategy can be optimised for maximised and sustainable performance.

## 3.5   Optimising the load shift control strategy

To address the problems faced by gold mines and Eskom, stated in Chapter 1, the developed control strategy requires further optimisation to remain sustainable when implemented. The optimisation focuses on maximising the cost-saving potential of the control strategy with a minimal impact on the operational conditions of refrigeration. Optimisation will also ensure that gold mines benefit from maximised cost savings, Eskom from an increased reserve margin in peak periods and ESCos from continued DSM involvement. Figure 36 shows the procedure to be followed during the optimisation of the strategy.
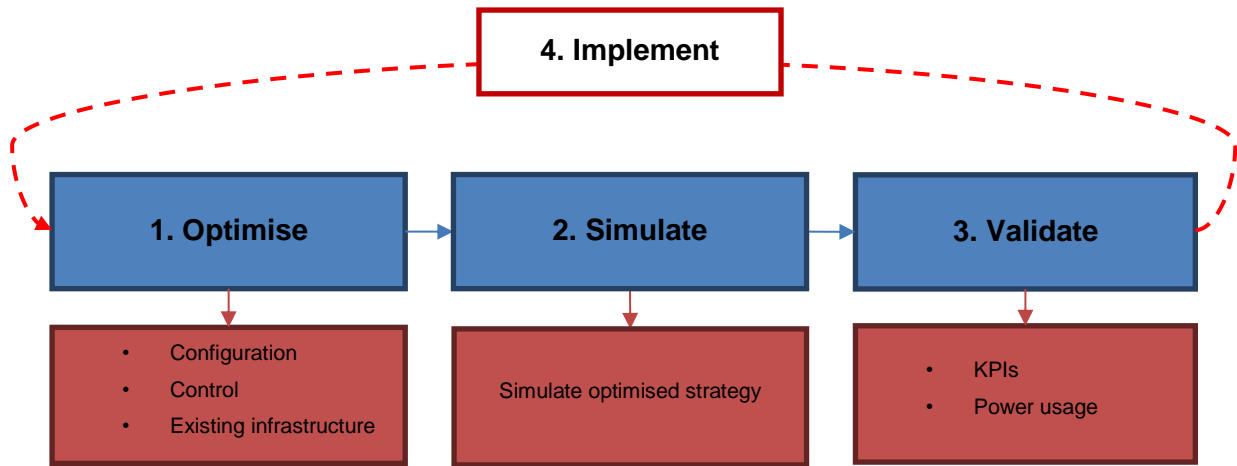
**Figure 36: Optimising load shift control strategy**

When optimising the control strategy, the methodology remains mostly the same as with the original development. The main difference is altering the system's configuration and control while utilising existing infrastructure to keep costs to a minimum. As discussed, the optimisation should ideally lead to increased cost savings and a reduced impact on the KPIs. The reduced impact will improve the sustainability of the load shift. The next and final step is to implement the optimised control strategy.

## 3.6 Implementing the optimised control strategy

Once the optimised control strategy simulation has been validated, it needs to be implemented. Implementation will require the identified refrigeration system to be operated on the optimise control strategy. Most refrigeration systems on deep-level gold mines can be operated from a mine's SCADA system, which contributes to the successful execution of the control strategy. Mine personnel must ensure refrigeration components are switched off in the correct sequence during Eskom's evening peak periods. Any configuration changes required during the load shift must also be implemented by mine personnel.

If the optimised control strategy involves changing the configuration of the refrigeration system, suitable training needs to be arranged. Mine control room operators will require training to ensure a thorough understanding of the control strategy. Monitoring the correct KPIs during and after load shifts should also be clarified to mine personnel. By understanding the control strategy and its effects on the refrigeration system, mine employees can efficiently and sustainably implement manual load shifts.

The sustainability of the project depends on the impact of the load shifting on the KPIs. Although the verified simulations may indicate that the KPIs are not affected by load management, they still need to be continuously monitored during and after implementation.

## 3.7  Conclusion

A methodology for an optimised control strategy to ensure sustainable cost savings on deep-level mine refrigeration systems was developed as described in this chapter. The methodology mainly consists of identifying potential scope, characterising the refrigeration system, developing an optimised control strategy and implementing the optimised control strategy on a practical system.

The development of the optimised control strategy is based on the revised Eskom DSM model. The methodology therefore adheres to the objective stated in Chapter 1, which is to develop a low-cost, simplified and sustainable control strategy for maximised cost savings. Implementing the methodology will ensure that gold mines benefit from maximised costs savings, Eskom from an increased reserve margin in peak periods and ESCos from continued DSM involvement .

The next section will focus on the actual implementation of the proposed methodology on two case studies.

# Chapter 4

# 4 Implementing optimised control strategies on mine refrigeration systems

## 4.1 Introduction

The methodology developed in Chapter 3 was used to develop optimised control strategies of two deep-level gold mine refrigeration systems. Due to confidentiality, the respective mines are further referred to as Mine D and Mine R.

Due to the lower ambient conditions during winter months, most mines use their refrigeration systems at a reduced capacity during this period. For the purposes of this study, the two case studies will only focus on the summer operation of the refrigeration systems. This chapter will also only focus on the results obtained from Mine D. The results of the case study implemented on Mine R are provided in Appendix C of this document.

## 4.2 Identifying load reduction potential

### 4.2.1 Electrical power usage

The electrical power usage profile for Mine D was compiled with three months' pre-implementation data. The electrical power profile can be seen in Figure 37.
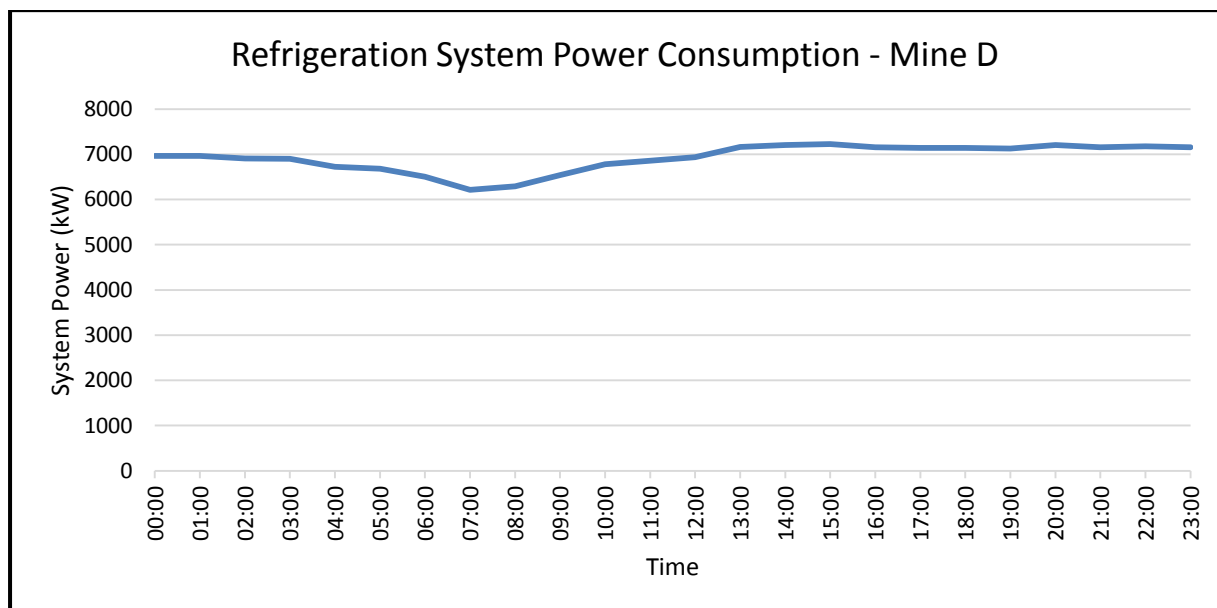


**Figure 37: Refrigeration system power consumption – Mine D**

From the average daily power consumption profile illustrated by Figure 37 it is evident that scope is present for a load shift on Mine D's refrigeration system. The evening peak to average power ratio supports this finding.

**Equation 28: Evening peak to average ratio – Mine D**

$$Ratio = \frac{\frac{\sum Evening\ Peak\ Energy\ Usage}{2}}{\frac{\sum Total\ Energy\ Usage}{24}}$$

$$Ratio = \frac{7133\ [kW]}{6922\ [kW]}$$

$$Ratio = 1.03\ [-]$$

### 4.2.2 Listing major components and data collection

Table 7 indicates the major components of Mine D's refrigeration system. The detailed component characteristic tables for both mines are available in Appendix A.

**Table 7: Major components in refrigeration system – Mine D**

| Component | Quantity |
|---|---|
| Fridge plants | 4 |
| Evaporator pumps | 3 |
| Condenser pumps | 5 |
| Pre-cooling transfer pumps | 2 |
| BAC transfer pumps | 4 |
| Pre-cooling fans | 4 |
| BAC fans | 4 |
| Condenser cooling fans | 4 |
| Dams (excluding sump dams) | 4 |
| Isolation valves | 3 |

### 4.2.3 Refrigeration system layout and operation

Figure 38 indicates the layout of Mine D's refrigeration system. Normal operating conditions consist of running four chillers, three evaporator pumps and three condenser pumps during the summer months. All the condenser cooling towers and BAC fans run through all seasons of the year. During winter months Mine D uses their refrigeration system at half capacity, using only two chillers. The assumption is made that load management will be plausible during winter if it is proven successful in summer months due to the lower ambient temperatures.
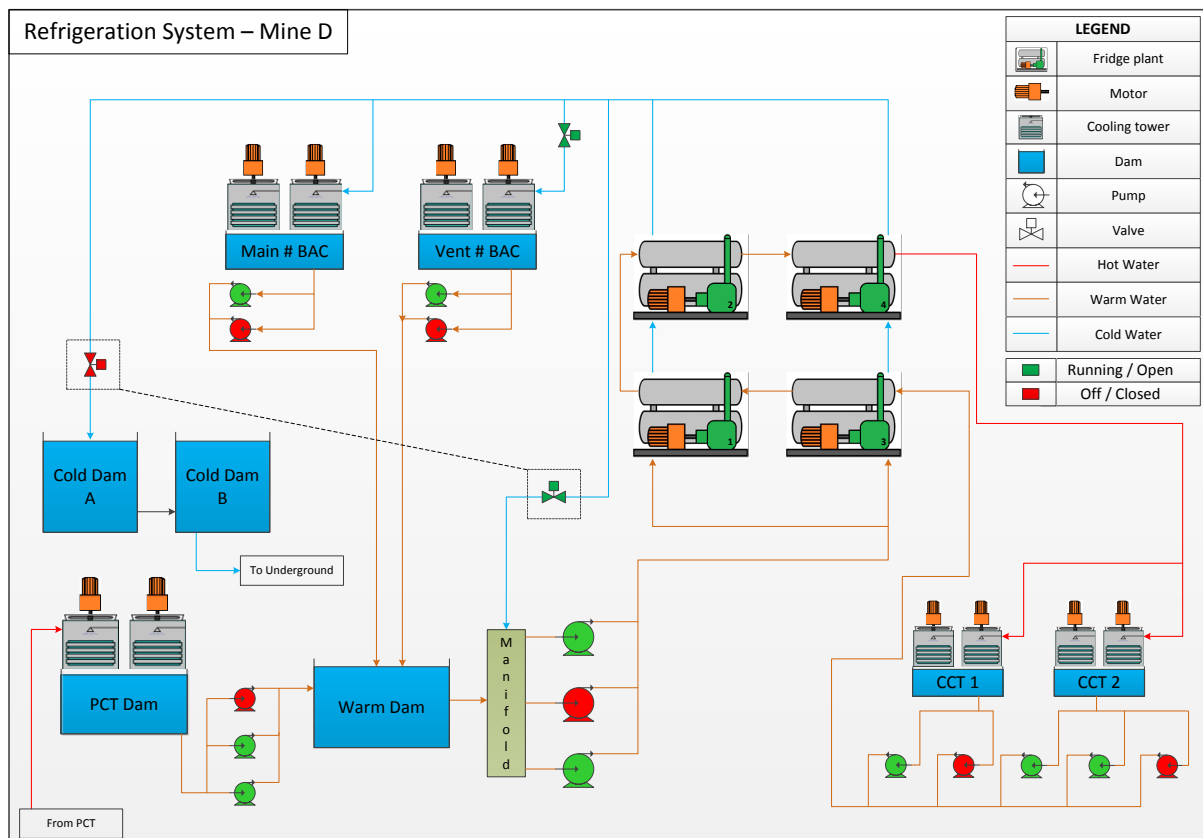


**Figure 38: Layout for normal summer operation – Mine D**

### 4.2.4 System constraints

During the investigation the following constraints were identified at Mine D:

- Chiller start-up issues
- Main # BAC sump dam capacity
- Condenser cooling tower fan start-up issues
- Underground environmental temperature

Table 8 discusses the risks associated with these constraints as well as the mitigation for each constraint.

**Table 8: Refrigeration system constraints – Mine D**

| Constraints | Risk | Mitigation |
|---|---|---|
| Chiller start-up | Chillers won't start-up when evaporator flow is too low. | Run both evaporator pumps before chillers are started. |
| Main # BAC sump dam capacity | Sump dam can overflow onto electrical transformers if incoming flow is too high. | Run second BAC sump pump when sump level reaches 90% of its capacity. |
| CCT fan start-up issues | One fan starts with difficulty after being shut down. | Assign mine electrician to investigate fan and rectify the problem. |
| Underground environmental temperature | Underground temperatures may increase to unsafe levels during load shift. | Constantly monitor underground temperatures and start refrigeration system if unsafe levels are reached. |

## 4.3   Developing baselines and adjustment models

### 4.3.1   Electrical power baselines and adjustment

Figure 39 shows the average weekday electrical power baseline for Mine D during summer months. The baseline was approved by an independent Measurement and Verification (M&V) team. As discussed, SLA will be conducted due to the dynamic nature of Mine D's refrigeration system power consumption.

## Summer Electrical Power Baseline - Mine D
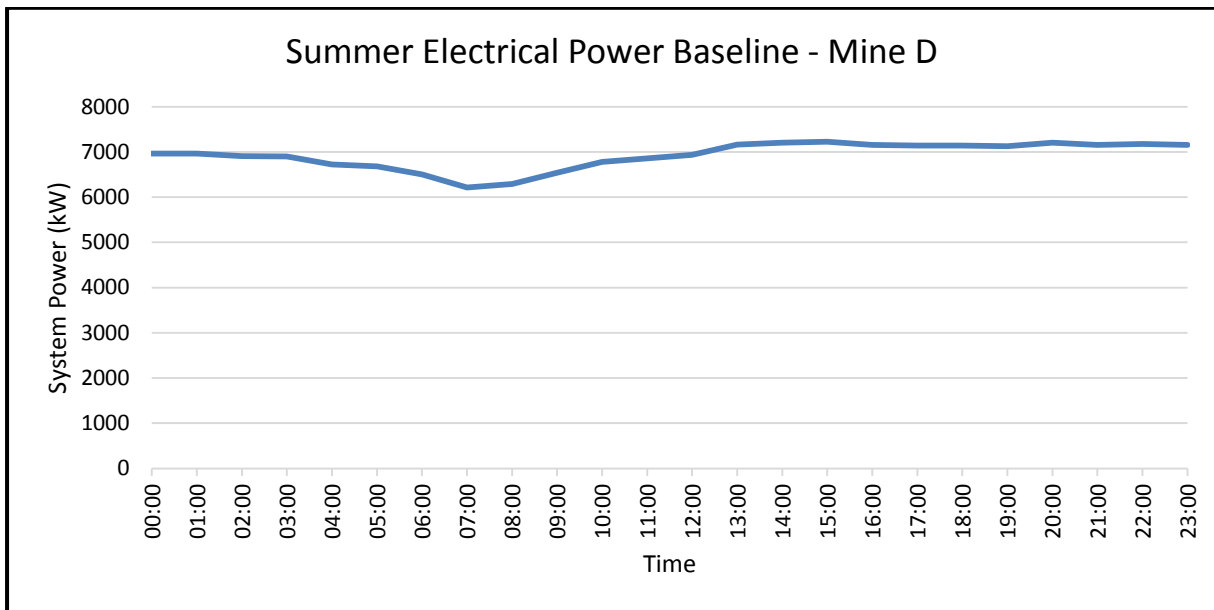


**Figure 39: Electrical power baseline – Mine D**

### 4.3.2 Operational baselines

Table 9 lists the four most important KPIs and the respective minimum and maximum for daily average parameters. The identified limits for the KPIs remain constant during summer and winter months.

**Table 9: Operational baseline – Mine D**

| KPI | Minimum | Maximum |
|---|---|---|
| Cold water storage level | 80% | 100% |
| Cold water storage temperature | - | 5 °C |
| BAC air temperature sent underground | - | 12 °C |
| Underground ambient temperature (dry-bulb) | - | 30 °C |

## 4.4 Developing a load shift control strategy

### 4.4.1 Developing the control strategy

Table 10 shows the developed control strategy for Mine D's refrigeration system. The evaporator pumps were kept running during evening peak period to ensure the cold dam level remained constant.

**Table 10: Load shift control strategy – Mine D**

| Installed quantity | Component | Normal operating status | Evening peak period status | Shutdown sequence |
|---|---|---|---|---|
| 4 | Fridge plants | 3 | 0 | 1 |
| 3 | Evaporator pumps | 2 | 2 | - |
| 5 | Condenser pumps | 3 | 0 | 2a |
| 4 | Condenser cooling tower fans | 4 | 0 | 2b |
| 4 | BAC transfer pumps* | 2 | 2 | - |
| 4 | BAC fans | 4 | 0 | 3 |

\* Controlled automatically on BAC sump dam level

### 4.4.2 Simulating the control strategy

The simulation for Mine D's refrigeration system was verified against actual data for a normal operating day. Detail on the simulation verification for Mine D is available in Appendix B. The average error between the simulated and actual KPIs was 1.4%. After verification deemed the simulation accurate, the developed control strategy was simulated. The simulation results in terms of electric power and KPIs are provided as follows:

Figure 40 shows the proposed power consumption of Mine D's refrigeration system. The chiller water outlet temperature was set at 1.1 °C. An average load shift of 4.7 MW was achieved through the simulation.
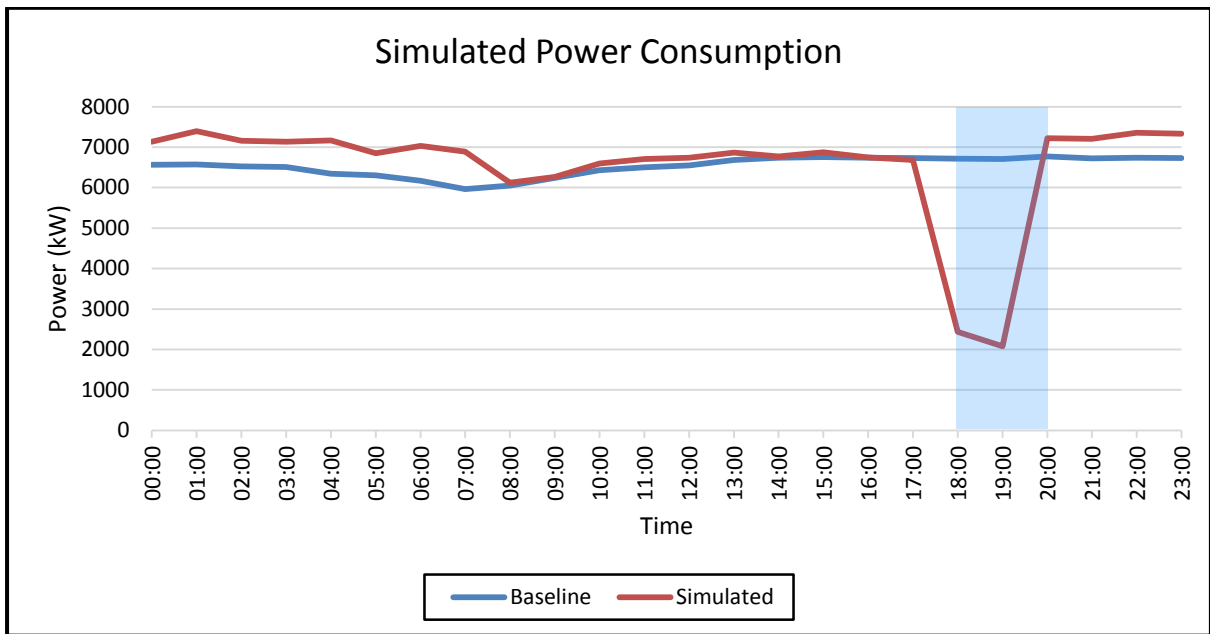
**Figure 40: Simulated power consumption – Mine D**

Figure 41 shows that the simulated cold storage dam temperature increased rapidly during the load shift. This is due to the evaporator pumps running to ensure a constant cold storage dam level. Warmer water is therefore constantly added to the cold storage dam. Although the maximum limit for the cold dam temperature was not reached, the increase threatens the sustainability of the project.
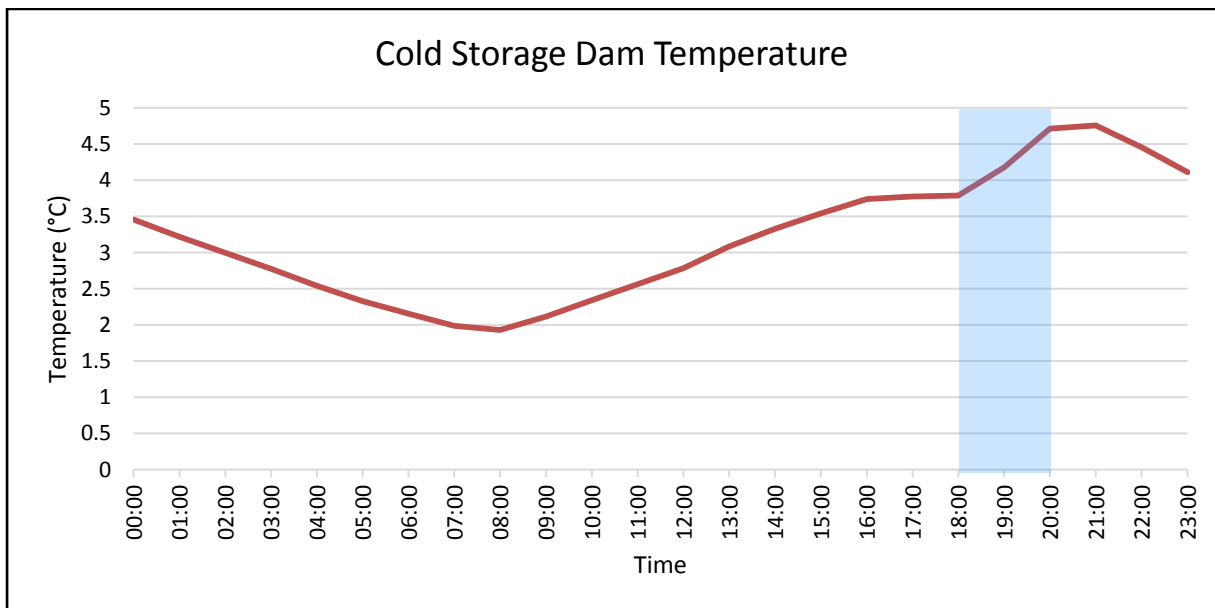


**Figure 41: Cold storage dam temperature – Mine D**

As expected, the BACs' outlet air temperature increased when the refrigeration system was shut down during Eskom's evening peak period. The increase in temperature is illustrated in Figure 42 and Figure 43 for the Main # BAC and Vent # BAC respectively. The Main # BAC remained below its maximum limit, while the Vent # BAC's outlet air temperature increased to just over 12 °C.



**Figure 42: Main # BAC outlet air temperature – Mine D**
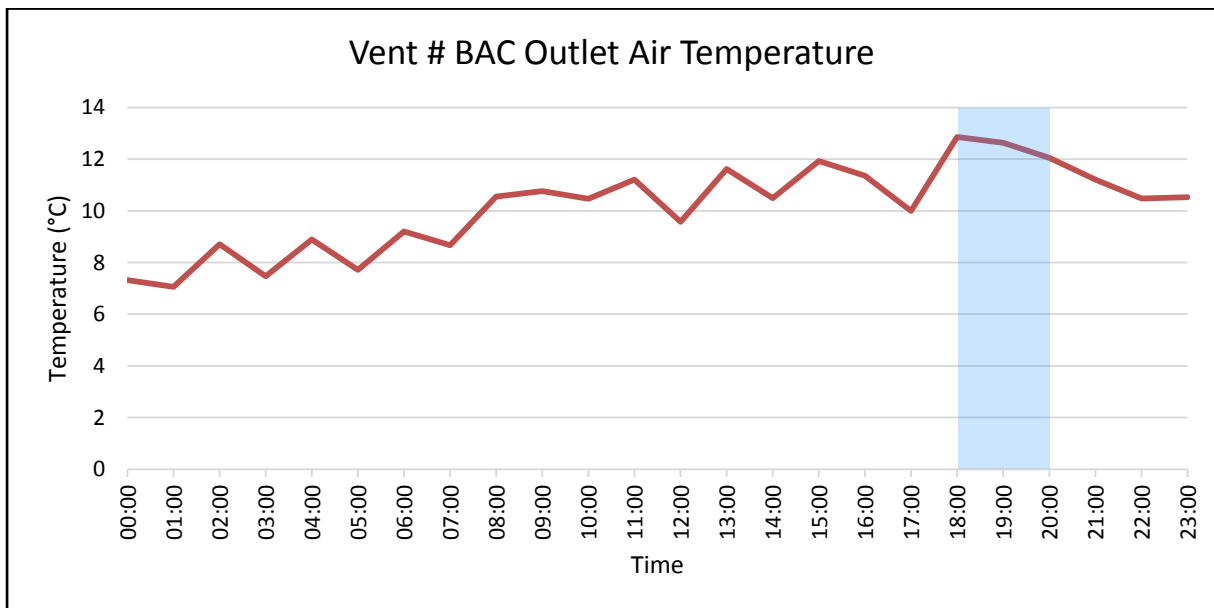


**Figure 43: Vent # BAC outlet air temperature – Mine D**

### 4.4.3 Validating the control strategy

The simulated strategy was implemented on Mine D's refrigeration system for validation. Table 11 provides an average comparison of the simulation with the actual test data. Figure 44 to Figure 47 provide the comparison of the power consumption and various KPIs over a 24-hour profile.

**Table 11: Control strategy validation – Mine D**

| Comparison | Simulated | Test | Percentage Error |
|---|---|---|---|
| Power consumption | 7608 [kW] | 7659 [kW] | 3.65 [%] |
| Load shift | 4707 [kW] | 4062 [kW] | 13.70 [%] |
| Cold storage dam temperature | 3.19 [°C] | 3.15 [°C] | 1.29 [%] |
| Main # BAC outlet air temperature | 6.95 [°C] | 7.26 [°C] | 4.34 [%] |
| Vent # BAC outlet air temperature | 10.11 [°C] | 8.60 [°C] | 17.75 [%] |

As seen in Table 11, the largest errors between the simulated and actual values occurred for the predicted load shift and Ve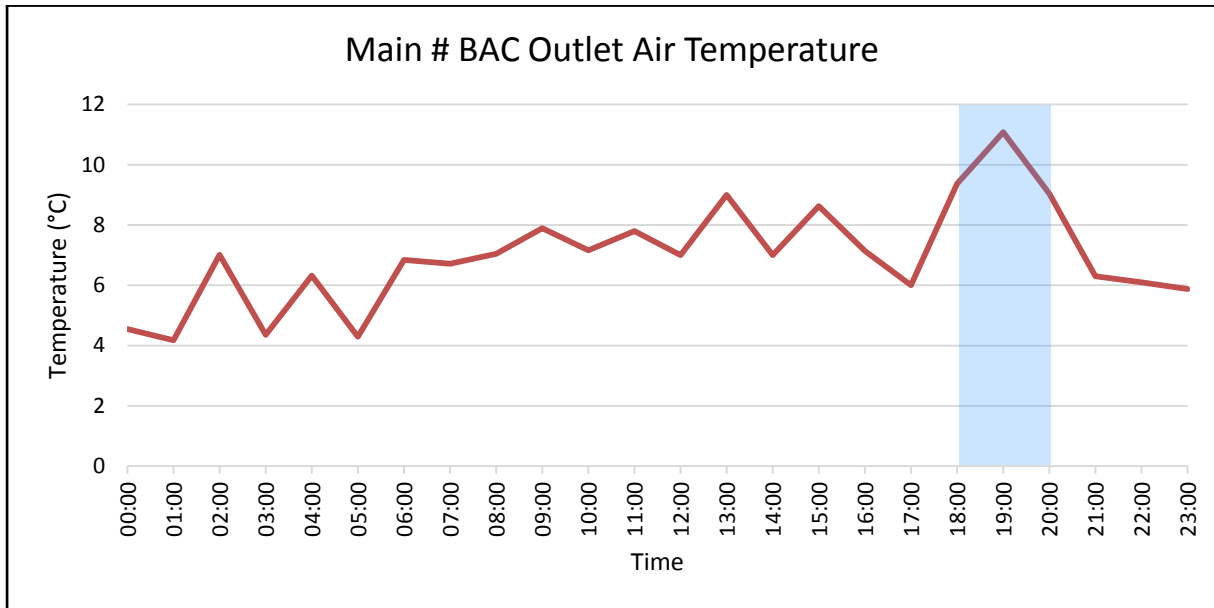nt # BAC outlet air temperature. The main reason for the load shift prediction error was that the actual tests involved switching off the refrigeration components from 18:00, resulting in some components running during the first 15 minutes of the evening peak period, whereas the simulation instantaneously switches off all components at the start of the Eskom evening peak period (18:00). This resulted in the large error between the simulated and actual load shift.

The difference between the actual and simulated Vent # BAC temperatures can be ascribed to the simulation not employing heat exchange dynamically on piping. A set amount of heat needed to be added to the simulation to compensate for the sun shining on uninsulated pipes. The actual Vent # BAC temperature, however, remained below the maximum limit during the load shift. The Main # BAC is situated much closer to the chiller complex, and subsequently was not affected by the same issue on the specific test day.

The heat added to the pipes was identified during the simulation verification, specific to the weather conditions of that day. This was not changed during the control strategy simulations as it could not be accurately predicted. This results in the different errors being experienced between the simulations as weather conditions differed for each.

The average daily profiles of the comparisons summarised in Table 11 are provided as follows:
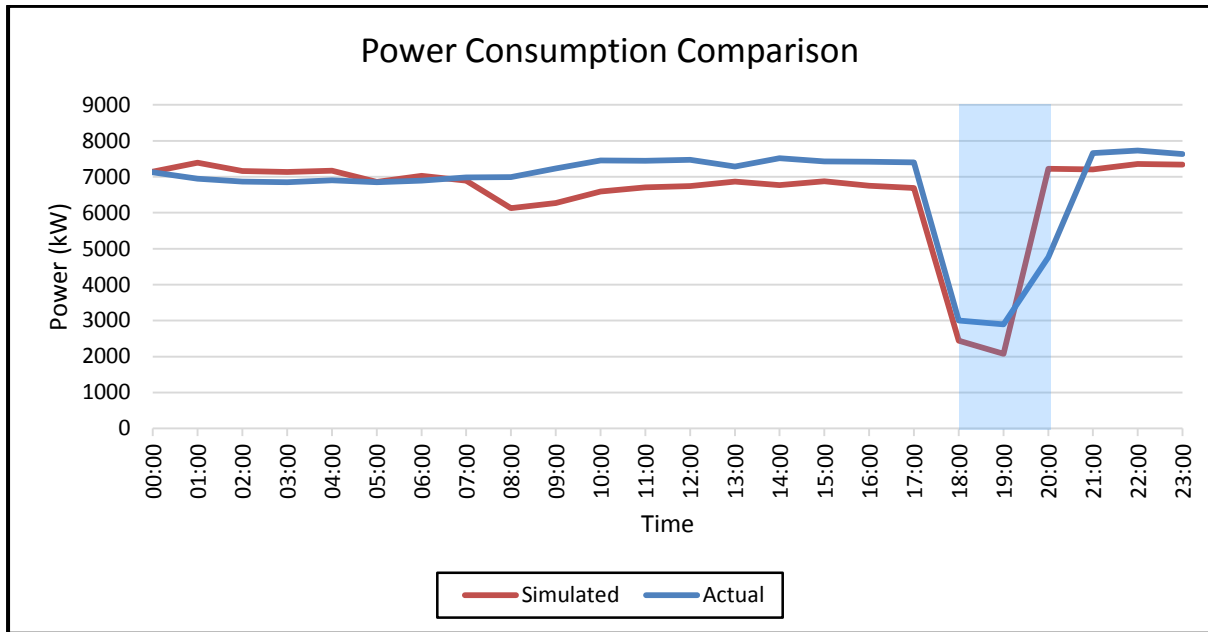


**Figure 44: Power consumption comparison – Mine D**
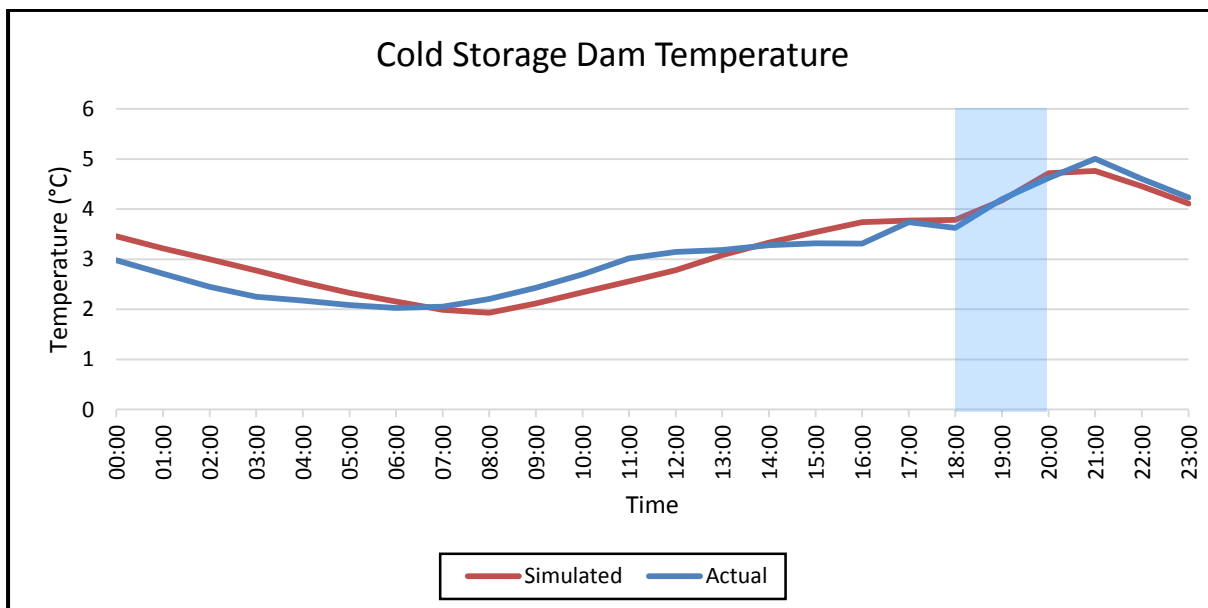


**Figure 45: Cold storage dam temperature comparison – Mine D**
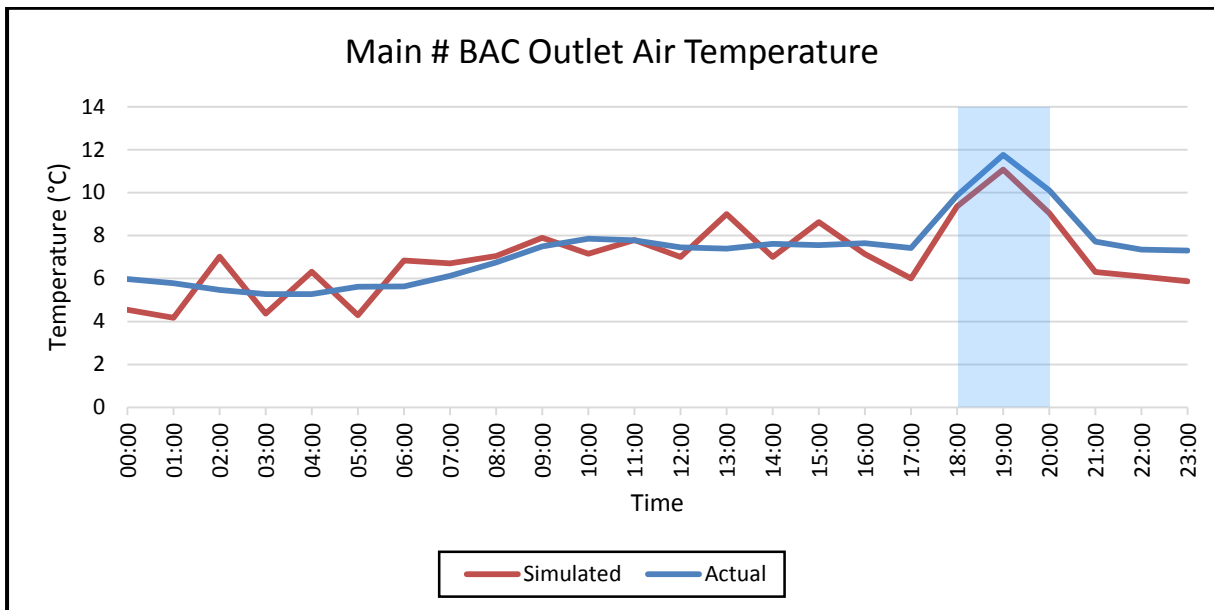
**Figure 46: Main # BAC outlet air temperature comparison – Mine D**
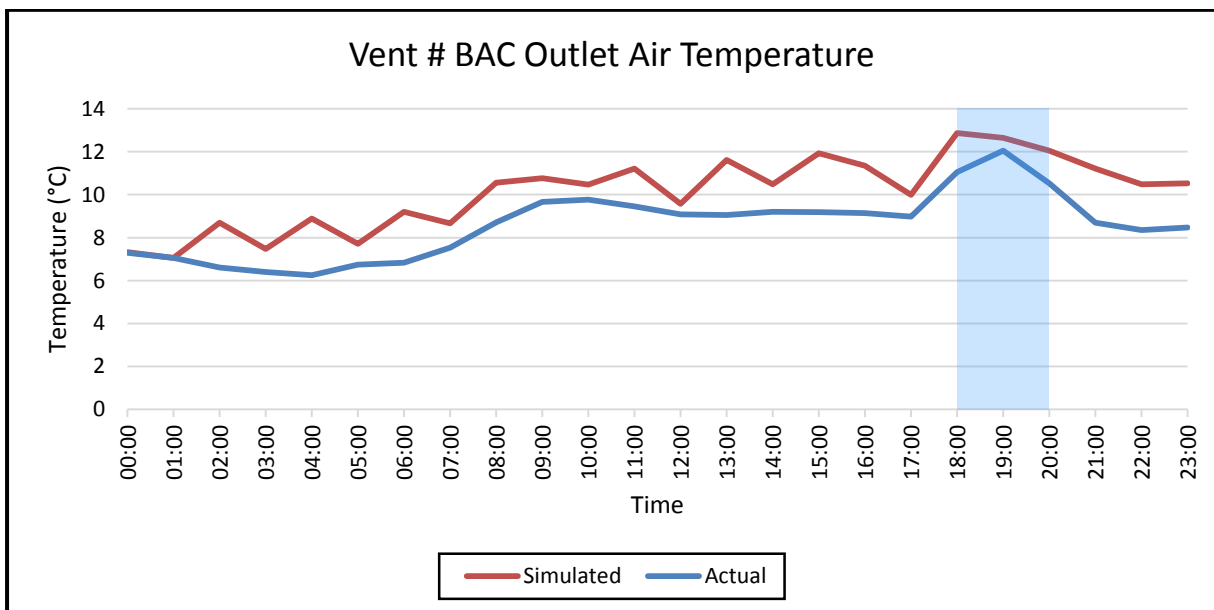


**Figure 47: Vent # BAC outlet air temperature comparison – Mine D**

The temperature at the 20 level (20L) station was monitored during the test. The 20L station was chosen as it is the deepest level on the mine and had real-time temperature monitoring present at the time of testing. Figure 48 shows that the temperature remained constant and the load shift had almost no impact on the underground temperature.
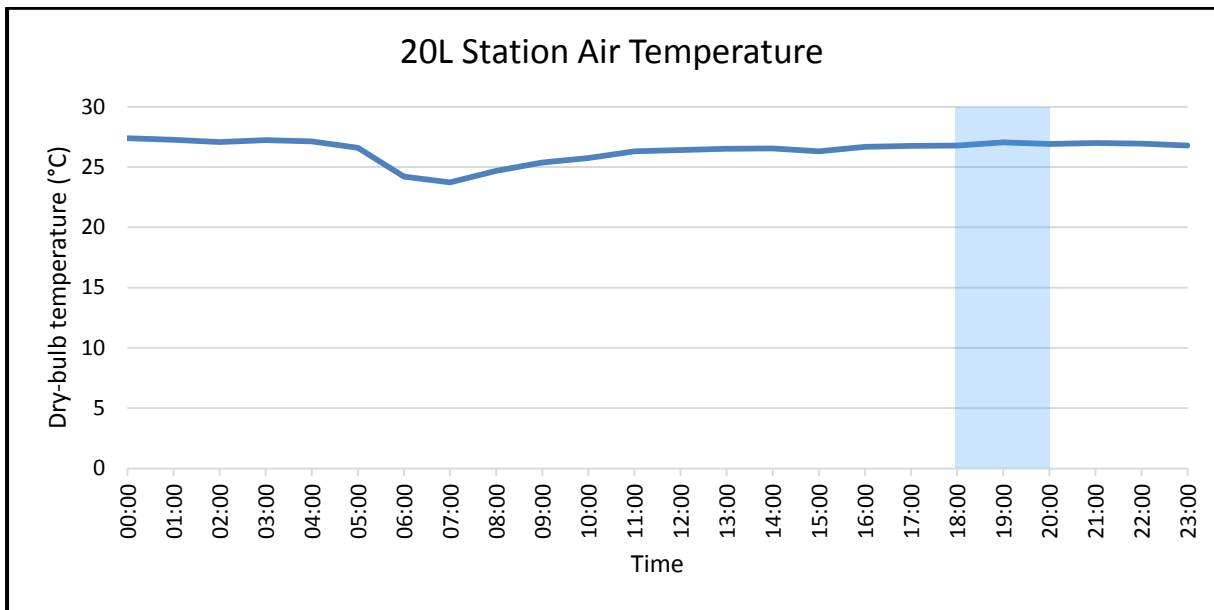
**Figure 48: 20L Station dry-bulb air temperature – Mine D**

The simulation model proved to be accurate within a small degree of error after validation was completed. The next step was to optimise the control strategy in order to improve cost savings and reduce the effect thereof on the KPIs. The next section discusses the results obtained through optimisation.

## 4.5 Optimising the load shift control strategy

### 4.5.1 Developing the optimised control strategy

Optimising the control strategy entails controlling the cold storage dam and recirculation valves (indicated by Figure 49) during the load shift. After all the components have been switched off at the beginning of the load shift, the cold storage dam valve is closed. At the same time the recirculation valve is opened. This ensures that warmer water is not introduced into the cold storage dam directly after the load shift. As soon as the chiller exit water temperature reaches the temperature of the cold storage dam water after start-up, the storage dam valve is opened again. The recirculation valve is then set back to automatic control.

The optimisation also involves switching off the evaporator pumps during the Eskom evening peak periods. Figure 49 illustrates the concept of the optimised control strategy.
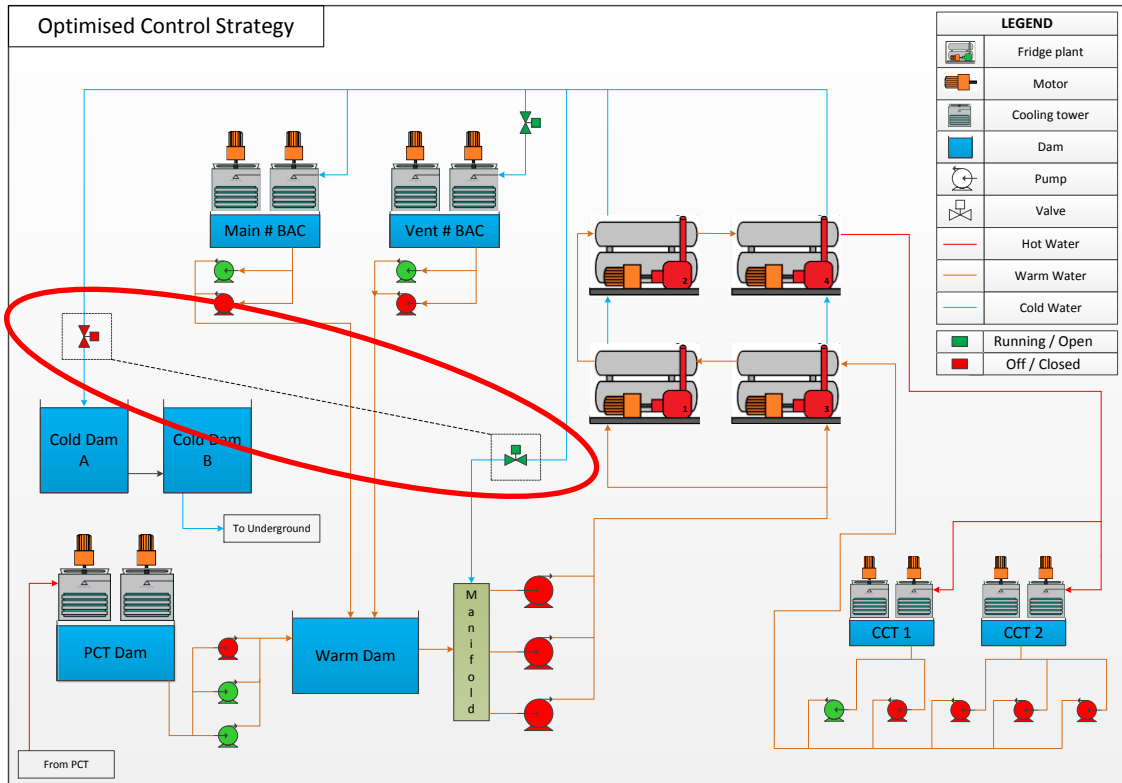
**Figure 49: Optimised load shift control strategy – Mine D**

Table 12 indicates the optimised control strategy for Mine D's refrigeration system.

**Table 12: Optimised load shift control strategy – Mine D**

| Installed quantity | Component | Normal operating status | Evening peak period status | Shutdown sequence |
|---|---|---|---|---|
| 4 | Fridge plants | 3 | 0 | 1 |
| 3 | Evaporator pumps | 2 | 0 | 2 |
| 5 | Condenser pumps | 3 | 0 | 3a |
| 4 | Condenser cooling tower fans | 4 | 0 | 3b |
| 4 | BAC transfer pumps* | 2 | 2 | - |
| 4 | BAC fans | 4 | 0 | 4 |

* Controlled automatically on BAC sump dam level

The next step was to simulate the optimised control strategy to determine the theoretical impact on Mine D's refrigeration system.

### 4.5.2 Simulating the optimised control strategy

Figure 50 shows the simulated power consumption for the optimised control strategy on Mine D's refrigeration system. The simulation proved that a potential load shift of 7.12 MW is possible.
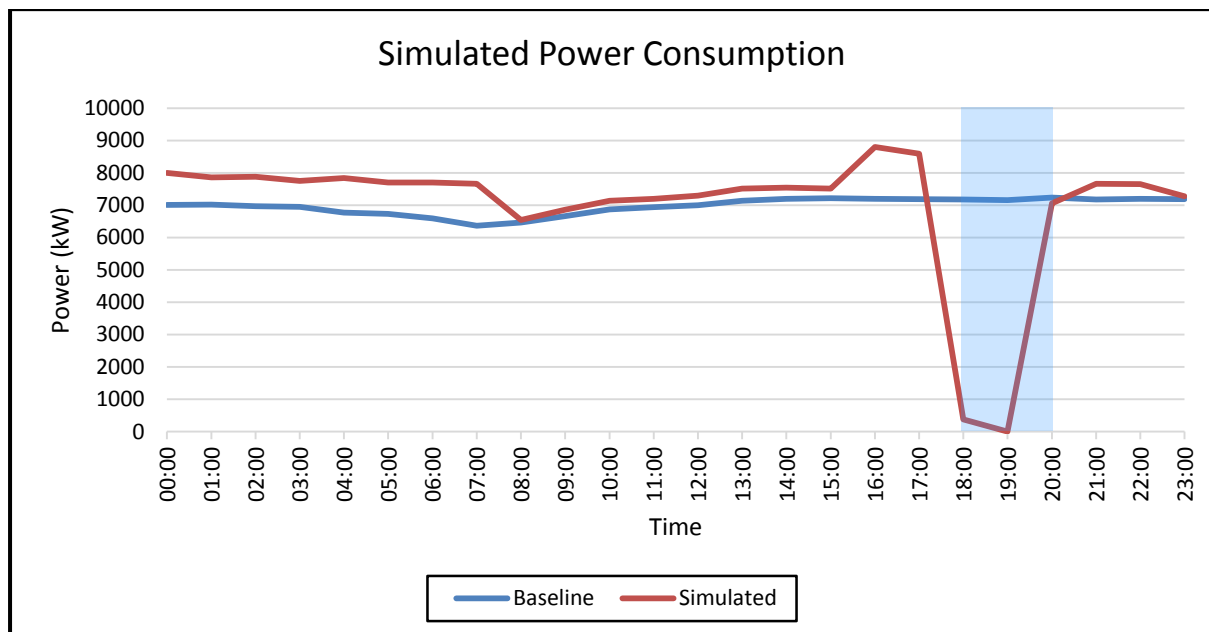


**Figure 50: Simulated power consumption for the optimised control strategy – Mine D**

Figure 51 shows that the cold storage dam temperature does not increase as much with the optimised strategy. This is due to the cold storage dam being isolated during and shortly after the load shift. This results in no warm water being introduced to the cold storage dam. The cold storage dam level also remains above 80% during the peak periods and recovers immediately after the refrigeration system is started. The optimised control strategy improves the sustainability of the load shift as it can be implemented daily without affecting the cold storage dam water temperature or cold water supply to underground operations.

## Cold Storage Dam Temperature
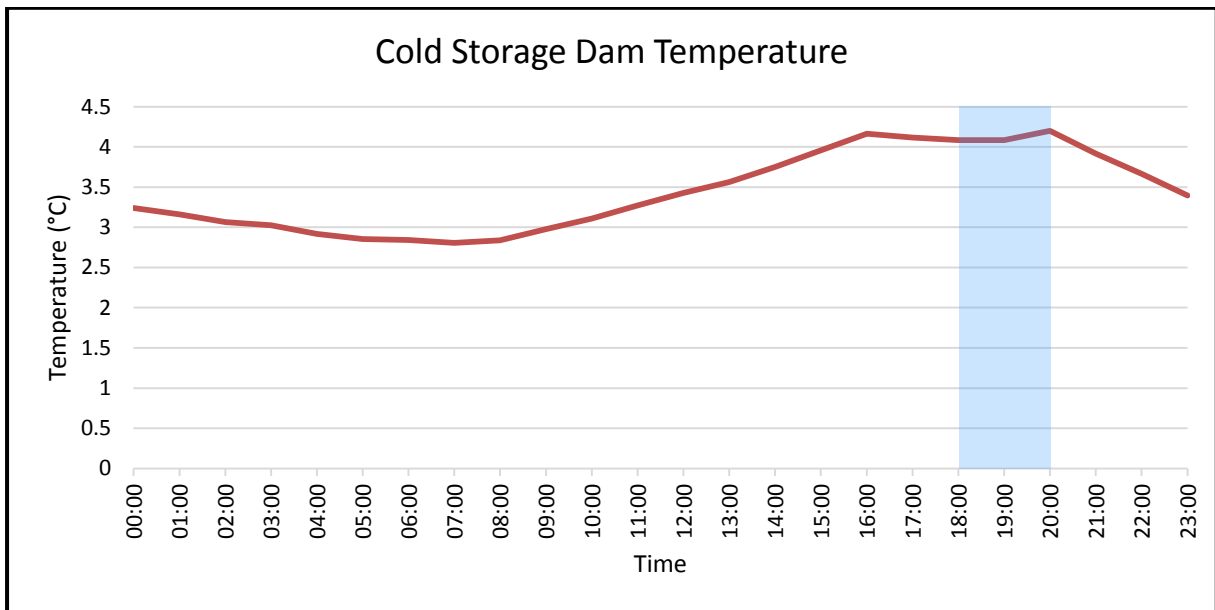


**Figure 51: Cold storage dam temperature – Mine D**

The outlet air temperature of both the Main- and Vent # BACs increases to approximately 20 °C during the simulated load shift. However, since the fans are also switched off, this warmer air will not be introduced underground. The outlet temperature for both BACs, however, recovered within one hour after the load shift. The simulated Main # and Vent # BAC outlet air temperatures are depicted by Figure 52 and Figure 53, respectively.

## Main # BAC Outlet Air Temperature
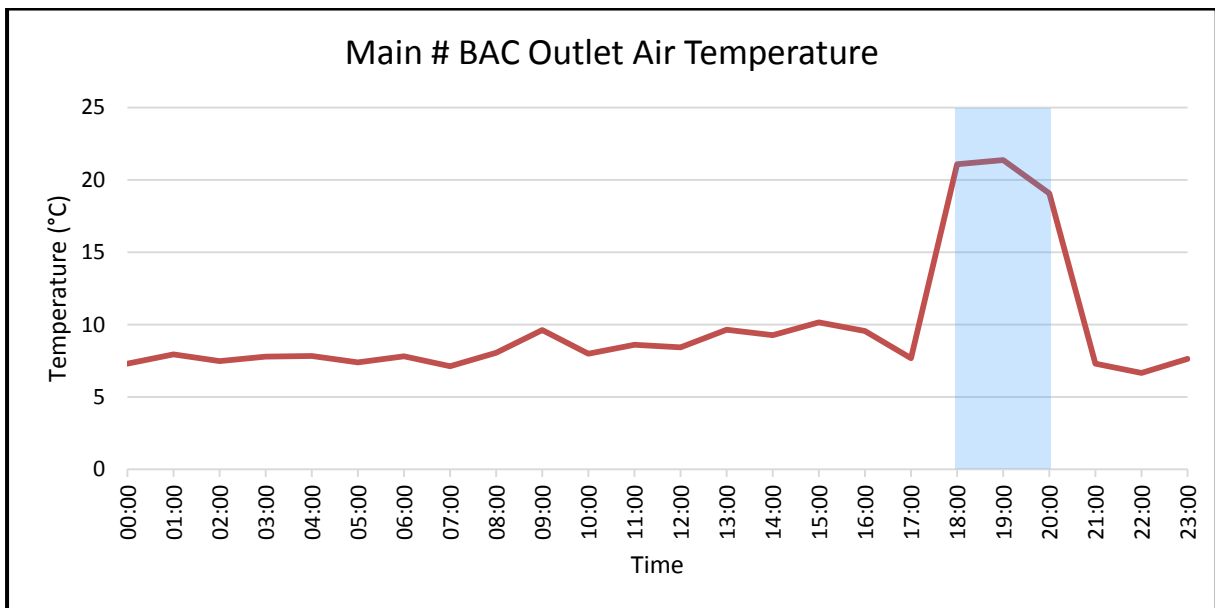


**Figure 52: Main # BAC outlet air temperature – Mine D**
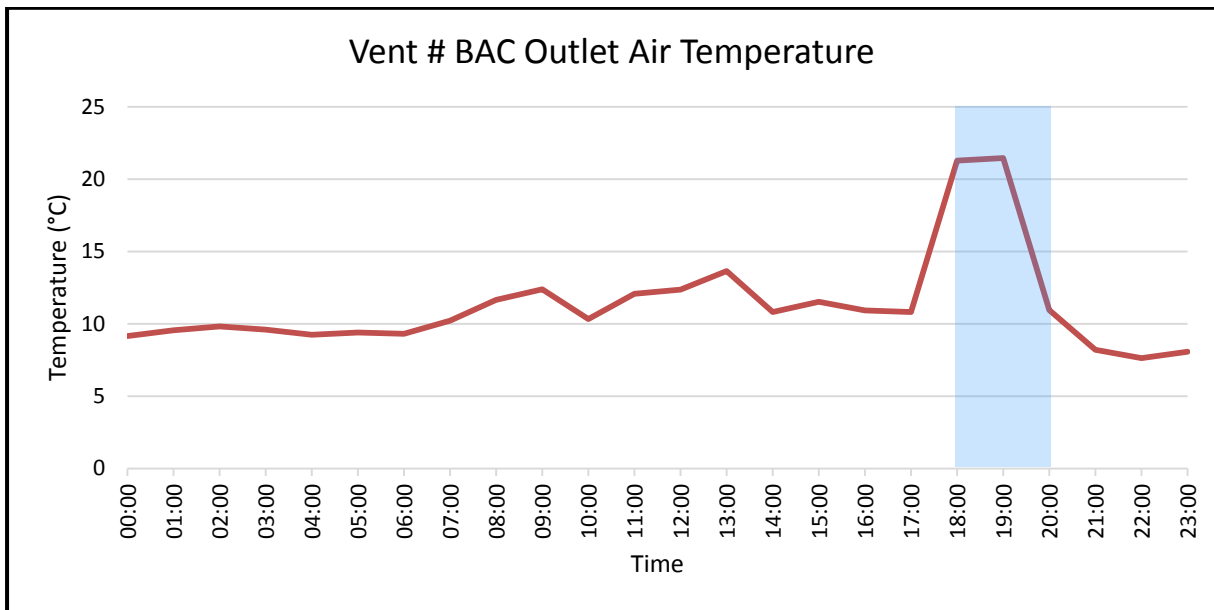
**Figure 53: Vent # BAC outlet air temperature – Mine D**

The next step was to validate the actual impact of the optimised control strategy prior to implementation on Mine D's refrigeration system.

### 4.5.3 Validating the optimised control strategy

The simulated optimised strategy was implemented on Mine D's refrigeration system for validation. Table 13 provides an average comparison of the simulation with the actual test data. Figure 54 to Figure 57 provide the comparison of the power consumption and various KPIs over a 24-hour profile.

**Table 13: Optimised control strategy validation – Mine D**

| Comparison | Simulated | Test | Percentage Error |
|---|---|---|---|
| Power consumption | 6975 [kW] | 7112 [kW] | 1.94 [%] |
| Load shift | 7118 [kW] | 6989 [kW] | 1.82 [%] |
| Cold storage dam temperature | 3.43 [°C] | 3.75 [°C] | 8.45 [%] |
| Main # BAC outlet air temperature | 9.69 [°C] | 9.21 [°C] | 5.17 [%] |
| Vent # BAC outlet air temperature | 11.26 [°C] | 10.96 [°C] | 2.73 [%] |

The shutdown procedure for the refrigeration components was commenced at 17:45 for the optimised control strategy test. This ensured all components were switched off at the start of the Eskom evening peak period, resulting in a smaller percentage error for the load shift. The actual power consumption is higher than the simulated value between 08:00 and 15:00 due to ambient weather data not being taken on the refrigeration site. The actual refrigeration system uses more power due to a higher local ambient temperature than used in the simulation. The deviation between actual and simulated power between 20:00 and 21:00 is due to the simulation instantly starting up all equipment, whereas in actuality this process takes approximately 30 minutes.

The difference between the actual and simulated cold storage dam temperature is due to the simulation recirculating a fixed amount of water, whereas the actual refrigeration system increases the flow to recover the dam level faster. This results in the actual dam level recovering faster than simulated. Although actual cold storage dam level data was not available, it remained above the minimum prescribed level throughout the test day. The error between the actual and simulated Main # BAC air outlet temperature can be attributed to the heat exchange not reacting dynamically as explained in section 4.4.3.

The average daily profiles of the comparisons summarised in Table 13 are provided as follows:
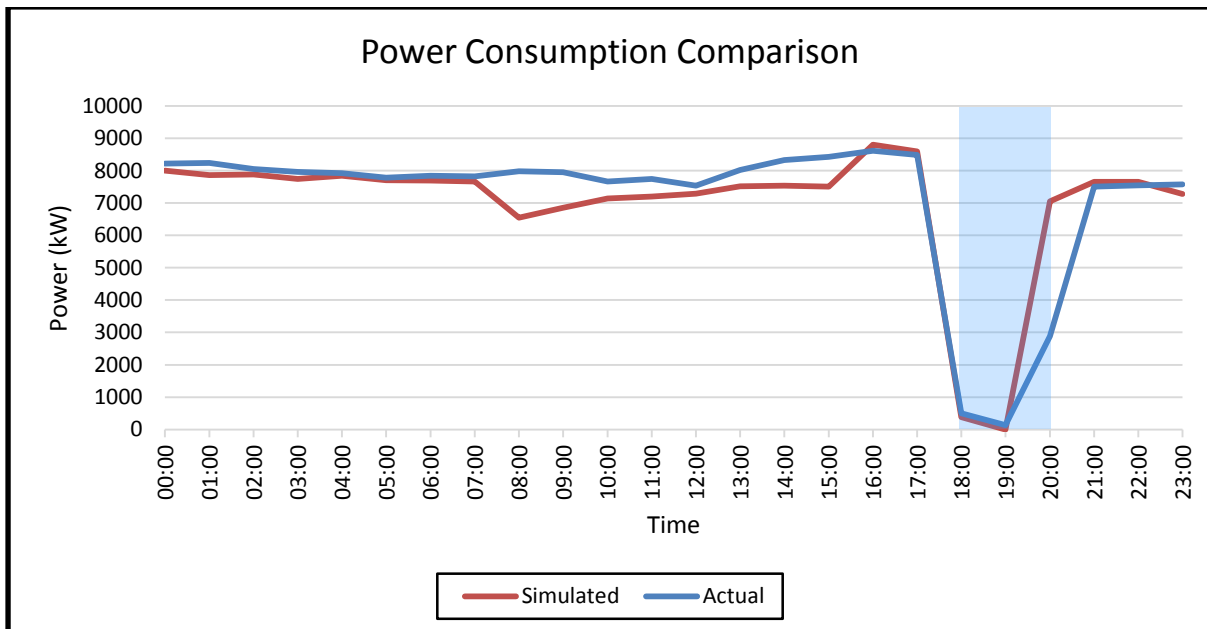


**Figure 54: Power consumption comparison – Mine D**
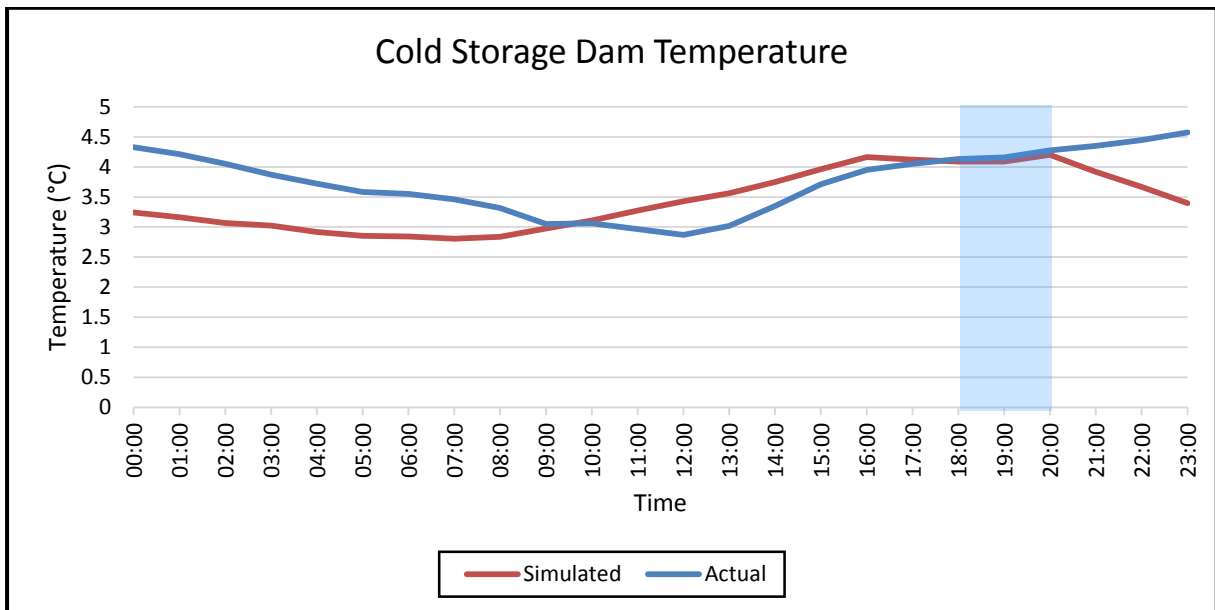
**Figure 55: Cold storage dam temperature comparison – Mine D**
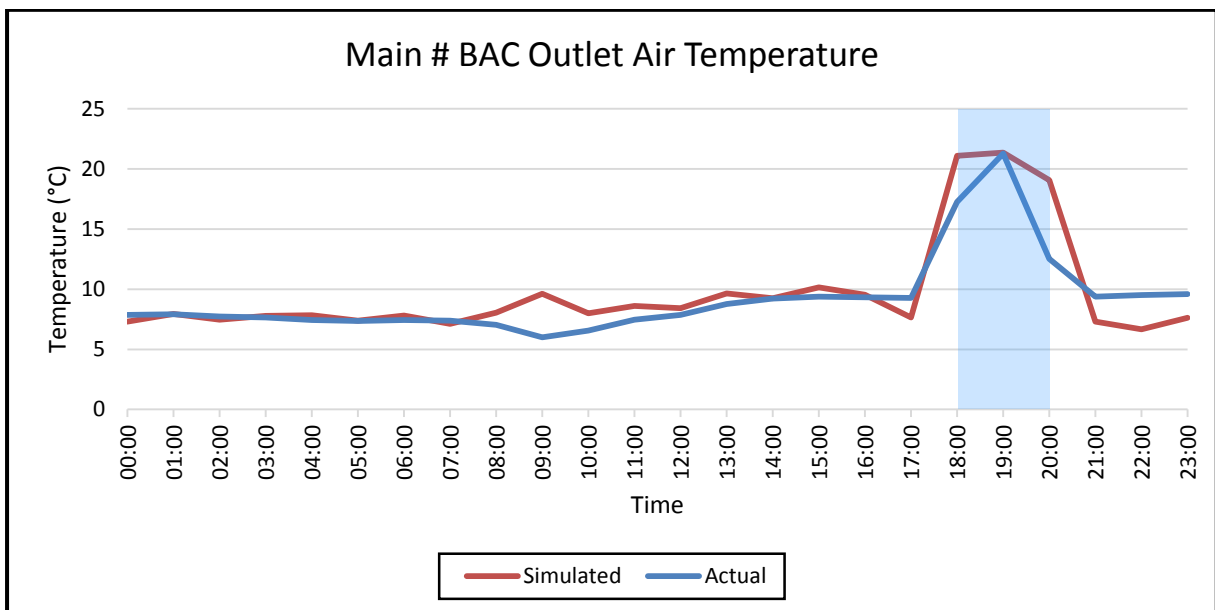


**Figure 56: Main # BAC outlet air temperature comparison – Mine D**
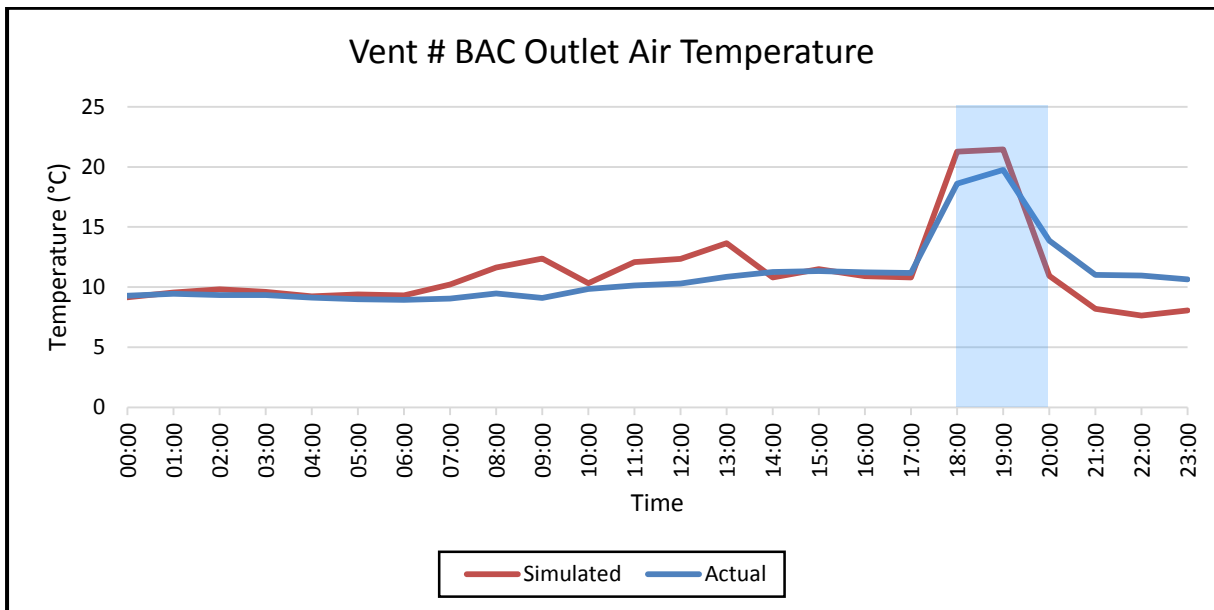
**Figure 57: Vent # BAC outlet air temperature comparison – Mine D**

The temperature at the 20L station was monitored during the test. As illustrated in Figure 58, the temperature remained constant and the load shift had almost no impact on the underground temperature.
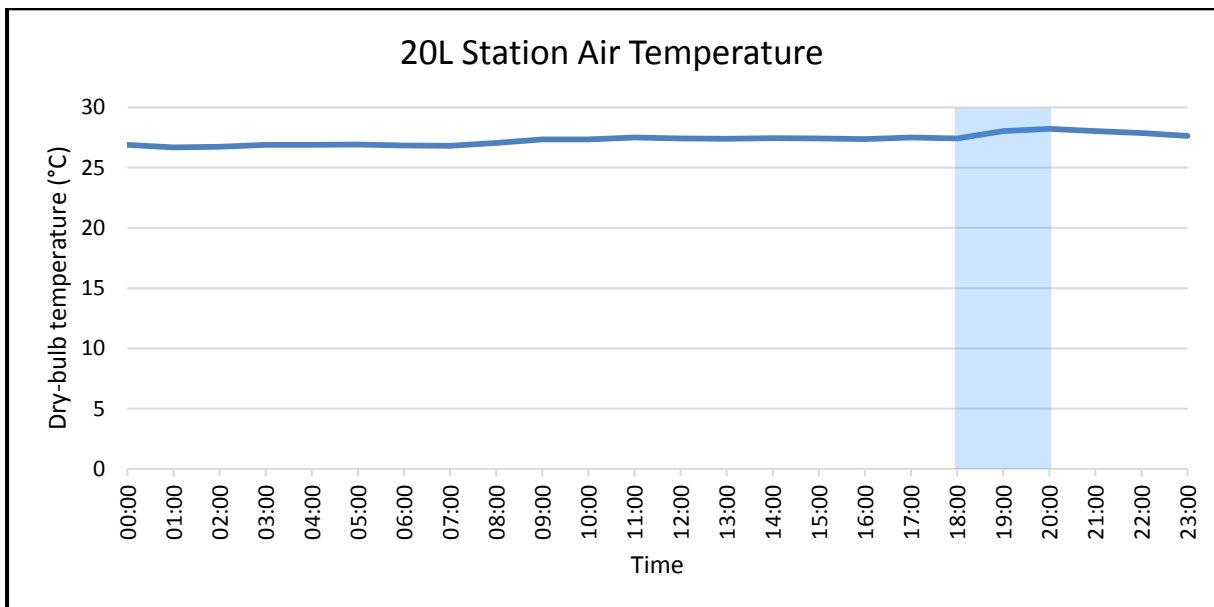


**Figure 58: 20L Station dry-bulb air temperature– Mine D**

Figure 55 to Figure 58 show that the optimised control strategy had no lasting impact on the operations of Mine D's refrigeration system. Although some temperatures increased during the load shift, they all recovered within four hours after the load shift. Most importantly, the underground ambient temperatures were not affected by load shifting. This is an indication that the optimised control strategy can be implemented sustainably over long periods of time.

## 4.6 Implementing the optimised control strategy

### 4.6.1 Preamble

Optimised simulations and feasibility tests proved that load management can be sustainably implemented on deep-level gold mine refrigeration systems. The optimised control strategy was implemented on the refrigeration system of Mine D. The implementation details in terms of cost, time and sustainability are highlighted for Case study 1. The implementation details of Case study 2 are available in Appendix D.

### 4.6.2 Case Study 1

Mine personnel were trained to implement the optimised control strategy on a daily basis. This resulted in the optimised strategy to be implemented within one month. Furthermore, only existing infrastructure was utilised, meaning that no implementation costs were incurred.

Figure 59 illustrates the baseline and post-implementation power profile, averaged over a period of eight months. The post implementation profile includes summer.
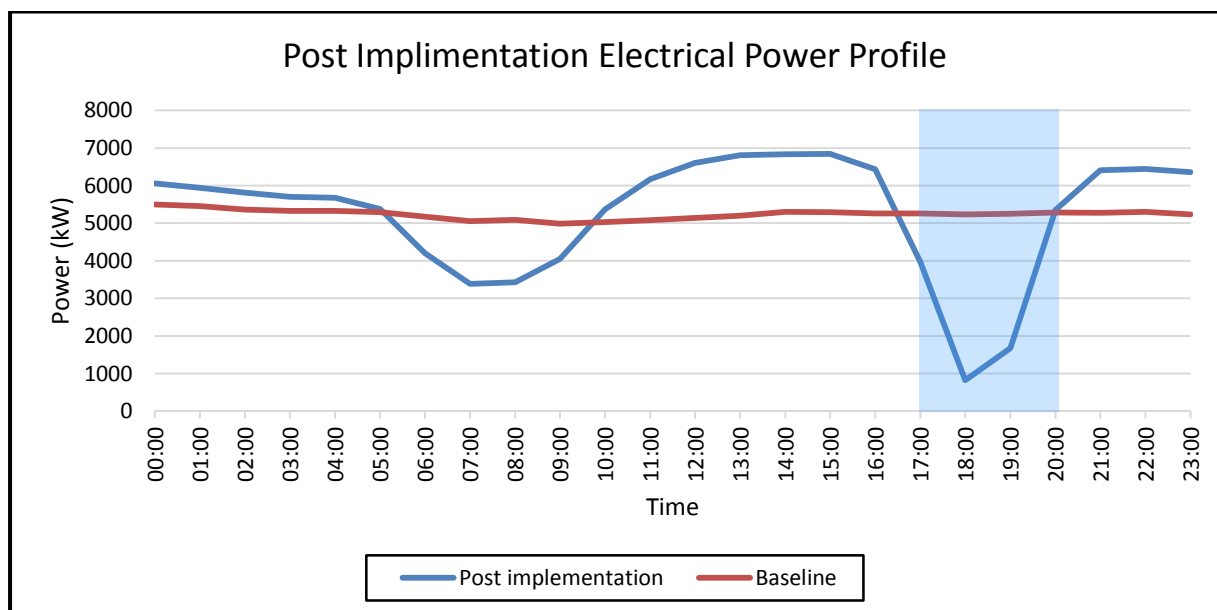


**Figure 59: Post implementation power profile – Mine D**

The presence of the evening peak period load shift indicates the project was implemented sustainably. Cost savings up to date realised to R 1 170 000. Cost savings based on the evening peak period load shift is expected to result in an approximate annual financial saving of R 1 755 000. The mine started implementing a morning load shift on the refrigeration system after the implementation of the evening load shift. The cost savings amounted to R 3 million annually when including the morning load shift. It has not been included in this discussion as it falls outside the scope of this study.

Table 14 compares the predicted and achieved (post-implementation) summer evening peak period load shift and annual cost savings. The predicted average summer load shift correlates closely to the achieved reduction with an average error of approximately 2%. The average annual cost savings realised by the evening peak period load shift falls within an approximate error of 1%.

**Table 14: Implementation validation – Mine D**

| Predicted summer evening peak load shift | Achieved summer evening peak load shift |
|---|---|
| 7.12 MW | 7.28 MW |
| **Predicted annual cost savings** | **Achieved annual cost savings\*** |
| R 1 770 000 | R 1 755 000[7] |

\*Based on eight months post-implementation data

## 4.7  Conclusion

Simulations were used to develop optimised control strategies for the refrigeration systems of two deep-level gold mines.  The simulations indicated that load management techniques could be implemented without affecting the operational parameters of the refrigeration systems. The predicted results of the simulations were validated in the form of practical tests prior to permanent implementation. The validation proved an average error of 2% between the simulated and actual results.

The optimised control strategies were implemented on the respective refrigeration systems of Mine D and Mine R. The control strategies were easily incorporated within the systems at a

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[7] Savings resulting from Eskom evening peak period load shift only, excludes morning load shift savings

low cost and short implementation period. Furthermore, the optimised control strategies proved to have a sustainable load shift over a consecutive eight month period for both refrigeration systems (still in progress by the time of the study). The sustainability was confirmed by validating the actual summer load shift to the predicted summer load shift after eight months. The average error was confirmed at 2% for Mine D and 3% for Mine R.

Optimised control strategies proved to have a significant impact on the sustainability of load management initiatives on deep-level mine refrigeration systems. The sustainability ultimately contributes to continuous cost savings for the gold-mining industry, a stable reserve margin for Eskom and the assurance for ESCos to perform under the new Eskom DSM model.

# Chapter 5

# 5 Conclusion and recommendations

## 5.1 Summary

The productivity and profitability of the South African gold-mining industry are influenced by numerous challenges. One of the challenges is the cost of electricity due to the gold mining industry's intensive use and higher-than-inflation increases. This challenge, however, presents large potential for gold mines to reduce operating costs in the form of load management initiatives. On the other hand, not only the mines benefit from these initiatives, but it also enables Eskom to sustain its electricity reserve margin during peak periods.

Refrigeration systems were highlighted as the largest electricity consumers on South African deep-level gold mines. Due to its intensive electricity usage, these systems offer large potential for cost and load reduction through the implementation of load management initiatives. For this reason, a large variety of load management projects have been implemented on these particular systems in the past by ESCos as part of the Eskom DSM model.

Historically, implemented load management initiatives were, however, not sustainable in terms of load shifting and financial cost savings for the mines. This is mainly due to the old DSM model only requiring ESCos to maintain targeted savings for a period of three months after implementation. Eskom, however, revised the DSM model to address the issue and challenged ESCos to implement low budget projects that would be sustainable for at least 36 months. This presented the need for ESCos to develop sustainable load management techniques that will be cost effective and easy to implement.

This study therefore focused on developing and simulating optimised control strategies for deep-level mine refrigeration systems. The development mainly focused on low-cost strategies that would be easy to implement and would ensure maximised cost savings over at least 36 months. It was also important to develop the optimised strategies in such a manner that it would not influence the safety regulations of deep-level gold mines in terms of acceptable underground temperatures.

Control strategies were developed for the refrigeration systems of two South African gold mines. The strategies were simulated to determine the theoretical impact of the control strategies on the respective refrigeration systems. The simulations were verified with actual data of the refrigeration systems to ensure credibility of the developed control strategies' potential impact. The potential results of the simulated strategies, in terms of load shift

achieved and operational impact, were validated with actual tests. Table 15 shows a summary of the validation results.

**Table 15: Control strategies validation results**

| Comparison | Case study 1 | | | Case study 2 | | |
|---|---|---|---|---|---|---|
| | Simulated | Test | Percentage Error | Simulated | Test | Percentage Error |
| Average power consumption | 7608 [kW] | 7659 [kW] | 3.65 [%] | 2264 [kW] | 2182 [kW] | 3.59 [%] |
| Average summer load shift | 4707 [kW] | 4062 [kW] | 13.70 [%] | 1780 [kW] | 1700 [kW] | 4.47 [%] |
| Cold storage dam temperature increase over evening peak period | 0.94 [°C] | 1 [°C] | 6 [%] | 1.53 [°C] | 1.58 [°C] | 3.3 [%] |

The tests concluded low cost and fast implementation for the developed control strategies. The issue of sustainability was, however, not addressed through the sole development of the control strategies. The simulation and tests proved that the cold storage dam temperature for both Mine D and Mine R increased during the load shift. Implementing these strategies on a daily basis could lead to a systematic increase in the average cold storage dam temperatures. This increase in temperature would have compromised the sustainability of the load shift.

To ensure sustainability of the load management initiatives, optimisation of the control strategies was required. The optimisation consisted of altering the configuration and control of the refrigeration systems using only existing infrastructure. Through control optimisation, the cold storage water could be isolated from warmer water. This would result in smaller increases of the cold storage dam temperatures over the course of each load shift. The optimised control strategies were also simulated and validated with actual tests. Table 16 shows the results of the validation.

**Table 16: Optimised control strategies validation results**

| Comparison | Case study 1 | | | Case study 2 | | |
|---|---|---|---|---|---|---|
| | Simulated | Test | Percentage Error | Simulated | Test | Percentage Error |
| Average power consumption | 6975 [kW] | 7112 [kW] | 1.94 [%] | 2258 [kW] | 2217 [kW] | 1.80 [%] |
| Average summer load shift | 7118 [kW] | 6989 [kW] | 1.82 [%] | 1939 [kW] | 1938 [kW] | 0.05 [%] |
| Cold storage dam temperature increase over evening peak period | 0.11 [°C] | 0.15 [°C] | 27 [%][8] | 0.9 [°C] | 0.5 [°C] | 44.4 [%][7] |

The optimised control strategies were implemented on the refrigeration systems of Mine D and Mine R. By the time of this study, load management proved to be sustainable for a consecutive period of eight months at Mine D and nine months at Mine R. An average evening peak period load reduction of 7.28 MW (Mine D) and 2.00 MW (Mine R) was measured at the respective mines. This accumulates to financial cost savings of R 1.17 million (Mine D) and R 143 000 (Mine R) over the respective measuring periods. Assuming sustainability over a period of 36 months, a total financial saving of approximately R 6 million is expected. The expected annual cost savings is R 1.76 million for Mine D and R 215 000 for Mine R.

Optimised control strategies further resulted in low cost and fast implementation of load management initiatives. There was also minimal effect on the cold storage dam temperatures, which ensured sustainability of load shifting. More components were also switched off in each refrigeration system to facilitate the isolation of cold water from warm water sources.

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[8] Note the large percentage is ascribed to the differences between very small values.

The study concludes that low-cost, easy to implement and sustainable load management initiatives can be implemented on deep-level gold mine refrigeration systems through optimised control strategies. Gold mines will benefit from the cost savings to improve profit margins while Eskom will improve their supply reserve margin. From an ESCo's point of view, by sustainably implementing these initiatives, continued involvement in DSM is secured.

## 5.2  Recommendations for future work

Due to the successful implementation of the optimised control strategies on mine refrigeration systems, the feasibility of expanding this methodology to other electricity intensive systems of deep-level mines should be investigated. The compressed air and dewatering systems of gold mines are ideal targets as they consume a large portion of the total electricity usage on a gold mine.

It is also recommended to expand the use of optimised control strategies on energy efficiency initiatives. During this study the optimised control strategies were implemented to maximise and sustain the cost savings of load management initiatives. Utilising optimised control strategies to realise sustainable energy efficiency would result in larger cost savings for clients and contribute to sustaining the Eskom reserve margin over a 24-hour period.

This study only focused on optimising refrigeration control strategies during summer months. Although load management was implemented during winter months on Mine D, optimising and simulating a winter control strategy should be investigated as it may lead to increased cost savings and improved operation. Implementing load management during the morning peak periods should also be investigated to further increase the cost savings potential.

Load management sustainability was proven for up to nine months for this study, which is already much longer than initiatives implemented under the old Eskom DSM model. The aim is, however, to maintain the performance of the load management initiatives for a minimum period of 36 months. Since sustainability was one of the main objectives of this study, it is recommended that the load management initiatives' performances be tracked for the remainder of the period.

By optimising the control strategies of implementing load management initiatives on the two identified case studies, the overall impact on operational parameters were reduced.  This reduced the comeback load required to recover the refrigeration system to normal operating conditions after load shifts. This may be an indication that energy savings are present due to overall improved refrigeration system control. This should, however, be investigated.

Due to similar operations to gold mines, the possibility of implementing optimised control strategies for cost savings on platinum mine refrigeration systems can be investigated. Optimised control can even be expanded to any other industry using large refrigeration systems within their operations.

# REFERENCE LIST

[1]     "Chamber of mines-Gold," 2015. [Online]. Available:
        http://www.chamberofmines.org.za/sa-mining/gold. [Accessed: 05-Mar-2016].

[2]     K. Crowley, "South African Gold on the Brink With Half of Mines Losing Money,"
        *Bloomberg Business*, 2015. [Online]. Available:
        http://www.bloomberg.com/news/articles/2015-09-08/south-africa-gold-industry-fades-
        as-margin-squeeze-erodes-output. [Accessed: 07-Mar-2016].

[3]     M. A. McCrae, "The stunning collapse of gold production in South Africa," 2015.
        [Online]. Available: http://www.mining.com/the-stunning-collapse-of-gold-production-
        in-south-africa/. [Accessed: 07-Mar-2016].

[4]     J. I. G. Bredenkamp, M. J. Mathews, and J. C. Vosloo, "An integrated energy
        management strategy for the deep-level gold mining industry," in *Conference on the
        Industrial and Commercial Use of Energy, ICUE*, 2016, no. August, pp. 133–138.

[5]     "SOUTH AFRICAN GOLD , TODAY AND TOMORROW." [Online]. Available:
        http://www.thisisgold.co.za/facts-and-figures/fact-sheets. [Accessed: 08-Mar-2016].

[6]     "MINING AND MINERAL PROCESSING Remains Vital for African Economy.pdf,"
        *Eng. Min. J.*, vol. 205, no. 5, pp. 21–30.

[7]     "Company Information," *Eskom company information*. [Online]. Available:
        http://www.eskom.co.za/OurCompany/CompanyInformation/Pages/Company_Informa
        tion_1.aspx. [Accessed: 10-Mar-2016].

[8]     K. Crowley, "Eskom Declares Power Emergency, Asks South Africa to Cut Use,"
        *Bloomberg Business*, 2014. [Online]. Available:
        http://www.bloomberg.com/news/articles/2014-02-20/eskom-declares-power-
        emergency-and-asks-south-africa-to-cut-use. [Accessed: 22-Mar-2016].

[9]     P. Cohen, Mike; Burkhardt, "How Eskom lost its lustre," *Fin24*, 2015. [Online].
        Available: http://www.fin24.com/Economy/Eskom/How-Eskom-lost-its-lustre-
        20150608. [Accessed: 22-Mar-2016].

[10]    Eskom, "Eskom fact sheets 2015," 2015. [Online]. Available:
        http://www.eskom.co.za/IR2015/Documents/Eskom_fact_sheets_2015.pdf.

[11] Eskom DSM, "Towards an energy efficient mining sector," *The Energy Efficiency series*, 2010. [Online]. Available: http://www.eskom.co.za/sites/idm/Documents/121040ESKD_Mining_Brochure_paths. pdf. [Accessed: 12-Mar-2016].

[12] H. Trollip, A. Butler, J. Burton, T. Caetano, and C. Godinho, "Energy security in South Africa," *Mitig. Action Plans Scenar. i*, no. 17, p. 45, 2014.

[13] D. de Vos, "Eskom's dim understanding of the market," *Mail & Guardian*, 2013. [Online]. Available: http://mg.co.za/article/2013-05-03-00-eskoms-dim-understanding-of-the-market. [Accessed: 18-Apr-2016].

[14] S. Mantshantsha, "Eskom to decommission generating units," *Financial mail*, 2012. [Online]. Available: http://www.financialmail.co.za/economy/2012/12/12/eskom-to-decommission-generating-units. [Accessed: 22-Mar-2016].

[15] RSA Goverment, "Mine Health And Safety act 1996," no. 967, 1996.

[16] L. F. van der Zee and R. Pelzer, "Modelling of electricity cost risks and opportunities in the gold mining industry," Dissertation submitted in partial fulfillment of the requirements for the degree of PHILOSOPHIAE DOCTOR of ENGINEERING, Potchefstroom Campus of the North West University, 2014.

[17] "8 slides about Eskom you should see," *Fin24*. [Online]. Available: http://www.fin24.com/Economy/Eskom/8-slides-about-eskom-you-should-see-20151116. [Accessed: 18-Apr-2016].

[18] Eskom, "Schedule of standard prices for Eskom tariffs," 2015. [Online]. Available: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/WhatsNew/Documents/ScheduleStdPrices2015_16_27Feb2015.pdf. [Accessed: 16-Apr-2016].

[19] "Eskom Demand Management Funding Models," *Eskom IDM Business Unit*, 2011. [Online]. Available: http://www.ameu.co.za/Portals/16/Documents/EEDSM and Renewable Energy/Eskom IDM funding options - 2011 12 13.pdf. [Accessed: 18-Apr-2016].

[20] "Funding through ESCo Model," *Eskom IDM Business Unit*. [Online]. Available: http://www.eskom.co.za/sites/idm/Business/Pages/Funding.aspx. [Accessed: 19-Apr-2016].

[21]   D. Stephenson, "Distibution of water in deep gold mines in South Africa," *Int. J. Mine Water*, vol. II, no. 2, pp. 21–30, 1983.

[22]   M. Karsten and L. Mackay, "Underground environmental challenges in deep platinum mining and some suggested solutions," *South. African Inst. Min. Metall.*, pp. 177–192, 2012.

[23]   R. E. Sonntag, C. Borgnakke, and G. J. Van Wylen, *Fundamentals of Thermodynamics*, Sixth edit. Wiley, 2002.

[24]   "Refrigeration Compressors and Air Conditioning Compressors Information." [Online]. Available: http://www.globalspec.com/learnmore/building_construction/hvac/ventilation/refrigerati on_compressors_air_conditioning_compressors. [Accessed: 04-Sep-2016].

[25]   A. J. Schutte, R. Pelzer, and E. H. Mathews, "Improving cooling system efficiency with pre-cooling," *9th Ind. Commer. Use Energy Conf. Conf.*, vol. 9, pp. 1–4, 2012.

[26]   G. E. du Plessis, E. H. Mathews, and J. C. Vosloo, "A variable water flow energy efficiency strategy for mine cooling systems," in *Proc. of the 10th Industrial and Commercial Use of Energy (ICUE) Conference, Cape Town*, 2013.

[27]   A. J. Schutte, R. Pelzer, and M. Kleingeld, "DEMAND-SIDE ENERGY MANAGEMENT OF A CASCADE MINE SURFACE REFRIGERATION SYSTEM," in *Proc. of the 5th Industrial and Commercial Use of Energy (ICUE) Conference, Cape Town*, 2008.

[28]   K. J. Oberholzer and M. Kleingeld, "Reconfiguring mine cooling auxiliaries for optimal operation," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, Potchefstroom Campus of the North West University, 2016.

[29]   Y. A. Cengel, *Heat and Mass Transfer: A Practical Approach*. New York, NY: McGraw-Hill, 2006.

[30]   "Adaptive Frequency Drive for chillers." Ingersoll Rand, p. 2, 2011.

[31]   J. Engles and M. Kleingeld, "Cost effective control of a platinum mine cooling system using combined DSM strategies," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, Potchefstroom Campus

of the North West University, 2015.

[32]    J. Van der bijl and M. Kleingeld, "Sustainable DSM on Deep Mine Refrigeration Systems - A Novel Approach," Dissertation submitted in partial fulfillment of the requirements for the degree of PHILOSOPHIAE DOCTOR of ENGINEERING, Potchefstroom Campus of the North West University, 2007.

[33]    G. E. Du Plessis, L. Liebenberg, and E. H. Mathews, "The use of variable speed drives for cost-effective energy savings in South African mine cooling systems," *Appl. Energy*, vol. 111, pp. 16–27.

[34]    A. J. Schutte and M. Kleingeld, "An intergrated energy-efficiency strategy for deep-mine ventilation and refrigeration," Dissertation submitted in partial fulfillment of the requirements for the degree of PHILOSOPHIAE DOCTOR of ENGINEERING, Potchefstroom Campus of the North West University, 2013.

[35]    F. M. White, *Fluid Mechanics*, Sixth Edit. Boston: McGraw-Hill, 2008.

[36]    J. Van der Walt and E. M. De Kock, "Developments in the engineering of refrigeration installations for cooling mines," *Int. J. Refrig.*, vol. 7, no. 1, pp. 27–40, 1984.

[37]    A. J. Schutte and M. Kleingeld, "Demand side managment of a cascade mine surface refridgeration system," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, Potchefstroom Campus of the North West University, 2007.

[38]    J. Vermeulen and J. F. van Rensburg, "Cost effective management strategies for platinum mine cooling systems," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, Potchefstroom Campus of the North West University, 2015.

[39]    M. den Boef, "Integrated thermal simulation of underground mobile cooling systems," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, Potchefstroom Campus of the North West University, 2001.

[40]    D. C. Arndt, "Integrated dynamic simulation of large thermal systems," Dissertation submitted in fulfillment of the requirements for the degree of PHILOSOPHIAE DOCTOR of ENGINEERING, University of Pretoria, 2000.

[41]    P. G. Rousseau and J. H. R. Moodie, "Computer program for energy policy support

and energy savings in buildings: Appendix to the final report," 1995.

[42]   D. F. Y. B.R. Munson  T.H. Okiishi, *Fundamentals of Fluid Mechanics fith edition*. United States of America: Wiley, 2006.

[43]   A. T. Sayers, *Hydraulic and compressible flow turbomachines*. London: McGraw-Hill, 1990.

[44]   R. Els and E. H. Mathews, "POTENTIAL FOR LOAD SHIFTING VENTILATION AND COOLING SYSTEMS," Dissertation submitted in fulfillment of the requirements for the degree of MASTER of ENGINEERING, University of Pretoria, 2000.

[45]   T. L. Bergmann, F. P. Incropera, D. P. DeWitt, and A. S. Lavine, *Fundementals of heat and mass transfer*. John Wiley & Sons, 2011.

[46]   C. Swart, "Optimising the operations of underground mine refrigeration plants and ventilation fans for minimum electricity cost," Thesis, North-West University, Pretoria, 2003.

[47]   W. M. Marx, F. H. Von Glehn, S. J. Bluhm, and M. Biffi, "VUMA - A mine ventilation and cooling network simulation tool," in *International Mine Ventilation Congress*, 2001.

[48]   D. Arndt, *PROCESS TOOLBOX THERMAL HYDRAULIC SIMULATION FLOW SOLVER - USER MANUAL*. 2015.

[49]   P. Mare, J. H. Marais, and J. Van Rensburg, "Improved implementation strategies to sustain energy saving measures on mine cooling systems," in *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, 2015, vol. 2015–Sep, pp. 102–109.

[50]   W. Booysen and M. Kleingeld, "Measurement and verification of industrial DSM projects," Dissertation submitted in partial fulfillment of the requirements for the degree of PHILOSOPHIAE DOCTOR of ENGINEERING, Potchefstroom Campus of the North West University, 2014.

# Appendix A: Simulation overview & inputs

The values contained in Table 17 and Table 18 indicate the design inputs for all refrigeration system machinery required for the simulation and its verification. Actual simulated values may differ due to operational changes in the refrigeration system and changes in efficiency. This is due to the systems not necessarily operating at the same service level as when they were first installed. Figure 60 and Figure 61 show the refrigeration layouts within PTB for each case study.

**Table 17: Simulation inputs – Mine D**

| Component | Required Data | |
|---|---|---|
| Fridge Plants (Chillers) | Compressor motor installed capacity | 1850 [kW] |
| | Evaporator inlet temperature | 12 [°C] |
| | Evaporator outlet temperature | 5 [°C] |
| | Condenser inlet temperature | 22 [°C] |
| | Condenser outlet temperature | 30 [°C] |
| | Evaporator flow rate | 450 [l/s] |
| | Condenser flow rate | 650 [l/s] |
| Pumps | Evaporator pump motor installed capacity | 650 [kW] |
| | Evaporator pump flow | 450 [l/s] |
| | Evaporator pumping head | 5 [m] |
| | Condenser pump motor installed capacity | 400 [kW] |
| | Condenser pump flow | 650 [l/s] |
| | Condenser pumping head | 5 [m] |
| | BAC pump motor installed capacity | 150 [kW] |
| | BAC pump flow | 200 [l/s] |

| Component | Required Data | |
|---|---|---|
| | BAC pumping head | 10 [m] |
| | Pre-cooling pump motor installed capacity | 100 [kW] |
| | Pre-cooling pump flow | 350 [l/s] |
| | Pre-cooling pumping head | 5 [m] |
| Cooling towers and BACs | BAC water inlet temperature | 5 [°C] |
| | BAC water outlet temperature | 11 [°C] |
| | BAC air inlet temperature | Ambient |
| | BAC air outlet temperature | 9 [°C] |
| | BAC water flow rate | 200 [l/s] |
| | BAC airflow rate | 200 [l/s] |
| | CCT water inlet temperature | 30 [°C] |
| | CCT water outlet temperature | 22 [°C] |
| | CCT air inlet temperature | Ambient |
| | CCT air outlet temperature | N/A |
| | CCT water flow rate | 650 [l/s] |
| | CCT airflow rate | 390 [kg/s] |
| | PCT water inlet temperature | 28 [°C] |
| | PCT water outlet temperature | 20 [°C] |
| | PCT air inlet temperature | Ambient |
| | PCT air outlet temperature | N/A |
| | PCT water flow rate | 350 [l/s] |

| Component | Required Data | |
|---|---|---|
| | PCT airflow rate | 350 [kg/s] |
| Fans | BAC fan motor power | 150 [kW] |
| | BAC fan airflow rate | 100 [kg/s] |
| | CCT fan motor power | 150 [kW] |
| | CCT fan airflow rate | 195 [kg/s] |
| | PCT fan motor power | 100 [kW] |
| | PCT fan airflow rate | 350 [kg/s] |
| Dams | Main BAC sump dam water temperature | 11 [°C] |
| | Main BAC sump dam volume | 624 [m$^3$] |
| | Main BAC sump dam operating levels | 40% ~ 90% |
| | Vent BAC sump dam water temperature | 11 [°C] |
| | Vent BAC sump dam volume | 924 [m$^3$] |
| | Vent BAC sump dam operating levels | 40% ~ 90% |
| | CCT dam water temperature | 22 [°C] |
| | CCT dam volume | 1755 [m$^3$] |
| | CCT dam operating levels | 85% |
| | PCT dam water temperature | 20 [°C] |
| | PCT dam volume | 1755 [m$^3$] |
| | PCT dam operating levels | 85% |
| | Cold dam water temperature | 5 [°C] |
| | Cold dam volume | 2500 [m$^3$] x2 |

| Component | Required Data | |
|---|---|---|
| | Cold dam operating levels | 90% |
| | Warm dam water temperature | 12 [°C] |
| | Warm dam volume | 2500 [m$^3$] |
| | Warm dam operating levels | 85% |

The following valves are used within the system:

- Automated Vent # BAC isolation/throttling valve
- Automated cold dam isolation/throttling valve
- Automated recycling valve at fridge plant exit towards evaporator inlet
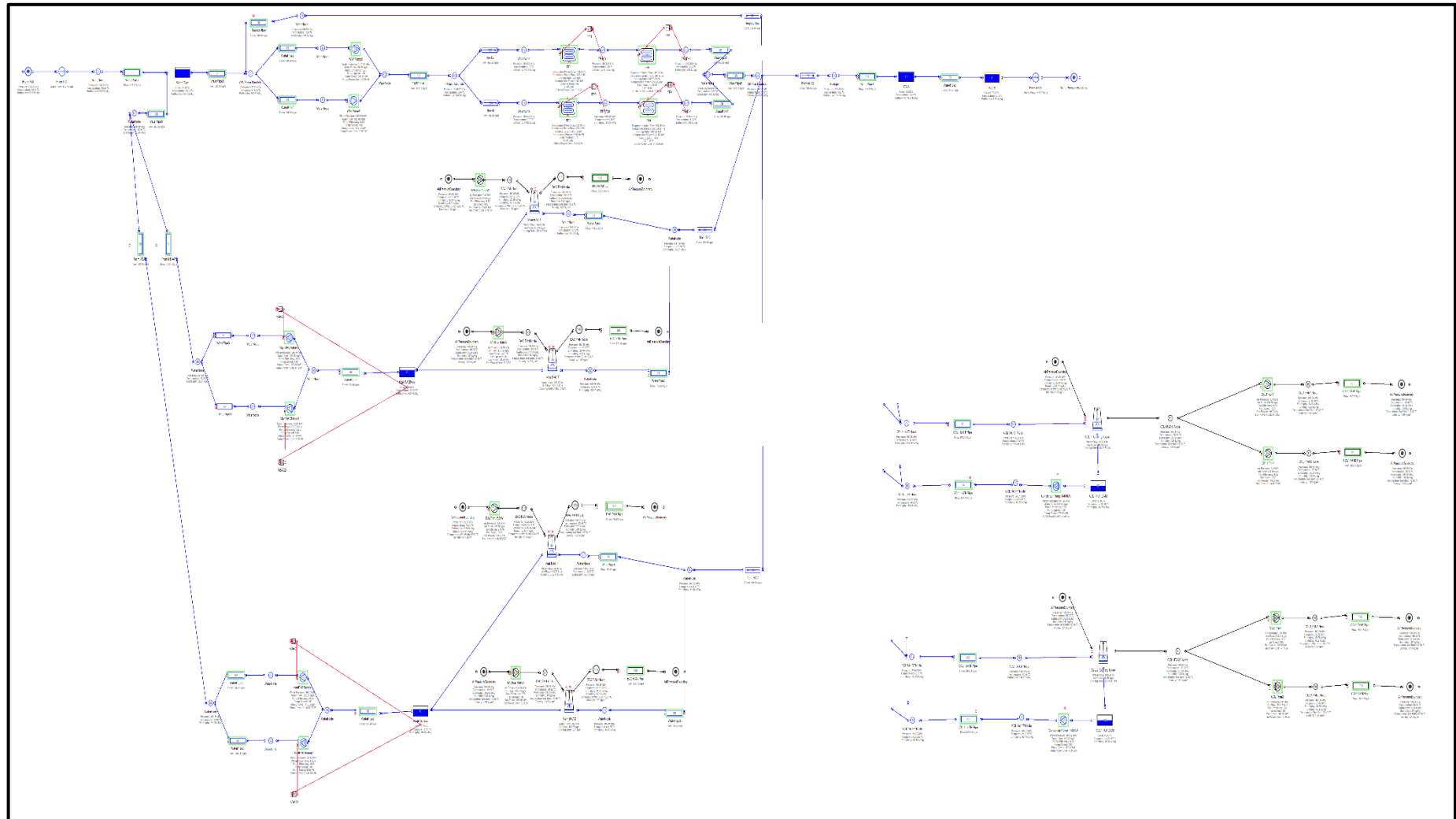
**Figure 60: Mine D simulation layout**

**Table 18: Simulation inputs – Mine R**

| Component | Required Data | |
|---|---|---|
| Fridge Plants (Chillers) | Compressor motor installed capacity | 1500 [kW] |
| | Evaporator inlet temperature | 9 [°C] |
| | Evaporator outlet temperature | 4 [°C] |
| | Condenser inlet temperature | 22 [°C] |
| | Condenser outlet temperature | 26 [°C] |
| | Evaporator flow rate | 265 [l/s] |
| | Condenser flow rate | 380 [l/s] |
| Pumps | Evaporator pump motor installed capacity | 75 [kW] |
| | Evaporator pump flow | 265 [l/s] |
| | Evaporator pumping head | 5 [m] |
| | Condenser pump motor installed capacity | 90 [kW] |
| | Condenser pump flow | 380 [l/s] |
| | Condenser pumping head | 5 [m] |
| | BAC pump motor installed capacity | 110 [kW] |
| | BAC pump flow | 400 [l/s] |
| | BAC pumping head | 10 [m] |
| | Pre-cooling pump motor installed capacity | 175 [kW] |
| | Pre-cooling pump flow | 210 [l/s] |
| | Pre-cooling pumping head | 5 [m] |
| | BAC water inlet temperature | 5 [°C] |

| Component | Required Data | |
|---|---|---|
| Cooling towers and BACs | BAC water outlet temperature | 10 [°C] |
| | BAC air inlet temperature | Ambient |
| | BAC air outlet temperature | 10 [°C] |
| | BAC water flow rate | 200 [l/s] |
| | BAC airflow rate | 200 [l/s] |
| | CCT water inlet temperature | 26 [°C] |
| | CCT water outlet temperature | 22 [°C] |
| | CCT air inlet temperature | Ambient |
| | CCT air outlet temperature | N/A |
| | CCT water flow rate | 380 [l/s] |
| | CCT airflow rate | 228 [kg/s] |
| | PCT water inlet temperature | 30 [°C] |
| | PCT water outlet temperature | 24 [°C] |
| | PCT air inlet temperature | Ambient |
| | PCT air outlet temperature | N/A |
| | PCT water flow rate | 90 [l/s] |
| | PCT airflow rate | 90 [kg/s] |
| Fans | BAC fan motor power | 150 [kW] |
| | BAC fan airflow rate | 200 [kg/s] |
| | CCT fan motor power | 22 [kW] |
| | CCT fan airflow rate | 57 [kg/s] |

| Component | Required Data | |
|---|---|---|
| | PCT fan motor power | 45 [kW] |
| | PCT fan airflow rate | 90 [kg/s] |
| Dams | BAC dam water temperature | 13 [°C] |
| | BAC dam volume | 5000 [m$^3$] |
| | BAC dam operating levels | 60% ~ 75% |
| | CCT sump dam water temperature | 22 [°C] |
| | CCT sump dam volume | 80 [m$^3$] |
| | CCT sump dam operating levels | 60% |
| | PCT dam water temperature | 24 [°C] |
| | PCT dam volume | 7500 [m$^3$] |
| | PCT dam operating levels | 85% |
| | Cold dam water temperature | 5 [°C] |
| | Cold dam volume | 2000 [m$^3$] |
| | Cold dam operating levels | 90% |

The following valves are used within the system:

- Manual shut-off valve at cold dam exit
- Automated recycling valve at BAC exit towards evaporator inlet
- Automated recycling valve at cold dam exit towards evaporator inlet
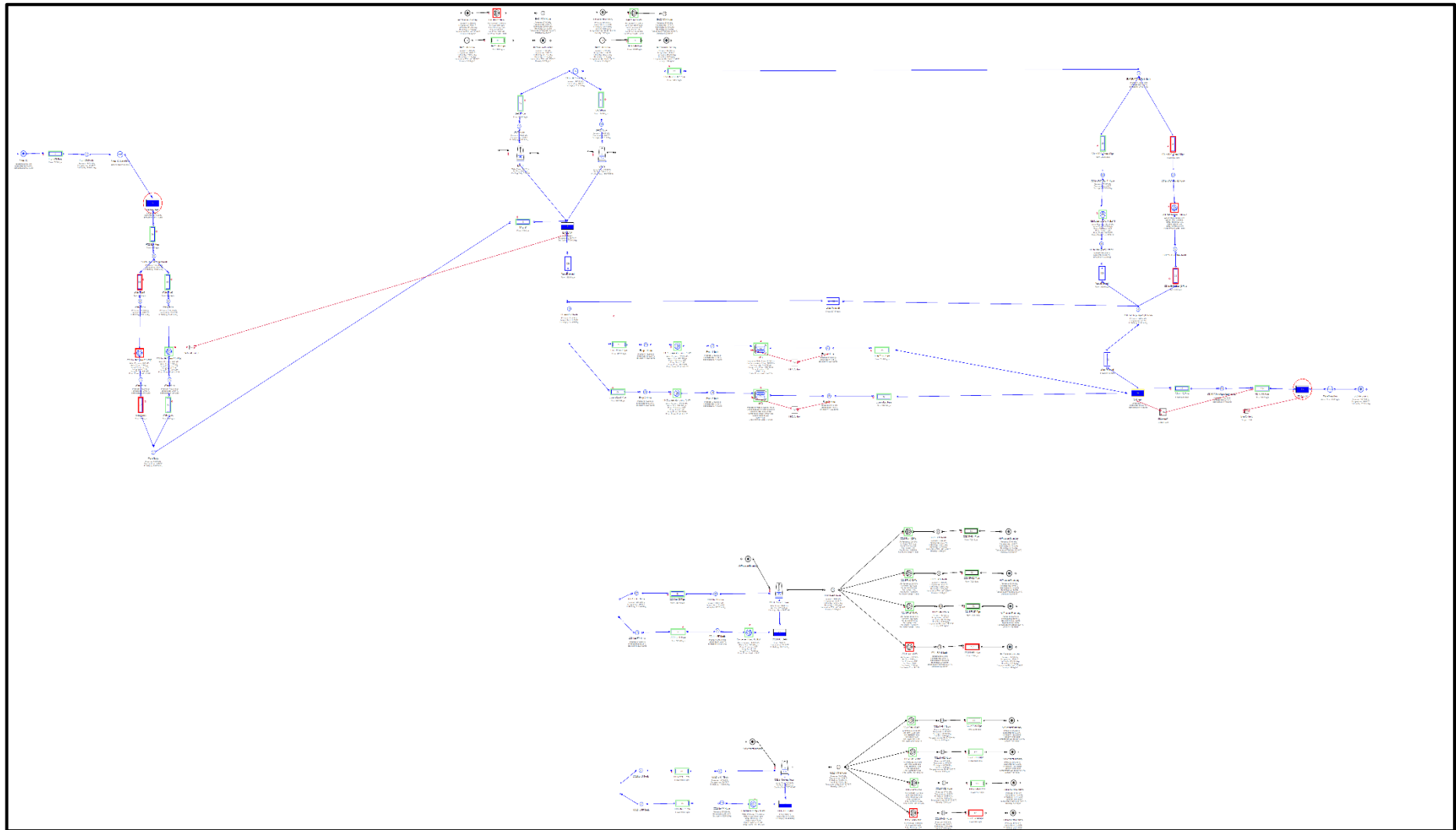
**Figure 61: Mine R simulation layout**

# Appendix B: Case Study 1 verification

Mine D's refrigeration system's normal operation was simulated and verified against the actual data. Table 19 below compares the daily average value of the power and various KPIs between the actual data and simulated results. The 24 hour profiles are also compared below for each of the variables listed in Table 19.

**Table 19: Simulation verification – Mine D**

| Comparison | Simulated | Actual | Percentage Error |
|---|---|---|---|
| Power consumption | 7608 [kW] | 7659 [kW] | 0.66 [%] |
| Cold dam level* | 90.43 [%] | - | - |
| Cold dam temperature | 2.91 [°C] | 2.89 [°C] | 0.71 [%] |
| Main BAC outlet air temperature | 8.51 [°C] | 8.75 [°C] | 0.97 [%] |
| Vent BAC outlet air temperature | 10.58 [°C] | 10.25 [°C] | 3.25 [%] |

*Actual data not available
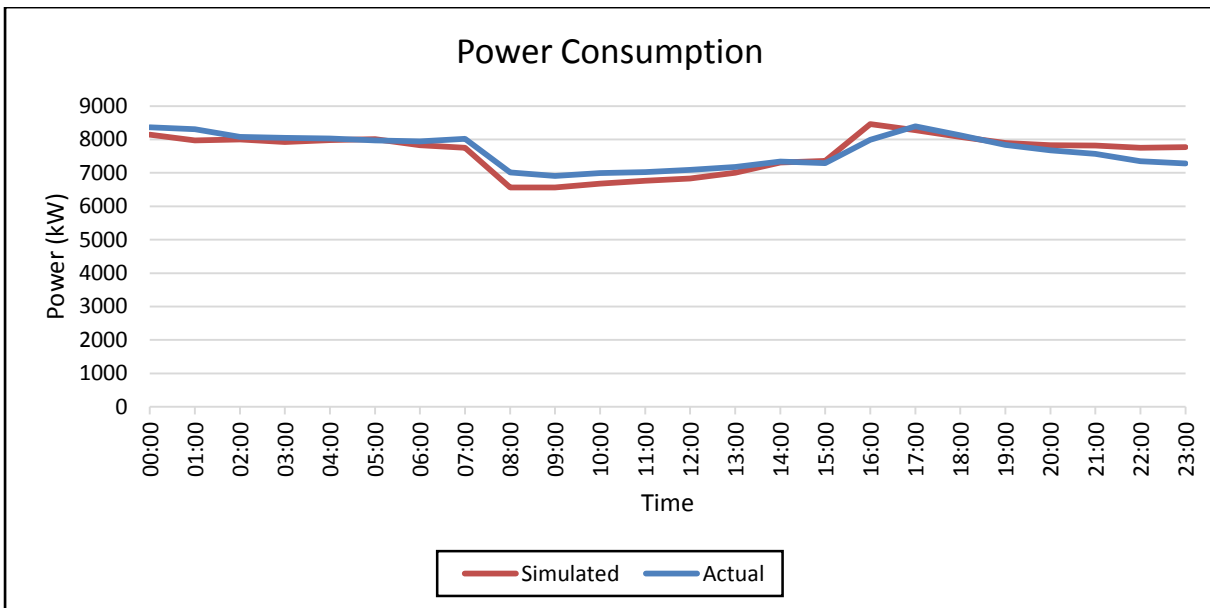


**Figure 62: Power consumption verification – Mine D**
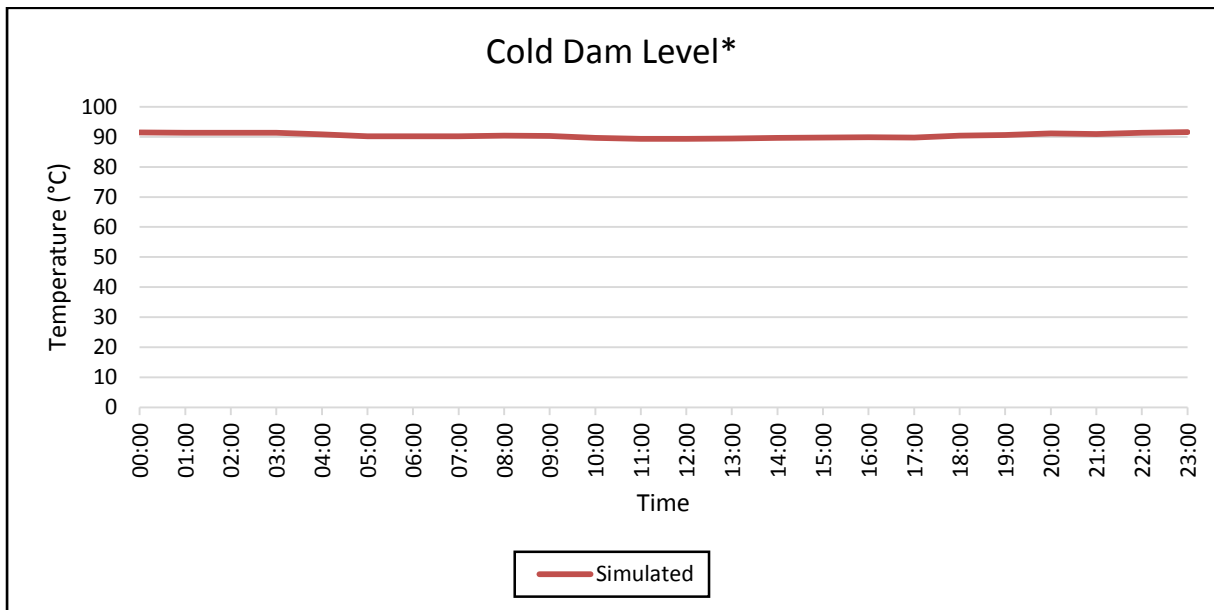
## Cold Dam Level*



**Figure 63: Cold dam level verification – Mine D**

## Cold Dam Temperature
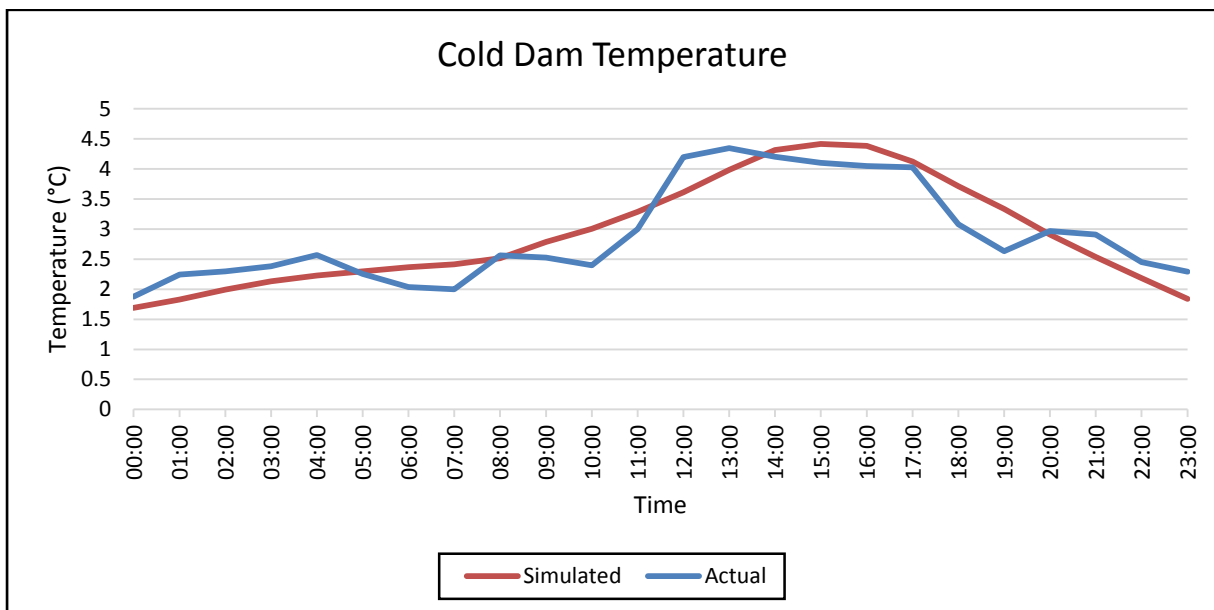


**Figure 64: Cold dam temperature verification – Mine D**
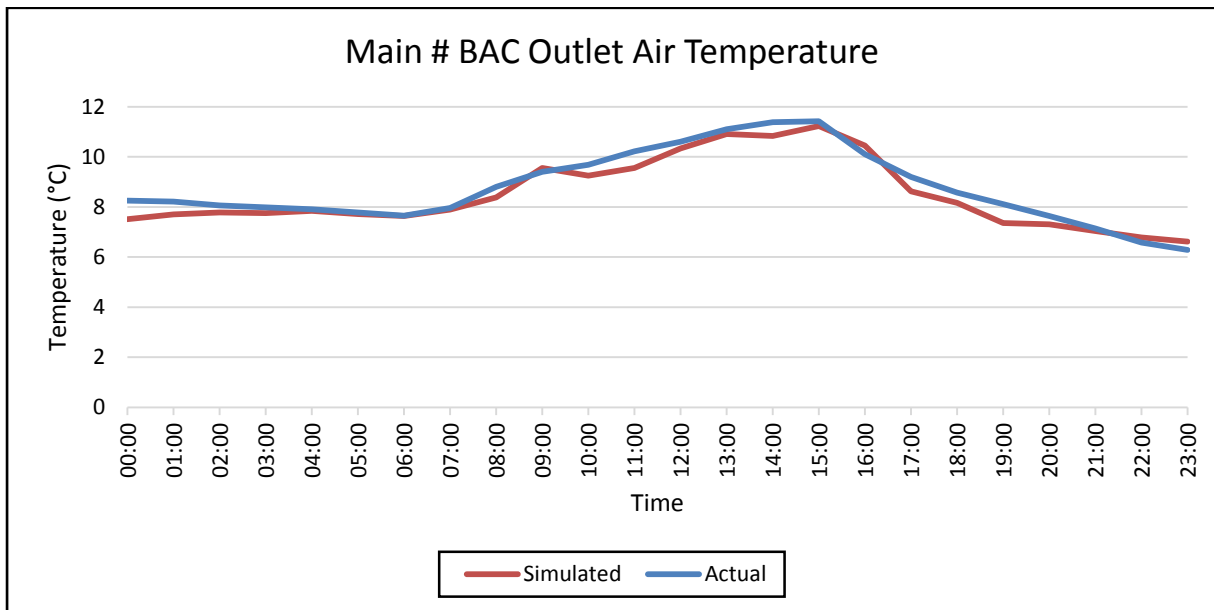
**Figure 65: Main BAC outlet air temperature verification – Mine D**
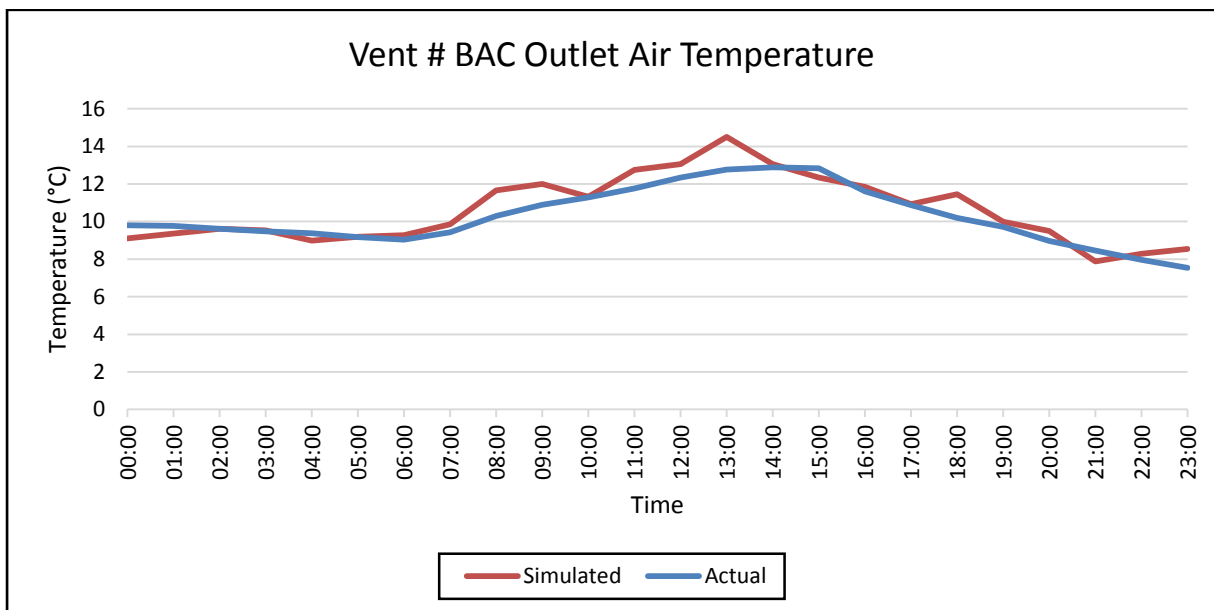


**Figure 66: Vent BAC outlet air temperature verification – Mine D**

# Appendix C: Case Study 2 development and optimisation

## 1.1 Identifying load reduction potential

### 1.1.1 Electrical power usage

The electrical power usage profile for Mine R was compiled with three months' pre-implementation data. The electrical power profile can be seen in Figure 67.
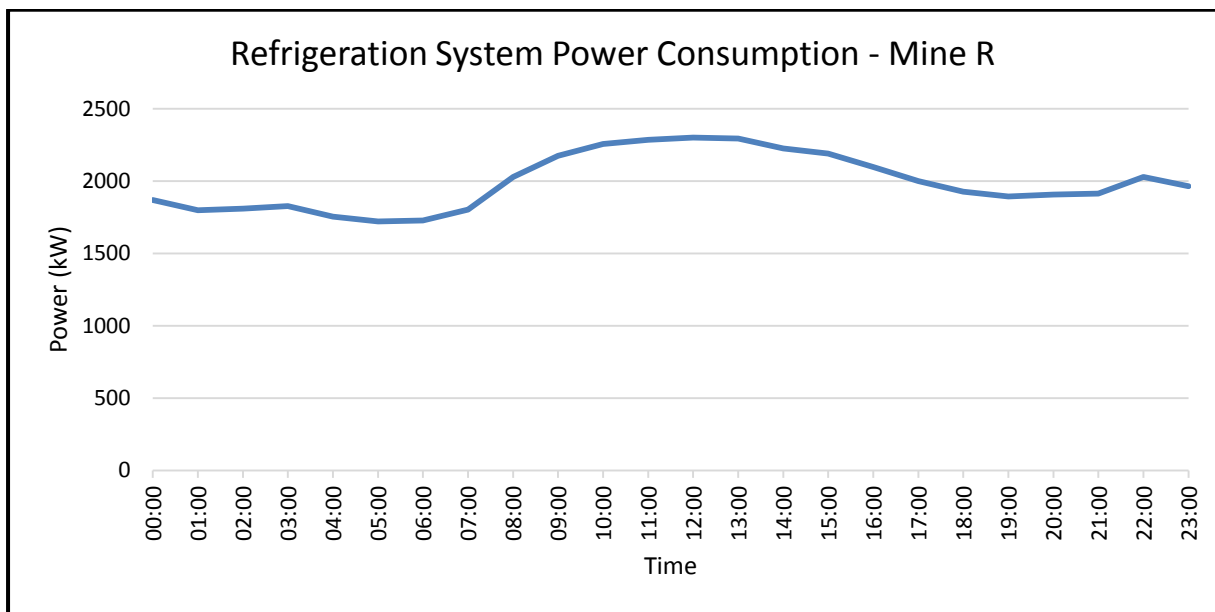


**Figure 67: Refrigeration system power consumption – Mine R**

From the average daily power consumption profile illustrated by Figure 67, it is evident that scope is present for a load shift on Mine R's refrigeration system. The evening peak to average power ratio supports this finding.

**Equation 29: Evening peak to average ratio – Mine R**

$$Ratio = \frac{\frac{\sum Evening\ Peak\ Energy\ Usage}{2}}{\frac{\sum Total\ Energy\ Usage}{24}}$$

$$Ratio = \frac{1909\ [kW]}{1991\ [kW]}$$

$$Ratio = 0.96\ [-]$$

### 1.1.2 Listing major components and data collection

Table 20 indicates the major components of Mine R's refrigeration system. The detailed component characteristic tables for both mines are available in Appendix A.

**Table 20: Major components in refrigeration system – Mine R**

| Component | Quantity |
|---|---|
| Fridge plant | 3 |
| Evaporator pumps | 3 |
| Condenser pumps | 3 |
| Pre-cooling transfer pumps | 2 |
| BAC transfer pumps | 2 |
| Pre-cooling fans | 2 |
| BAC fans | 2 |
| Condenser cooling fans | 12 |
| Dams (excluding sump dams) | 3 |
| Isolation valves | 1 |

### 1.1.3 Refrigeration system layout and operation

Figure 68 indicates the layout of Mine R's refrigeration system. Normal operating conditions consist of running two chillers, two evaporator pumps and two condenser pumps during the summer months. Six condenser cooling towers and both BAC fans are used as well. During the winter months Mine R switches off their entire refrigeration system.
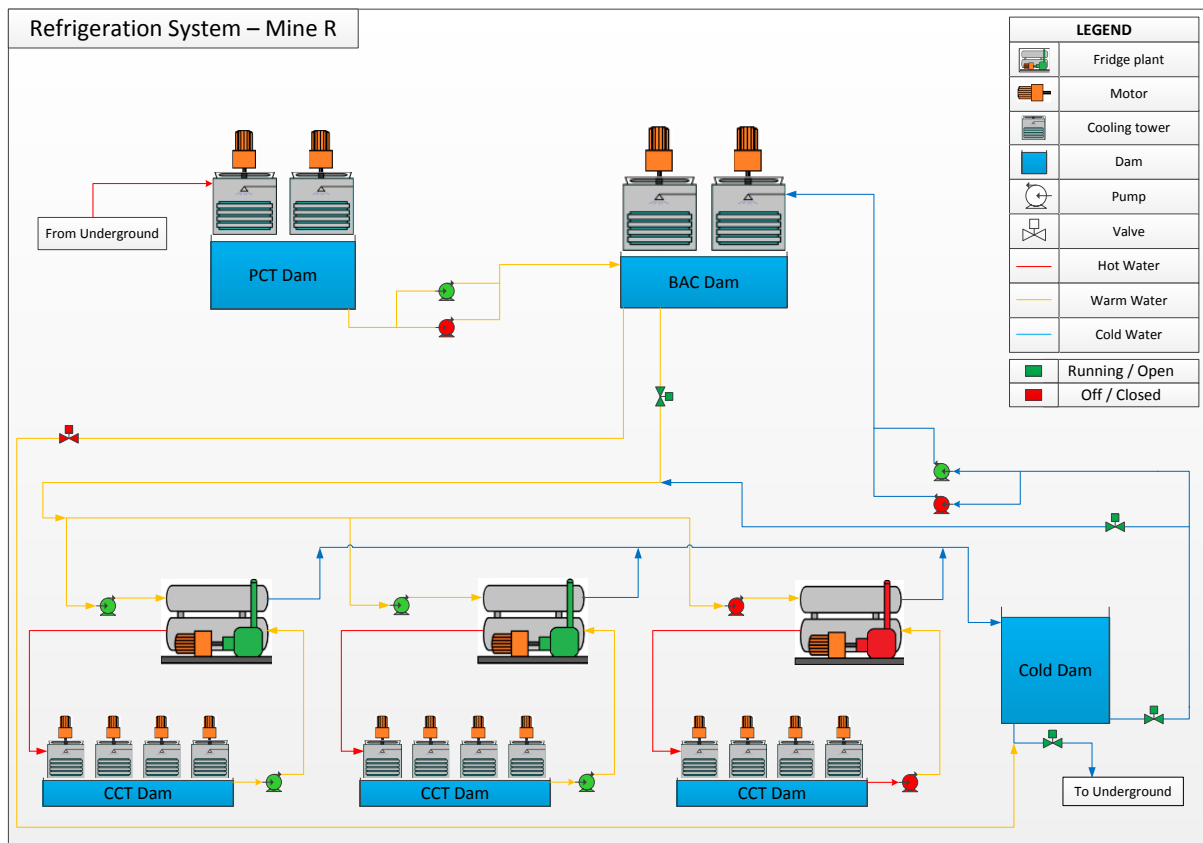
**Figure 68: Normal summer operating layout – Mine R**

### 1.1.4 System constraints

During the investigation the following constraints were identified at Mine R:

- Cold water storage capacity
- Lack of automated isolation valves
- Underground environmental temperature
- BAC fan start-up issues

Table 21 discusses the risk associated with these constraints as well as the mitigation for each constraint.

**Table 21: Refrigeration system constraints – Mine R**

| Constraints | Risk | Mitigation |
|---|---|---|
| Cold water storage capacity | Cold water storage dam level decreases when chillers and evaporator pumps are switched off. | Monitor dam level to ensure it remains above 60% during load shift. |
| Lack of automated isolation valves | Cold water cannot be isolated from warmer water automatically. | Manually close off isolation valve with each load shift. |
| Underground environmental temperature | Underground temperatures may increase to unsafe levels during load shift. | Constantly monitor underground temperatures and start refrigeration system if unsafe levels are reached. |
| BAC fan start-up problems | Fans suffer from excess vibration when started. | Remove BAC fans from control strategy due to risk of breakdown. |

## 1.2 Developing baselines and adjustment models

### 1.2.1 Electrical power baselines and adjustment

Figure 69 shows the average weekday electrical power baseline for Mine R during summer months. The baseline was approved by an independent M&V team. As discussed, SLA will be conducted due to the dynamic nature of Mine R's refrigeration system power consumption.
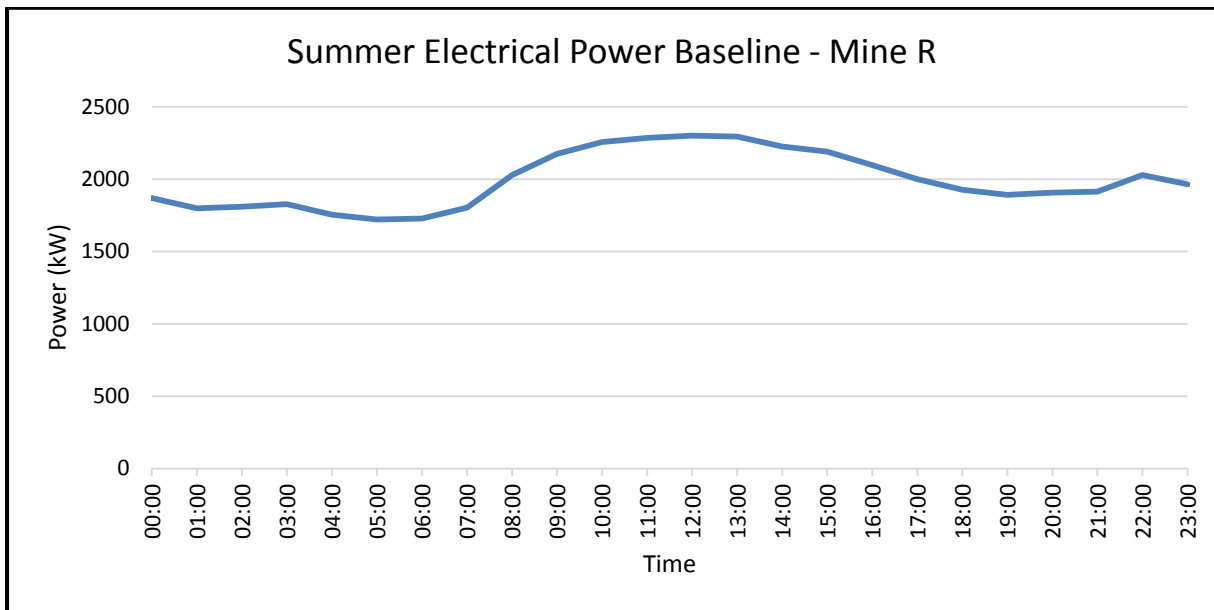
**Figure 69: Electrical power baseline – Mine R**

## 1.2.2 Operational baselines

Table 22 lists the four most important KPIs and the respective minimum and maximum for daily average parameters. The identified limits for the KPIs remain constant during summer and winter months.

**Table 22: Operational baseline – Mine R**

| KPI | Minimum | Maximum |
|---|---|---|
| Cold water storage level | 60% | 100% |
| Cold water storage temperature | - | 6 °C |
| BAC air temperature sent underground | - | 12 °C |
| Underground ambient temperature (dry-bulb) | - | 32 °C |

## 1.3 Developing a load shift control strategy

### 1.3.1 Developing the control strategy

The control strategy for Mine R can be seen in Table 23, indicating the operating status of the refrigeration components during the peak period. The evaporator and BAC transfer pumps were kept running during peak periods to prevent the BAC dam from overflowing.

**Table 23: Load shift control strategy – Mine R**

| Installed quantity | Component | Normal operating status | Evening peak period status | Shutdown sequence |
|---|---|---|---|---|
| 3 | Fridge plants | 2 | 0 | 1 |
| 3 | Evaporator pumps | 2 | 2 | - |
| 3 | Condenser pumps | 2 | 0 | 3a |
| 12 | Condenser cooling tower fans | 6 | 0 | 3b |
| 2 | BAC transfer pumps | 1 | 1 | 2 |
| 2 | BAC fans | 2 | 2 | - |

### 1.3.2 Simulation verification

The simulation for Mine R's refrigeration system was verified against actual data for a normal operating day. Table 24 below compares the daily average value of KPIs between the actual data and simulated results. The 24 hour profiles are also compared below for each of the variables listed in Table 24.

**Table 24: Simulation verification – Mine R**

| Comparison | Simulated | Actual | Percentage Error |
|---|---|---|---|
| Power consumption | 2315 [kW] | 2359 [kW] | 1.91 [%] |
| Cold dam level | 86.61 [%] | 86.54 [%] | 0.09 [%] |
| Cold dam temperature | 4.90 [°C] | 4.81 [°C] | 1.22 [%] |
| BAC outlet air temperature | 9.81 [°C] | 9.97 [°C] | 1.64 [%] |
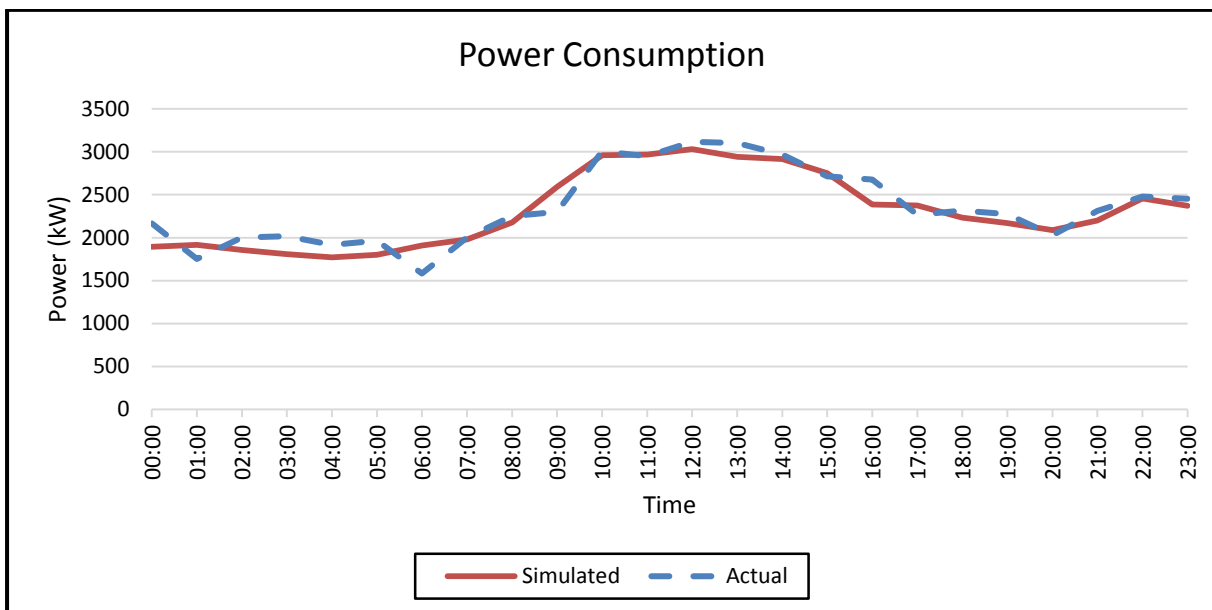


**Figure 70: Power consumption verification – Mine R**
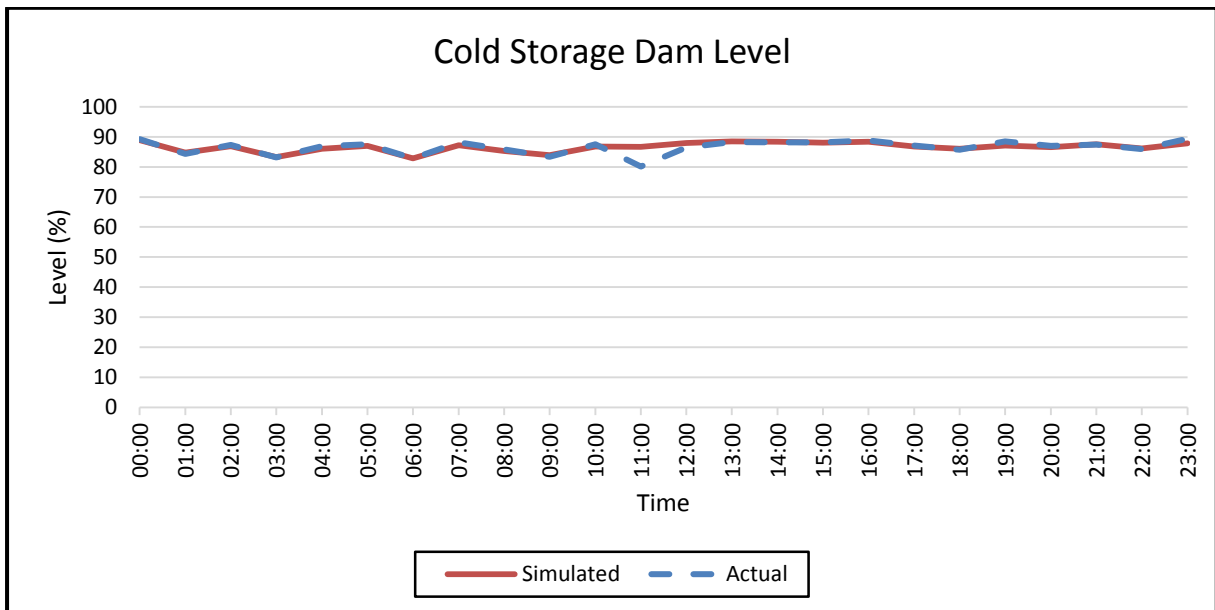
**Figure 71: Cold storage dam level verification – Mine R**
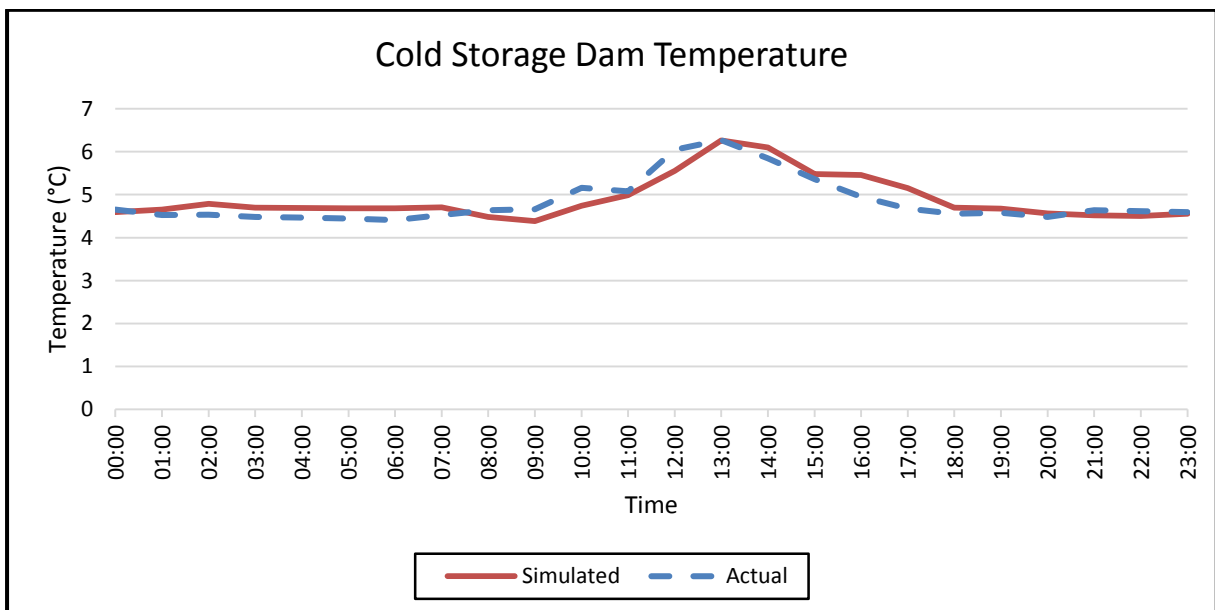


**Figure 72: Cold storage dam temperature verification – Mine R**
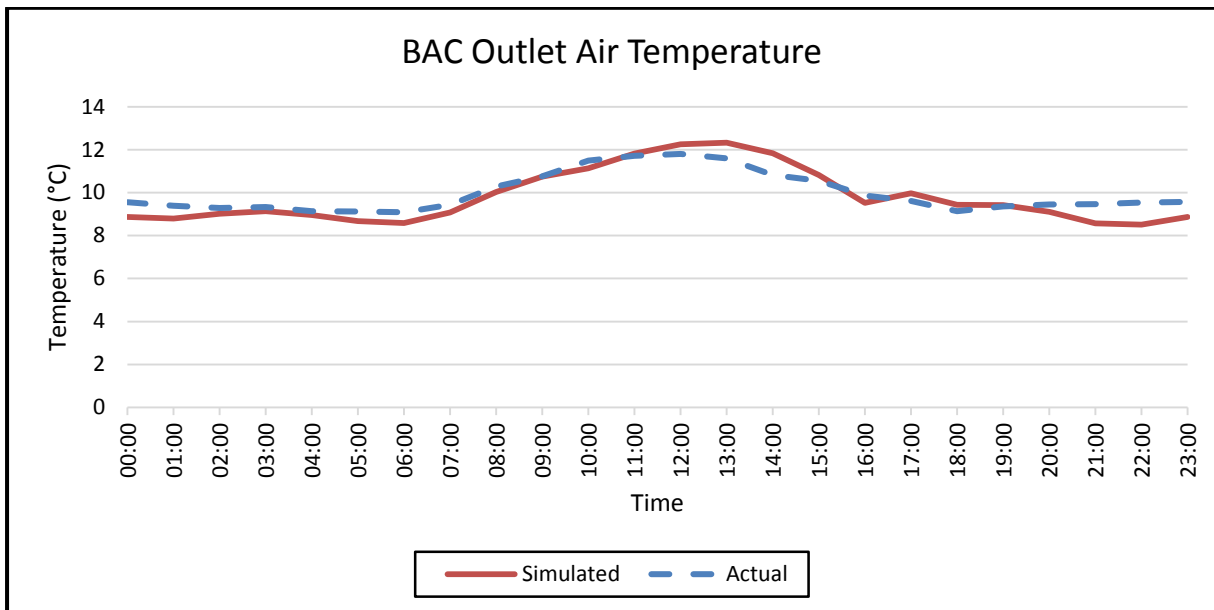
**Figure 73: BAC outlet air temperature verification – Mine R**

### 1.3.3  Simulating the control strategy

The average error between the simulated and actual KPIs was 1.2%. After verification deemed the simulation accurate, the developed control strategy was simulated. The simulation results in terms of electric power and KPIs are provided as follows:

Figure 74 shows the proposed power consumption of Mine R's refrigeration system. The chiller water outlet temperature was set at 4 °C. An average load shift of 1.78 MW was achieved through simulation.
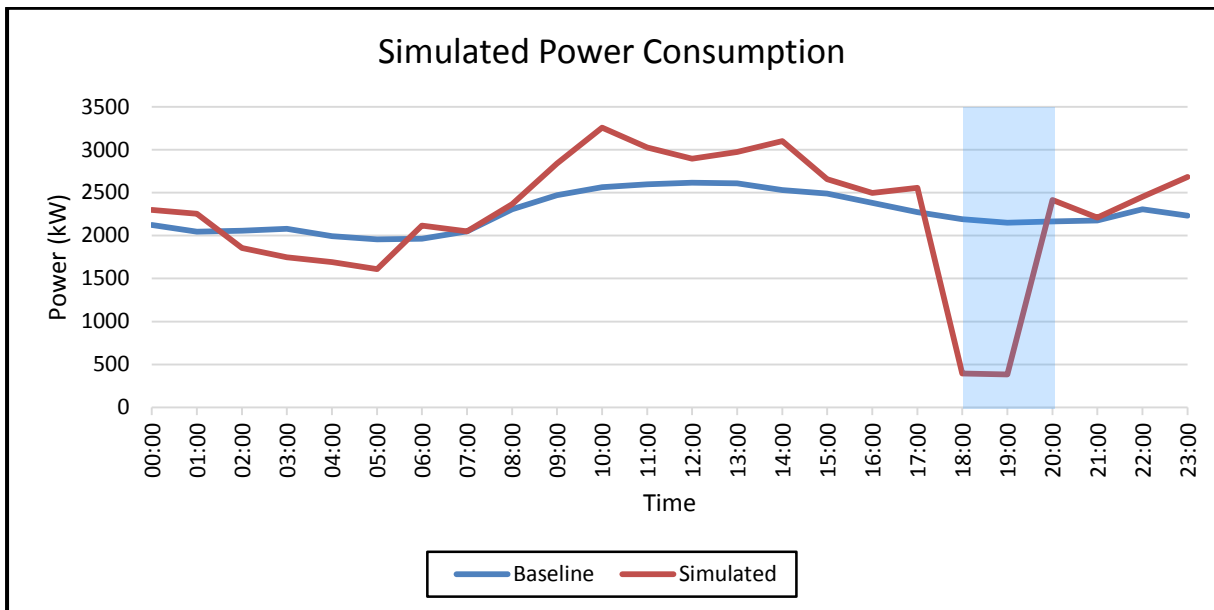
**Figure 74: Simulated power consumption – Mine R**

The average simulated cold storage dam level remained above 75% at all times during the simulated period as can be seen in Figure 75.
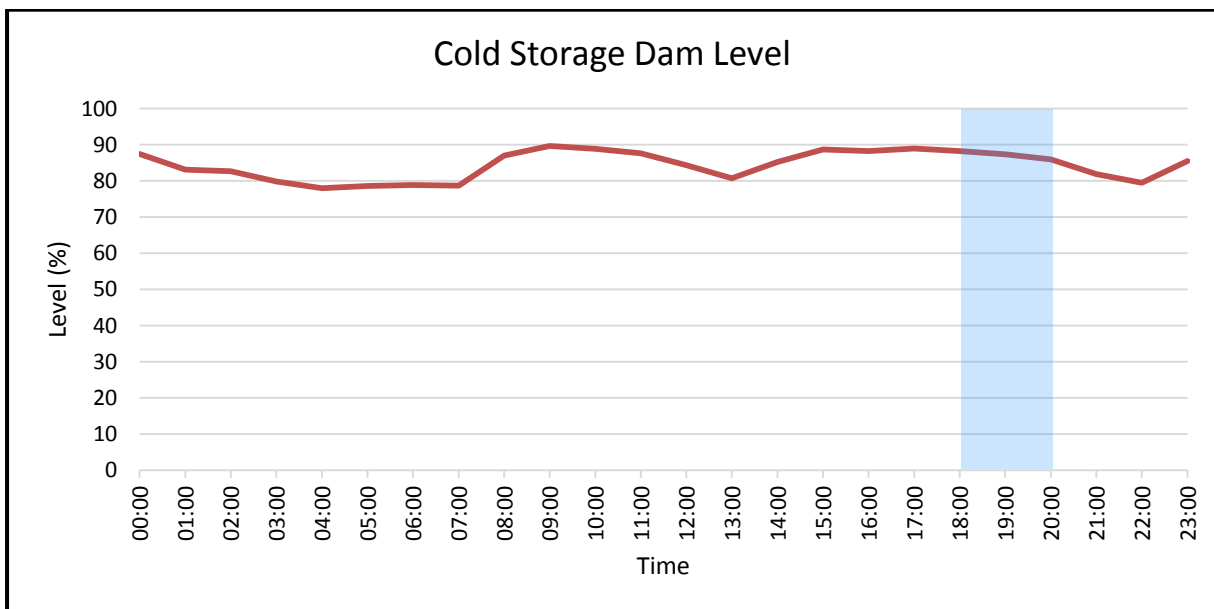


**Figure 75: Cold storage dam level– Mine R**

Figure 76 shows that the simulated cold storage dam temperature increased rapidly during the load shift. The increase in cold dam temperature during evening peak period is due to the evaporator and BAC transfer pumps being left running to keep the BAC dam from overflowing. As indicated by Figure 76, the average cold dam storage temperature is recovered within four hours after the load shift.
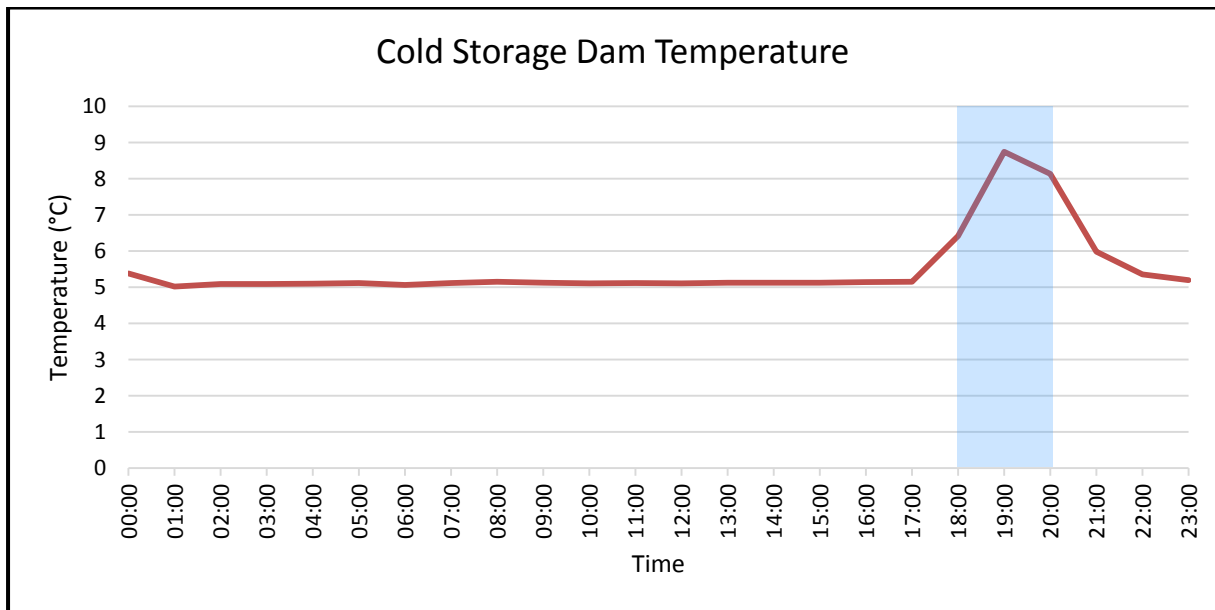


**Figure 76: Cold storage dam temperature – Mine R**

Figure 77 illustrates that the BAC outlet air temperature increases during the load shift. This is due to the BAC water inlet temperature increasing during this time. This temperature increase is due to the evaporator and BAC transfer pumps left running during peak periods. As indicated by Figure 77, the average BAC outlet air temperature is recovered within three hours after the load shift.
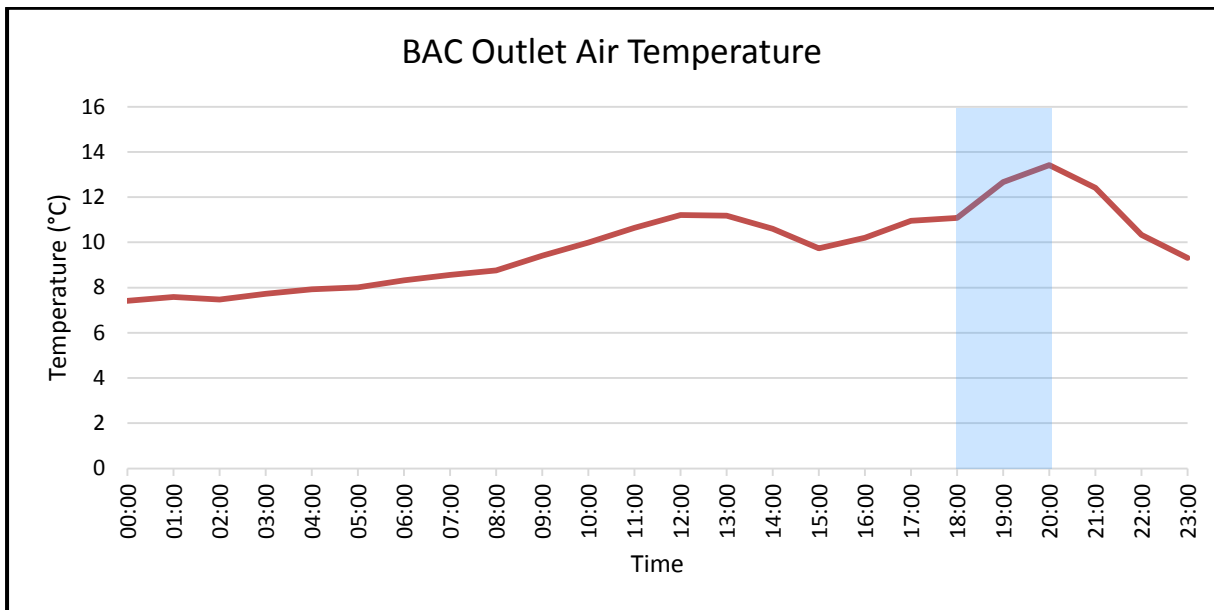
**Figure 77: BAC outlet air temperature – Mine R**

### 1.3.4  Validating the control strategy

The simulated strategy was implemented on the refrigeration system for validation. The graphs below compare the power consumption and various KPIs from the simulation with the actual test data. Table 25 provides an average comparison of the same data.

**Table 25: Control strategy validation – Mine R**

| Comparison | Simulated | Test | Percentage Error |
|---|---|---|---|
| Power consumption | 2264 [kW] | 2182 [kW] | 3.59 [%] |
| Load shift | 1780 [kW] | 1700 [kW] | 4.47 [%] |
| Cold dam level | 84.40 [%] | 84.13 [%] | 0.32 [%] |
| Cold dam temperature | 5.51 [°C] | 5.35 [°C] | 2.73 [%] |
| BAC outlet air temperature | 9.79 [°C] | 10.01 [°C] | 2.30 [%] |

The cold dam temperature increases above the maximum limit of 6 °C during the load shift, negatively impacting the sustainability of the load shift. However, as indicated by Figure 80, the temperature of the cold dam water recovers within two hours after the load shift.

Figure 81 shows the BAC air temperature sent underground. The simulation indicated that the maximum allowable temperature was reached during the load shift, but recovered within an hour after the load shift. The actual test results indicate the temperature was slightly lower, not exceeding the maximum limit. This is due to the simulation not accounting for the exact weather conditions of the specific test day.

The average daily profiles of the comparisons summarised in Table 25 are provided as follows:
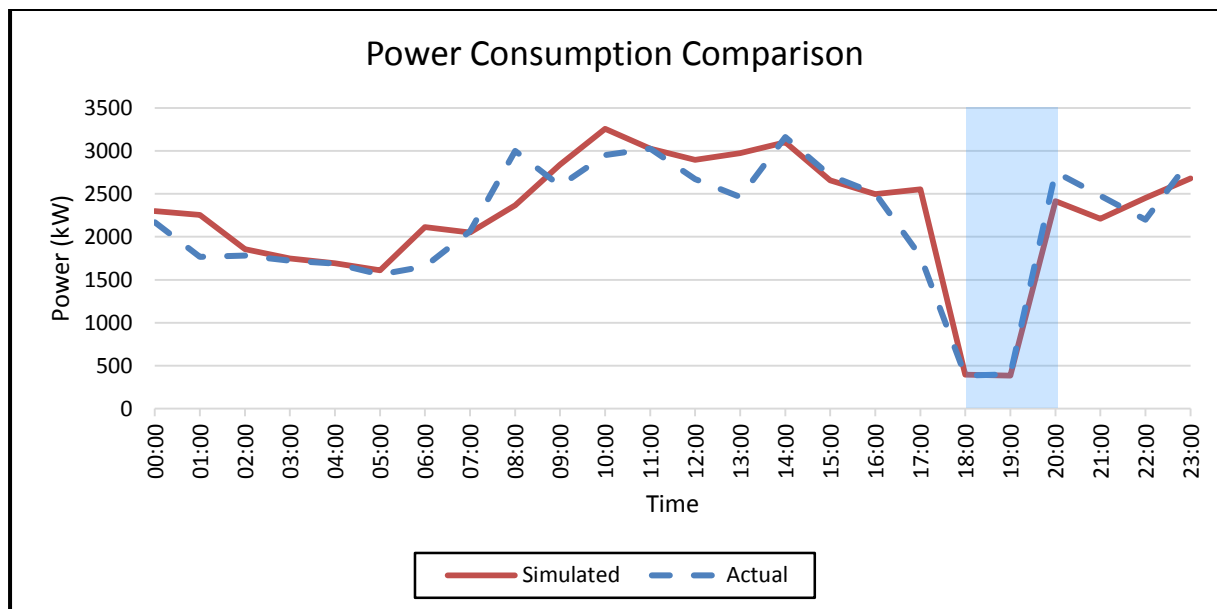


**Figure 78: Power consumption comparison – Mine R**
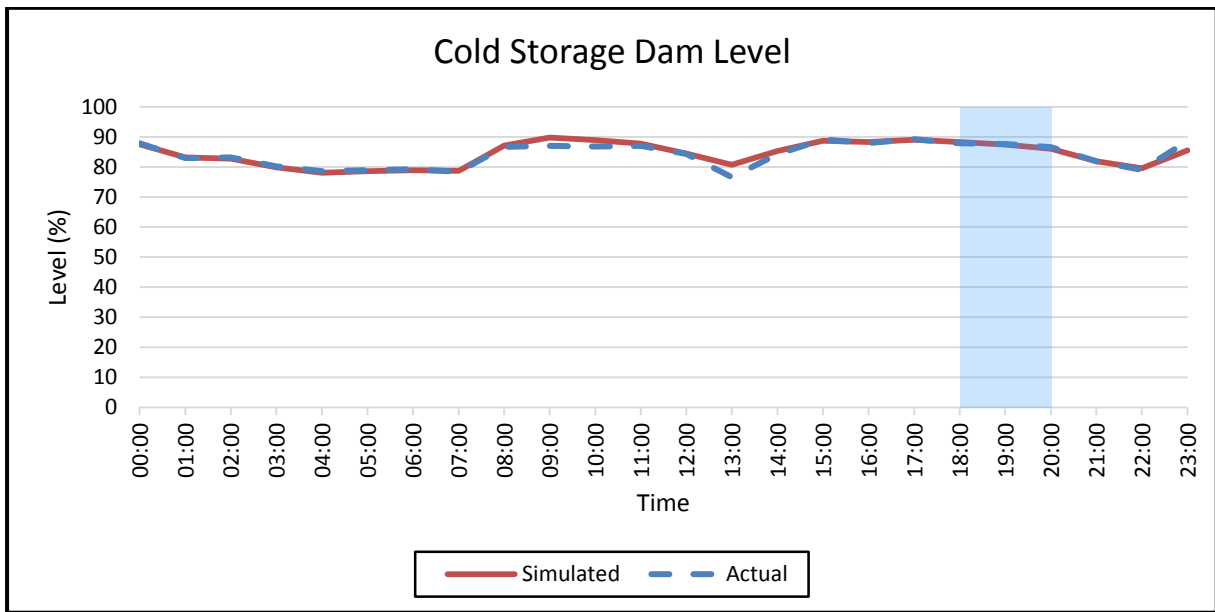
**Figure 79: Cold storage dam level comparison – Mine R**
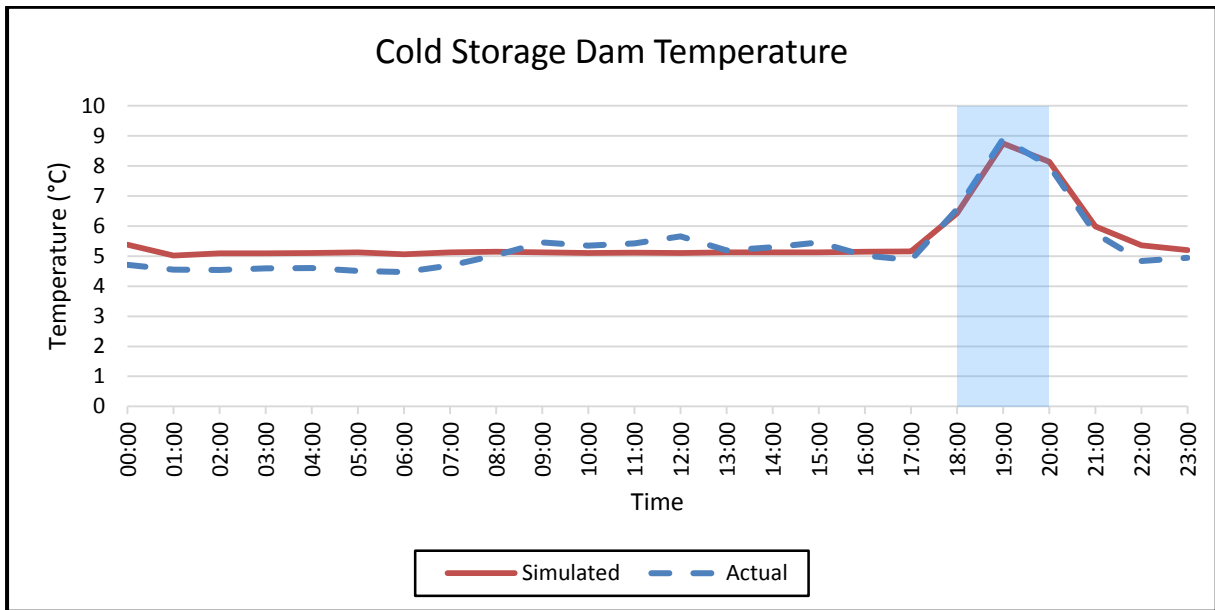


**Figure 80: Cold storage dam temperature comparison – Mine R**
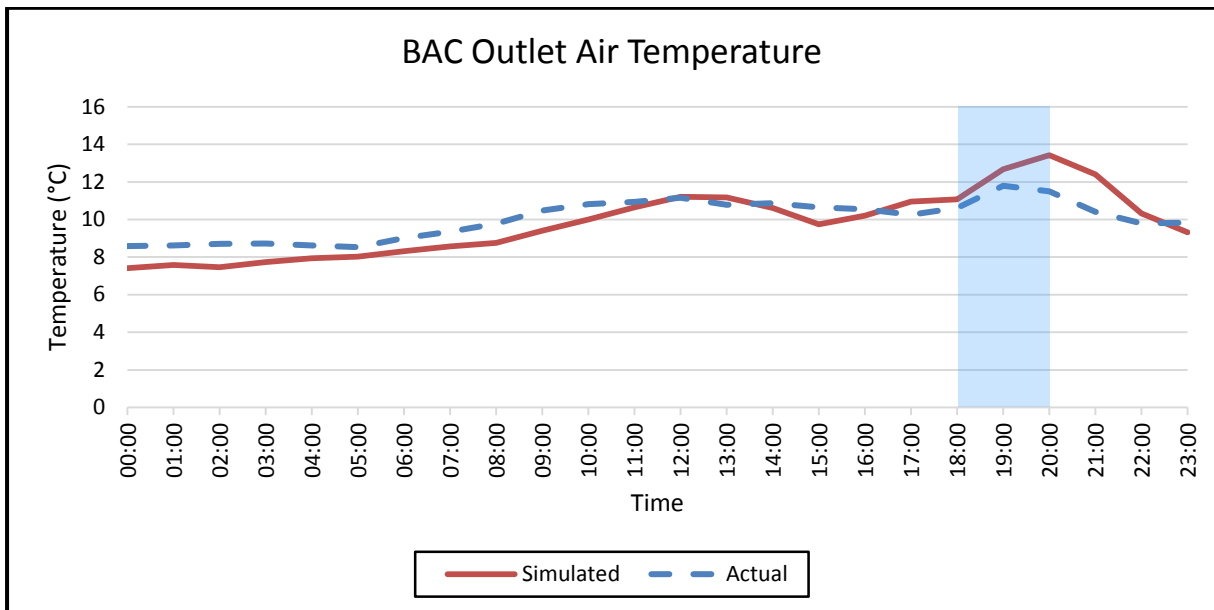
**Figure 81: BAC outlet air temperature comparison – Mine R**

The temperature at the 2010 level (2010L) station was monitored during the test. The 2010L station was chosen as it is the deepest level on the mine that had real-time temperature monitoring present at the time of testing. From Figure 82, the dry-bulb temperature remained constant and the load shift had almost no impact on the underground temperature.
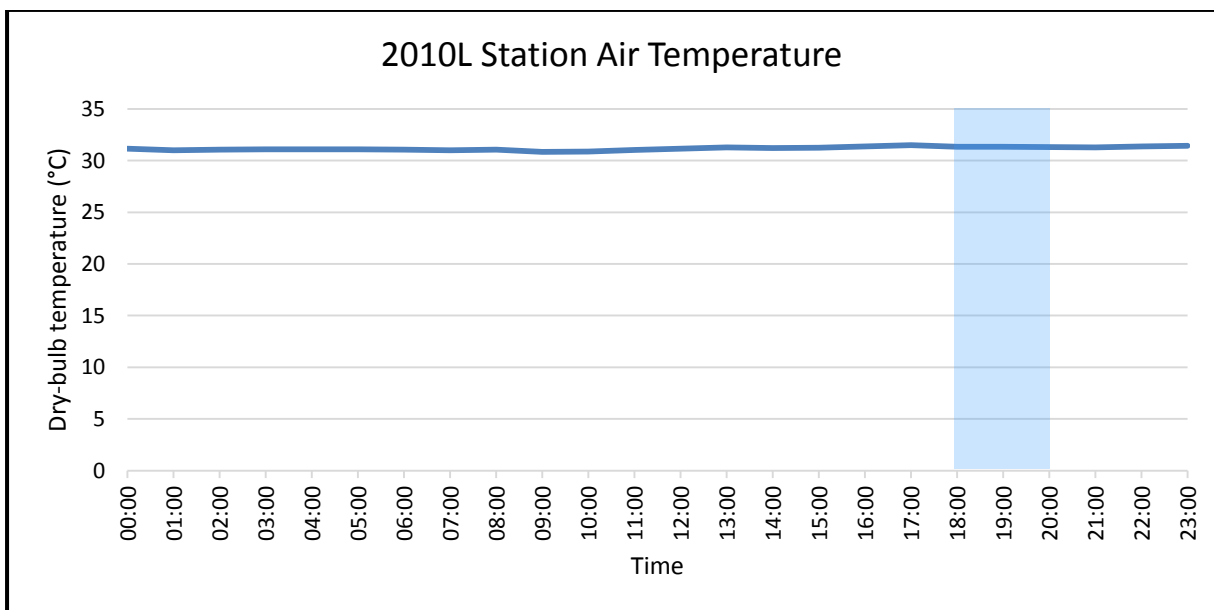


**Figure 82: 2010L Station dry-bulb air temperature – Mine R**

The simulation model was proved accurate and subsequently the control strategy was optimised. The next section discusses the results obtained through optimisation.

## 1.4 Optimising the load shift control strategy

### 1.4.1 Developing the optimised control strategy

Optimising the control strategy entails closing the chill dam isolation valve during the load shift. This will enable additional pumps to be shut down and cold water to be isolated from warmer water. Figure 83 indicates the position of the cold dam isolation valve within the refrigeration system.
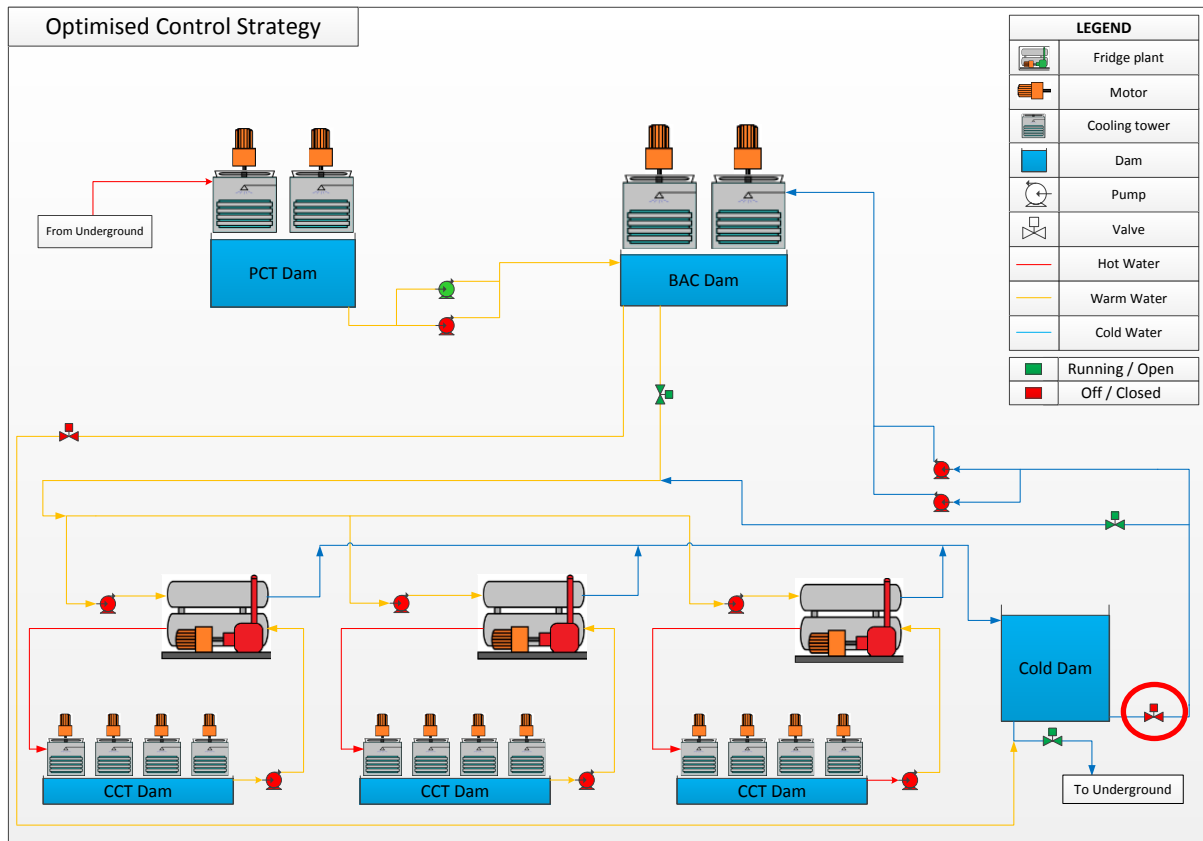


**Figure 83: Optimised load shift control strategy – Mine R**

Table 26 indicates the optimised control strategy for Mine R's refrigeration system.

**Table 26: Optimised load shift control strategy – Mine R**

| Installed quantity | Component | Normal operating status | Evening peak period status | Shutdown sequence |
|:---:|:---:|:---:|:---:|:---:|
| 3 | Fridge plants | 2 | 0 | 1 |
| 3 | Evaporator pumps | 2 | 0 | 2 |
| 3 | Condenser pumps | 2 | 0 | 4a |
| 12 | Condenser cooling tower fans | 6 | 0 | 4b |
| 2 | BAC transfer pumps | 1 | 0 | 3 |
| 2 | BAC fans | 2 | 2 | - |

### 1.4.2 Simulating the optimised control strategy

Figure 84 shows the simulated power consumption for the optimised control strategy on Mine R's refrigeration system. The simulation proved that a potential load shift of 1.94 MW is possible.
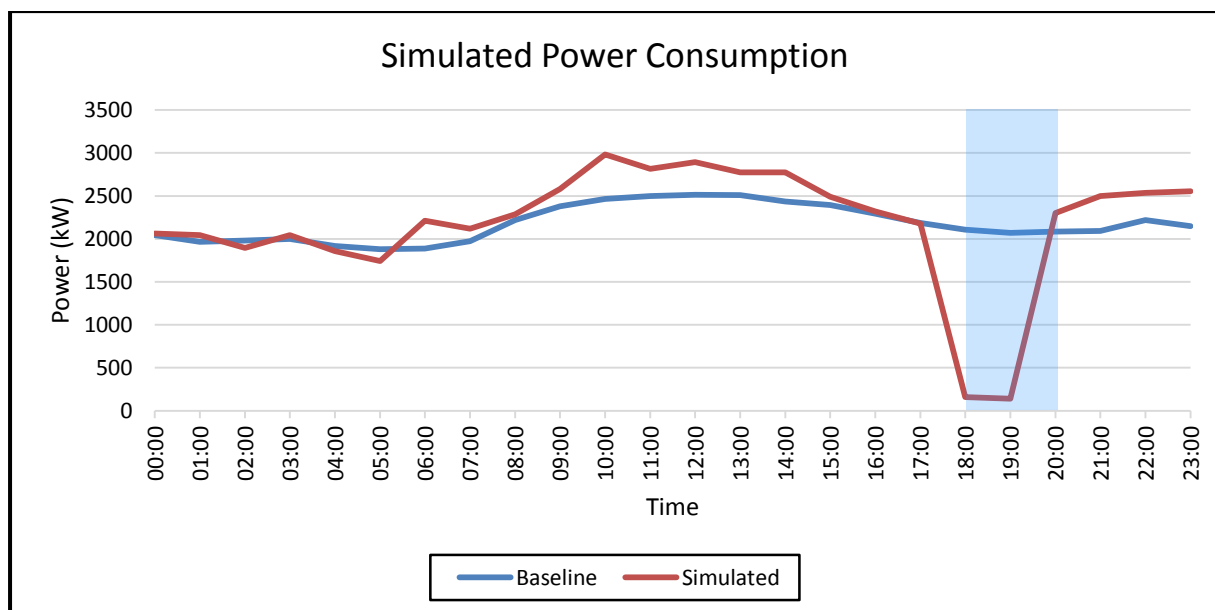


**Figure 84: Simulated power consumption for the optimised control strategy – Mine R**

Figure 85 indicates the average simulated cold storage dam level for the optimised control strategy. The dam level remains above 80% throughout the simulation.
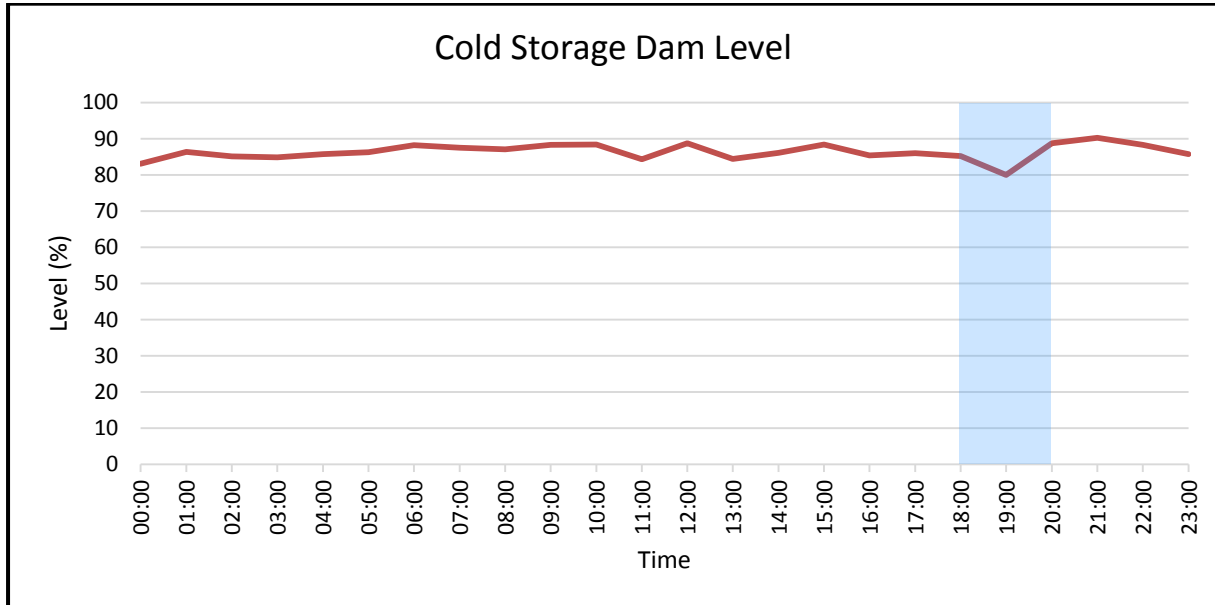


**Figure 85: Cold storage dam level – Mine R**

Figure 86 shows that the simulated cold storage dam temperature only increased by 2 °C, and recovered within four hours after the load shift. Isolating the cold dam from the BAC dam ensures that the cold and warm water do not mix, improving the sustainability of the load shift.
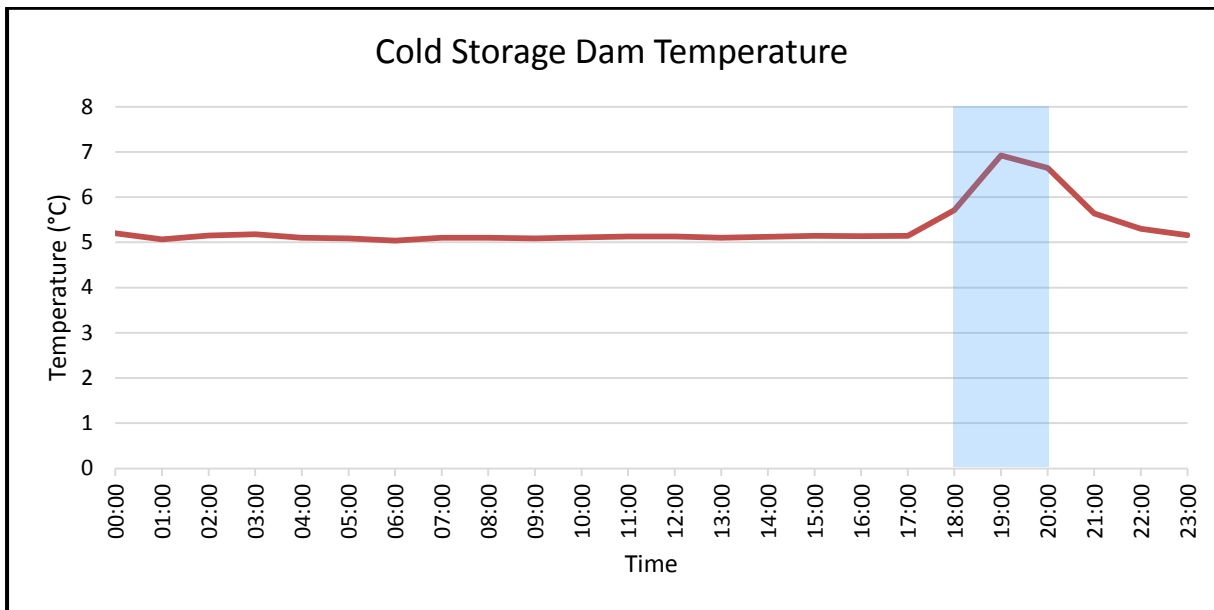
**Figure 86: Cold storage dam temperature – Mine R**

Figure 87 indicates the simulated temperature increase during peak period for the optimised strategy. This is due to the water flow to the BAC being stopped during evening peak period. The temperature is recovered within two hours after the load shift. This can be attributed to the lower cold storage dam temperature achieved by isolating it from warmer water.
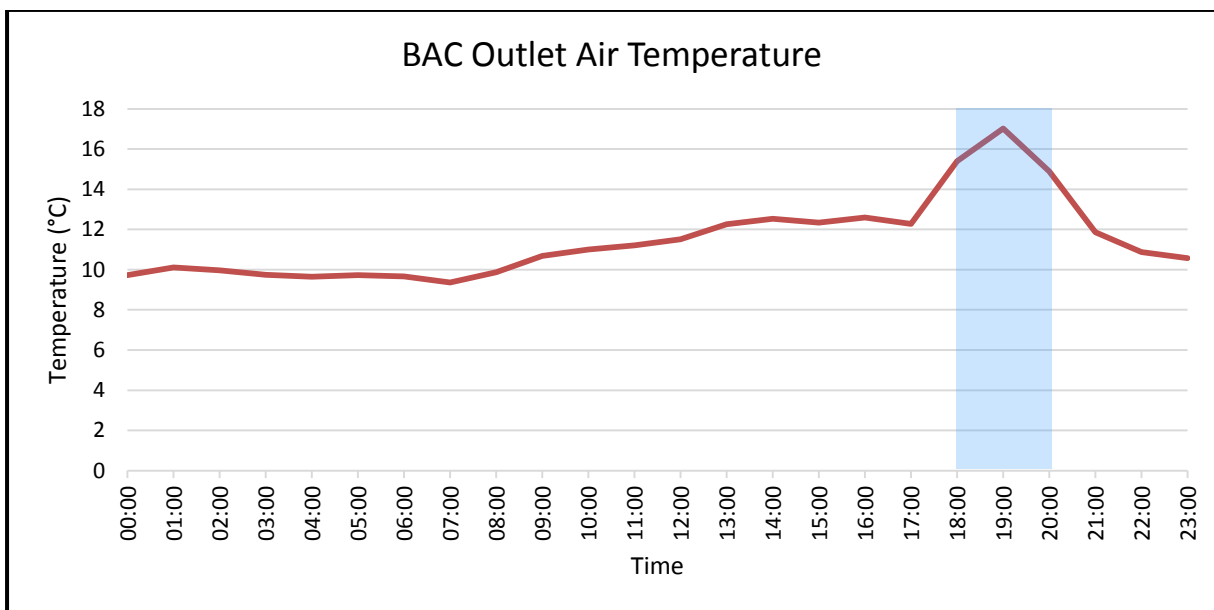


**Figure 87: BAC outlet air temperature – Mine R**

### 1.4.3 Validating the optimised control strategy

Table 27 below compares the daily average value of critical variables between the actual data and simulated results. The 24 hour profiles are also compared below for each of the variables listed in Table 27.

**Table 27: Optimised control strategy validation – Mine R**

| Comparison | Simulated | Test | Percentage Error |
|---|---|---|---|
| Power consumption | 2258 [kW] | 2217 [kW] | 1.80 [%] |
| Load shift | 1939 [kW] | 1938 [kW] | 0.05 [%] |
| Cold dam level | 86.38 [%] | 86.02 [%] | 0.41 [%] |
| Cold dam temperature | 5.31 [°C] | 5.15 [°C] | 3.09 [%] |
| BAC outlet air temperature | 11.45 [°C] | 10.91 [°C] | 4.72 [%] |

The average daily profiles of the comparisons summarised in Table 27 are provided as follows:
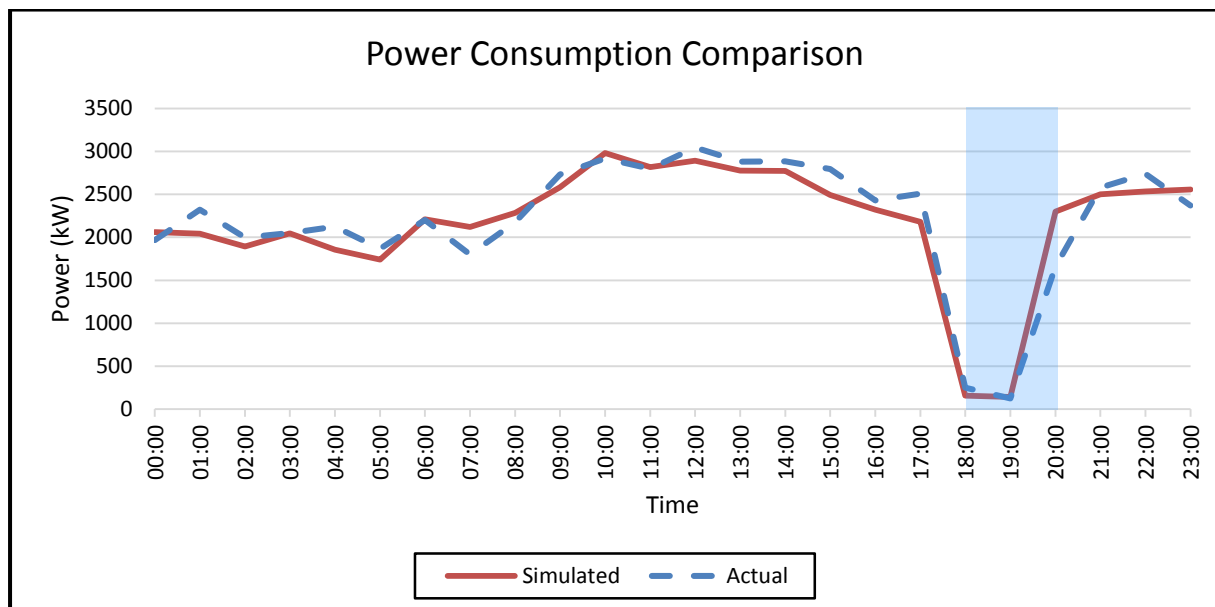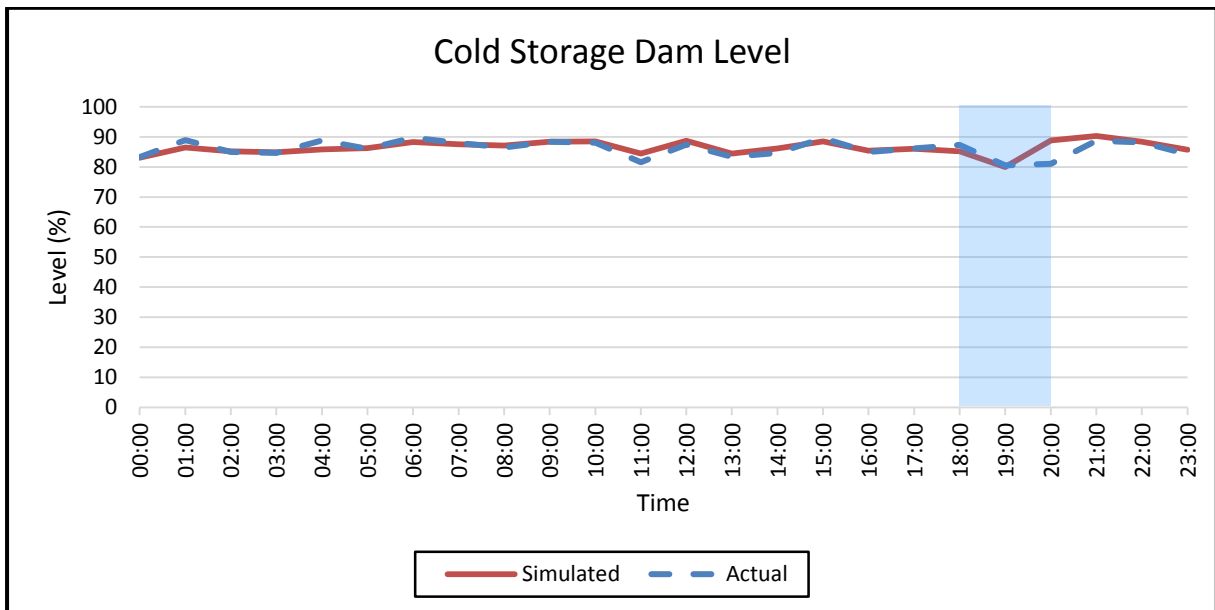


**Figure 88: Power consumption comparison – Mine R**

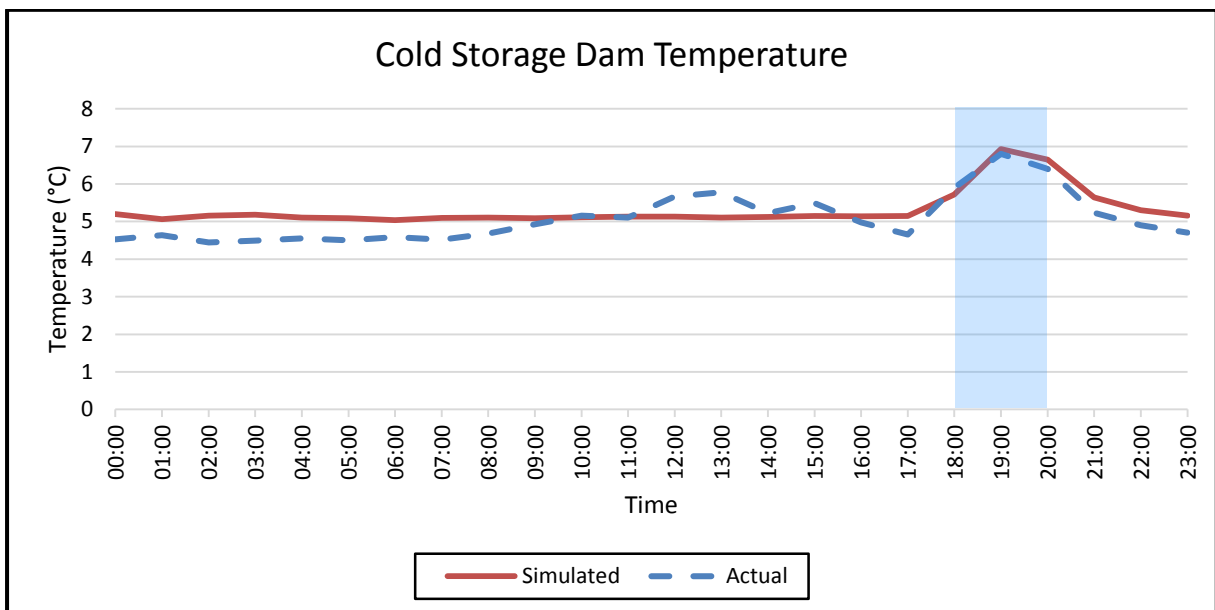**Figure 89: Cold storage dam level comparison – Mine R**



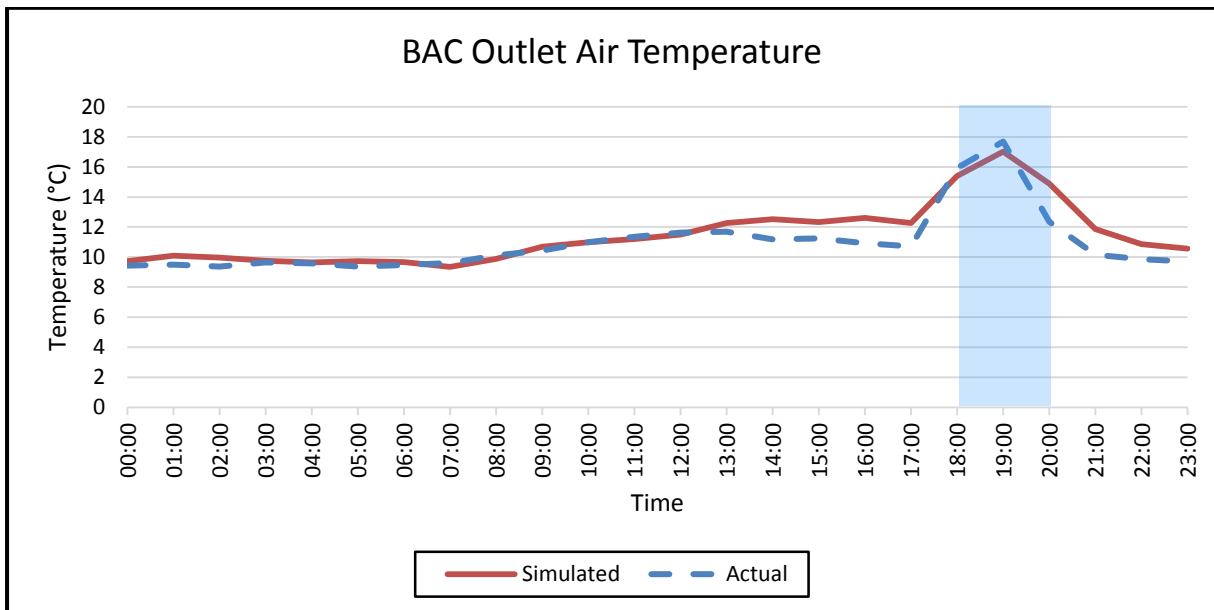**Figure 90: Cold storage dam temperature comparison – Mine R**

**Figure 91: BAC outlet air temperature comparison – Mine R**

The temperature at the 2010L station was monitored during the test. From Figure 92, the dry-bulb temperature remained constant and the load shift had almost no impact on the underground temperature.
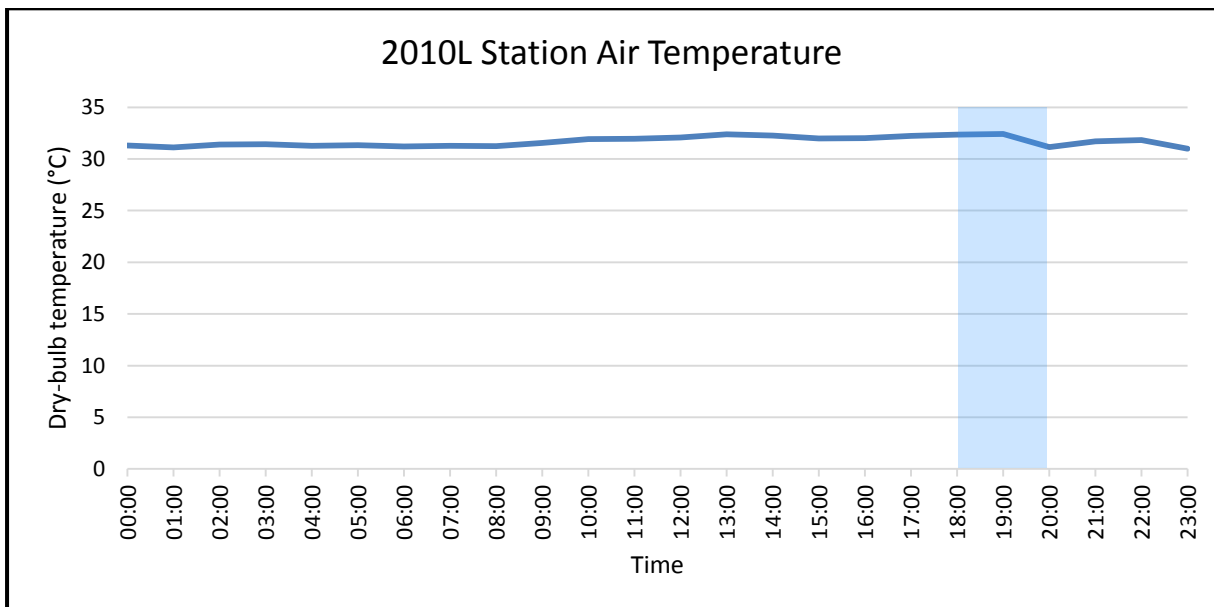


**Figure 92: 2010L Station dry-bulb air temperature – Mine R**

Figure 89 to Figure 92 show that the optimised control strategy had no lasting impact on the operation of Mine R's refrigeration system.

# Appendix D: Case study 2 implementation

Implementation consisted of simulating the optimised control strategy and validating it with tests. Mine personnel were trained to implement the optimised control strategy on a daily basis. This resulted in the optimised strategy to be implemented within one month. Only existing infrastructure was utilised and no implementation costs were incurred.

Figure 93 illustrates the baseline and post-implementation power profile, averaged over a period of nine months. The presence of the evening peak period load shift indicates the project was implemented sustainably thus far. Cost savings based on the evening peak period load shift shown in Figure 93 results in R 215 000 annually.
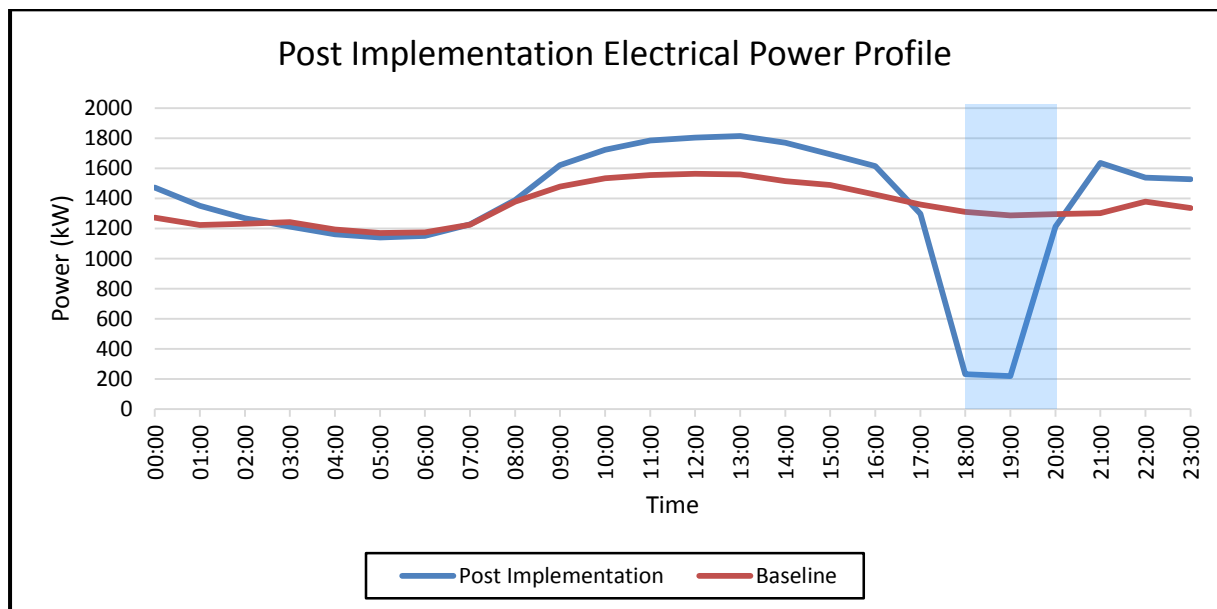


**Figure 93: Post implementation power profile – Mine R**

Table 28 compares the predicted and achieved (post-implementation) summer evening peak period load shift and annual cost savings. The predicted average summer load shift correlates closely with the achieved reduction with an average error of approximately 3%. The average annual cost savings realised by the evening peak period load shift falls within an approximate error of 8%.

**Table 28: Implementation validation – Mine R**

| Predicted summer evening peak load shift | Achieved summer evening peak load shift |
|---|---|
| 1.94 MW | 2.00 MW |
| **Predicted annual cost savings** | **Achieved annual cost savings\*** |
| R 232 000 | R 215 000 |

\*Based on nine months post-implementation data