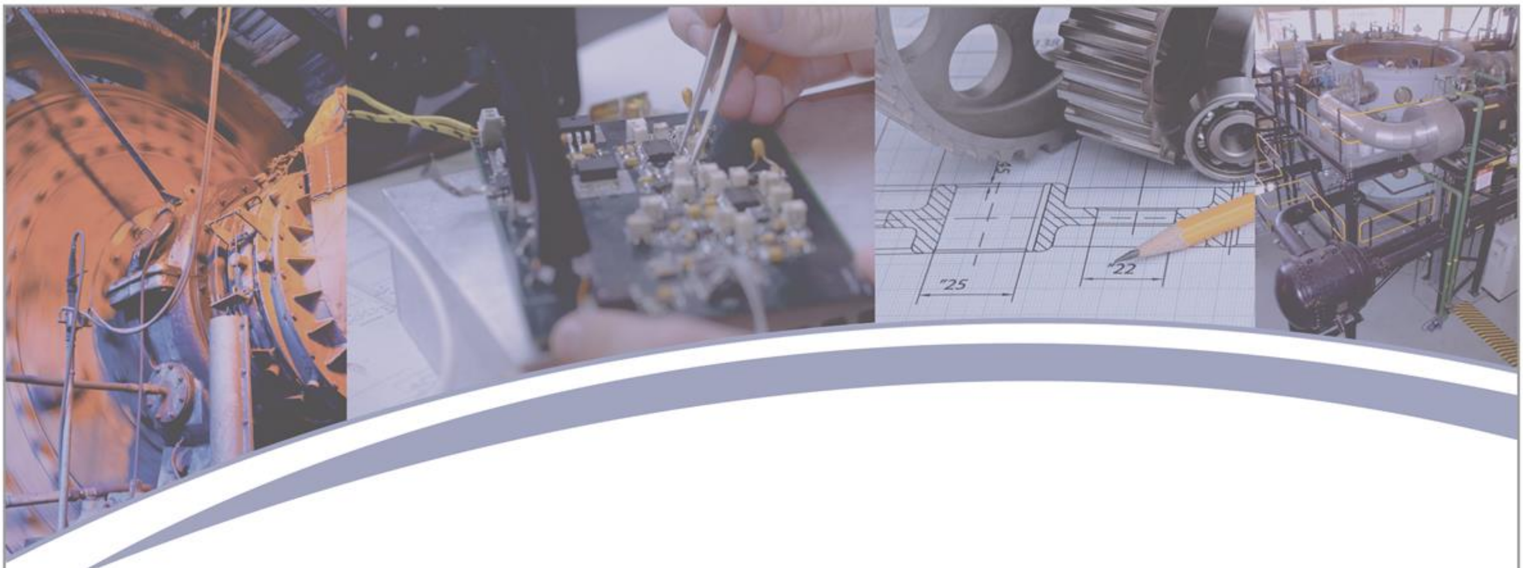

# Cost effective management strategies for platinum mine cooling systems


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

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November 2015


NORTH-WEST UNIVERSITY
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# Abstract


| | |
|---|---|
| Title: | Cost effective management strategies for platinum mine cooling systems |
| Author: | Janco Vermeulen |
| Promoter: | Dr JF van Rensburg |
| School: | Mechanical Engineering |
| Faculty: | Engineering |
| Degree: | Master of Engineering (Mechanical) |

Due to economic reasons, the demand for platinum has decreased in countries that previously consumed it in large quantities. Electricity, diesel fuel, reinforced steel, wages and salaries play a big role in the rising costs within the South African platinum mining sector. Amongst these expenditures, electricity costs increased most. Therefore, platinum mining companies have to minimise costs where possible. Because refrigeration systems are one of the systems that consume the most electricity on a platinum mine, energy saving strategies are necessary on these systems.

Incentive programmes provided crucial financial support for implementing energy saving projects to save possible electricity costs. Eskom's Integrated Demand Management (IDM) funding has been restricted due to financial constraints. Therefore, a need exists for ESCos to implement cost effective strategies.

Investigations were done on existing load management strategies that included load shifting, load clipping and energy efficiency through control strategies. In this study, a mine was reviewed by evaluating the layout, system specification, cooling requirements and operations. A simulation model was developed together with a cost effective control and monitoring strategy. The strategy was simulated on a mine and the results proved that the strategy would be feasible

The strategy was implemented on the cooling system of a mine by using existing infrastructure and labour. Savings were achieved by switching off the main energy-consuming components during Eskom's evening peak period (18:00–20:00). This helped the mine achieve energy savings and energy cost reduction without high implementation costs. The implementation period was short and no funding was required. An average demand reduction of 4 MW was achieved during tests. As a result, an estimated annual cost saving of R1.53 million was achieved by implementing this strategy.

The dissertation proves that manual control and monitoring can be done on platinum mine refrigeration systems. Although manual control and monitoring require low implementation costs, automated DSM projects are still more reliable and sustainable. Manual control and monitoring are short-term alternatives when the client or ESCo are not able to afford the implementation of automated DSM projects.

# Acknowledgements

I would like to thank:

- First of all, my Maker for blessing me with the opportunity to complete this study.
- HVAC International (Pty) Ltd and TEMM International (Pty) Ltd for providing me with the opportunity, support and funding to complete this study.
- Dr Deon Arndt for providing assistance and technical advice with the simulation model.
- Dr Johann van Rensburg, Dr Hendrik Brand, Dr Charl Cilliers, Dr Ruaan Pelzer and Dr Lodewyk van der Zee for their guidance and assistance during the study.
- My colleagues for their guidance and assistance with the case study project implementation.
- My friends, family and loved ones for their continued support.

I apologise if any sources or authors have been omitted. Please inform me so that I can rectify the omission.

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# Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| GW | Gigawatt | (GW) |
| kW | Kilowatt | (kW) |
| m | Meter | (m) |
| MW | Megawatt | (MW) |
| η | Efficiency | (%) |
| RH | Relative Humidity | (%) |
| W | Watt | (W) |
| °C | Temperature | (°C) |
| % | Percentage | (%) |

# Abbreviations

| | |
|---|---|
| BAC | Bulk Air Cooler |
| DSM | Demand Side Management |
| ESCo | Energy Service Company |
| GDP | Gross Domestic Productions |
| IDM | Integrated Demand Management |
| GDP | Gross Domestic Product |
| M&V | Measurement and Verification |
| PGM | Platinum Group Metals |
| PLC | Programmable Logic Controller |
| PTB | Process Toolbox |
| REMS | Real Time Energy Management System |
| SCADA | Supervisory Control and Data Acquisition |
| SD&L | Supplier Development and Localisation |
| TOU | Time-of-Use |
| VSD | Variable Speed Drive |
| WB | Wet Bulb |

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# Chapter 1. Introduction

*Escalating production costs are crippling the platinum industry*

## 1.1 Platinum industry challenges

### 1.1.1 Preamble

South Africa is one of the world's most prominent mining countries and is the leading producer of platinum group metals (PGM) [1]. The platinum industry is a major contributor to the South African economy [2]. By 2012, the platinum industry was South Africa's second-largest mineral export after gold, with an overall gross domestic production (GDP) contribution of 4.1% [3]. Even though the platinum mining industry is a leading contributor to South Africa's mining sector, the industry faces many challenges. These challenges are a combination of slowing global demand, lower productivity and escalating production costs [3].

### 1.1.2 Slowing global demand

The 2007/2008 international financial crisis caused a slowing global demand for PGM [3]. In 2007, the global demand was 8 270 ounces. The demand then decreased to a low of 6 795 ounces in 2009. After four years, the global platinum demand recuperated to 8 420 ounces in 2013 [4]. Therefore, as shown in Figure 1, the platinum demand took approximately six years to recover from the global financial crisis. This contributes to the challenges that the platinum industry faces today.

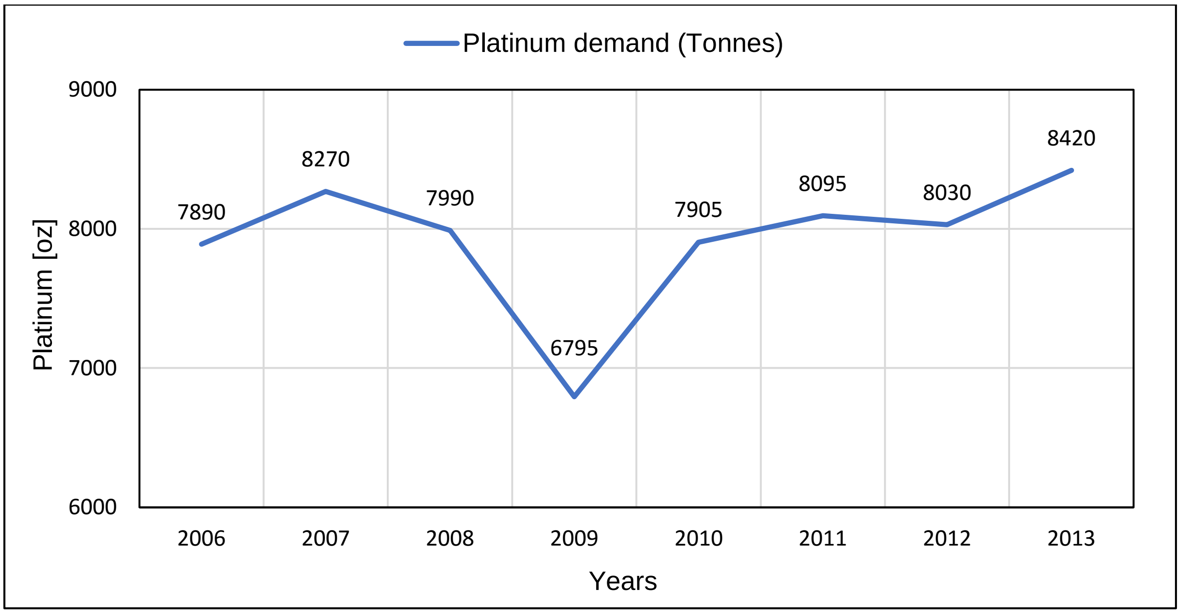


Figure 1: Total gross platinum demand, adapted from [4]

Although the demand for platinum recovered, the platinum price has been under financial pressure since the 2007/2008 crisis. As seen in Figure 2, the average platinum price was at an all-time high in 2008. After the price peak in 2008, the platinum price dropped quickly in late 2008 [4]. Although the platinum price improved after late 2008, a platinum reserve of more than 1 million ounces was gathered from 2009 to 2011. This led to an oversupply of platinum, which placed further pressure on the platinum price [3], [4].

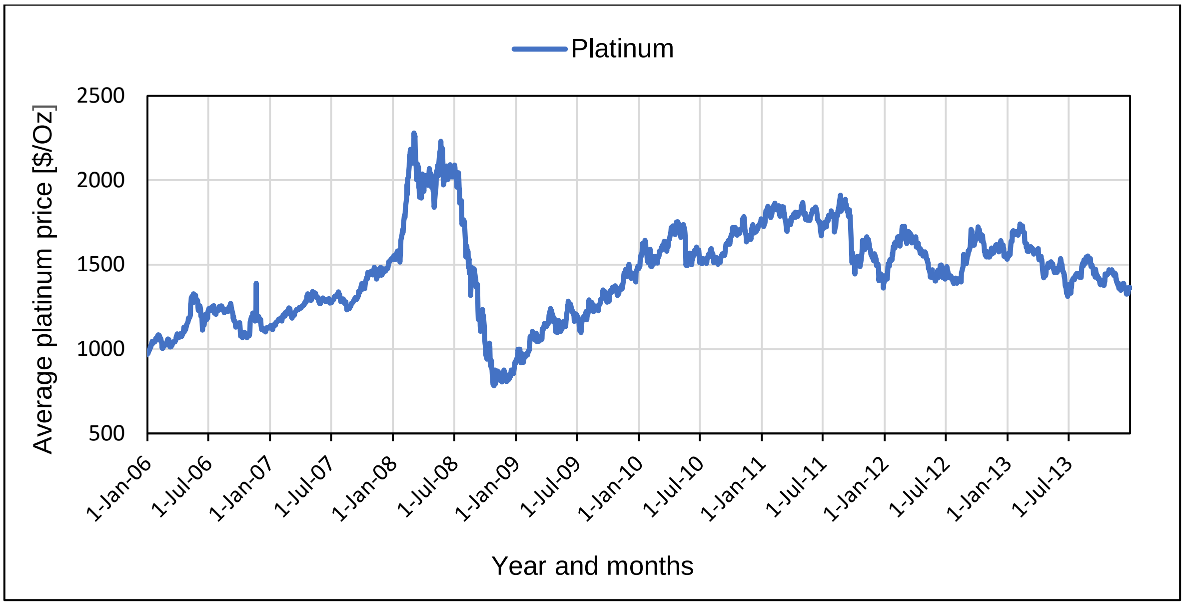


Figure 2: Average platinum price, adapted from [4]

South Africa's reputation as a primary platinum supplier will deteriorate with time as markets move more towards secondary suppliers. Between 2003 and 2013, the country's share of the global supply of main PGMs reduced by almost 11% [3]. This primary supply reduction was due to opposition such as lower cost producers and growing recycling markets [3]. There are countries that have new legislations to recycle electronic waste, therefore, more metal is recycled [4], [5].

Figure 3 shows the effect recycling has on the total net platinum demand. Platinum recycling has increased by almost 32% from 2009 to 2013 [4]. The compounded growth of recycling has increased by 5.6% from 2006 to 2012, while the total net demand increased by less than 1%. Therefore, recycling is increasing at a faster rate than the total gross demand. This contributes to a decrease in the platinum demand.

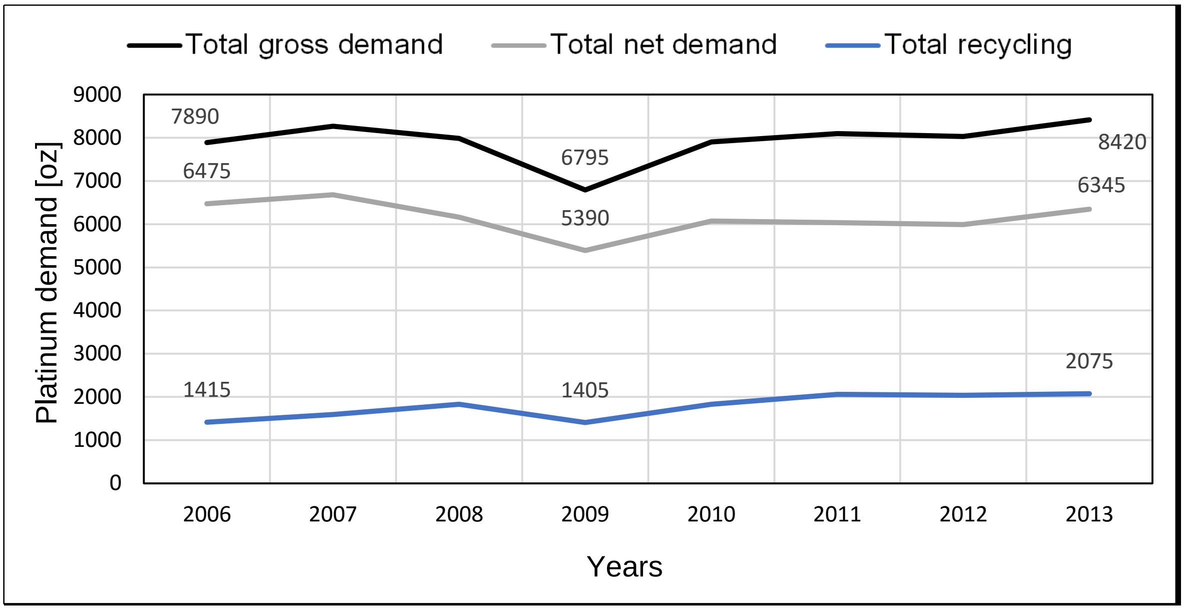


Figure 3: The effect of recycling on the global platinum demand [4]

Autocatalysts and jewellery manufacturers are the main markets for platinum as can be seen in Figure 4 [4]. These markets also have the highest number of suppliers for recycled platinum, which will likely increase in the future [6].

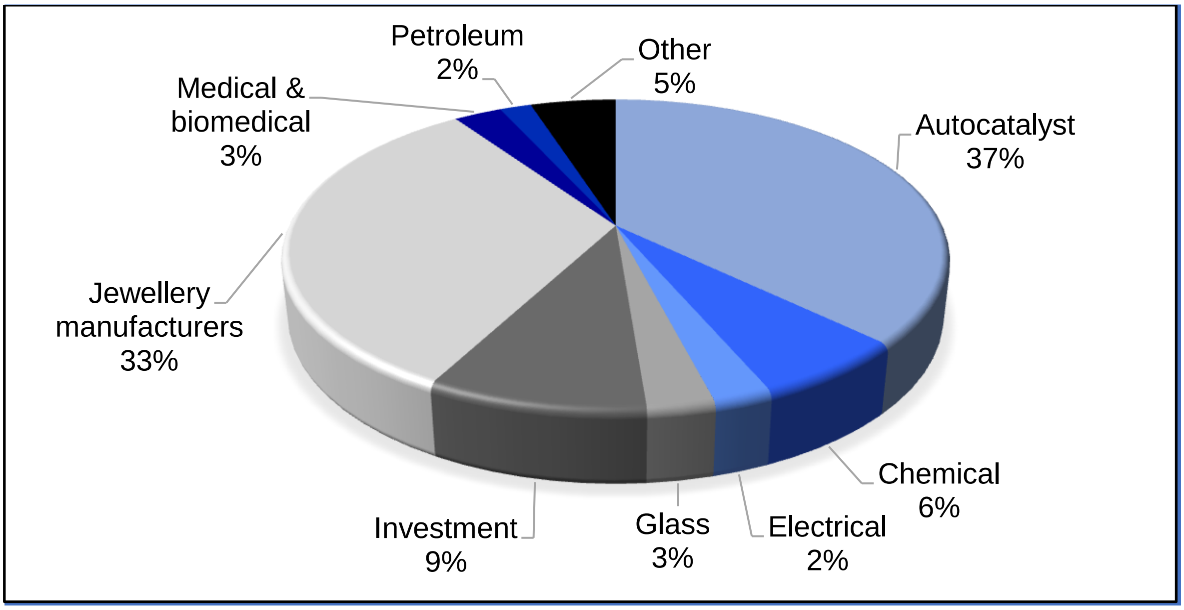


Figure 4: Breakdown of the largest platinum demand market sectors in 2013, adapted from [4]

By 2013, China was the largest consumer of platinum and the main consumer in the jewellery sector. Europe is accountable for the majority of the platinum consumption in the Autocatalysts sector. The platinum industry is, therefore, dependent on the recovery of the economies of these countries, as the platinum price is influenced negatively by the slowing demand.

### 1.1.3 Lower productivity

Although productivity has decreased, workers in the mining sector were demanding higher salaries and wages [7]. Growing wage bills contribute to the reduced profitability in the mining sector. Labour productivity, measured in kilogram PGM per employee, decreased by almost 46% from 1999 to 2012. During these thirteen years, the real labour cost increased 233% per kilogram of PGM produced. The drastic divergence between labour cost and labour productivity after 2006 is something that stakeholders should give attention to, in order to reverse the trend shown in Figure 5 [3].

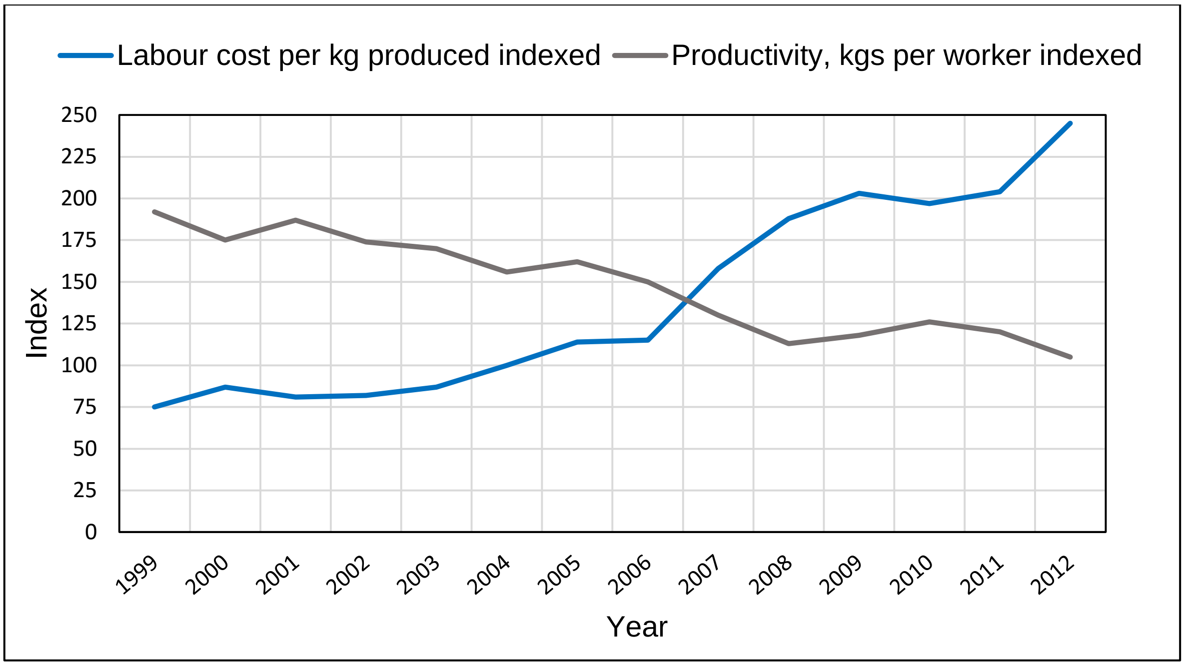


Figure 5: Labour productivity versus labour costs, adapted from [3]

A leading contributor to the decrease in worker productivity could be the strikes experienced by the platinum sector. Strikes are one of the most concerning challenges for the platinum sector. In 2012, strikes in Marikana had a huge impact on the PGM producers. The strikes led to increasing labour costs and decreasing productivity while overhead costs still needed to be covered [3].

### 1.1.4 Escalating production costs

In 2011, the production cost for the top five platinum companies was estimated at R83.2 billion. As can be seen in Figure 6, the largest expenditure was identified as labour costs, which accounted for R21.6 billion (26%). An expenditure of approximately R5 billion (6%) went towards electricity [3].

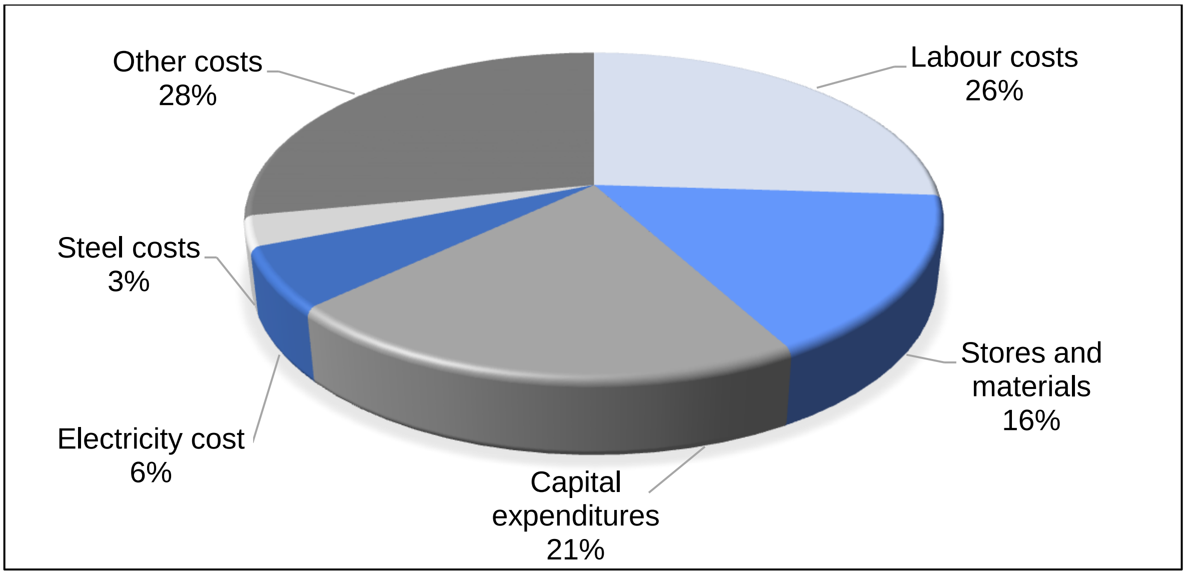


Figure 6: Platinum sector cost and expenditures [3]

Electricity, diesel fuel, reinforced steel, wages and salaries play a big role in the rising cost within the South African platinum mining sector. The average annual production cost increased by 18% per ounce from 2007 to 2012. During this five-year period, salaries and wages increased by 60% (five percentage points higher than producer inflation), while the electricity price has increased 238%, as seen in Figure 7 [3]. Thus, electricity is the fastest growing expense and it should be managed more efficiently.

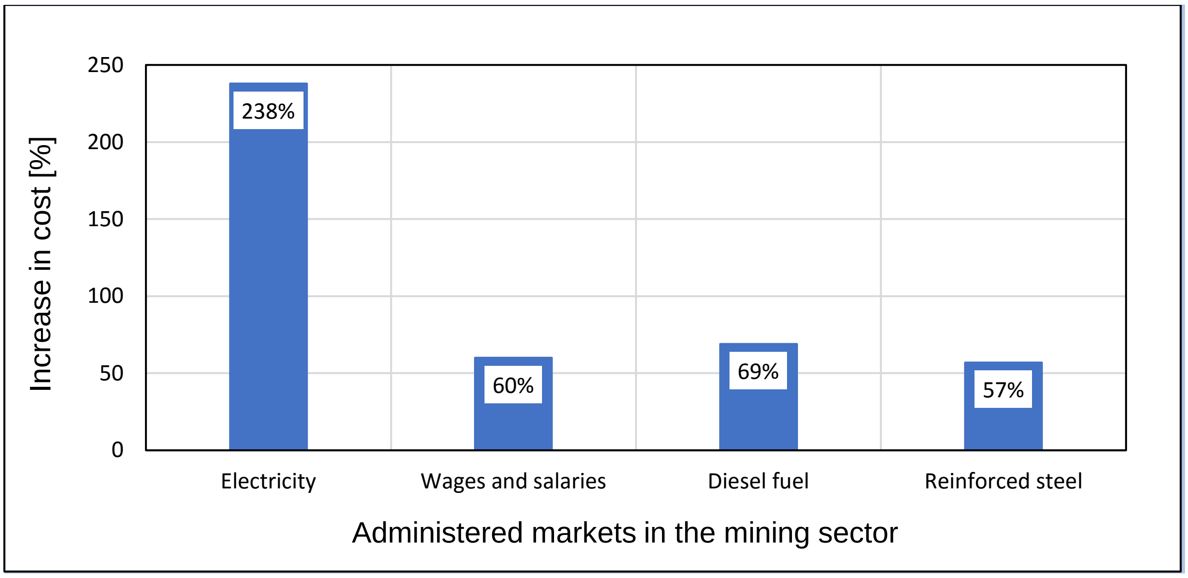


Figure 7: Average annual increase in cost between 2007 and 2012, adapted from [3]

If electricity is not managed in order to use it more efficiently, it may lead to unsustainable operating costs. In mines with a depth of 1 600 m and deeper, cooling systems can consume up to 25% of the total electricity consumed [8]. A breakdown of the electricity usage in the platinum industry is indicated in Figure 8.

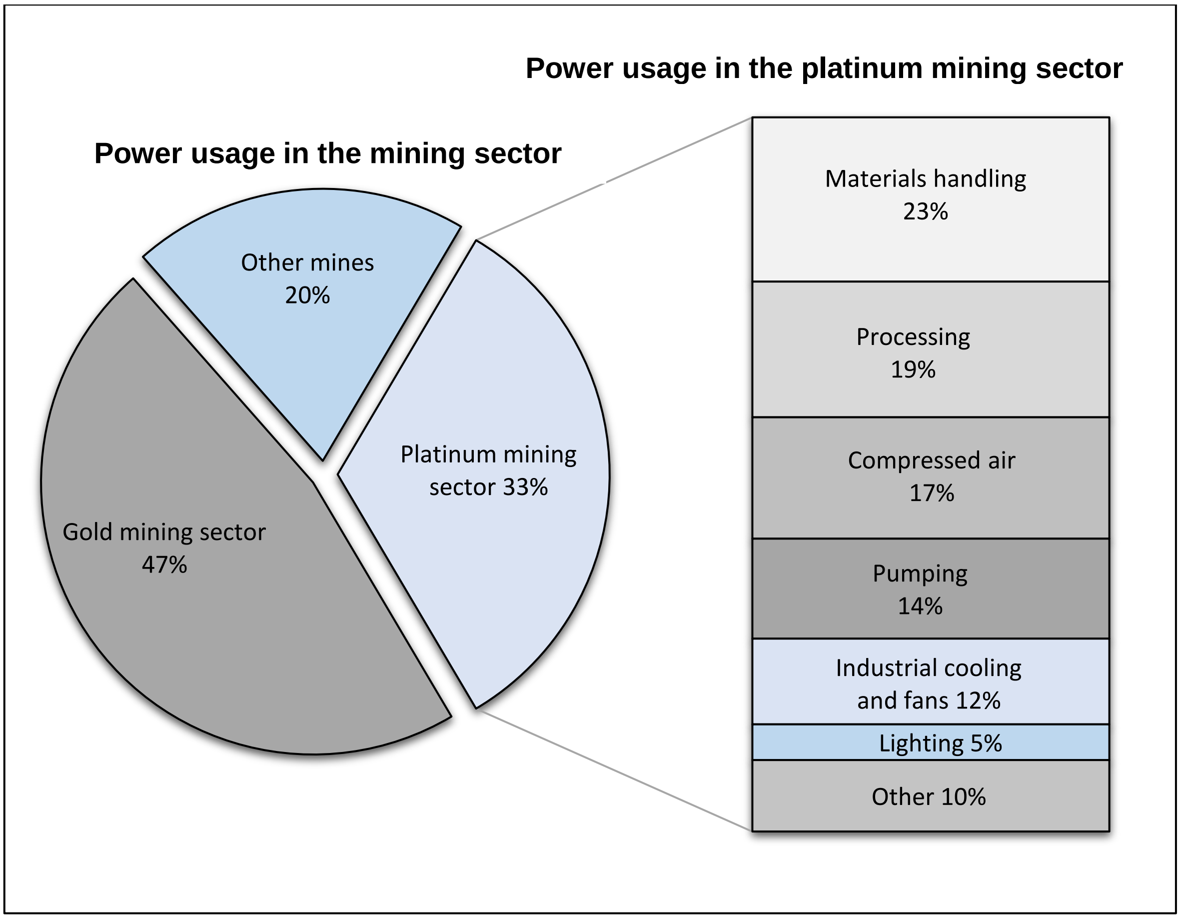


Figure 8: Breakdown of the power usage in platinum mining

By 2010, industrial cooling and fans accounted for 12% of the total electricity usage within the platinum mining sector [9]. Therefore, cooling and fans are some of the largest electricity consumers. The mining industry in South Africa is using approximately 15% of the total output produced by the South African electricity utility (Eskom). The platinum mining sector is the second-largest electricity user after gold mining and account for 33% of the mining industry's total electricity usage [9].

## 1.2 The South African energy market

### 1.2.1 Preamble

Eskom is within the top twenty utilities in the world in terms of electricity generation capacity. Eskom provides an estimated 95% of the electricity used in South Africa [10]. The economy and electricity demand of South Africa have outgrown the generation capacity of Eskom. Thus, new power stations are needed, which leads to great capital cost and escalated electricity costs [11].

In 2007, the South African electricity sector could not meet the demand of the national grid [12]. Eskom failed to increase the generation capacity at the same rate as economic expansion and had to force load shedding and enrol Demand Side Management (DSM) initiatives [11]. Thus, the increasingly demanding economy challenges companies to remain competitive by operating at higher efficiencies and scaling down their energy budgets [13]–[15].

### 1.2.2 Demand Side Management

Eskom implemented numerous DSM incentives to encourage companies to reduce their electricity usage. DSM measures encourage companies to use electricity less intensively and outside peak demand periods. DSM incentives help to decrease the energy demand and delay the need for greater generation capacity [16].

Projects that save cost by reducing the electricity consumption without affecting service delivery are known as energy efficiency projects. Projects that make use of Eskom's cheaper time-of-use (TOU) tariffs to save cost are known as load management projects [17], [18]. These projects are researched and implemented with results that are calculated according to measurement and verification (M&V) guidelines. The implementation of these projects is dependent on the availability of ad hoc funding [19].

Eskom's Integrated Demand Management (IDM) programme provides funding for clients to reduce energy consumption and thus the demand for energy. Reducing the energy demand or consumption of industries, potentially requires investing in new technologies, processes and equipment. Therefore, these incentives may be expensive but still possible due to IDM funding [20].

In the past, Eskom had five funding models to enable clients to reduce their energy consumption. These models can be explained as follows [20]:

- *Rebate Model*: Consumers are paid incentives when converting inefficient technologies to energy saving solutions.
- *ESCo Funding*: Energy services companies (ESCos) are paid when submitting projects with potential savings of 100 kW or more.
- *Performance Contracting*: Contracts with a single developer to purchase bulk verified energy savings across numerous sites. The savings of the smallest project should be more than 30 GWh over a sustainable period of three years.
- *Customer Models*: This model allows electricity end users to contribute to energy-reduction initiatives.

- *Standard Product and Offer Models*: The Standard Product model is for clients with potential savings between 1 kW and 100 kW. The Standard Offer is for clients with potential savings between 50 kW and 5 MW. These models were designed to enable a quicker payment process.

In 2013, it was stated that Eskom had a shortfall of R7.9 billion for its IDM funding. On 30 September 2013, Eskom announced that changes would be implemented to its IDM programmes due to funding restrictions [21], [22]. Due to financial constraints, industries could not rely on funding anymore, as was the case in the past.

Figure 9 shows the stages that must be followed to conduct a successful DSM project. As seen from the stages in Figure 9, approval and funding play a vital role.

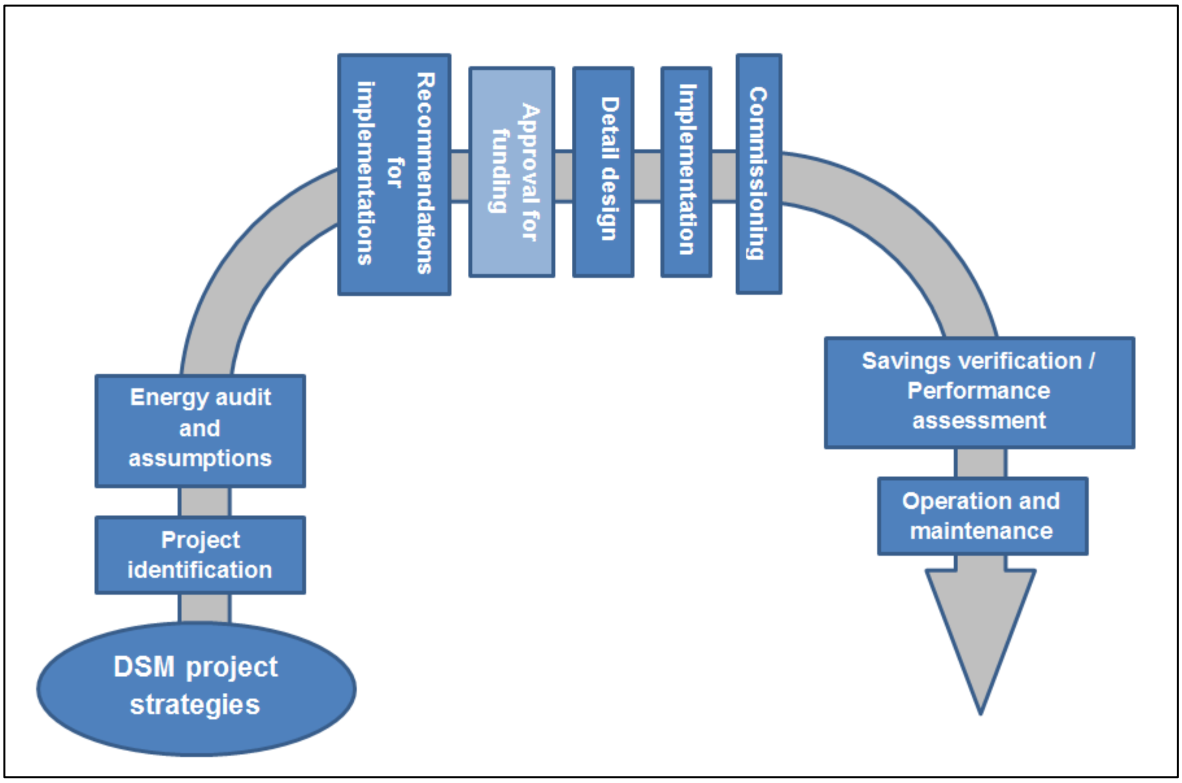


Figure 9: DSM project stages, adapted from [23]

### 1.2.3 New ESCo process overview

In 2015, Eskom's IDM department implemented new M&V guidelines to deal with new ESCo projects. The new ESCo process is based on performance contracting, which originated from one of the older models (as explained in Section 1.2.2). ESCos are paid based on project performance and not on project implementation as was the case in the past [21]. This contributes to the need for short-term and cost effective energy saving strategies.

Due to electricity constraints in South Africa, there was a need to revise and reintroduce the ESCo model funding programme for low cost energy saving projects that could be implemented fast and complied with the terms and conditions of the programme. The new ESCo process can briefly be discussed as follows [21]:

- Savings must be achieved in evening peak periods.
- The project must be sustained for 36 months (12 × three-month periods). The ESCo is responsible for savings during the entire period.
- Evening peak demand savings greater or equal to 500 kW must be achieved as per the Megaflex TOU tariff.
- Implementation must occur within a period of six months.
- After the first three-month period, 30% of the contract value is paid. The balance of the contract value is paid per three-month period over the remainder of the 36-month term.
- ESCos are paid every three months (per three-month period) based on the evening peak reduction achieved.
- There is 10% retention applicable to each invoice. The retention is payable if the ESCo proved that they complied with the Supplier Development and Localisation (SD&L) evaluation criteria.
- Savings equal or lower than the target may be claimed for payment. The ESCo is not be paid for savings higher than the target.
- Eskom can recoup overpayments if savings achieved during the first three-month period is not sustained in the following three-month period.

## 1.3 Problem statement

Platinum mine cooling systems were identified in Section 1.1 as a sector with a need for alternative and cost effective energy saving solutions. Mines are implementing self- and Eskom-funded projects to achieve load management and energy efficiency. Due to economic reasons, the demand for platinum has decreased in countries that previously consumed the most platinum. Platinum prices dropped with the decreasing demand, which has a big impact on South African producers [3].

Considering increasing operating cost, inflation and strike actions, it becomes more challenging financially for mines to invest in energy saving incentives. In 2014, the low platinum price, high operating cost and high capital expenditure caused about half of the platinum industry to become marginal industries or to lose money. Therefore, platinum mining companies have to minimise costs where possible [3].

Incentive programmes provided crucial financial support for implementing energy saving projects to reduce possible electricity costs. Eskom is, however, shifting focus away from these programmes. The new ESCo project process will make it more challenging for ESCos to implement DSM projects.

ESCos do not receive funding during the implementation period because payments are based on a project's performance. An ESCo only receives payment after the first performance period [21]. Figure 10 describes how the gap between present operation and more efficient operation is mostly filled with DSM incentives [24].

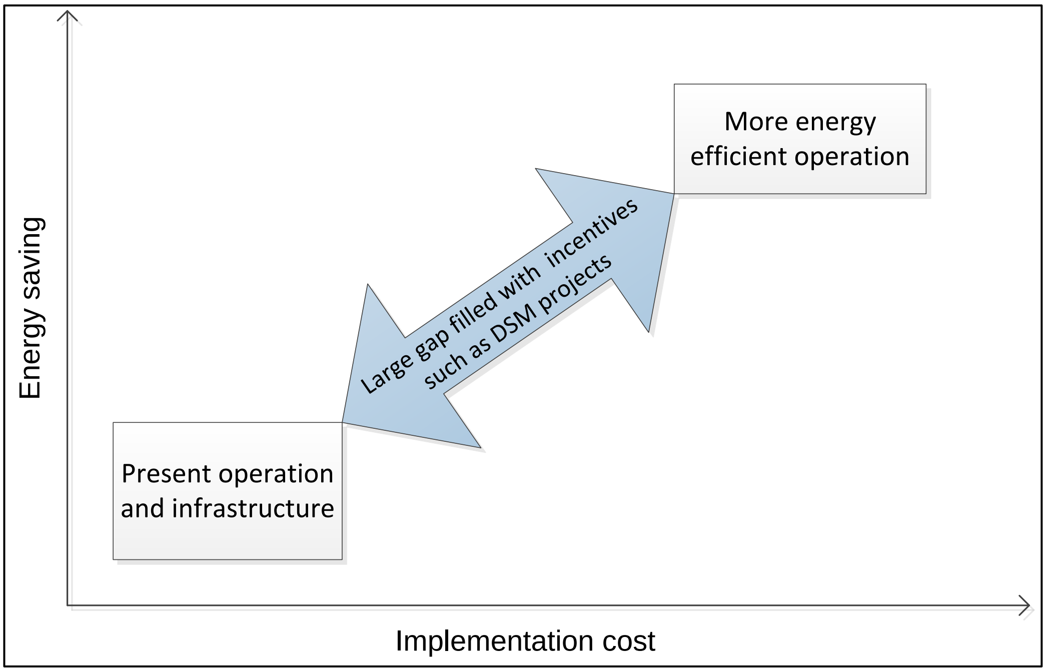


Figure 10: Improving energy saving with incentives, adapted from [24]

Apart from the lack of funding during implementation due to the new ESCo project process, ESCos are also finding it more challenging to fill the gap described in Figure 10.

Due to Eskom's funding constraints, the new ESCo project process and the challenges experienced by the platinum industry, alternative and cost effective strategies are needed. The platinum mining sector needs to reduce electrical cost expenditure without major capital investments. The interventions and energy efficiency improvements need to be self-funded, which remains difficult in marginal and highly competitive environments [24].

The self-funded energy saving strategies must be accomplished without affecting the underground working temperature or mining production. In order to boost the productivity of workers underground, mines need to maintain acceptable environmental conditions. Therefore, large cooling systems are found in the majority of deep-level mines [25]. Figure 11 shows how the workers' productivity decreases as the underground temperature increases.

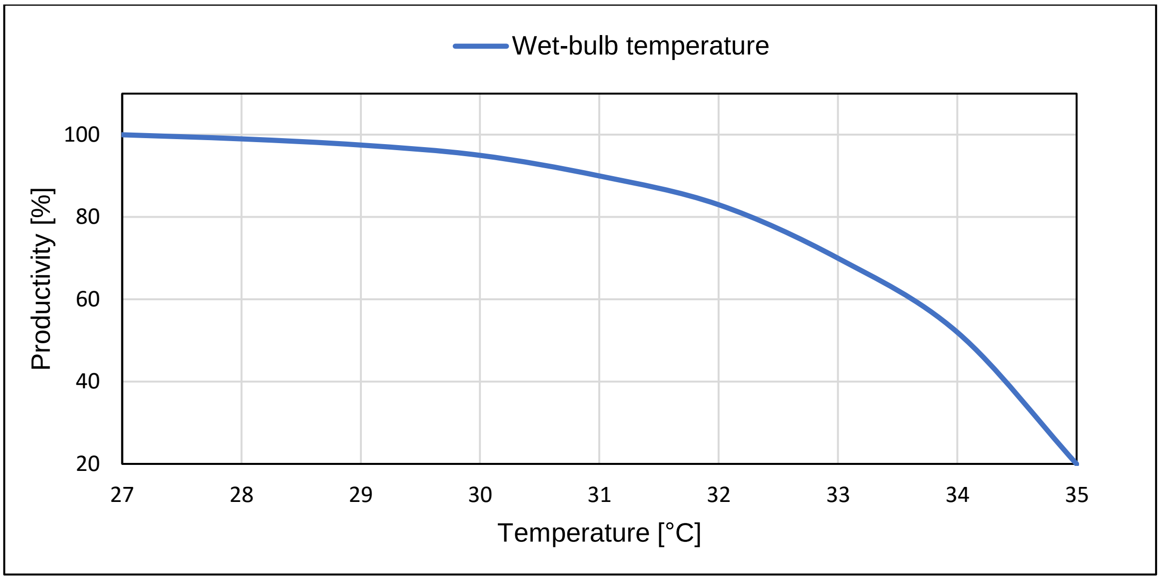


Figure 11: Productivity versus environmental conditions, adapted from [26]

The leading platinum mines in South Africa are situated in the warm Bushveld Complex [2]. Underground temperature increases due to the virgin rock temperature that rises up to 64 °C along with the growing depths of the mines. High temperatures, excess humidity and sufficient oxygen are issues of concern to maintain acceptable environmental conditions [11].

Therefore, an underground wet-bulb (WB) temperature limit of 27.5 °C has to be established to sustain a safe mining environment [27]. Figure 12 shows how the underground temperature increases along with the mining depths at different mining areas in South Africa.

It is shown that the Bushveld area is much warmer than the Johannesburg area. The cooling requirements are thus more intense for the Bushveld. Each deep-level mine in South Africa has different refrigeration demands in order to fulfil the underground cooling requirements.

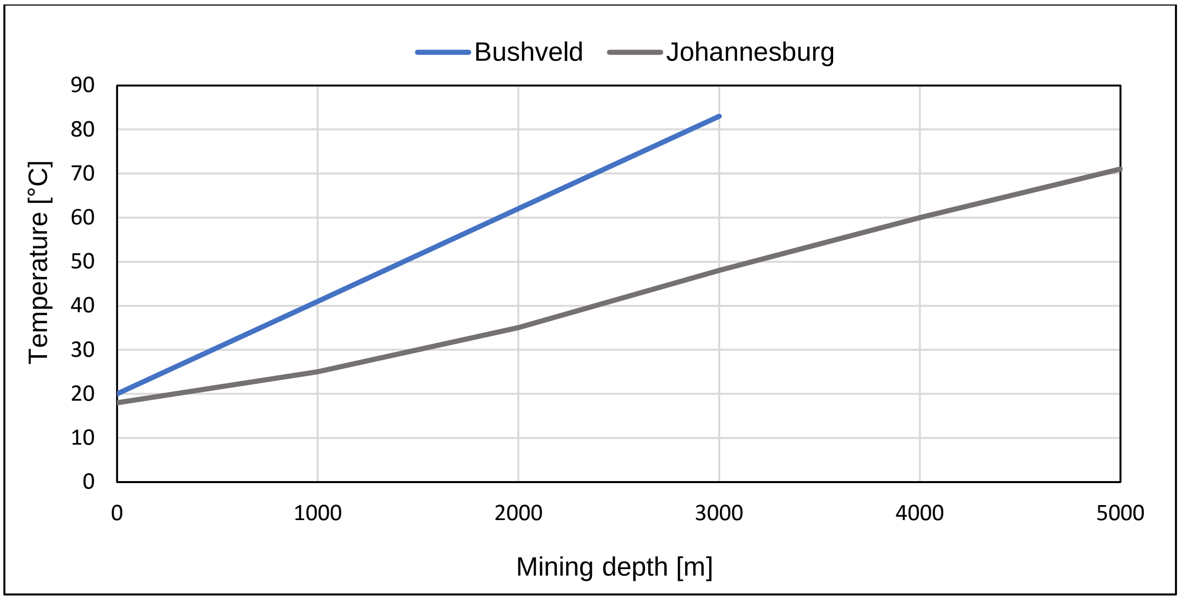


Figure 12: Underground temperatures in different areas, adapted from [28]

With all the requirements for ventilation and cooling, the future of deep-level mining is subject to how cost effective industry achieves these requirements [8]. Cooling and ventilation services are some of the largest energy users. These services have potential to be controlled in a more efficient manner to achieve optimisation [29].

## 1.4 Objective of the study

Investigations were done on existing load management strategies, which include load shifting, load clipping and energy efficiency through control strategies. It was identified that existing energy saving strategies require significant funding. Due to a combination of Eskom’s funding constraints, the new ESCo process and the challenges experienced by the platinum industry, low cost energy saving strategies are required.

The goal of this study is to decrease the energy usage of platinum mine cooling systems in a cost effective manner. A low cost energy saving strategy is required to reduce energy while support funding is not available for implementing DSM projects.

A cost effective energy saving strategy is developed in this study. The strategy requires minimum funding and a short implementation period. The savings achieved with the developed strategy can potentially contribute to the funding support required for future DSM projects. Thus, the strategy could serve as an alternative to fill the gap described in Figure 10.

## 1.5 Overview of the dissertation

Chapter 1 provided a background to the study, which included the challenges experienced by the platinum industry and the energy market. The background was followed by the motivation for the study, the goal and overview of the dissertation.

Chapter 2 offers an overview of refrigeration systems and load management with a more detailed background. This overview details existing strategies implemented on cooling and ventilation systems, the need for cost effective energy saving strategies and the necessity for developing and implementing an alternative strategy.

In Chapter 3, the refrigeration system on Platinum Mine A is investigated in detail. The investigation includes the layout, specifications, requirements and operating procedures of the refrigeration system. An estimated saving range of a potential load management strategy is obtained with the information gained from the investigation. A simulation designed in Process Toolbox along with Microsoft Excel® is used to simulate a newly developed cost effective control and monitoring strategy. The expected cooling and power usage demand due to the implementation of the developed strategy is discussed in Chapter 3.

In Chapter 4, the strategy (developed in Chapter 3) is implemented on Platinum Mine A. Two tests are done to verify the results. The expected results of the strategy implementation are discussed and compared with the estimated saving range and the simulation results of Chapter 3. The cost effective control and monitoring strategy is then be compared with a potential DSM project to determine advantages, disadvantages and the ideal combination of the two different strategies.

Chapter 5 concludes the outcome of the study. Recommendations are provided for other possible strategies on mine refrigeration systems.

# Chapter 2. Load management strategies on refrigeration systems

*Background to develop a cost effective energy saving strategy for implementation on platinum mines*

## 2.1 Introduction

As highlighted in Chapter 1, platinum mines need to reduce potential cost expenditures. According to Baxter, electricity is the fastest growing expenditure [3]. Therefore, the need to be more energy efficient is growing. Cooling systems were identified as an electricity service that has potential to reduce energy. Energy saving strategies such as DSM projects are solutions, but there is a need for alternative cost effective strategies to reduce energy without major capital expenditure.

The following topics are reviewed in this chapter:

- *Refrigeration and cooling systems*: To understand how refrigeration forms part of the overall water reticulation system as found on the majority of platinum mines.
- *Major electricity auxiliaries:* To identify the components within refrigeration systems that consume the most electricity. The potential to reduce the consumption of these components can then be determined.
- *Existing energy saving projects:* To understand which energy saving strategies are currently used on refrigeration and cooling systems.
- *Manual and automated control:* To evaluate the types of management strategy on mine cooling systems.

## 2.2 Refrigeration and cooling systems

The purpose of large mine refrigeration systems is to ensure safe environmental conditions so that mining can continue safely and efficiently. The main heat sources in underground mines are hot rock faces, fissure water and autocompression of air moving down shafts [30]. Heat sources cause underground temperatures to rise, which must then be cooled down artificially.

The cooling capacity required for a mine depends on the surface and depth of underground operations [27]. A cooling system is a combination of chillers, dams and auxiliaries such as water pumps and ventilation fans. These components consume the majority of the energy in cooling systems [31]. Cooling systems can differ in terms of layout, configuration, operation and control sequence. Thus, the type of cooling system is determined by distribution systems and specific constraints on different mines [31], [32].

The system extracts hot water (fissure water and used chilled water) from underground; the hot water then undergoes a cooling process. After the hot water is cooled down, it is used for surface air cooling and for cold service water underground [8], [32].

This dissertation focuses on surface refrigeration systems. The layout in Figure 13 illustrates the function of the different components in a cooling process.

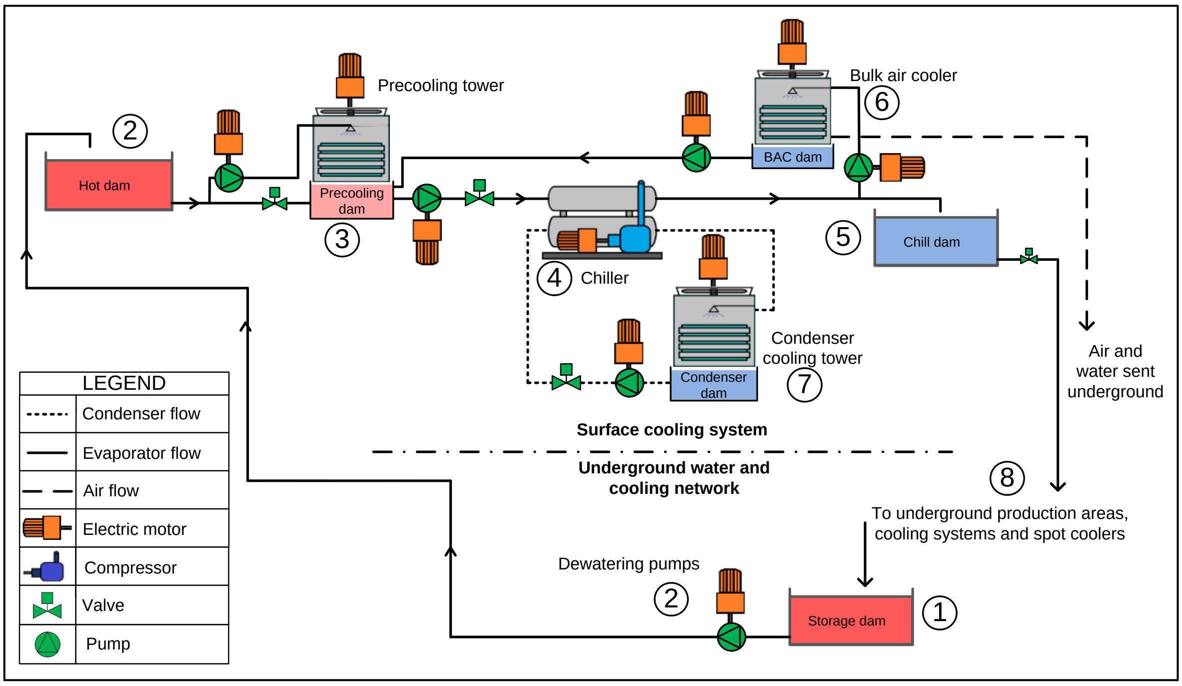


Figure 13: Typical platinum mine cooling and water reticulation system, adapted from [31]

The function of the different components in a cooling cycle process is as follows [31]:

1. *Hot water storage dam:* Hot water from underground mining operations is stored underground.
2. *Dewatering pumps:* Underground water pumps are used to extract hot water from hot water storage dams, which are located underground. The extracted hot water from underground is then pumped to the hot surface dams.
3. *Precooling tower:* Hot water is pumped from the hot surface dam through the precooling tower and is gathered in the precooling dam. The water is then pumped from the precooling dam through to the evaporator side of the chiller (heat exchanger).
4. *Chillers*: The water passes through the chillers from the precooling tower to be cooled down to a desired output temperature. The chillers use either an absorption or a vapour-compression process. The number of chillers varies according to the underground chilled water and ventilation air required.
5. *Chilled water storage:* Chilled water from the chillers is pumped into chill dams to be stored. Chilled water is then sent underground by controlling the flow with an actuated valve. The flow is controlled depending on the demand for chilled water.

6. *Bulk air cooler (BAC):* The chilled water storage dam is also used to supply BACs with chilled water. BACs use chilled water along with different fan configurations to force air into the shaft for cool ventilation. Once water has cooled the air down, the water is pumped back to the precooling tower.

7. *Condenser cooling tower:* This is a heat-rejection phase where the heat generated through the refrigeration cycle is extracted.

8. *Underground chilled service:* After mining operations (such as drilling and cleaning), the water flows back into hot water storage dams (Component 1, Figure 13), from where the process starts again.

In practice, the number of refrigeration machines (and their motor ratings), pumps and fans vary according to mine-specific requirements. When considered as a single entity, electric motors on water pumps and fans consume large amounts of electricity [31].

## 2.3 High energy-consuming auxiliary equipment

### 2.3.1 Preamble

In this section, the components mentioned in Section 2.2 are investigated further. These components include:

- Refrigeration cycle
- Heat-rejection components
- Heat-absorption components
- Electric motors, pumps and dams

### 2.3.2 Refrigeration cycle

It is preferable for mines to use the vapour-compression cycle due to its relative low maintenance and simplicity when compared with other processes [8]. The vapour-compression cycle is illustrated in Figure 14.

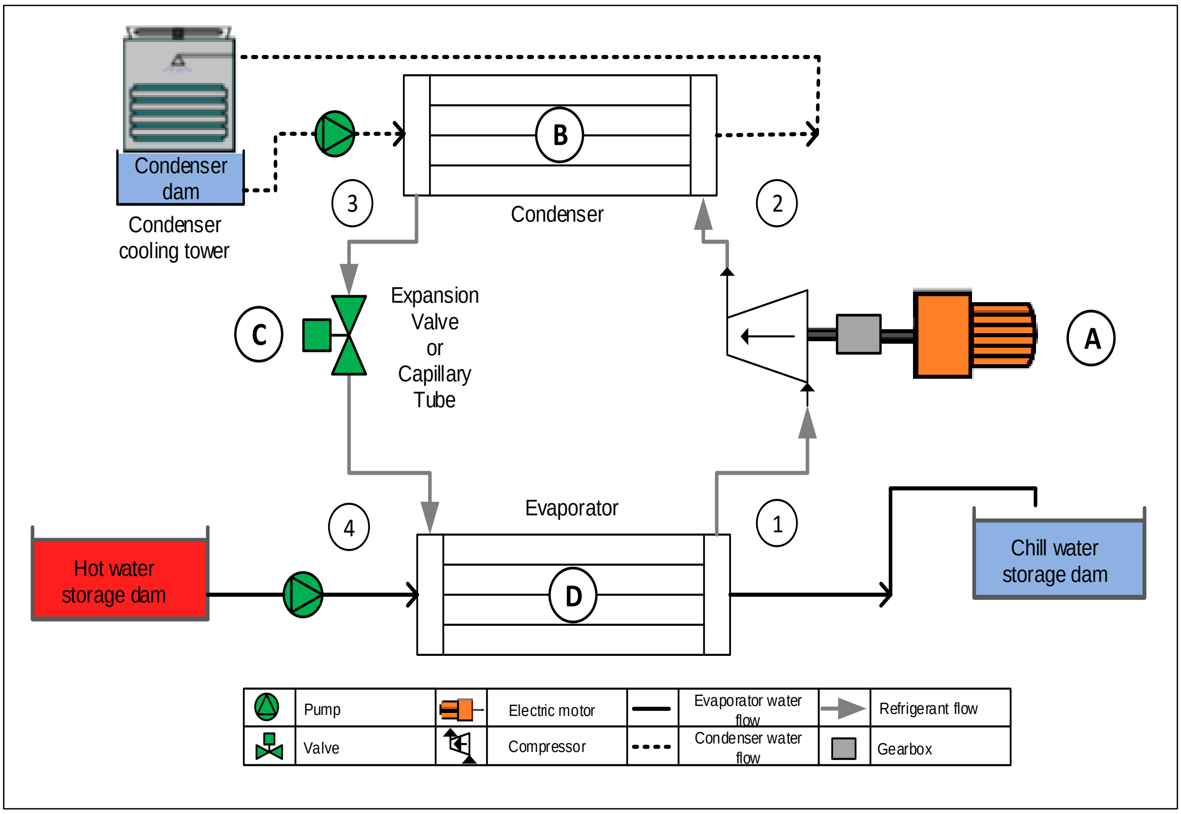


Figure 14: The vapour-compression system process and layout, adapted from [31]

The compression cycle illustrated in Figure 14 can be explained as follows [31]:

A. *Compressor*: From Stage 1 to Stage 2, the refrigerant, as a heated vapour, is adiabatically compressed to an elevated pressure. As a result, heated vapour enters the condenser at a high pressure.

B. *Condenser*: The heat of the vapour is transferred to the condenser water, causing the vapour to condense. As a result, a high-pressure liquid forms at Stage 3.

C. *Expansion valve*: The highly pressured liquid is then flashed through the expansion valve and becomes a cold vapour.

D. *Stage 4:* At Stage 4, the refrigerant is a low-pressure mixture of vapour and liquid that enters the evaporator.

E. *Evaporator*: The refrigerant mixture then passes through the evaporator at a constant pressure. The refrigerant mixture absorbs the heat of the warm evaporator water. As a result, the refrigerant mixture cools the evaporator water down, which causes the mixture to turn into a heated vapour. The refrigerant then closes the cycle by re-entering the compressor at Stage 1 as a low-pressure, heated vapour.

Figure 15 shows chillers being used in a refrigeration system at a mine. Mines decrease cooling during the winter periods due to the cold ambient conditions. During cold conditions, cooling towers can overcool the air. By turning off unnecessary chillers, large electricity savings are achieved and overcooling is prevented [33].

Figure 15: Illustration of chillers used in a refrigeration systems at a mine [34]

### 2.3.3 Heat-rejection components

Mines generally use induced draft cooling towers with counterflowing air and water streams as shown in Figure 16 [31]. Cold water is stored in a dam (sump) within the tower. Hot water is sprayed from the top of the tower while cold air enters the tower at the bottom. The hot water is cooled down by transferring the heat to the cool inlet air. The heated air is extracted from the top of the tower into the atmosphere. The cooling efficiency is dependent on the contact time between the air and water that move in opposite directions [35].

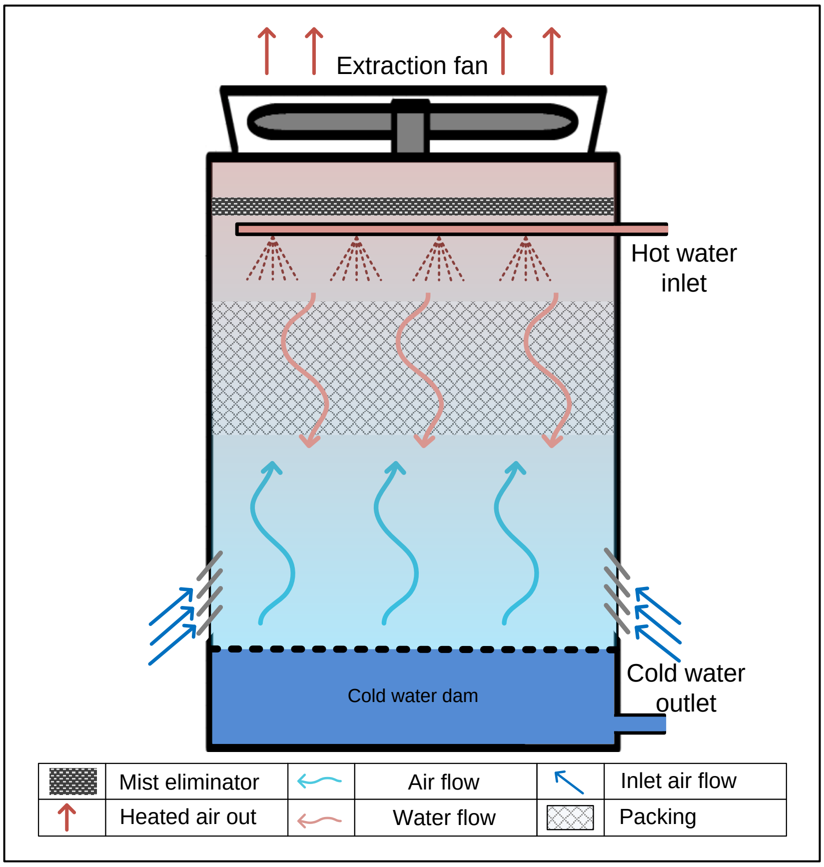


Figure 16: Illustration of a heat-rejection cooling tower [31]

At a typical platinum mine, the precooling tower and condenser tower work on the same principle. The difference is that the condenser tower normally has more heat-rejection towers placed next to each other for a larger cooling capacity. In refrigeration systems, condenser towers extract the heat generated by the condensers of the chillers into the atmosphere [35]. A typical condenser tower can be seen in Figure 17.

Figure 17: Condenser cooling tower at a platinum mine [31]

Precooling towers are used by mines to precool surface water from underground before it re-enters the refrigeration system [31]. An example of an actual precooling tower can be seen in Figure 18.

Figure 18: Actual precooling tower at a platinum mine [31]

Cooling towers are designed according to the average ambient WB temperature, water flow rates and the desired water temperature expected for the system. Overcooling can occur when ambient WB temperatures are lower than the designed temperature. This can lead to overcooling in the refrigeration system. Overcooling provides potential for energy saving. By decreasing the speed of the water pumps and fans with VSDs, the water and airflow can be reduced accordingly to prevent overcooling [31].

### 2.3.4 Heat-absorption components

In order to sustain a productive, safe and healthy work environment, artificial cooling is required underground. BACs are installed on surface or underground to supply cold air required for ventilation [31]. BACs reduce energy by reducing the amount of water that circulates underground. BACs are also the least expensive method for underground cooling [32].

Secondary cooling methods, such as cooling cars and spot coolers, can also reduce the energy consumption of platinum mine cooling systems [27]. BACs work on the same principle as heat-rejection towers (discussed in Section 2.3.3). Typically, two types of BAC are used on mines, a crossflow BAC (horizontal forced draft chamber) and a vertical-flow BAC (vertical forced draft tower) [36].

Similar to heat-rejection towers (precooling and condenser towers), the heat-absorption towers (BACs) are designed according to average WB temperatures. With heat-rejection towers, the outlet temperature of water is the only concern. What makes heat-absorption towers different is that the outlet air temperature should be at desired temperature [31].

Therefore, the heat-absorption towers perform according to the ambient WB temperature. If the ambient WB temperature is colder than the designed temperature, the BAC will cool the air down to below the desired temperature, which causes the BAC to overperform. Thus, potential for energy saving occurs due to overperformance. Energy can be reduced by reducing the speed of the water pumps and fans [31].

### *Crossflow BAC*

Figure 19 is a schematic illustration of a typical crossflow BAC used at platinum mines. Chilled water from the chillers is pumped into the BAC from where it is sprayed uniformly across the chamber using nozzles. The spray water can exchange heat by making contact with the air in a crossflow or direct-flow [37].

The cooled air then flows to underground mining levels. The crossflow BAC in Figure 19 is a multi-stage BAC. The optimal performance of the BAC depends on the distribution of the sprayed water and the airflow. Therefore, the positions of the nozzles and fans are important [37].

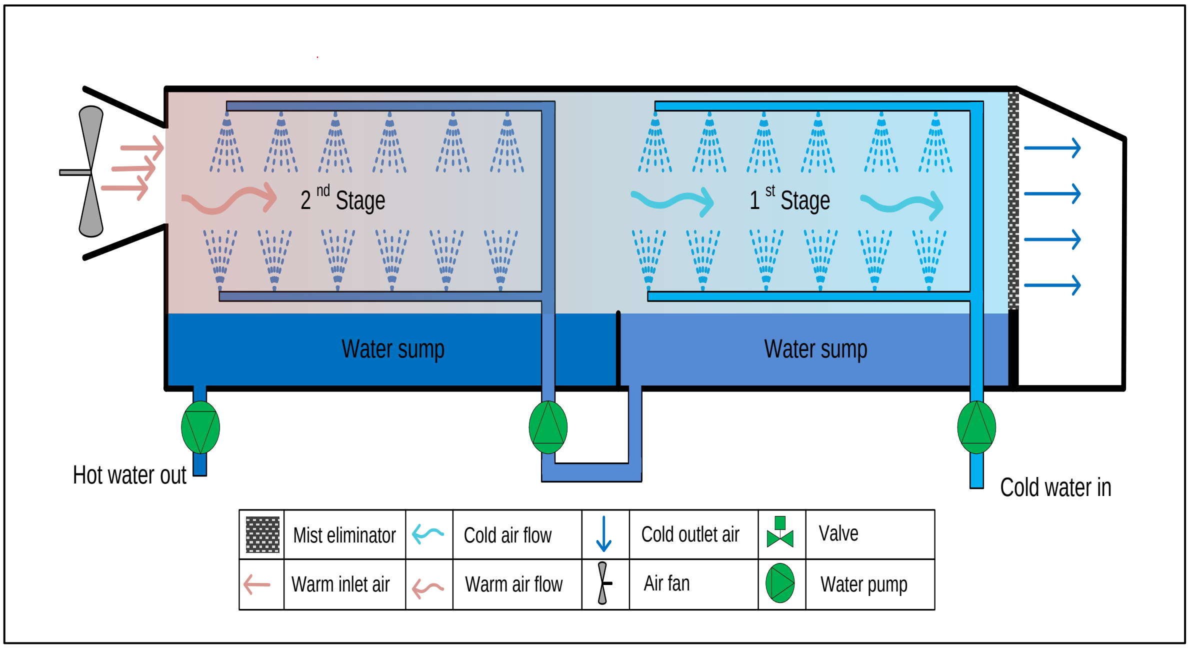


Figure 19: Schematic illustration of a typical crossflow BAC at a platinum mine [31]

Figure 20 shows an actual multi-stage horizontal BAC that is being used on a platinum mine. This particular BAC has four fans that extract ambient air into the BAC.

Figure 20: Actual horizontal-flow BAC at a platinum mine [31]

***Vertical-flow BAC***

Vertical-flow BACs have superior cooling capacities to crossflow BACs [35]. Figure 21 is a schematic illustration of a typical vertical-flow BAC at a platinum mine. The spray nozzles are positioned at the top of the chambers and make direct contact with ambient air. The uniformly distributed cold spray water cools the air, which is being forced through the chambers, down. The cooled air flows to the underground mining levels [31].

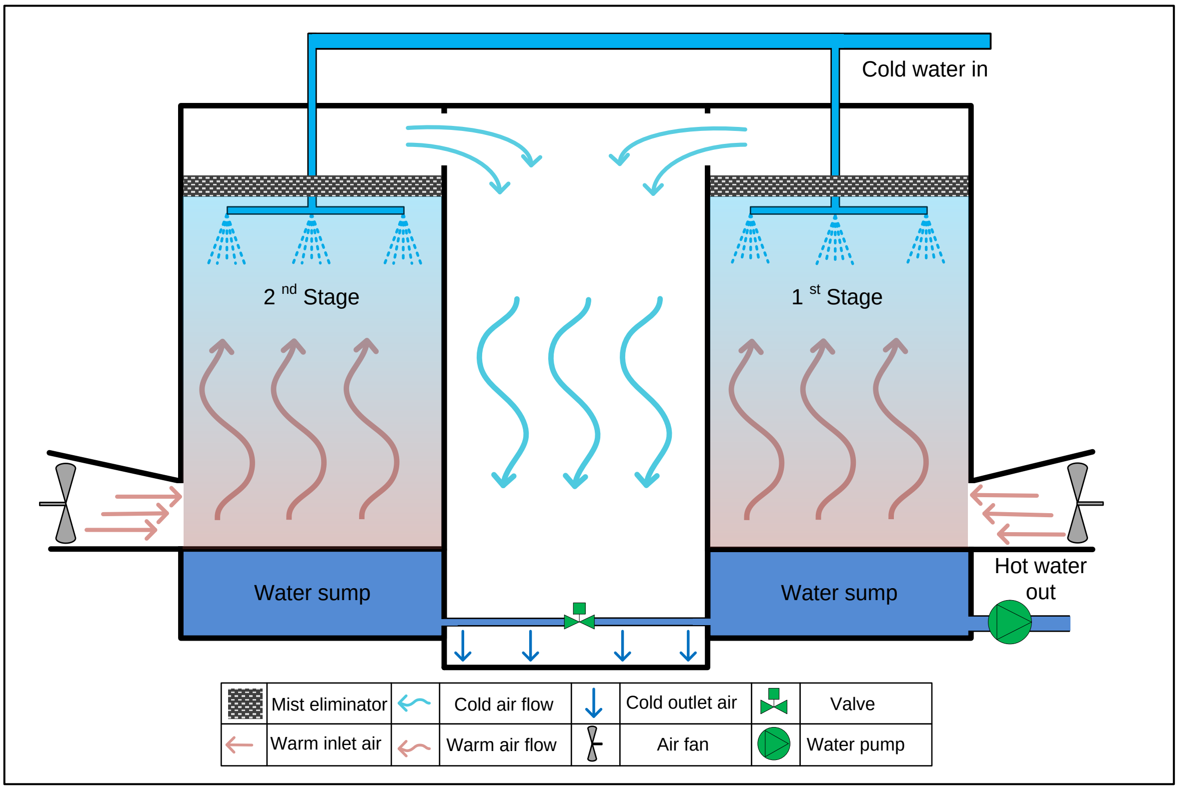


Figure 21: Schematic illustration of a typical vertical-flow BAC at a platinum mine [31]

Figure 22 is an actual multi-stage vertical-flow BAC that is being used at a platinum mine. As seen in Figure 22, four fans supply the ambient air. Two fans are positioned on each side of the outer chamber wall.

Figure 22: Multi-stage vertical-flow BAC at a platinum mine [31]

***Electric motors, pumps and dams***

Mines make use of cooling towers to reject or absorb heat within water reticulation systems. Chillers are used to produce chilled water, while storage dams are used as buffer capacity for the water. These methods require the use of water pumps to transfer the water within the cooling systems.

Mines typically use two types of pump – axial flow pumps or centrifugal pumps. The basic principle of these pumps is to accelerate liquid. This increases the energy (velocity) of the liquid as it flows through the impellers. The impellers are driven by electric motors [38].

The design of the impeller blade, diffuser and volute (casing) determines the efficiency of the energy conversion. Figure 23 is an illustration of an actual centrifugal pump. The pump is driven by fixed-speed electric motor [39].

Figure 23: Typical centrifugal water pump and electric motor configuration [31]

The centrifugal water pump supplies water to the evaporator, condenser and BAC circuits. The motor ratings of these pumps range from 30–400 kW. The operating point of these pumps should be selected at the region of optimal pumping efficiency [39]. According to the US Department of Energy, most electric motors are designed to run at 50–100% of their rated load [40].

The maximum efficiency of a motor is normally close to 75% of its rated load [40]. Savings can be achieved by ensuring that pump efficiencies stay as high as possible [31]. Reducing the speed of pumps with VSDs, which are over designed, can also reduce energy usage. The minimum required flow rate and pressure within the pumping system should be considered while reducing the speed of pumps.

Table 1 indicates the typical motor ratings of fans, water pumps and chillers found in platinum mine cooling systems. Chillers are the largest energy consumers in the cooling system with ratings of about 1 800 kW.

Table 1: Typical motor ratings of fans, pumps and chillers [31]

| Mine | Pumps [kW] | Qty. | Fans [kW] | Qty. | Chillers [kW] | Qty. |
|---|---|---|---|---|---|---|
| A | 30–330 | 8 | 90–160 | 7 | 1 800 | 3 |
| B | 45–275 | 4 | 90–300 | 6 | 1 800 | 2 |
| C | 75–400 | 8 | 90 | 4 | 1 300 | 5 |

Dams are used for thermal storage (hot or cold) to serve as buffer capacity [8]. The main purpose of these dams is to ensure that sufficient water is available for production and underground cooling purposes. This is to ensure that production proceeds with minimal interferences [41], [42]. Figure 24 shows actual storage dams, which are normally installed close to mineshafts. Chill dams are closed so that temperature losses to the atmosphere are minimised [31].


Figure 24: Actual layout of chilled and hot water storage dams, adapted from [31]

The demand for chilled water fluctuates throughout the various shifts; therefore, storage dams are essential to absorb the fluctuating demand. Potential energy savings can be achieved if these dams are controlled optimally according to Eskom's TOU tariff structure [8], [43], [44].

## 2.4 Existing energy management strategies on refrigeration systems

### 2.4.1 Preamble

Refrigeration systems are energy intensive, which forces mines to operate cooling systems more effectively to reduce their electricity usage [45]. In this section, the existing load management strategies on mine cooling systems are evaluated. By considering the implementation costs of the current strategies, the need of the study will be identified.

Load management is mostly done through energy efficiency and load shifting projects. Energy efficiency focuses on the 24-hour energy demand problem, whereas load shifting concentrates on reducing electricity demand during peak periods [43]. Refrigeration systems are ideal for implementing load management projects. Implementing a load management project on a mine refrigeration system includes upgrading PLCs, motors and instrumentation such as temperature and dam level sensors [19].

In this section, the following existing energy saving strategies are investigated:

- Energy efficiency strategies through variable speed control.
- Load shifting by shifting chiller operations and back-passing chilled water.
- Load shifting by switching off chillers and cooling auxiliaries.
- Peak clipping on BACs.

### 2.4.2 Energy efficiency strategies through variable speed control

As highlighted, load management projects upgrade and improve refrigeration systems. In addition, research has found that variable-flow control on mine refrigeration systems increases the overall system efficiency. The flow is controlled by variable speed drives (VSDs) that provide automatic variable-flow control of water through the chillers and the cooling towers.

These VSDs are installed on the evaporator, condenser and transfer pumps, which combined is known as the cooling auxiliary system [19]. With VSD control, the least amount of recirculation can be achieved. As a result, the electricity usage of the motor is reduced [45]. The variable-flow control also minimises overcooling of the air sent underground by the BAC [19].

Figure 25 shows an overview of a generic refrigeration system with control instrumentation and pump VSDs. The temperature probes, dam level sensors and a digital psychrometer are shown. All the equipment is installed and integrated into a network that is controlled by an energy management system [25].

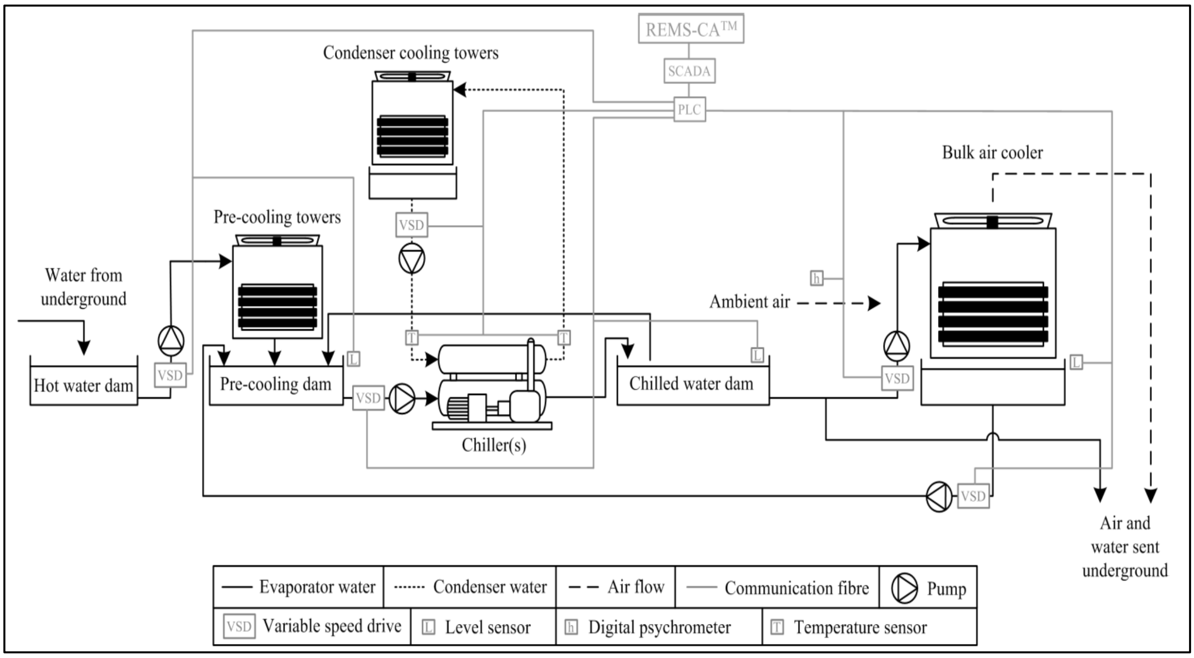


Figure 25: Generic refrigeration system with control instrumentation and pump VSDs [25]

A generic variable-flow control strategy was developed by Du Plessis, which can be implemented on all large mine cooling systems [25]. A short summary of the control strategy is shown in Table 2. The strategy was implemented on numerous refrigeration systems.

Table 2: Generic variable-flow control philosophy developed [25]

| Pump set | Control philosophy |
|---|---|
| Evaporator pumps | Modulate flow to maintain set chill water dam level |
| Condenser pumps | Modulate flow to maintain designed condenser water temperature rise |
| BAC pumps | Modulate supply flow in proportion to ambient enthalpy<br>Modulate return flow to maintain set BAC drainage dam level |
| Precooling pumps | Modulate supply flow to maintain set precooling dam level |

Data was gathered from five mines on which the variable-flow strategy was implemented. The average implementation cost for the strategy is high, as seen in Table 3. Installation costs include cabling, programmable logic controller (PLC), programming, equipment for communication networks, harmonic-protection units and commissioning [31]. The summary of the implementation costs, together with potential savings are shown in Table 3. The implementation cost is an estimated cost that includes inflation from 2012 to 2015. No critical service delivery areas were affected by the strategy [25].

Table 3: Average implementation cost for variable-flow control, adapted from [25], [45]

| Mine | Average power saving [MW] | Implementation cost in 2015 [R-million] |
|---|---|---|
| 1 | 2.6 | 6.2 |
| 2 | 1.9 | 6.4 |
| 3 | 0.6 | 3.8 |
| 4 | 1.2 | 2.3 |
| 5 | 1.5 | 1.9 |
| **Average** | **1.6** | **4.1** |

As seen in Table 3, implementation costs differ at the respective mines. The difference in cost is due to mine-specific conditions and required upgrades for implementation. A comparison between Mine 3 and Mine 4 in Table 4 illustrates the impact that mine-specific requirements have on the implementation costs.

Mine 3 required similar new equipment as Mine 4. But, the integration, installation and commissioning on Mine 3 were more complicated, thus the cost increased significantly. Note that Mine 4 required less new equipment, and that the cost of integration, installation and commissioning was also less than for Mine 3.

Table 4: Implementation cost breakdown

| Implementation cost [R-million] | Mine 3 | Mine 4 |
|---|---|---|
| Total cost | 3.8 | 2.3 |
| New equipment | 1.4 | 1.2 |
| Integration, installation, commissioning | 2.2 | 1 |

***Conclusion***

The variable-flow control implemented on four mines was effective with an average saving of 1.6 MW. The implementation required an average implementation cost of R4.1 million. In conclusion, this strategy requires substantial funding. Therefore, a need exists for low cost alternatives.

### 2.4.3 Load shifting by shifting chiller operations and back-passing chilled water

The purpose of DSM is to reduce or influence the amount of electricity being used. In 2007, Van der Bijl described a control philosophy for simulating and implementing generic load shifting with a real-time control system. The primary goal for the strategy was to shift the chiller operations out of Eskom's peak period [44].

The control philosophy can be described in two periods, namely, the preparation period and the peak period. The load shifting period that was targeted took place between 18:00 and 20:00. A summary of the philosophy is as follows [44]:

**During the preparation period (20:01–17:59)**

- Generate capacity for the hot water dam during the load shifting period by decreasing the hot dam level.
- Increase the water flow rate from the hot dam through the chillers to increase the chilled water supply. During this period, the chillers cool the mine water down (this is the period where the load is shifted to).
- Generate an increased storage capacity with the chill dam by increasing the chill dam level. The buffer of chilled water can then be used during the load shifting period (18:00–20:00).
- Reduce the power consumption of the chillers by decreasing the chillers' inlet temperatures. This is possible by back-passing chilled water either into the hot dam (for a slow but longer lasting effect) or directly into the chiller inlets (for a more direct effect).

**During the peak period (18:00–20:00)**

- The chillers must be stopped according to system constraints.
- The hot dam level must be increased and the hot water flow must be limited if possible.
- The chill dam level decreases as the mine consumes water.
- Back-pass the chilled water (as was done in the preparation period) to decrease the inlet temperature of the water flow to the chillers.

A schematic view of the control philosophy is shown in Figure 26.

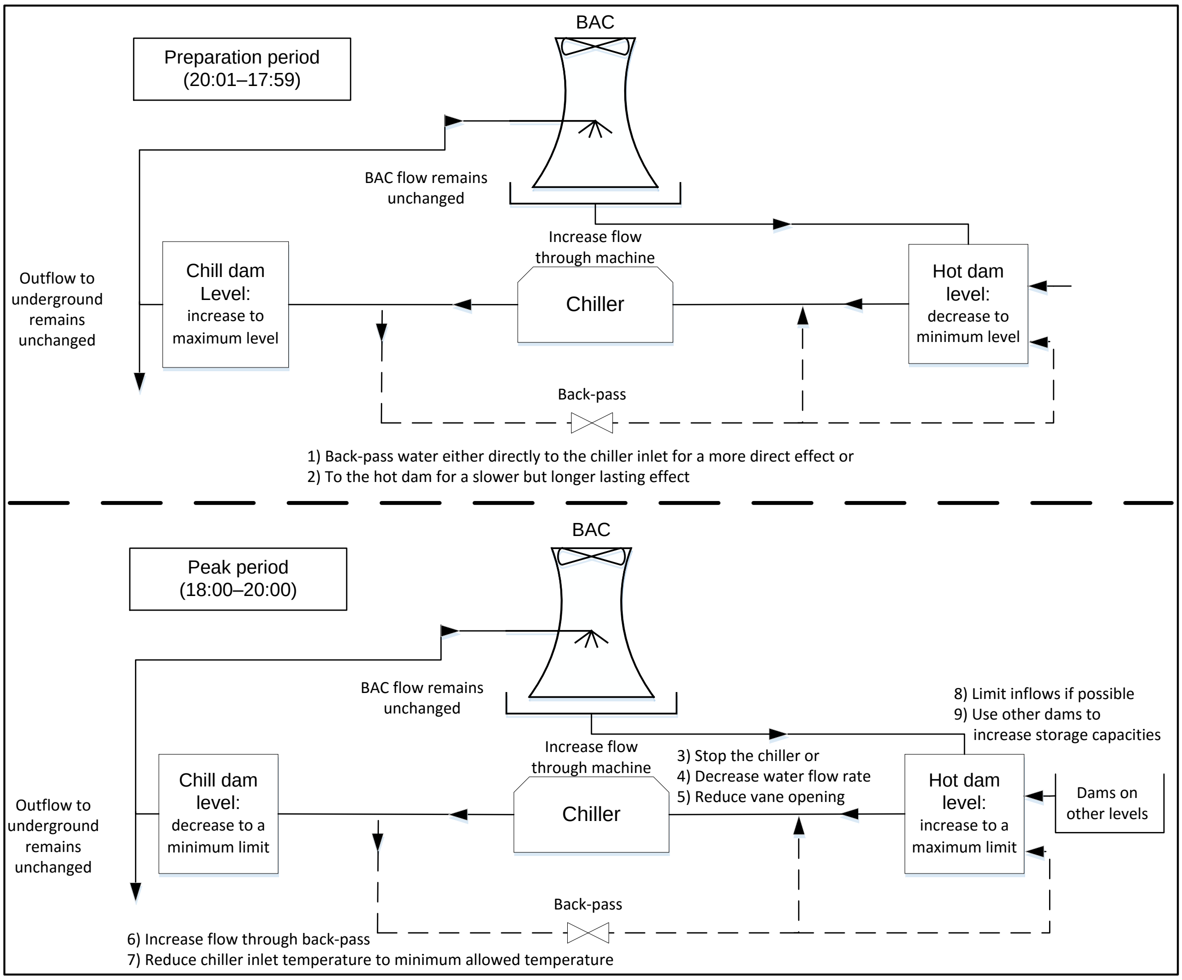


Figure 26: Schematic illustration of the generic control philosophy, adapted from [44]

Van der Bijl investigated four mines for potential DSM load shifting projects [44]. He determined:

- Process parameters and constraints.
- Load shifting potential through simulations.
- Required infrastructure and equipment to implement the control strategies.

To determine accurate load shifting potential on refrigeration systems, it is important to create process parameters. These parameters may not be compromised when applying the load shifting strategy. The process parameters and constraints were determined using input from the mining personnel. The parameters and constraints included [44]:

- Temperatures.
- Maximum and minimum dam level percentages.
- Flow rates.
- Machine operating constraints.

The equipment and infrastructure that had to be installed to implement the control strategy are in summary [44]:

- PLC machine automation.
- Actuator for back-passing valve control.
- Additional control valves and piping to establish back-passing capabilities.
- Upgrading and integrating the supervisory control and data acquisition (SCADA) system, PLC equipment and panels.
- Human-machine interface (HMI) equipment and backup power supply.
- Network equipment and fibre communication between equipment.
- Field instrumentation such as valve position sensors flow meters, temperature and pressure probes, transmitters, pressure switches and gauges, vibration transmitters etc.

A cost analysis was done and quotations for the required equipment and infrastructure were obtained from contractors. The summary of the implementation costs and the potential savings are shown in Table 5. The costs were estimated taking inflation from 2007 to 2015 into account. The potential savings by implementing the strategy were simulated and are shown in Table 5.

Table 5: Cost summary for required infrastructure [44]

| Mine | DSM potential saving [MW] | Projected implementation cost in 2015 [R-million] |
|---|---|---|
| 1 | 3.2 | 5.0 |
| 2 | 6.3 | 10,3 |
| 3 | 4.2 | 6,7 |
| 4 | 3.2 | 1,9 |
| **Average** | **4.2** | **6.0** |

Similarly in 2006, Calitz shifted load by scheduling chillers optimally. He achieved a load shift of 3.6 MW [43]. In 2007, Schutte implemented load shifting on a cascade surface cooling system and achieved an average load shift of 4.2 MW [8].

Load shifting research was also done on South Deep, one of the deepest mines in South Africa. It was concluded that the best method for load shifting is through thermal storage. This is possible by implementing control strategies and parameters on an existing system [46].

***Conclusion***

Shifting load by scheduling chillers optimally and back-passing chilled water has been proven effective. The cost predictions obtained by Van der Bijl showed that the average cost of four potential implementation projects was R6 million. In conclusion, this strategy requires substantial funding. Therefore, a need exists for low cost alternatives.

### 2.4.4 Investigations on potential load shifting by switching off chillers

Previous studies have found that refrigeration systems are ideal for implementing load shifting or peak clipping projects. With refrigeration load shifting projects, it is important to balance the refrigeration system's thermal energy. This is achieved by ensuring that the water is sufficiently chilled before going to underground mining operations [19].

In current load shifting projects, water that is chilled outside of Eskom's peak period (18:00–20:00) is stored in chill dams. The stored chilled water is then used for mining operations during the expensive peak periods (the cooling auxiliaries are switched off during these periods) [19]. Achieving load shifting with refrigeration systems generally entails automating the entire refrigeration system.

Thus, necessary automated control and instrumentation must be installed to stop and start all the chillers and water reticulation pumps during Eskom's evening peak period (18:00–20:00). Investigations to switch off chillers were done by a contractor assigned by an ESCo to investigate potential DSM load shifting projects. Eight mines were investigated.

Potential savings were identified during these investigations by switching off the refrigeration system during the peak periods. Infrastructure upgrades normally require control hardware (VSDs or valves), instrumentation hardware, PLC programming and SCADA development.

Implementing these upgrades necessitates installation and commissioning, which contributes to the total cost of DSM load shifting projects. Older mines generally present more installation challenges. Thus, additional time and effort are required for installations to upgrade existing infrastructure. The investigations represent a high-level description of the estimated cost and proposed savings. The cost and savings in Table 6 were simulated and provided by the contractor.

Table 6: Potential DSM load shifting projects

| Mine | Proposed saving [MW] | Installation cost in 2015 [R-million] |
|---|---|---|
| 1 | 2.5 | 1.4 |
| 2 | 3.0 | 1.7 |
| 3 | 3.8 | 2.3 |
| 4 | 4.1 | 2.3 |
| 5 | 2.6 | 1.7 |
| 6 | 2.4 | 1.4 |
| 7 | 3.7 | 2.3 |
| 8 | 3.0 | 2.3 |
| **Average** | **3.1** | **1.9** |

***Conclusion***

Switching off refrigeration systems during peak Eskom's period is less expensive on average than the implementation cost for variable speed control and shifting chiller operations by back-passing chilled water. Even with an average cost of R1.9 million, substantial funding is still required. Therefore, a need exists for a more cost effective strategy.

### 2.4.5 Peak clipping case study on BACs

***Background on the case study***

In 2013, Schutte did a case study by shutting down a mine refrigeration system during Eskom’s evening peak period. Schutte found that in winter, the cold and dry ambient air is sufficient for ventilation cooling. Therefore, surface BACs is not required during winter. The maximum dry-bulb temperature in winter is warmer than the minimum dry-bulb in summer. Thus, it is feasible to switch off the surface BAC during the summer [19].

The mine on which Schutte implemented his case study had already implemented a cooling auxiliary project with variable-flow control. Therefore, the mine’s system was already being controlled by an energy management system. The energy management system cools water down outside of Eskom’s peak period and then stores the water in chill dams [19].

The stored chilled water is then used in mining operations during the peak periods (hence, the cooling auxiliaries and BAC are switched off). It was shown that a saving on the BAC system relates to a saving on the chillers because less water is required. The mine's counterflow BAC draws air from the atmosphere, which is then cooled with the chilled water. The cooled air is discharged into the shaft to supply cool air underground.

The airflow is supplied by 3 × 250 kW fans while the water is pumped by 3 × 110 kW pumps. The rest of the refrigeration system's power consumption is 3 360 kW. The chillers and the BAC were controlled by using the infrastructure already available because of the cooling auxiliary project. Schutte predicted that a saving of 4 073 kW could be achieved before the implementation of the cooling auxiliary project and 3 181 kW could be achieved after the cooling auxiliary project [19].

***Case study investigation***

An empirical approach was used to determine the effect on the underground environmental conditions. Data loggers shown in Figure 27 were installed to measure the BAC outlet, underground and ambient conditions [19].


Figure 27: Tinytag data loggers [47]

The installed loggers measured the air conditions entering 38 Level and 75 Level. While the loggers were being installed, the mine operated as normal and no tests were conducted. The data was used for observation [19]. The data set was then separated into BAC-off and BAC-on groups.

The surface ambient conditions were then plotted against the underground conditions of 38 Level and 75 Level. Line equations were obtained, which indicated the predicted temperatures of the BAC outlet, 38 Level and 75 Level. Figure 28 is an example of the line equations obtained from a data set where the BAC was on [19].

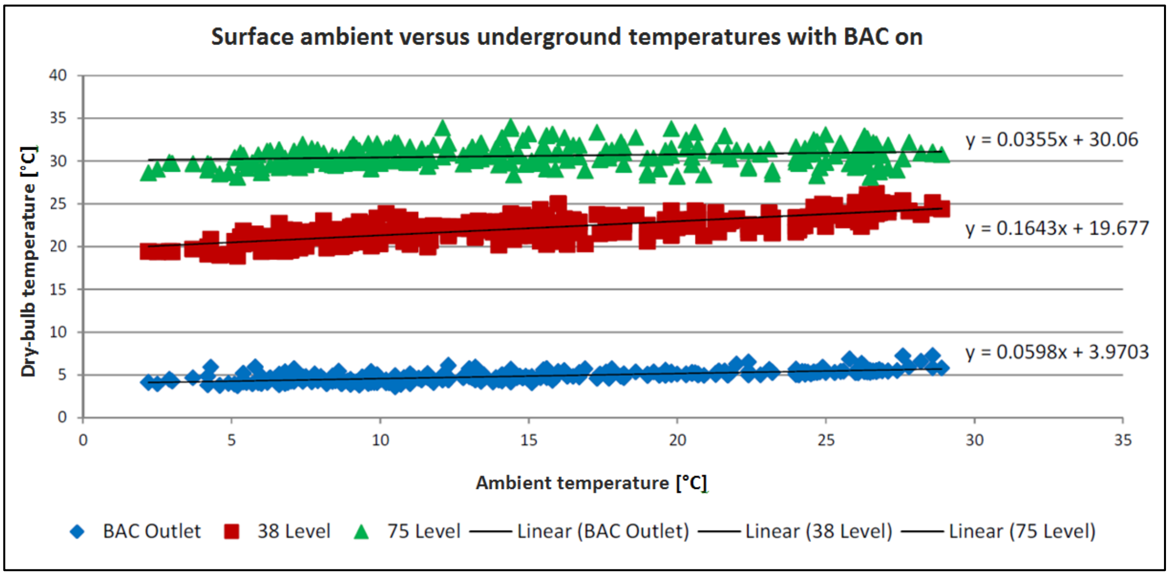


Figure 28: Obtaining a line equation from a data set where the BAC was on [19]

The simulation from the equations was compared with the data measured; the simulation proved accurate within 10%. Schutte found that the underground steel infrastructure and rock face were cooled down to such an extent that it would take time for these temperatures to increase if the BAC was off. Thus, infrastructure serves as a capacitor that would cool the air down with its thermal storage ability[19].

***Implementation phase of the case study***

Schutte's research concluded that an evening peak clip would not have a significant effect on underground temperatures [19]. The peak clipping initiative was then implemented on the mine. For the implementation, data loggers were installed on 53 Level, 56 Level, 62 Level and 64 Level. Figure 29 shows a schematic illustration of the underground levels of the mine.

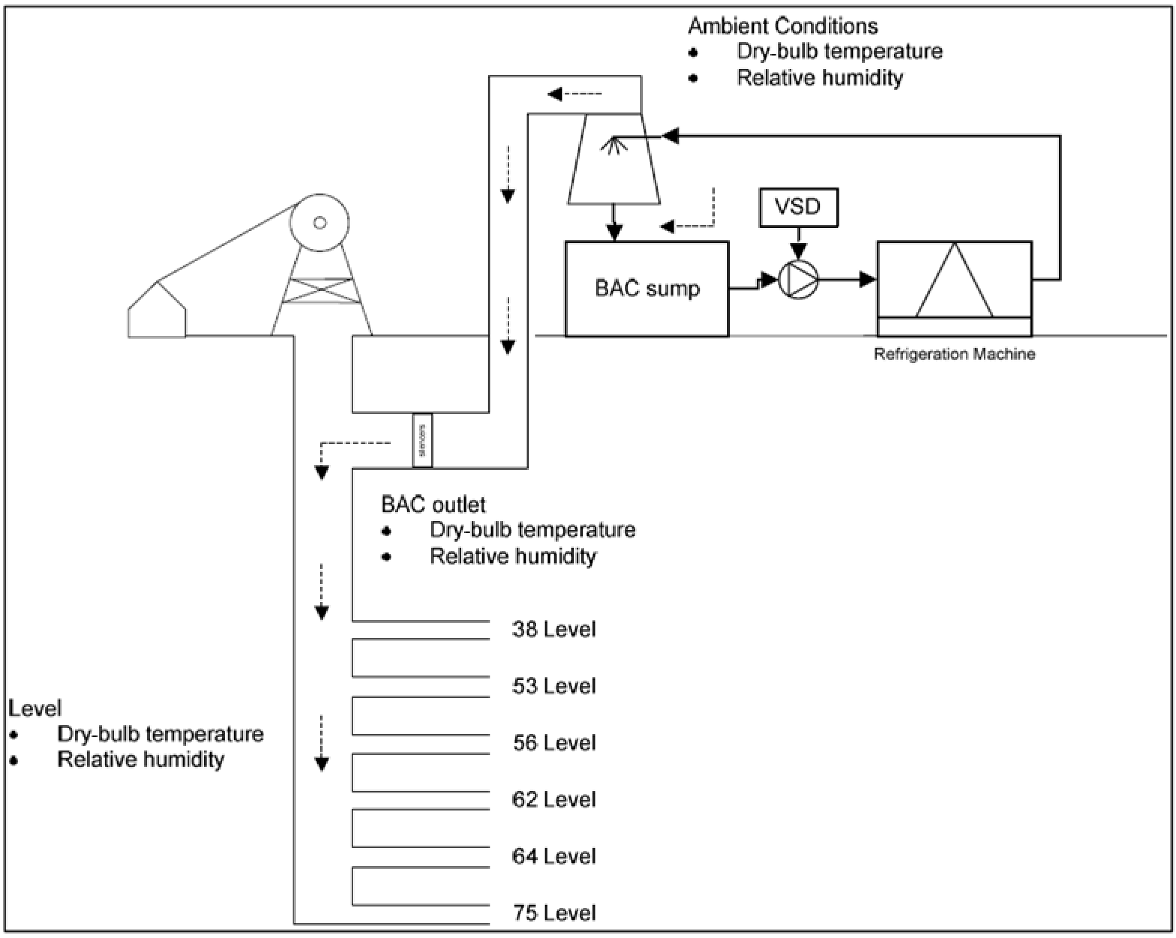


Figure 29: Schematic underground illustration of the mine used in the case study [19]

The effect of the BAC peak clipping strategy on the underground temperatures measured over a 24-hour period on the different levels is shown in Figure 30.

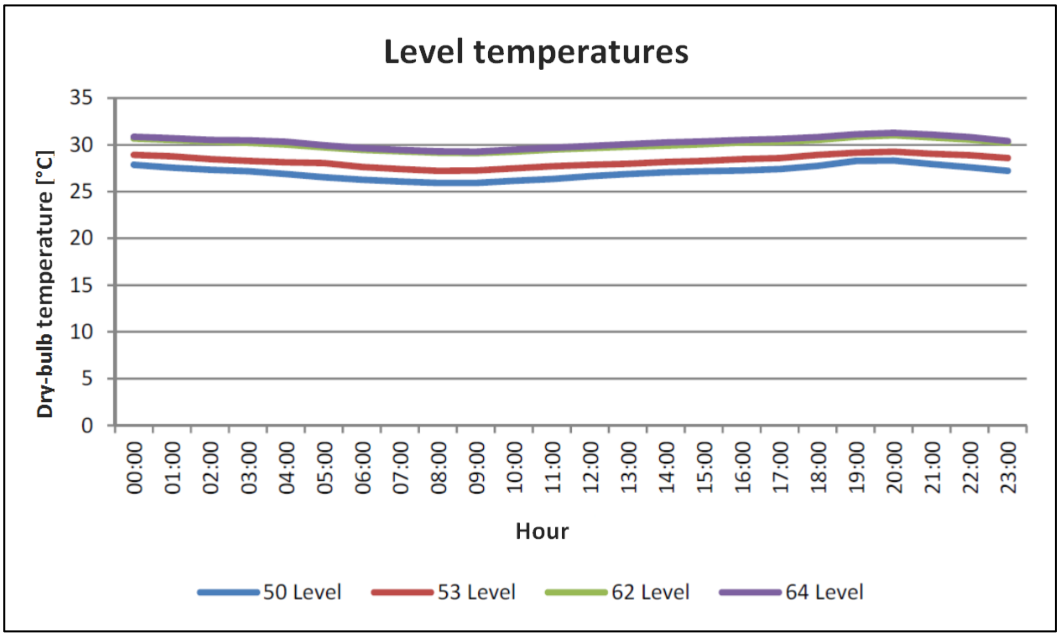


Figure 30: Underground dry-bulb temperatures during the BAC peak clipping strategy [19]

The effect of the BAC peak clipping strategy on the underground relative humidity measured over a 24-hour period on the different levels is shown in Figure 31.

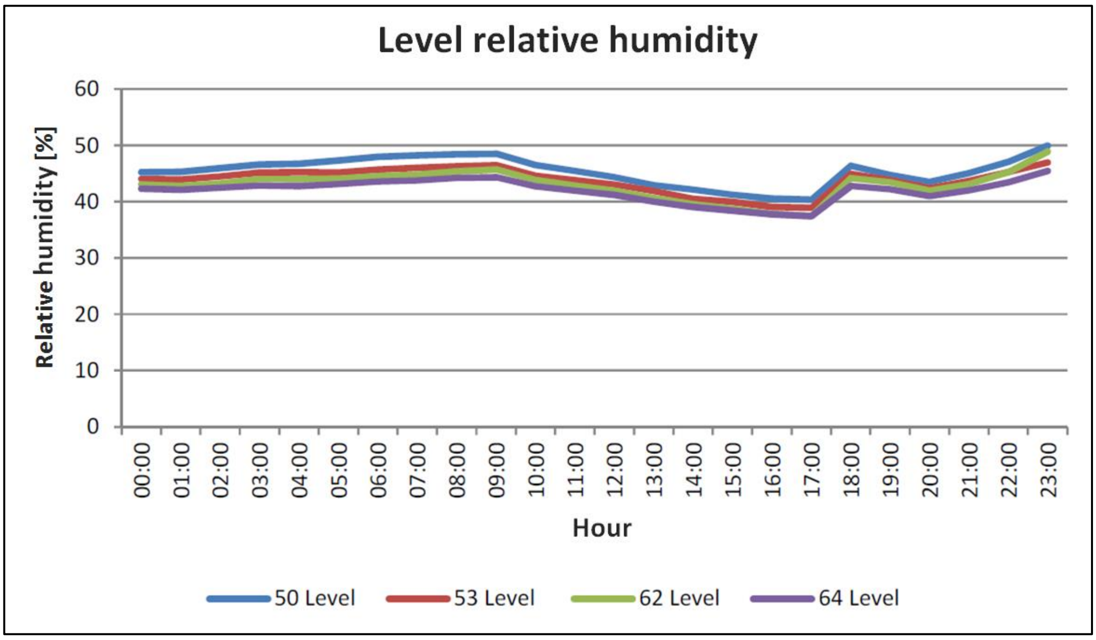


Figure 31: Relative humidity on the levels with the BAC peak clipping strategy [19]

The implementation results on the temperature and relative humidity show that the effect on the underground cooling was insignificant. A saving of 3.1 MW was achieved. The power results are shown over a 24-hour period in Figure 32. With the BAC peak clipping strategy, a summer saving of R1.38 million was realised by using Eskom's TOU structure [19].

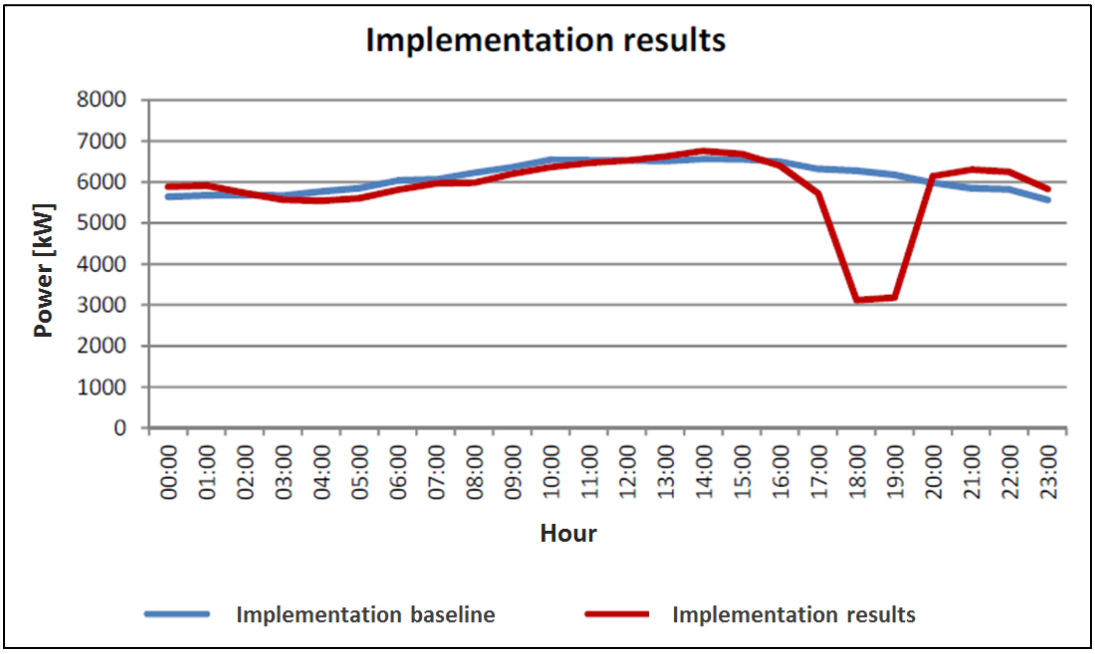


Figure 32: Implementation results of a case study on load clipping BACs [19]

***Other tests***

Holman carried out a test in Eskom's peak period by stopping the water flow of the BAC while two chillers were switched off. Temperature sensors were placed underground at the outlet of the BACs to monitor the effects of the test. The results showed no significant changes in humidity or temperature. Thus, the strategy was feasible and did not threaten the safety of underground workers [35].

***Conclusion***

It can be concluded that it is possible to stop the refrigeration system in Eskom's evening peak period. Schutte achieved a reduction 3.1 MW [19]. Schutte and Holman's research and tests showed an insignificant effect on the underground temperatures when the refrigeration system was stopped during the evening peak periods [19], [35].

### 2.4.6 Evaluating manual and automated control

Savings can be accomplished either by using a fully automated system or by using manual control. Both methods have their advantages and disadvantages. Various systems were once operated manually, but have since been upgraded to allow a computer to control the system in some way [48].

***Automated control***

With automated control, various control parameters must be monitored to safeguard the control of the system within preset values. With an automated system, the operational procedures are controlled without any human involvement. The infrastructure of a system must be upgraded to accommodate automation. These infrastructure requirements are [48]–[50]:

- *Connection cables*: Required for communication between different pumps, pumping levels and the central point. For example, these cables can be fibre-optic or copper cable.
- *Networking equipment*: Such as PLCs, switches and SCADA system.
- *Monitoring instrumentation*: Such as temperature sensors, flow meters, pressure transmitters, dam level indicators, vibration sensors and so forth.

The software uses transmitted data to manage the system according to preset parameters and schedules. Real Time Energy Management System (REMS) is an example of such a software package.

The advantages of automated control are [48]:

- Accurate data logging.
- Predetermined schedules can be used to stop and start equipment.
- Continuous monitoring.
- Immediate response to trip on preset limits.
- Sustainable savings can be achieved.

Typical disadvantages of automated control are [48]:

- Additional maintenance due to more installed equipment.
- Automated systems may be inadequate under specific emergencies.
- Potential long implementation times.
- Required infrastructure upgrades are expensive.

***Manual control***

With manual control, personnel on duty will have to stop and start the equipment manually while constantly monitoring the parameters. Some mines still prefer using manual control because it has been proven that manual control works. Some mines do not like change and want to keep on using old, but proven manual control.

The advantages of manual control are [48]:

- Constant human supervision.
- Lower infrastructure cost in comparison with automated systems.
- Short, to no implementation time.

Typical disadvantages of manual control are:

- Inadequate monitoring of temperature, dam levels, vibration and so forth.
- Due to human supervision, mines could fail to capitalise on cheaper tariffs due to oversight.
- Incorrect and unsustainable data logging.

Previously, manual control was implemented to control underground pumps. The surface (control room) operator observed the dams and gave instructions depending on the dam levels. The surface operator gave instructions to an underground pump operator to stop or start the pump. Manual control was applied by means of minimal computerised input and human intervention [51] Thus, communication is crucial with a manual control intervention.

## 2.5 Conclusion

Chapter 2 provided a better understanding of how refrigeration forms part of the overall water reticulation systems as found at the majority of platinum mines. The highest electricity consuming components within a refrigeration system are chillers, evaporator pumps, condenser pumps, transfer pumps, cooling towers and BAC fans.

Energy usage on refrigeration systems can be managed in order to use less electricity during Eskom's evening peak period (18:00–20:00). Electricity is the fastest growing cost expenditure [3]. Therefore, the electricity usage on platinum mines can be reduced by shifting load (by switching off major electricity consuming components during Eskom's peak periods). This will lessen expenses for platinum mines and reduce Eskom's power demand in peak periods.

Savings can be accomplished either by using a fully automated system (software control) or by using manual control. When implementing load shifting on refrigeration systems, the climate, baseload energy profile, infrastructure, storage capacity and chilled water demand must be considered. This is to ensure that savings can be achieved without affecting underground temperatures and normal production operations.

The infrastructure required to automate refrigeration systems are too expensive for marginal mines. Therefore, a cost effective method is required to implement a load shifting strategy.

In this study, a manual control and monitoring strategy is developed and implemented on Platinum Mine A. Manually stopping and starting machines has been found to be a feasible strategy, which potentially requires low to no funding to implement. The existing equipment and on-duty personnel can be used for a cost effective control and monitoring strategy. Thus, manually implementing a load shifting/clipping strategy could be a cost effective alternative to automated control. In Chapter 3, a feasibility investigation is done on Platinum Mine A to determine the potential for load management.

# Chapter 3. Developing a mine cooling control and monitoring strategy

*Developing and simulating a cost effective strategy by implementing control and monitoring*

## 3.1 Introduction

### 3.1.1 Preamble

As highlighted in Section 2.5, manual control and monitoring are less expensive to implement than automated control. Therefore, implementing cost effective manual control and monitoring may be an alternative to high cost initiatives such as automated DSM projects. In this study, cost effective control and monitoring are implemented on the refrigeration plant of Platinum Mine A.

First, it is necessary to establish if it is feasible to implement control and monitoring on Platinum Mine A. Thus, in Chapter 3, a review is done on Platinum Mine A. The review contributes to the development of a simulation model that predicts the effect of the strategy. The simulation is then compared with estimated savings and results achieved by implementing the strategy on Platinum Mine A.

In this section, Platinum Mine A is reviewed. The review is necessary to identify the following aspects:

- *Refrigeration system layout*: To understand the layout of the specific refrigeration system.
- *System specification*: To identify the major energy-consuming components.
- *Requirements and operating procedures of the refrigeration system*: To identify the parameters, constraints and the existing operating procedures used to ensure normal production operation and safe underground environmental conditions.

### 3.1.2 Refrigeration system layout of Platinum Mine A

The layout of the refrigeration system at Platinum Mine A is shown in Figure 33. A total of 8.6 Ml/day hot water at 22 °C is pumped from underground hot water storage dams. The hot water then flows through a precooling tower and into the precooling tower's sump.

In the sump, the hot water mixes with the surface outlet BAC chilled water. The mix of hot water and outlet BAC chilled water delivers an average temperature of 12 °C. Evaporator pumps then pump the mixed precooled water from the precooling tower's sump through two sets of fridge plants.

The condenser pumps transfer the precooled water from the condenser cooling towers to cool the refrigerant (ammonia gas) in the chillers. With the help of the transfer pumps, the chillers provide chilled water at 1.53 °C to the chill dam and the BAC. The chill water dam provides water for underground mining operations. The BAC cools the air down, which is being forced downwards by an induced draft caused by underground ventilation fans.

As seen in Figure 33, the two sets of fridge plant are configured in parallel. Set 1 consists of Chiller 1, Chiller 2 and Chiller 3. Chiller 1 and Chiller 3 are used during normal operating procedures while Chiller 2 serves as a backup. Set 2 consists of Chiller 4 and Chiller 5, which act as supporting chillers if the cooling demand cannot be satisfied by using only Chiller 1 and Chiller 3.

Therefore, Chiller 4 and Chiller 5 operate either alternatively or together during the warmer periods of the day. The larger evaporator and condenser pumps start up according to the operation of Chiller 1, Chiller 2 and Chiller 3. The smaller evaporator and condenser pumps operate according to the operation of Chiller 4 and Chiller 5.

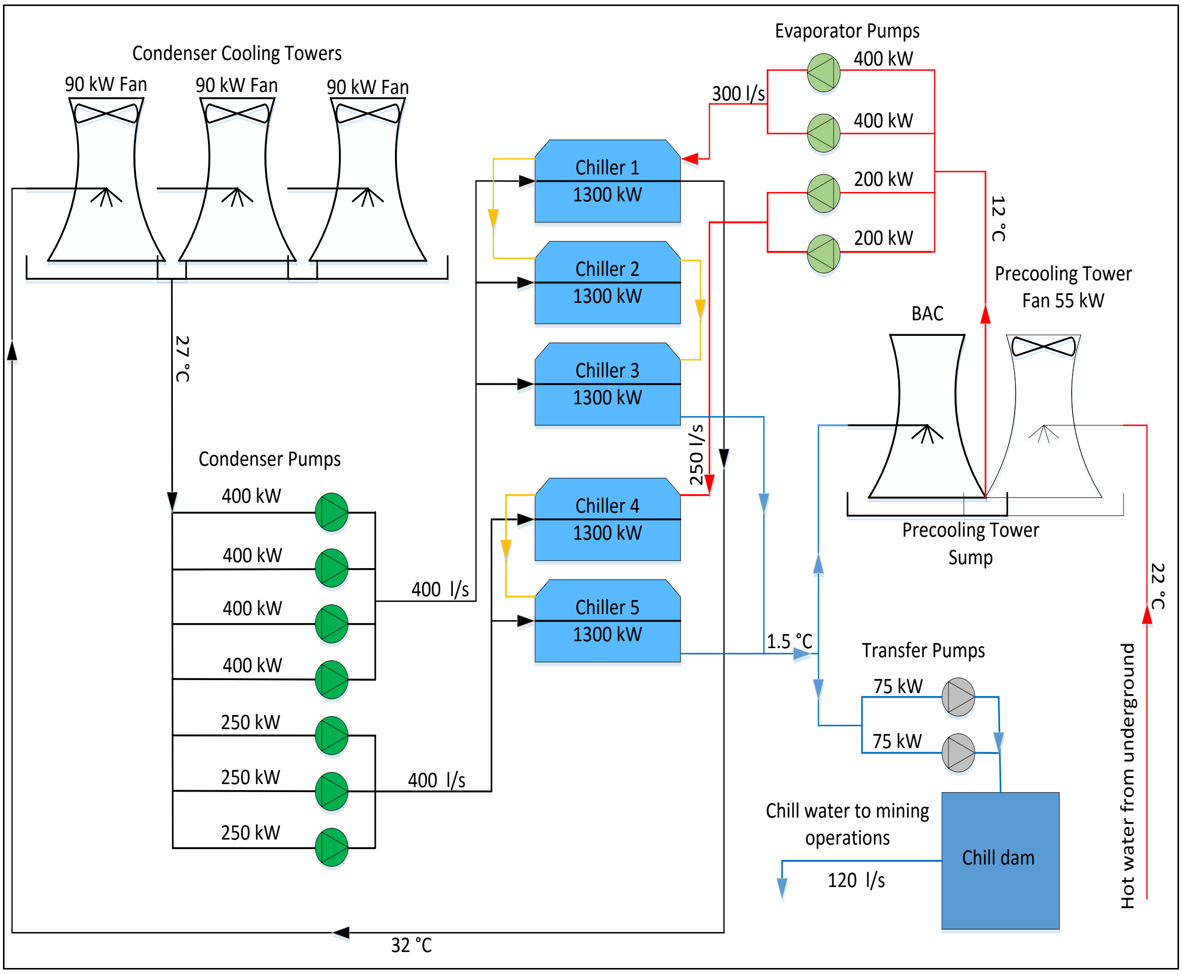


Figure 33: Schematic layout of the refrigeration system at Platinum Mine A

### 3.1.3 System specification of Platinum Mine A

This section displays the specifications of the fridge plant, pumps, precooling tower, condenser tower, BAC tower and chill dam. The cooling system specifications are shown in Table 7 to Table 12.

Table 7: Specifications for the refrigeration system at Platinum Mine A

| **Description** | **Chiller 1–3** | **Chiller 4–5** |
|---|---|---|
| Number of chillers | 3 | 2 |
| Make | Howden | Howden |
| Chiller rating (kW) | 1 300 | 1 300 |
| Compressor type | Screw | Screw |
| Refrigerant | Ammonia | Ammonia |
| Voltage (V) | 6 600 | 6 600 |
| Cooling capacity (kW) | 5 340 | 5 340 |
| Coefficient of performance | 5.75 | 5.75 |
| **Evaporator circuit** | **Chiller 1–3** | **Chiller 4–5** |
| Number of evaporator pumps | 2 | 2 |
| Average evaporator temperature (°C) | 5.6 | 5.6 |
| Evaporator water flow (kg/s) | 280 | 240 |
| Evaporator pump motor rating (kW) | 400 | 200 |
| **Condenser circuit** | **Chiller 1–3** | **Chiller 4–5** |
| Number of condenser pumps | 4 | 2 |
| Average condenser temperature (°C) | 20 | 20 |
| Condenser water flow (kg/s) | 400 | 400 |
| Condenser pump motor rating (kW) | 250 | 400 |

Table 8: Specifications for the surface precooling tower

| **Description** | **Surface** |
|---|---|
| Number of cooling towers | 1 |
| Precooling tower fan rating (kW) | 55 |
| Inlet water temperature (°C) | 20.9 |
| Outlet water temperature (°C) | 16.6 |
| Inlet air WB temperature (°C) | 15 |
| Water flow (kg/s) | 122 |

Table 9: Specifications for the surface condenser cooling tower

| Description | Surface |
|---|---|
| Number of cooling towers | 1 |
| Condenser cooling tower fan rating (kW) | 75 |
| Inlet water temperature (°C) | 32 |
| Outlet water temperature (°C) | 27.5 |
| Inlet air WB temperature (°C) | 22 |
| Water flow (kg/s) | 2 000 |

Table 10: Specifications for the surface BAC

| Description | Surface |
|---|---|
| Number of BACs | 1 |
| Inlet water temperature (°C) | 1.2 |
| Outlet water temperature (°C) | 11 |
| Air inlet WB temperature (°C) | 22 |
| Air outlet WB temperature (°C) | 7 |
| Water flow (kg/s) | 315 |
| Airflow (kg/s) | 315 |

Table 11: Specifications for the transfer pumps

| Transfer pumps | Chiller 1–3 |
|---|---|
| Shaft transfer pump motor rating (kW) | 400 |
| Number of shaft transfer pumps | 2 |

Table 12: Specifications for the surface chill dams

| Description | Chill Dam |
|---|---|
| Number of dams | 1 |
| Total capacity (Ml) | 3.7 |
| Upper limit | 100% |
| Lower limit | 20% |

By evaluating Table 7 to Table 12, the major electricity components can be identified. These components include pumps, BACs, heat exchangers, evaporators, condensers, fans etc. The components in Table 13 were identified at Platinum Mine A to be controlled during Eskom's evening peak periods (18:00–20:00).

### 3.1.4 Requirements and operational assumptions

For this study, an assumption was made that the actual power usage of the components in the refrigeration system was running at 75% (maximum efficiency) of their rated load. This was based on the fact sheet by the US Department of Energy. The fact sheet states that most motors run between 50% and 100% of their rated load. The motors are usually the most efficient near 75% of their rated load [40].

Table 13: Major energy using components

| Description | Quantity | Component power rating [kW] | Assumed power usage [75% of rated load kW] |
|---|---|---|---|
| Evaporator pumps | 2 | 400 | 300 |
| Evaporator pumps | 2 | 200 | 150 |
| Condenser pumps | 4 | 400 | 300 |
| Condenser pumps | 3 | 250 | 188 |
| Transfer pumps | 2 | 400 | 300 |
| Precooling fans | 1 | 55 | 42 |
| Condenser fans | 3 | 75 | 56 |
| Chillers | 5 | 1 300 | 975 |

Platinum Mine A requires cold air from the BAC to maintain an underground temperature below 27.5 °C WB. The chill water dam level must be sufficient during mining operations to satisfy the chilled water demand. Therefore, the chill water dam level should not be below the minimum chill dam level of 20%. No load clipping is currently being implemented on the refrigeration plant.

The operation (power usage) of the refrigeration plant at Platinum Mine A varies according to ambient conditions and underground chilled water demand. The chilled water is supplied to the chill dam for underground operations and to the BACs to cool the underground air supply down. The mining operations can be divided into three shifts, namely, a drilling, blasting and a sweeping shift. During the drilling shift, holes are drilled into the underground rock faces.

During the blasting shift, explosives are inserted into the holes and the mine personnel return to surface. When the underground staff is cleared, the explosives are set off. During the sweeping shift, raw materials and other minerals from the blasting shift are gathered and sent to surface for further processing. Figure 34 shows the three different shift periods and how the electricity tariffs change during the day. The electricity tariffs are based on the Megaflex tariffs of 2014/2015.

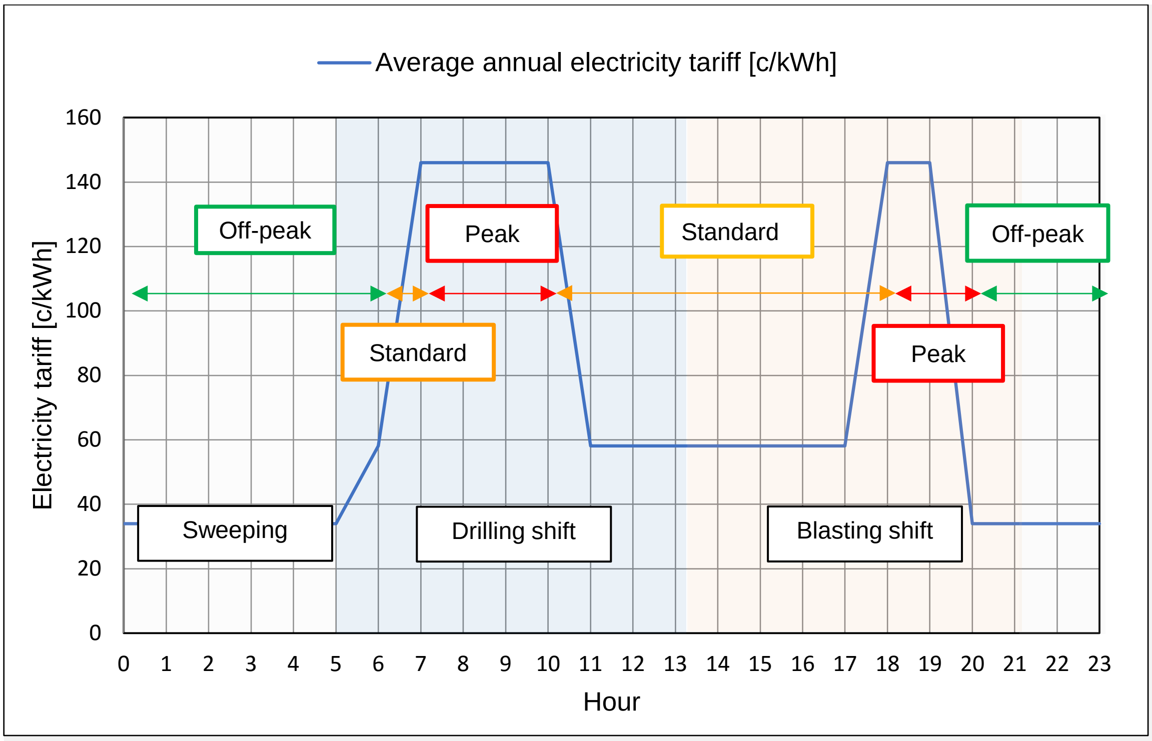


Figure 34: Mining shifts and annual electricity tariff, adapted from [52]

For this study, the operational procedure of the refrigeration plant was monitored and measured during the summer period. A power demand profile was measured, which included the power usage of the entire cooling and ventilation system. The cooling and ventilation system consists of the refrigeration system and the underground ventilation fans. These ventilation fans contribute largely to the total power usage within the cooling and ventilation system.

The usage of the ventilation fans is constant throughout the year due to ventilation and safety concerns. As a result, the power used throughout the year remains constant as well. The intricate operation of the refrigeration system relies on numerous components. These components must work in conjunction with each other to satisfy the cooling requirements. The components on Platinum Mine A work as follows:

- The number of chillers operates according to ambient temperature and underground cooling requirements.

- One evaporator pump is required when two or less chillers are operating.
- One condenser pump is required for each chiller operating.
- One transfer pump operates constantly.
- The precooling fan runs whenever a chiller is operated. Each condenser cooling tower starts up according to ambient conditions and the inlet water temperature.
- Underground ventilation and extraction fans run constantly throughout the year.
- The normal operating procedure of the refrigeration system, which is to deliver the required demand for chilled water and cooled air, is summarised in Table 14.

If the refrigeration system of Platinum Mine A was stopped during Eskom's evening peak period, an estimated average saving between the range of 2 948–4 617 kWh could be achieved. This is based on the assumed power usage of the components in Table 13 and the normal operating procedure in Table 14.

Table 14: Normal operating procedure in the summer periods of Platinum Mine A

| **Component (assumed power usage)** | **Average number of components operating during 00:00–18:00** | **Average number of components operating during 18:00–20:00** | **Average number of components operating during 20:00–00:00** |
|---|---|---|---|
| Chiller (975 kW) | 1–3 | 2–3 | 1–2 |
| Evaporator pump (150–300 kW) | 1–2 | 1–2 | 1–1 |
| Condenser pump (188–300 kW) | 1–3 | 2–3 | 1–2 |
| Transfer pumps (300 kW) | 1–1 | 1–1 | 1–1 |
| Precooling tower (42 kW) | 1–1 | 1–1 | 1–1 |
| Condenser cooling tower (56 kW) | 1–2 | 1–2 | 1–2 |
| Estimated total power usage range of the refrigeration system (kW) | (1 973–4 617) | (2 948–4 617) | (1 973–2 948) |

## 3.2 Simulation model verification

The review of Platinum Mine A in Section 3.1 provided sufficient background to develop a simulation model. Numerous accessible variables such as dam levels, BAC outlet air temperature, ambient air temperature and operating statuses were measured. These measurements were used as inputs to develop a simulation model.

The results obtained with the simulation were compared with the actual measured data to verify if the simulation was accurate. The simulation was done with a combination of Microsoft Excel® and a software programme named Process Toolbox (PTB). The simulation layout can be found in the Appendix.

The cooling demand is highest during the summer period. Platinum Mine A does not require the BAC during the winter period. Thus, the average total power usage of the cooling and ventilation system (including underground ventilation fans) and the ambient temperature was measured during the summer period. A baseline was then determined with the measured total power usage.

The baseline is used to determine the effect of implementing a cost effective strategy has on the total power usage. The PTB simulation results of the total power usage before implementation were on average 1 187 kW lower than the baseline. This power difference was due to the power consumption of the underground ventilation fans that was included in the measurement of the total power usage.

Only the refrigeration plant's power usage was simulated, thus the underground ventilation fans were not included in the simulation model. Therefore, the baseline needed to be scaled for a more accurate comparison between the simulation results and the measured baseline. The baseline scaling method was adapted from [51]. The baseline scaling method work as follows:

Calculating a scaling factor:

$$SF = \frac{\sum_0^{23} X[h]}{\sum_0^{23} Y[h]} \quad \text{(Eq. 1)}$$

Where:

$SF$ = Scaling factor.

$X$ = Simulation/measured average hourly power usage (over a 24-hour profile).

$Y$ = Baseline average hourly power usage (over a 24-hour profile).

$h$ = hour

Scaling the baseline:

$$SB[h] = SF \times Y[h] \qquad \text{(Eq. 2)}$$

Where $h$ ranges from 00 to 23 (0 = 00:00–1:00 and 23 = 23:00 and 00:00).

$SB$ = Scaled baseline hourly power usage (over 24-hour profile).

$Y$ = Baseline average hourly power usage (over a 24-hour profile).

$SF$ = Scaling factor.

Figure 35 shows the baseline (which includes the underground ventilation fans), the scaled baseline (which excludes the underground ventilation fans) and the simulated power usage. The scaled baseline and the simulated total power usage results had a correlation of 89%. Thus, the simulation model was accurate within 11 % when compared with the actual power measurement.

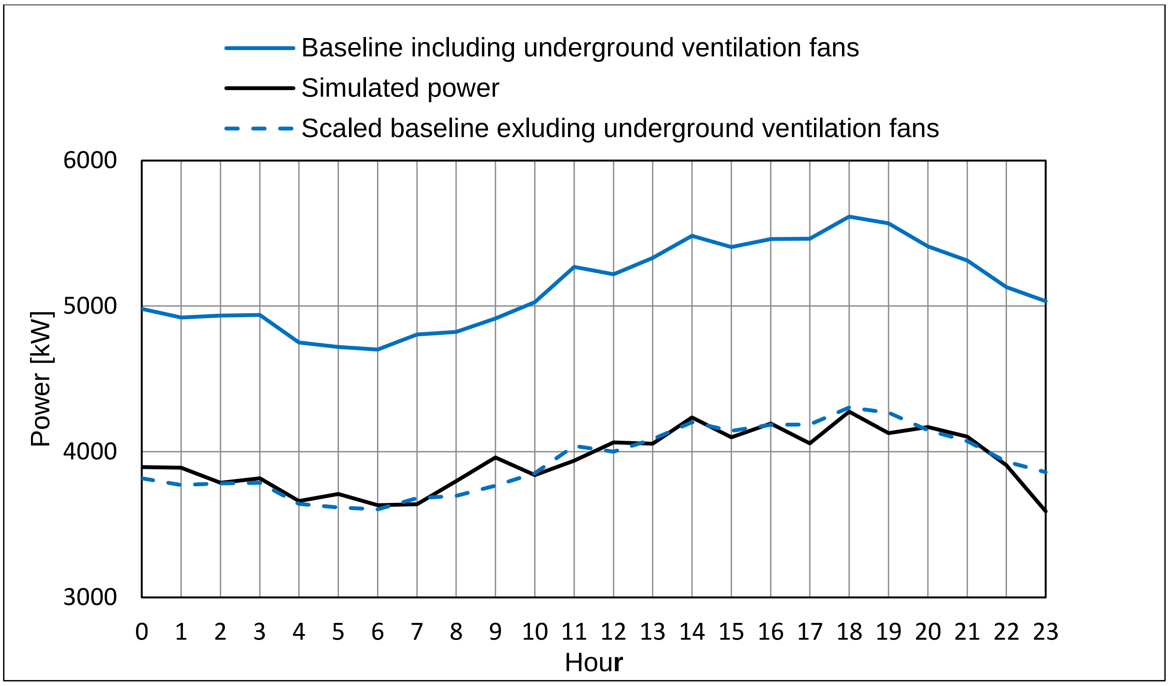


Figure 35: Average power usage and ambient temperatures of the summer period

Cooled air from the BAC and sufficient chilled water supply for underground operations were also simulated and compared with the measured data. The results are shown in Figure 36. The measured data in Figure 36 indicates the dam levels and BAC outlet temperatures required in order to sustain normal operating conditions.

The simulated BAC outlet temperature reacted sensitively to the simulation model's input variables. Therefore, the simulated temperature was not as stable as the measured temperature. The BAC outlet temperature fluctuated with a maximum deviation of 2.5 $^{o}$C WB. Although the simulation results deviated, the average simulated and measured BAC outlet temperature were the same at 5.3 $^{o}$C WB. Thus, the simulated temperature deviation was not a concern.

The simulated chill water dam level was not as sensitive to the input variables as the BAC outlet temperature (as seen in Figure 36). The simulated result of the chill dam level had an 86% correlation with the measured level. Thus, the simulation model was sufficient to simulate the effect of the developed strategy.

The flow data required to identify the chilled water flow rate to the chill dam was insufficient, thus the simulated chill dam level in Figure 36 was used along with Equation 3 to predict the chill dam level during implementation of the developed strategy. This also verified the simulated effect of the chill dam level.

$$PCL = \frac{\sum_{18}^{20} CCW[h]}{CC} \times \sum_{18}^{20}[h] \quad \text{(Eq. 3)}$$

Where $h$ ranges from 18:00 to 20:00.

$PCL$ = Percentage chilled water loss.

$CCW$ = Cubic metres of inlet chilled water.

$CC$ = Chill dam capacity.

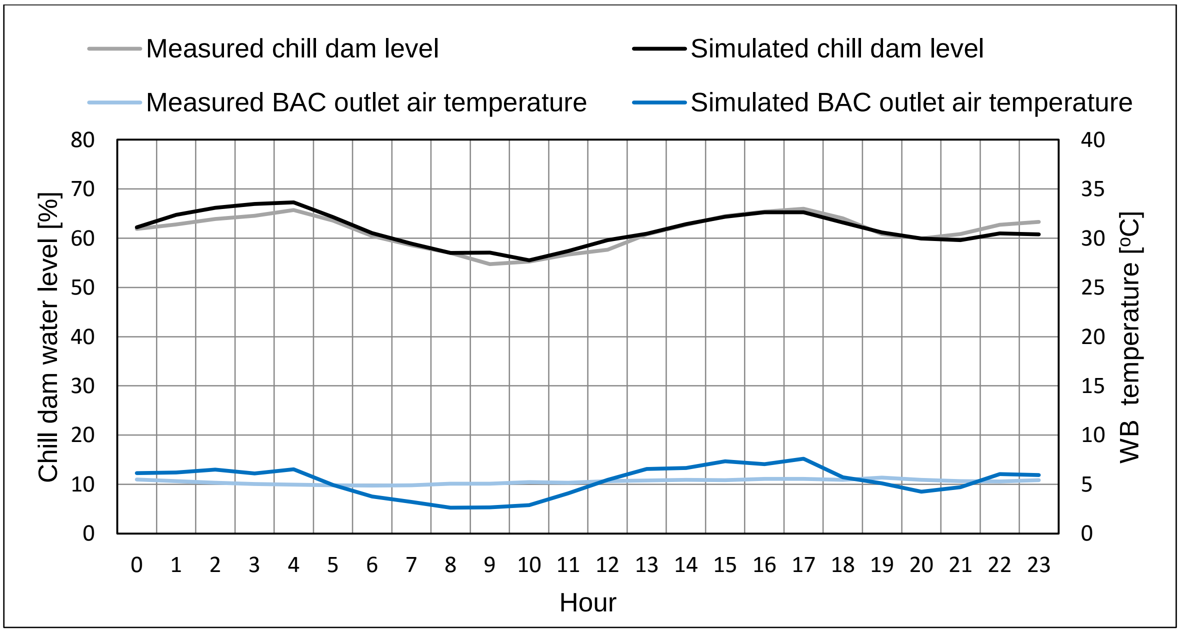


Figure 36: Measured chill dam and BAC outlet air temperature compared with simulated results

Tests were conducted on the underground temperature from previous investigations on Platinum Mine A. The tests were done to establish the temperature difference between the BAC outlet and the underground air temperature. A Tinytag temperature logger had already been installed underground to measure the underground air temperature during the previous investigations. Figure 37 indicates the location of the temperature logger used for the previous investigations. The location (bottom level) of the temperature logger level was provided by the ventilation department of the mine.

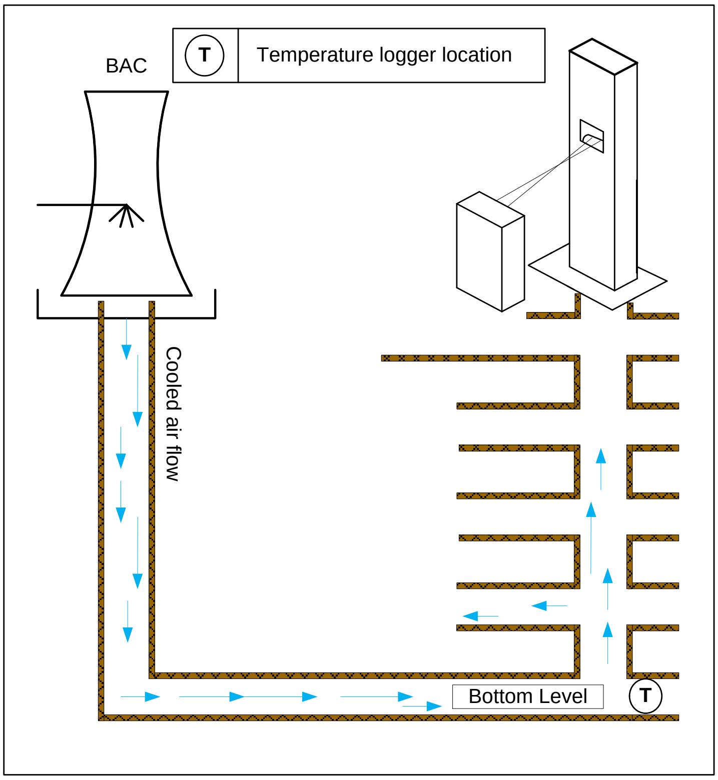


Figure 37: Underground layout of Platinum Mine A

The measured data in Figure 38 was used in a Microsoft Excel® LINEST function to obtain Equation 4, which had an 88% correlation with the variables measured. The measurement results of these tests are shown in Figure 39. Equation 4 was used with simulated variables to determine the predicted underground temperature in Chapter 3. The measured variables are used in Equation 4 to determine the underground temperature during the implementation of the strategy in Chapter 4. Equation 4 is as follows:

$$y = \sum_{0}^{23}(0.056732696a + 0.257321456b + 13.57364691)[h] \quad \text{(Eq. 4)}$$

$$R^2 = 0.88$$

Where

$y$ = Expected average underground WB air temperature (over a 24-hour profile).

$a$ = Ambient temperature (over a 24-hour profile).

$b$ = BAC WB outlet air temperature (over a 24-hour profile).

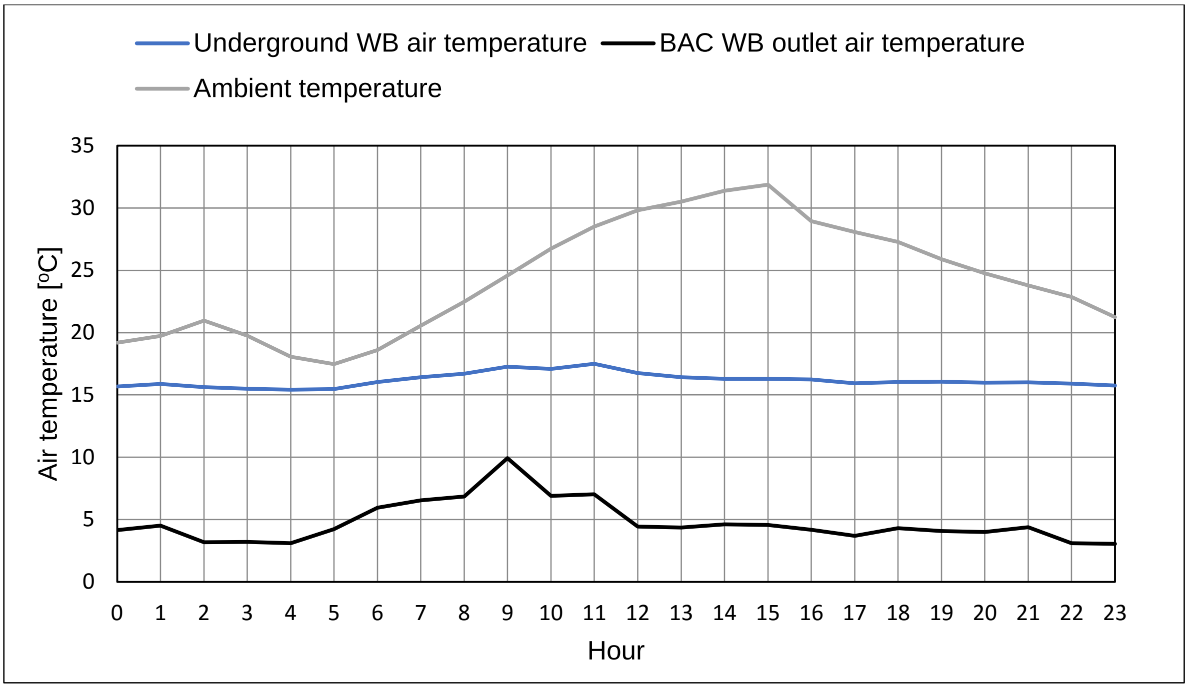


Figure 38: Air temperature measurement results from previous investigations

Section 3.2 provided the required information to show that the simulation model was accurate to simulate the effect of the developed strategy on Platinum Mine A. The simulation results satisfied the requirements for Platinum Mine A. Thus, approval was granted by Platinum Mine A's personnel to proceed with tests.

## 3.3 Control and monitoring strategy

In this section, the normal operating procedure of Platinum Mine A is adapted to accommodate a cost effective control and monitoring strategy. All chillers, condenser pumps, transfer pumps and cooling towers must be switched off manually during Eskom's evening peak period (18:00–20:00) if the underground conditions are safe and the dam level is sufficient.

Only the evaporator pumps must operate as normal due to water circulation concerns and to ensure residual cooling while the chillers are off. The ventilation and underground extraction fans remain operational during the load clipping period to ensure sufficient underground ventilation.

The on-duty surface (control room) operator must stop the refrigeration plant via the SCADA according to the underground WB temperature and the chill dam level. Labour costs can be saved by using operators already on duty in the control room. The strategy phases, which are schematically shown in Figure 39, can be explained as follows:

1) An on-duty control room operator must be aware of the strategy that will be implemented.

2) The control room operator must monitor time for the Eskom's peak period (18:00–20:00). If the time falls within the Eskom peak period (true), the operator must start to monitor the parameters. If the time falls outside of the Eskom peak period (false), the refrigeration system must continue with normal operations.

3) The control room operator must monitor the dam levels and the BAC outlet air temperature.

4) If the parameters are sufficient and under preset limits (true), the control room operator must stop the refrigeration system (excluding the evaporator pumps). If the parameters are not sufficient or under preset limits (false), the operation must continue as normal.

5) The control room operator must switch off the refrigeration system via the SCADA. The existing shutdown sequence programmed in the SCADA must be used to stop the refrigeration system.

6) When the refrigeration system is stopped (offline), the operator must monitor the parameters every 15 minutes. An alarm must be set to remind the operator to check the limits.

7) If the parameters remain within the limits during Eskom's peak period, then the refrigeration system must remain off. Once the parameters are not sufficient or within preset limits, then the system must be switched on again. If the time is not during Eskom's peak period, the system must also be switched on.

8) The control room operator must switch the refrigeration system on via the SCADA. The existing start-up sequence programmed in the SCADA, must be used for switching the refrigeration system on.

Once the refrigeration system is switched on, the operation continues as normal and the strategy starts again at Phase 1.

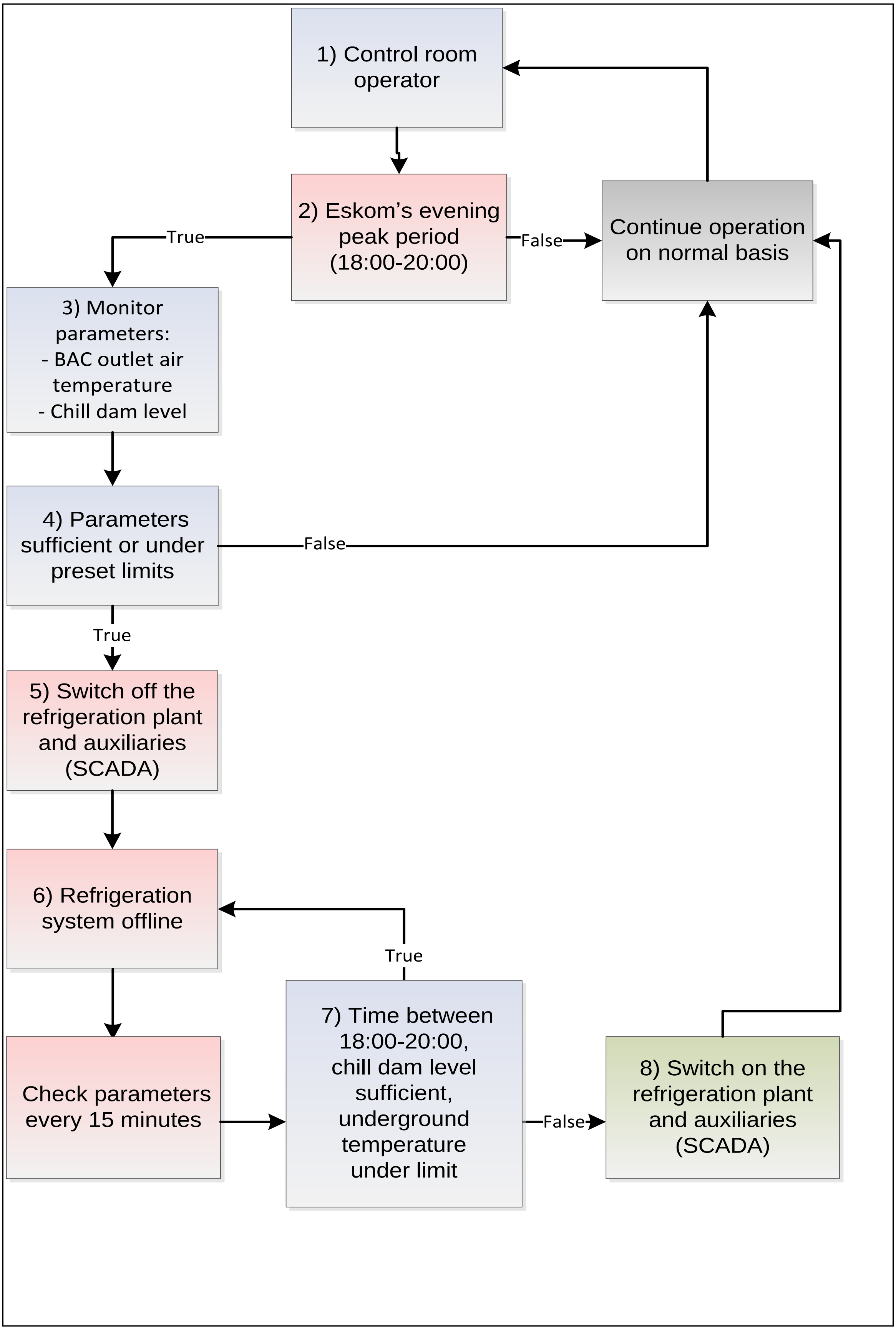


Figure 39: Block schematic of the control and monitoring strategy

Table 15 displays how the normal operating procedure during Eskom's peak period should be adjusted to accommodate the cost effective strategy shown in Figure 39. The projected savings are also shown in Table 15. The savings will vary according to the efficiencies of the auxiliaries that deteriorate with time if they are not maintained.

Table 15: Load clipping strategy during Eskom's peak period (18:00–20:00)

| Component (assumed power usage) | Number of components that is on without strategy | Number of components that is on with strategy | Projected savings due to strategy [kW] |
|---|---|---|---|
| Chiller (975 kW) | 2–3 | 0 | 1 950–2 925 |
| Evaporator pump (150–300 kW) | 1–2 | 1–2 | 0 |
| Condenser pump (188–300 kW) | 2–3 | 0 | 600–788 |
| Transfer pumps (300 kW) | 1–1 | 0 | 300 |
| Precooling tower (42 kW) | 1–1 | 0 | 42 |
| Condenser cooling tower (56 kW) | 1–2 | 0 | 56–12 |
| Total | 8–12 | 1–2 | (2 948–4 617) |

## 3.4 Assessing the developed strategy

### 3.4.1 Preamble

In Section 3.3, a cost effective control and monitoring strategy were developed with the requirements and normal operating procedures in mind. In Section 3.3, an estimated average saving, ranging between 2 948–4 617 kW, was determined by using the operating procedures and assumed power usages of the components.

In this section, the developed PTB simulation model in Section 3.2 is used to simulate the effect of implementing the strategy developed in Section 3.3. The total power usage, chill dam level and BAC WB outlet air temperature are simulated and analysed to determine if the strategy is feasible to be implemented on Platinum Mine A.

### 3.4.2 Total power usage with the strategy implemented

Figure 40 shows the potential saving that can be achieved by implementing the cost effective control and monitoring strategy. An average potential saving of 3 685 kW could be achieved during summer periods. The saving is based on the scaled baseline that was calculated in Section 3.3.

The potential saving of 3 685 kW that was obtained from the simulation is within the estimated saving range of 2 948–4 617 kW, which was based on the operating procedures and assumed power usage of the components. This verifies that the simulation saving results are within in the expected range. The area under the simulated power usage profile in Figure 40 is due to the evaporator pump not being switched off, as was highlighted in Section 3.3.

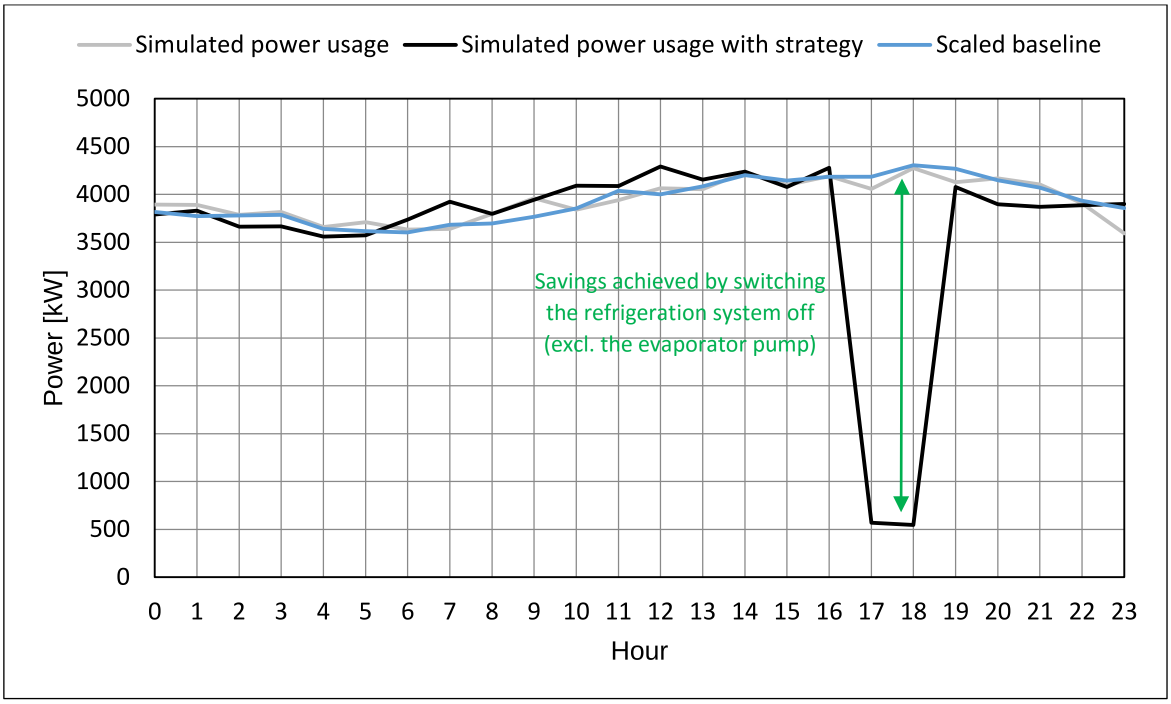


Figure 40: Simulated power saving results by implementing the developed strategy

It is clear from the results in Figure 40 that potential savings can be achieved by implementing the developed strategy. However, there was a concern whether the chill dam level and BAC outlet temperature would satisfy cooling requirements if the strategy was implemented. Thus, the chill dam level and BAC outlet temperature are simulated in Section 3.4.3 and Section 3.4.4.

### 3.4.3 The chill dam level with the simulated strategy implemented

The dam receives no water supply during the peak period (18:00–20:00) if the transfer pumps are switched off. The effect that the implementation of the developed strategy has on the chill dam level is predicted by using Equation 3 and by a simulation done in PTB.

The average simulated chilled water flow rate to the chill dam during Eskom's peak period is 170 ℓ/s. Thus, 610 $m^3$/h of chilled water is required to flow into the chill dam between 18:00 and 20:00 to sustain the simulated dam level. By using Equation 3, it is calculated that 1 220 $m^3$ of chilled water will be lost if the transfer pumps are switched off from 18:00 to 20:00.

The chill dam has a capacity of 3 700 $m^3$, thus with a loss of 1 220$m^3$ of chilled water the chill dam level is predicted to decrease by 33%. By adjusting the simulated dam level in Figure 41 to drop 33% (610 $m^3$/h), the predicted minimum chill dam level will be 30%. The simulated chill dam level in PTB showed a decrease of 25% and reached a minimum level of 38%.

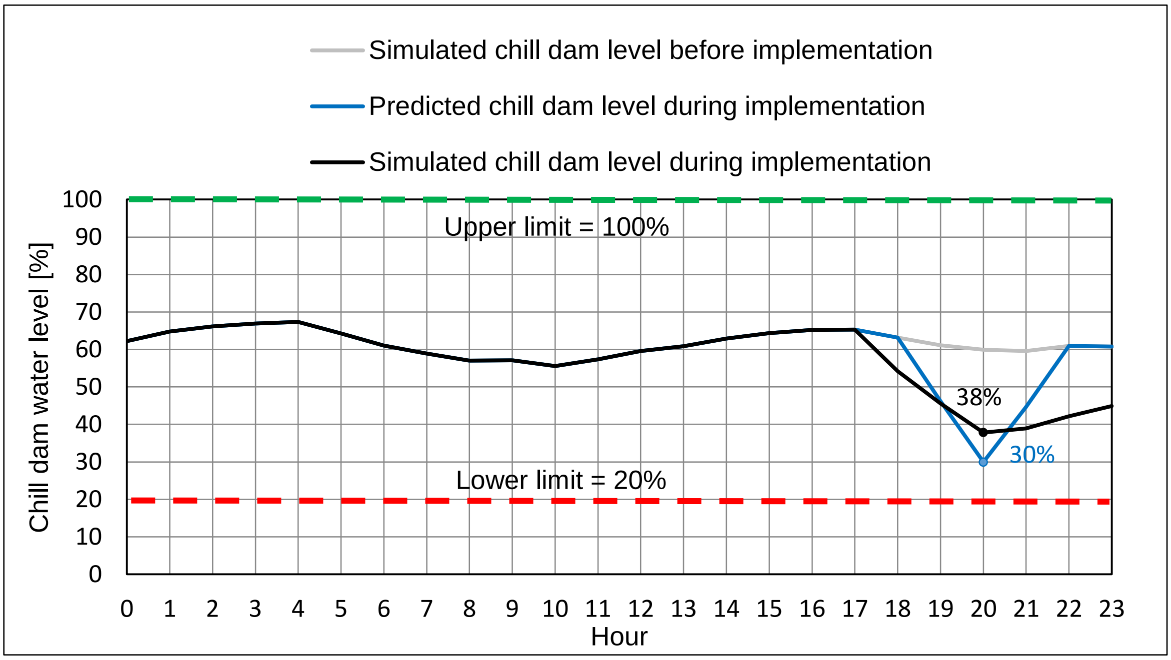


Figure 41: Simulated effect on the chill dam level during peak period (18:00–20:00)

The aim of the simulated and predicted chill dam level is to determine if the chilled water supply would be sufficient during the implementation of the developed strategy. As seen in Figure 41, the simulated and predicted chill dam levels were within the upper and lower limits of 100% and 20% respectively. Thus, the dam level will be of no concern during the implementation of the developed strategy.

### 3.4.4 The BAC outlet and underground air temperature with the simulated strategy implemented

Figure 42 shows the simulation results of the BAC outlet air temperature. By simulating the implementation of the developed strategy, the BAC outlet air temperature increased with 8.4 °C WB. A maximum temperature of 11.9 °C WB was reached after the simulated implementation period. The predicted underground air temperature was determined by using Equation 4. The average ambient temperature during the summer period and the simulated BAC WB outlet temperature were used as variables in Equation 4 to calculate the predicted underground temperature.

Due to the increase of the BAC outlet air temperature, the underground temperature increased by 2.2 °C WB. A maximum of 18 °C WB was reached, which was 9.5 °C WB below the underground air temperature limit. The BAC outlet and underground air temperatures recovered to normal within the first hour. Therefore, the cooling requirements for underground conditions would not be significantly affected during the implementation of the developed strategy.

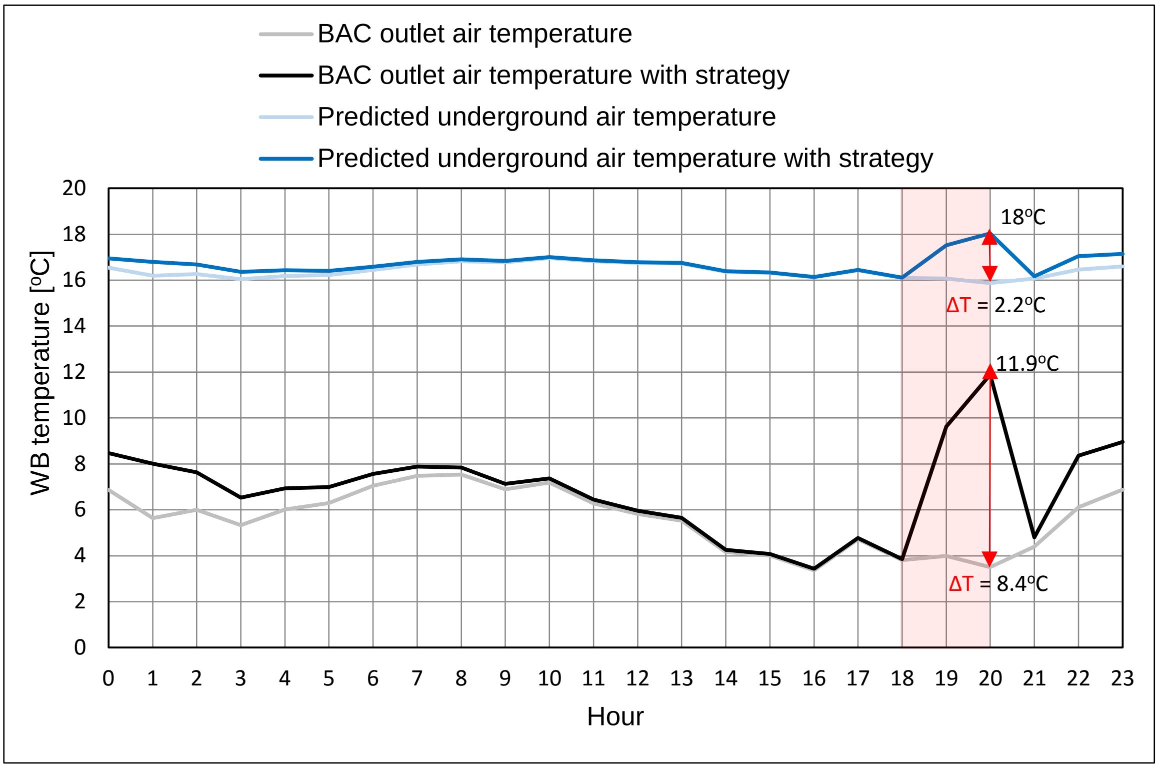


Figure 42: Simulated BAC outlet and predicted underground air temperatures

## 3.5 Conclusion

Chapter 3 provided the necessary information to understand the refrigeration system's parameters, constraints and the existing operating procedure. Chapter 3 also helped identify the main energy using components on the refrigeration system of Platinum Mine A. This contributed to the development of a cost effective control and monitoring strategy.

The existing operating procedure was adapted to save energy by switching off major electricity consuming components during the Eskom peak periods. By using the normal operating procedure and the assumed power usage of the refrigeration system's components, an estimated saving ranging between 2 948 and 4 617 kW was determined.

The developed strategy was simulated to investigate the effect that the strategy would have on the refrigeration system’s power consumption. The simulation result showed a potential average saving of 3 685 kW, which verified the estimated saving range. The chill dam level, BAC outlet and underground air temperatures were simulated.

The simulated dam level was predicted to be sufficient during the implementation of the developed strategy with a minimum level of 30%. The estimated underground air temperature was 9.5 C WB below the limit. Thus, the simulation results showed that the cooling requirements would be satisfied during the implementation period of the developed strategy.

# Chapter 4. Validating the cooling strategy results

*Implementing and validating the cost effective strategy*

## 4.1 Introduction

Chapter 3 gave an overview of a refrigeration plant and it was concluded that implementing the developed strategy would be feasible. The simulation results indicated that the cooling requirements would be satisfied during the implementation period. In this chapter, the strategy developed in Section 3.3 is implemented on the refrigeration plant of Platinum Mine A. The implementation consists of two tests that were conducted on different days during the summer period. The results are compared with the estimated range and simulation results.

As the tests were conducted, the control room operators assisted with monitoring the chill dam level and the BAC outlet temperature from the SCADA. Thus, sufficient chilled water supply for mining operations was ensured along with safe underground conditions. Figure 43 is an illustration of a refrigeration system's SCADA within the control room. The following parameters and constraints were measured from the SCADA during the tests:

- *Power usage*: The SCADA logged the power usage from the main incomer of the refrigeration plant. The power usage was measured to determine the energy saving during the implementation of the developed strategy.
- *BAC outlet temperature and ambient conditions*: The SCADA logged the temperature data from a temperature logger inside the BAC and a weather station outside the BAC.
- *Dam level*: The SCADA logged the chill dam level from a pressure sensor inside the dam. The dam level was measured to determine if the water availability during the implementation of the developed strategy would be sufficient.

Figure 43: SCADA monitor within the refrigeration system's control room

## 4.2 Energy saving during the tests

### 4.2.1 Preamble

In this section, the power measuring equipment and their locations are illustrated. The energy saving results of the two tests are compared with the estimated range in Table 14 of Section 3.1.3 and the simulated power results in Section 3.4.

The main incomer of the refrigeration plant has a digital power meter installed in one of the panels. The power meter displays the voltage (V), current (A) and power (W) measurements of the entire refrigeration system including the underground ventilation fans. The power meter sends the measurements to the SCADA via a PLC. These measurements are stored on the SCADA and historical data can then be obtained.

During Test 1 and Test 2, the power meter measured the power results. The power results were extracted in a comma separated value (CSV) format from the SCADA to analyse the power during the implementation of the strategy. Figure 44 is an illustration of the power meter installed into the incomer panel.


Figure 44: Digital power meter inside the main incomer

### 4.2.2 Power results for Test 1

The power data for Test 1 was extracted from the SCADA and processed further in Microsoft Excel®. The data processed for Test 1 is shown in Table 25 of the Appendix. As can be seen from the results, an average saving of 4 048 kW was achieved during Test 1.

The processed data from Table 25 is displayed in Figure 45. As seen in Figure 45, the power usage during Test 1 outside the peak period varied when compared with the baseline. The variation was due to the changing mining operations, conditions and chilled water demand during the day. Each day had a different power usage profile.

The baseline usage was determined with the average power usage during the summer period. Therefore, outside Eskom's peak period, the baseline usage profile differed from the power profile of Test 1. During Test 1, the entire refrigeration system was switched off. Only the evaporator pumps were operating as normal. The remaining power usage during the peak period was a combination of the underground fans and the evaporator pumps.

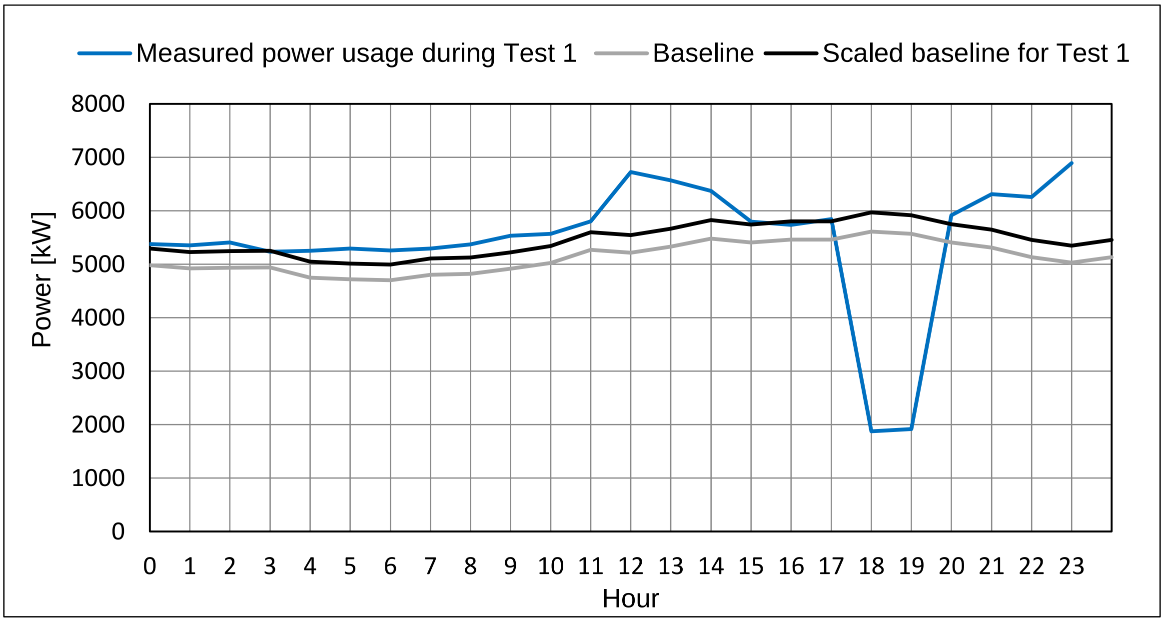


Figure 45: Test 1 energy saving results including underground ventilation fans

### 4.2.3 Test 1 power usage compared to the simulation

The simulated power usage profile in Figure 46 was based on the average power usage of the summer period, which excluded the underground ventilation fans. Only the components of the surface refrigeration system were included in the simulation profile. The power measurement on the SCADA during Test 1 included the power usage of the underground ventilation fans. Thus, the simulated baseline profile was scaled to be compared to the measured results of Test 1. Figure 46 show how the simulated and measured power usage differ due to impact of the underground ventilation fans.

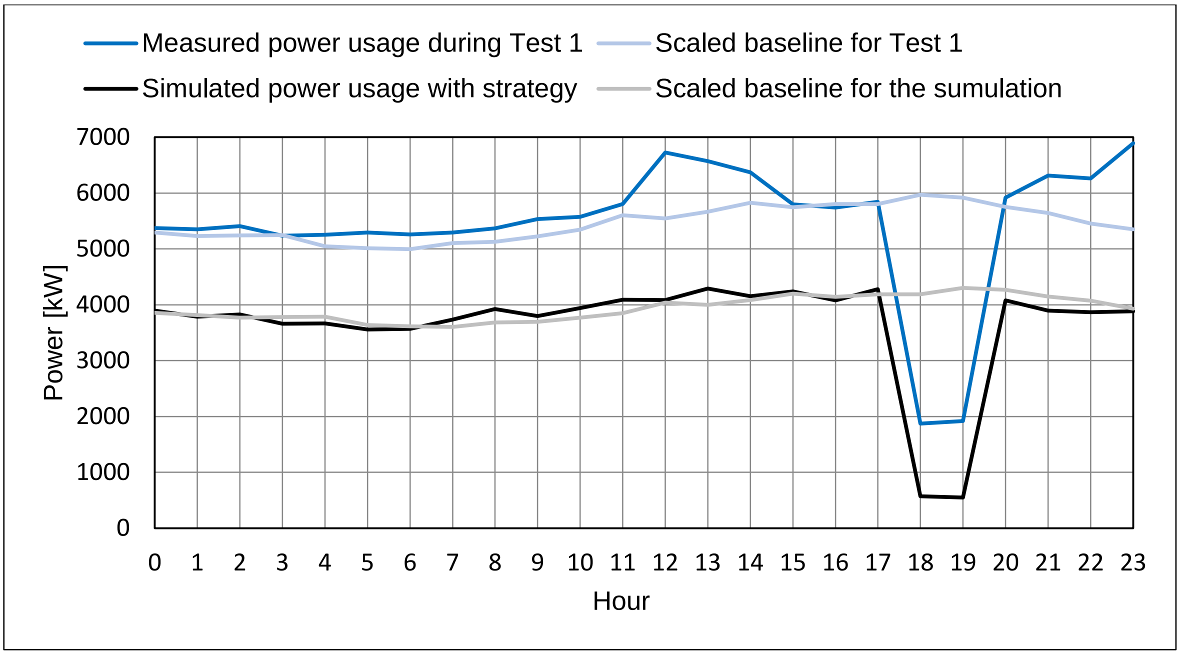


Figure 46: Simulated power results compared with Test 1

After using the scaled baseline to determine the saving, a larger saving was achieved with Test 1 than with the simulation results. The average power usage of Test 1, excluding the underground ventilation fans, was higher than the average power usage of the simulation. The saving result of Test 1 was compared with the estimated saving range and the simulation results in Table 16.

Table 16: Average saving comparison with Test 1

| | **Average saving [kW]** |
|---|---|
| **Estimated range** | 2 948–4 617 |
| **Simulation result** | 3 685 |
| **Test 1 result** | 4 048 |

The simulation results were 91% correct when compared with the results of Test 1. An assumption was made that the mining operations and chilled water demand during the simulation and the tests were similar. The power result of Test 1 was within the estimated saving range. Thus, the power result for Test 1 was validated.

### 4.2.4 Power results for Test 2

The power data for Test 2 was extracted from the SCADA and processed further in Microsoft Excel®. The data processed for Test 2 is shown in Table 26 in the Appendix. As seen from the results, an average saving of 3 774 kW was achieved during Test 2.

The processed data from Table 26 is displayed in Figure 47. As seen in Figure 47 the power usage during Test 2 outside the peak period varied when compared with the baseline. The variation was due to changing mining operations, conditions and chilled water demand during the day.

The baseline usage was determined with the average power usage during the summer period. Therefore, outside Eskom's peak period, the baseline usage profile differed from the power profile of Test 2. The entire refrigeration system was switched off during the implementation of Test 2. Only the evaporator pumps were operating as normal. Thus, the remaining power usage during the peak period was a combination of the underground fans and the evaporator pumps.

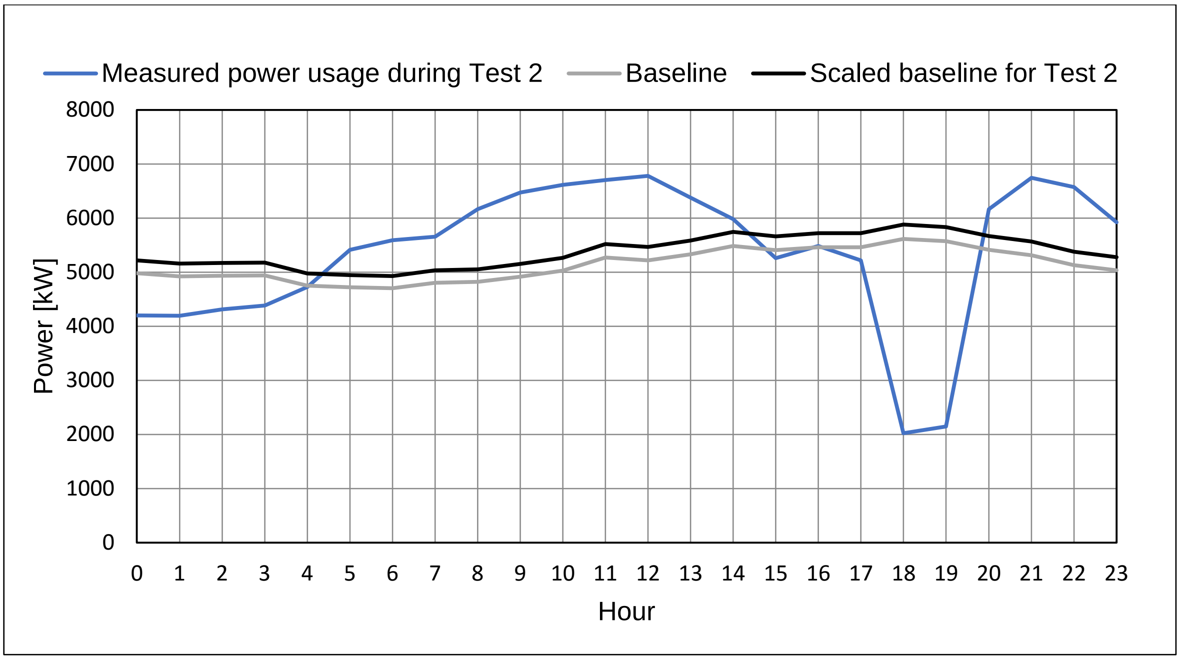


Figure 47: Test 2 power measurement including underground ventilation fans

### 4.2.5 Test 2 power usage compared with the simulation

The simulated power usage profile in Figure 48 was based on the average power usage of the summer period, which excluded the underground ventilation fans. The power usage profile of Test 2 was from a day within the summer period. Note that the power measurement on the SCADA during the Test 2 included the total power usage of the underground ventilation fans.

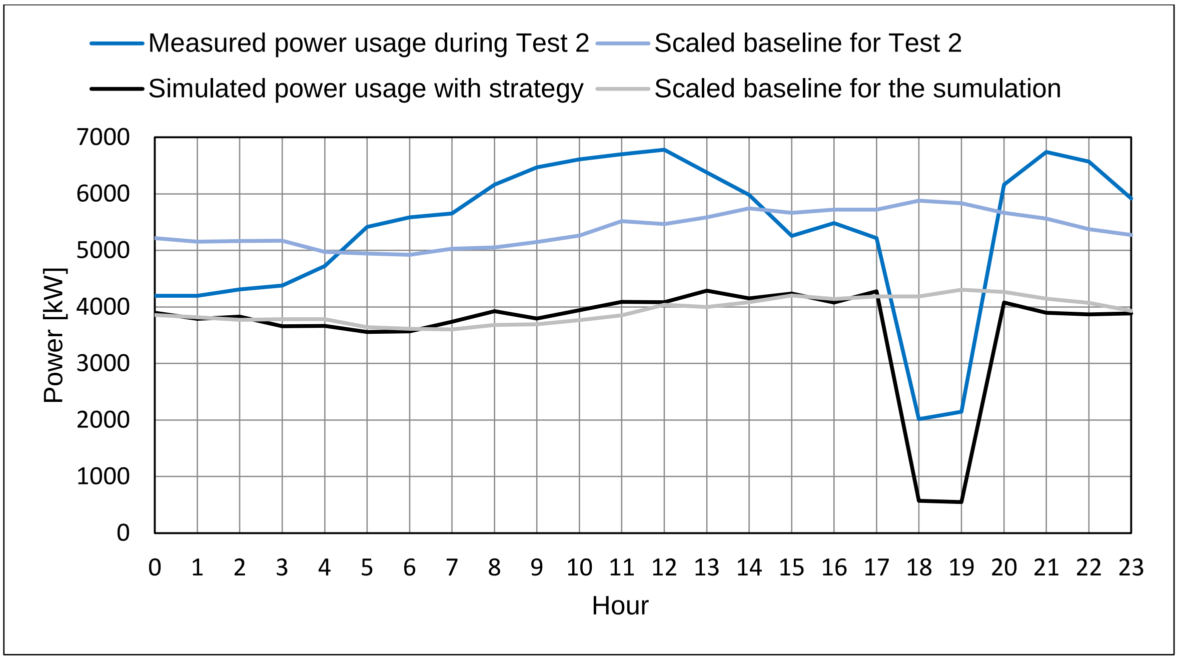


Figure 48: Simulated power results compared with Test 2

The average power usage of Test 2, excluding the underground ventilation fans, was higher than the average power usage of the simulation. Thus, by using the scaled baseline to determine the saving, a higher saving was achieved during Test 2 when compared with the simulation results. The saving result of Test 2 was compared with the estimated saving range and the simulation results in Table 17.

Table 17: Average saving comparison with Test 2

| | **Average saving [kW]** |
|---|---|
| **Estimated range** | 2 948–4 617 |
| **Simulation result** | 3 685 |
| **Test 2 result** | 3 774 |

The simulation results were 98% correct when compared with the results of Test 2. An assumption could be made that the mining operations and chilled water demand during the simulation and the tests were similar. The power result of Test 2 was within the estimated savings range. Thus, the power result for Test 2 was validated.

### 4.2.6 The power usage difference between the two tests and the simulation

The power usage profile in Figure 49 of the two tests was from two different days within the summer period. Note that the power measurement on the SCADA during the tests included the total power usage including the underground ventilation fans.

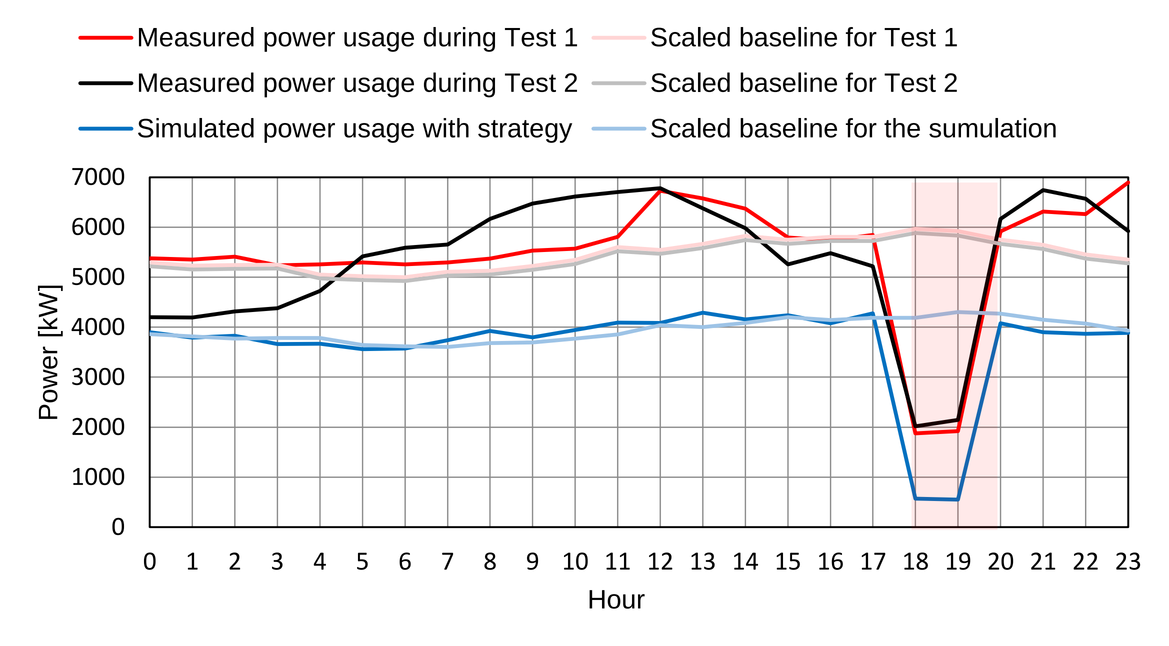


Figure 49: Simulated power results compared with Test 1 and Test 2

As seen from Figure 49, the power demand profiles for Test 1 and Test 2 were different. This was due to different mining operations and chilled water demand on each day. Between the two tests, an assumption could be made that the mining operations and chilled water demand during Test 2 were more similar to the simulation than Test 1. Based on the average saving of 3 991 kW between two tests, the simulation was 95% accurate (see Table 18). Therefore, the power saving for the two tests was as predicted and was validated.

Table 18: Average overall saving comparison

| | **Average saving [kW]** |
|---|---|
| **Estimated range** | 2 948–4 617 |
| **Simulation result** | 3 685 |
| **Average test saving** | 3 911 |

## 4.3 Meeting underground air cooling requirements

### 4.3.1 Preamble

During the tests, the BAC WB outlet air temperature was measured along with the ambient temperature. The measured temperatures were logged on a SCADA. The underground air temperature was calculated with Equation 4 by using the measured BAC outlet and ambient temperatures during the tests. The tests were done on two different days during the summer period.

The BAC WB outlet temperatures were measured with temperature sensor inside the BAC. Figure 50 is an illustration of the temperature sensor inside the BAC.

Figure 50: Temperature sensor inside the BAC

The ambient temperatures were measured with a weather station located outside the BAC. Figure 51 is an illustration of the weather station.

Figure 51: Weather station at Platinum Mine A

### 4.3.2 Temperature results for Test 1

The Test 1 temperature data was extracted from the SCADA and processed further in Excel®. The temperature data processed for Test 1 is shown in Table 27 of the Appendix. During Test 1, the BAC WB outlet temperature increased to a maximum of 11 °C.

As a result, the maximum calculated underground temperature based on the ambient and BAC outlet air temperature was 18 °C WB. Therefore, the maximum underground temperature during Test 1 was 9 °C WB below the underground temperature limit of 27.5 °C WB. Thus, the underground temperature during Test 1 satisfied the mine's cooling requirements.

### 4.3.3 Test 1 temperature results compared with the simulation

The simulated, calculated and Test 1 results are shown in Figure 52. The difference between the simulation results and the test results were due to varying ambient and underground mining conditions. The simulated results were based on the average temperatures during the summer period. The temperatures for Test 1 were based only on the temperatures on the day of the test.

As discussed in Section 3.4.4 and Section 4.3.1 the underground temperature could not be simulated or measured. Thus, the predicted underground temperature was determined with simulated variables and the calculated temperature was determined with measured variables during the tests by using Equation 4.

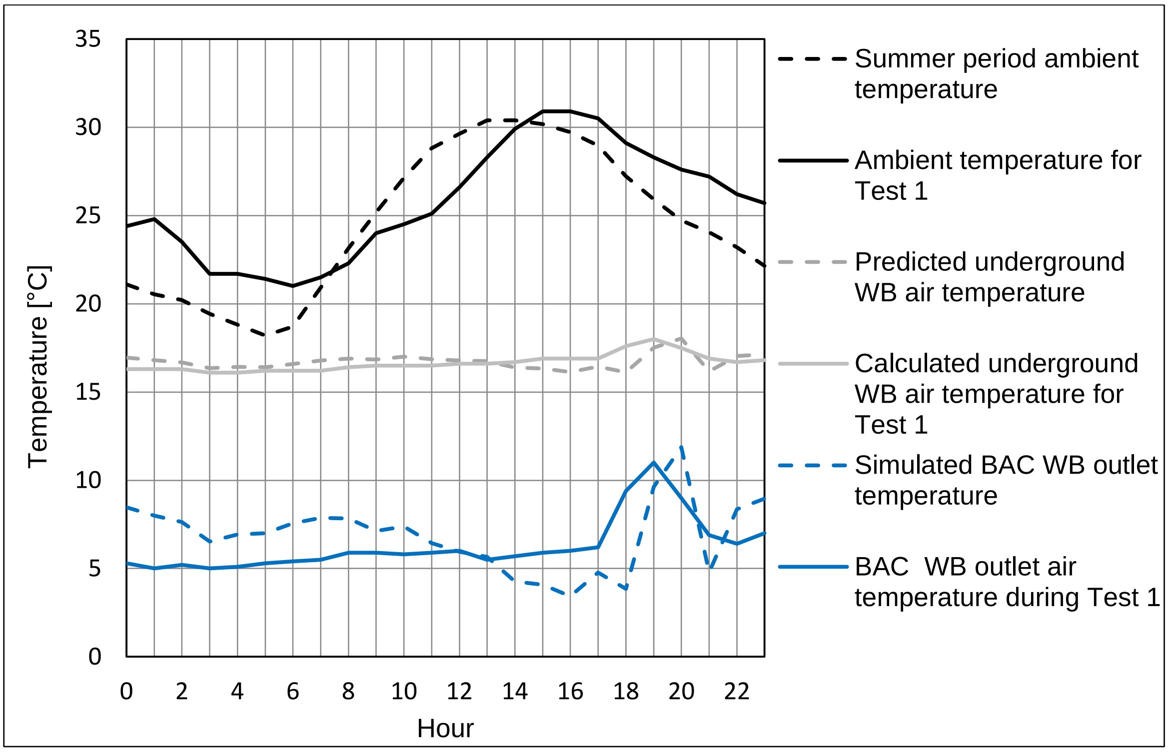


Figure 52: Simulated and calculated results compared with Test 1

The simulated and predicted results are stated as expected results in Table 19. The expected results were compared with the results of Test 1 in Table 19. The calculated maximum underground temperature during the implementation of the developed strategy was 97% accurate when compared with the results of Test 1.

Table 19: Temperature results during Test 1

| | Average ambient temperature [°C] | Maximum WB BAC outlet temperature [°C] | Maximum WB underground temperature [°C] |
|---|---|---|---|
| **Expected result** | 29 | 9.6 | 17.5 |
| **Test 1 result** | 30 | 11 | 18.0 |

### 4.3.4 Temperature results for Test 2

The temperature data for Test 2 was extracted from the SCADA and processed further in Excel®. The data processed for Test 2 is shown in Table 28 in the Appendix. During Test 2, the BAC WB outlet temperature increased to a maximum of 9.1 °C.

As a result, the maximum calculated underground temperature based on the ambient and BAC outlet air temperature was 17.5 °C WB. The maximum underground temperature during Test 2 was, therefore, 10 °C WB below the underground temperature limit of 27.5 °C WB. Thus, the underground temperature during Test 2 satisfied the mine's cooling requirements.

### 4.3.5 Test 2 temperature results compared with the simulation

Figure 53 shows the simulated and calculated results from Test 2. The difference between the simulation results and the test results was due to varying ambient and underground mining conditions. The simulated results were based on the average temperatures during the summer period. The temperatures for Test 2 were based only on the temperatures on the day of the test. Note that the underground temperature could not be measured during the tests and was therefore calculated with Equation 4.

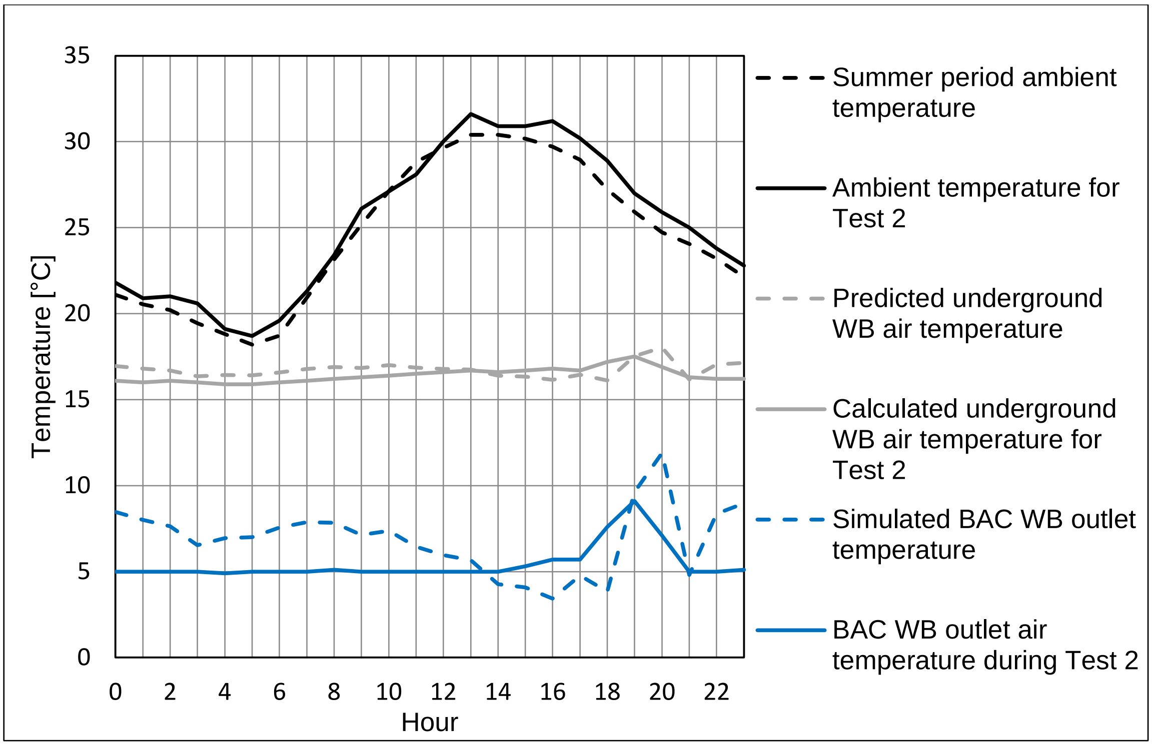


Figure 53: Simulated and predicted results compared with Test 2

The simulated and predicted results are stated as expected results in Table 20. The expected results and Test 2 results are compared in Table 20. The expected maximum underground temperature during the implementation of the developed strategy correlated 100% when accurate compared with the results of Test 2.

Table 20: Temperature results during Test 2

| | Average ambient temperature [°C] | Maximum WB BAC outlet temperature [°C] | Maximum WB underground temperature [°C] |
|---|---|---|---|
| **Expected result** | 29.0 | 9.6 | 17.5 |
| **Test 2 result** | 28.9 | 9.1 | 17.5 |

### 4.3.6 The temperature differences between the two tests and the simulation

The measured ambient temperature results of the two tests are shown in Figure 54 along with the summer period’s ambient temperature results. The ambient temperatures of the two tests had a 76% correlation.

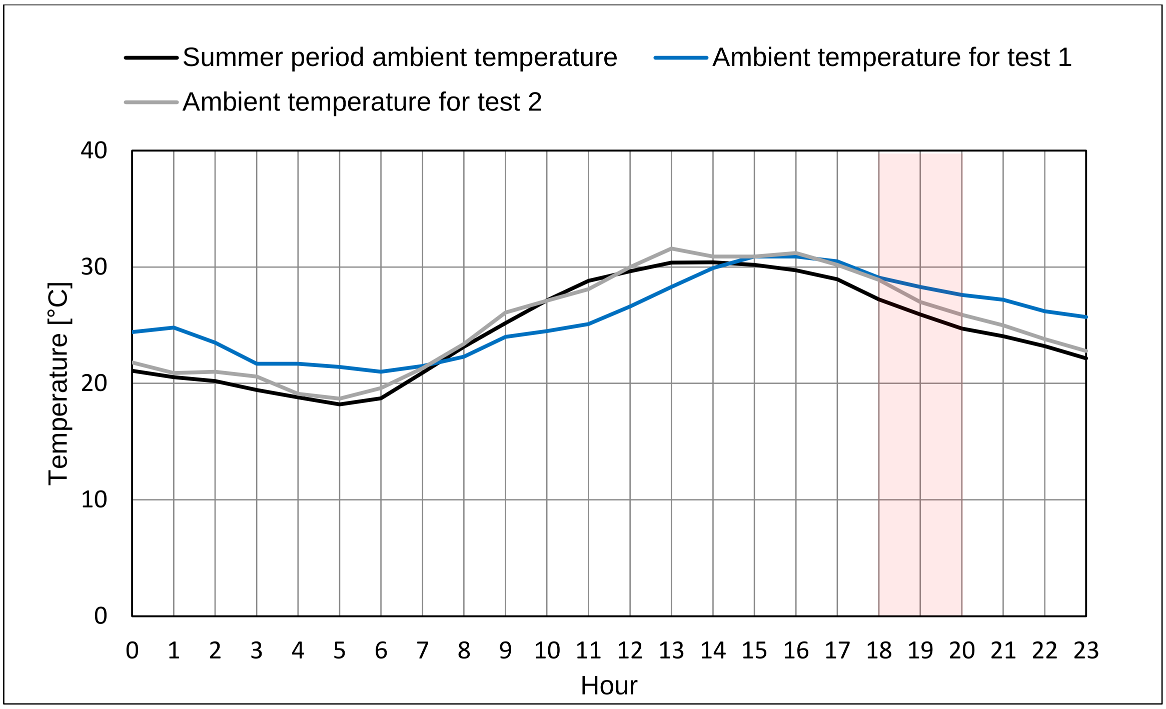


Figure 54: Ambient temperature results from Test 1 and Test 2

The BAC WB outlet temperature results during the two tests had an 88% correlation and the calculated underground temperatures had an 84% correlation (See Figure 55).

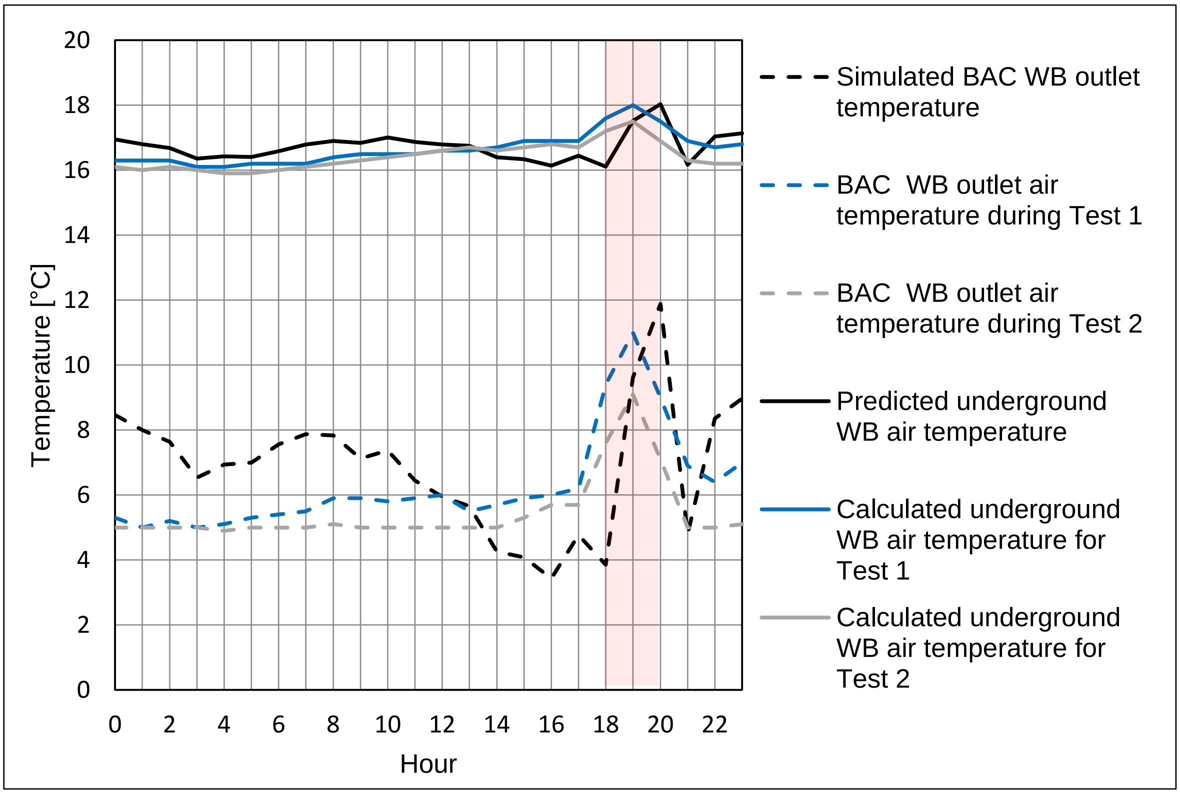


Figure 55: BAC outlet and underground temperature results from Test 1 and Test 2

The ambient temperature profile measured in the summer period correlated 70% with the temperatures of Test 1, and 99% with the temperatures of Test 2. Due to the strong ambient temperature correlation of Test 2, the expected temperature was more accurate during Test 2.

Table 21 shows the average maximum temperatures obtained by implementing the developed strategy. The expected maximum underground temperature was 98% accurate when compared with the average results. The results of both tests showed that the underground temperature did not exceed the underground temperature limit of 27.5 °C WB. Thus, expected results were validated with the two tests and proved that the underground cooling requirements were satisfied during implementation.

Table 21: Maximum temperatures by implementing the developed strategy

| | Average ambient temperature [°C] | Maximum WB BAC outlet temperature [°C] | Maximum WB underground temperature [°C] |
|---|---|---|---|
| **Expected result** | 29.0 | 9.6 | 17.5 |
| **Average test result** | 29.5 | 10 | 17.8 |

## 4.4 Effect of the cooling strategy on water availability

The chill dam level was measured during Test 1 and Test 2. The results from Test 1 are shown in Figure 56 The chill dam level results from Test 2 could not be used because of instrumentation problems that occurred during the measurement of the data. The chill dam level was predicted and simulated by using Equation 3 and a PTB simulation.

The predicted and simulated chill dam level started at 62%; on the day of Test 1 the level started at 80%. The predicted chill dam level showed that a decrease of 33% could be expected, with a minimum level of 30%. The simulated chill dam level showed that a decrease of 25% could be expected, with a minimum level of 38% (See Figure 56).

Due to miscommunication problems, the operator did not immediately switch the transfer pump back on. As a result, the chill dam level kept on decreasing after the implementation of the developed strategy. Thus, with Test 1, the chill dam decreased by 29% during the implementation and reached a minimum level of 45% before the level recovered. Note that the predicted chill dam level was determined with Equation 3 and the simulated chill dam level was simulated with the simulation model.

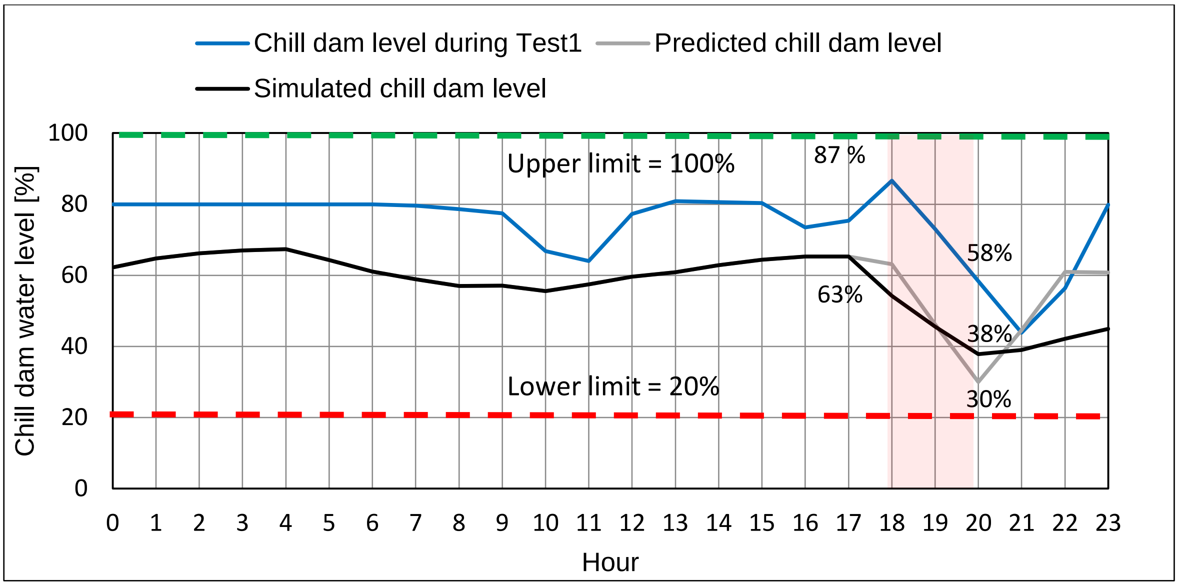


Figure 56: Chill dam level during Test 1 compared with the predicted chill dam level

Table 22 shows how the chill water dam level decreased during Test 1. The predicted chill water dam level indicated a decrease of 4% more than what was obtained during Test 1. The simulated chill water dam level indicated a decrease of 4% less than what was obtained during Test 1. Thus, the predicted and simulated chill water dam level were accurate within 4%. The decreased level during implementation in Table 22 indicates how much the chill water dam level decreased due to the implementation of the strategy.

Table 22: Expected chill dam level compared with the result of Test 1

| | Minimum level during implementation (%) | Decreased level during implementation (%) |
|---|---|---|
| **Predicted chill dam level** | 30% | 33% |
| **Simulated chill dam level** | 38% | 25% |
| **Chill dam level during Test 1** | 45% | 29% |

As highlighted in Section 3.4.3, the aim of the simulated and predicted chill dam level was to determine if the chilled water supply would be sufficient during the implementation of the developed strategy. The predicted and simulated results showed that the chill dam level would be sufficient during the implementation of the developed strategy.

The chill dam level during Test 1 validated that the chill dam level was sufficient during the implementation of the developed strategy. Although the data of Test 2 could not be used due to instrumentation problems, the operators had no concerns regarding the chill dam level during Test 2. Therefore, it can be concluded that the chill dam level was sufficient during the implementation of the developed strategy.

## 4.5 Validation of this study

A DSM project could potentially be implemented if Platinum Mine A had the necessary funding support. In this section, the developed strategy is evaluated along with a potential DSM project. The potential DSM project information was provided by a company that was contracted by ESCos to simulate and estimate budgets for DSM projects. The strategy and potential DSM project is discussed as follows:

- Implementation time
- Cost
- Sustainability
- Savings and payback period

### 4.5.1 Implementation time

***Developed strategy***

No implementation time is required to implement manual control and monitoring. The mine can implement the strategy immediately. No equipment needs to be installed. On-duty operators can be used for the strategy (as was done in the tests that were conducted). The control room operator can monitor the parameters and manage the required components from the SCADA.

***DSM project***

The implementation time for a DSM project is approximately 35 working days. The entire cooling system must be automated to stop and start the evaporator pumps, condenser pumps, precooling towers, condenser towers and transfer pumps from the SCADA system. The required control and instrumentation must be installed to operate according to a load management strategy. This ensures that load shifting is executed with safe underground conditions and a sufficient chilled water supply.

### 4.5.2 Cost

***Developed strategy***

No extra labour cost is required when making use of on-duty operators. No capital expenditure is required if the control room operators manage the required equipment from the SCADA. The developed strategy can, therefore, be seen as a cost effective alternative to automated control systems.

***DSM project***

Table 23 is adapted from a budget breakdown provided by a contractor. According to the budget breakdown, the automated control and instrumentation hardware is the largest expense on a DSM project. As seen from Table 23 a DSM project requires substantial funding. The manual control and monitoring cost is based on the condition that all of the required infrastructure used during the two tests are already in place.

Table 23: Cost breakdown for implementing a DSM project and a developed strategy

| Item | Description | DSM project cost (Rand) | Manual control and monitoring cost (Rand) |
|---|---|---|---|
| 1 | Control and instrumentation hardware | 1 600 000 | 0 |
| 2 | Installation and commissioning | 300 000 | 0 |
| 3 | PLC programming and SCADA development | 100 000 | 0 |
| | **Total:** | **2 000 000** | **0** |

### 4.5.3 Sustainability

***Developed strategy***

Achieving sustainable savings play a vital role in the long term. By relying on human intervention and communication, manual control and monitoring are not as sustainable as automated systems. Good preparation work is essential to arrange with the operator to stop and start the equipment when it is required. If the personnel has to be changed, more cost will potentially be required to retrain the new personnel.

***DSM project***

With automated control (DSM project), predetermined schedules can be used to stop and start equipment. Thus, the risk of failing to capitalise on cheaper tariffs due to oversight is low. Maintenance on the equipment is crucial for an automated system to work according to design specifications.

### 4.5.4 Savings and payback period on Platinum Mine A

A target of 3.9 MW saving can be achieved by both manual control and monitoring and by implementing a DSM project. Based on the Megaflex tariffs from April 2014 to March 2015, an estimated annual saving of R1.53 million can be achieved. By implementing manual control and monitoring, immediate savings will be achieved with no payback period. The payback period for implementing a DSM project is approximately 15 months.

## 4.6 Conclusion

Table 24 is a summary of the comparison between manual control and monitoring and a DSM project. It can be concluded that savings can be achieved in a cost effective manner, by implementing manual control and monitoring if the measuring equipment is already installed. However, a DSM project is more reliable than manual control and monitoring. A DSM project is preferable in the long term if funding support is available.

Table 24: Manual control and monitoring compared with a DSM project

| Topic | Control and monitoring (manual) | Potential DSM project (automated) |
|---|---|---|
| **Implementation time:** | Immediate | 7 months |
| **Cost:** | None | R2 000 000 |
| **Sustainability:** | Reliant on human intervention, communication, discipline and motivation | Is sustainable with good maintenance |
| **Savings and payback:** | Immediate savings with no payback period | Savings will be achieved after implementation with a 15-month payback period |

It would be ideal to combine the advantages of the two different approaches. As a result, the cost effective control and monitoring strategy could reduce energy (electricity costs) while the mine prepares for a DSM project. If Platinum Mine A implemented the developed strategy for 15 months, the electricity costs that were saved could then be used to implement a DSM project. Thus, the manual control and monitoring could serve as a short-term solution to supply funding for implementing a more sustainable DSM project.

If the cost effective strategy was used as a short-term alternative to implementing a DSM project, then the strategy would satisfy the requirements of the new ESCo model process. The savings would be achieved during peak periods. The implementation period would be within six months. The mine must sustain the savings for the first 16 months and then the automated DSM project could sustain the savings for the remainder of the 36 months.

Figure 57 illustrates a potential cash flow if the cost effective strategy is used as a short-term alternative until necessary funding has been saved for a DSM project. Based on the calculations in the study, the first nine months will be used to save R1.1 million with the cost effective strategy, which requires no funding or an implementation period. Then the DSM project could be implemented, which requires an implementation cost of R2 million and has an implementation period of seven months.

During the seven-month implementation period, the cost effective strategy can continue to achieve savings. If an assumption is made that the R2 million implementation cost could be distributed equally throughout the seven-month period, then after 16 months an automated and sustainable DSM project could be implemented, which requires no payback.

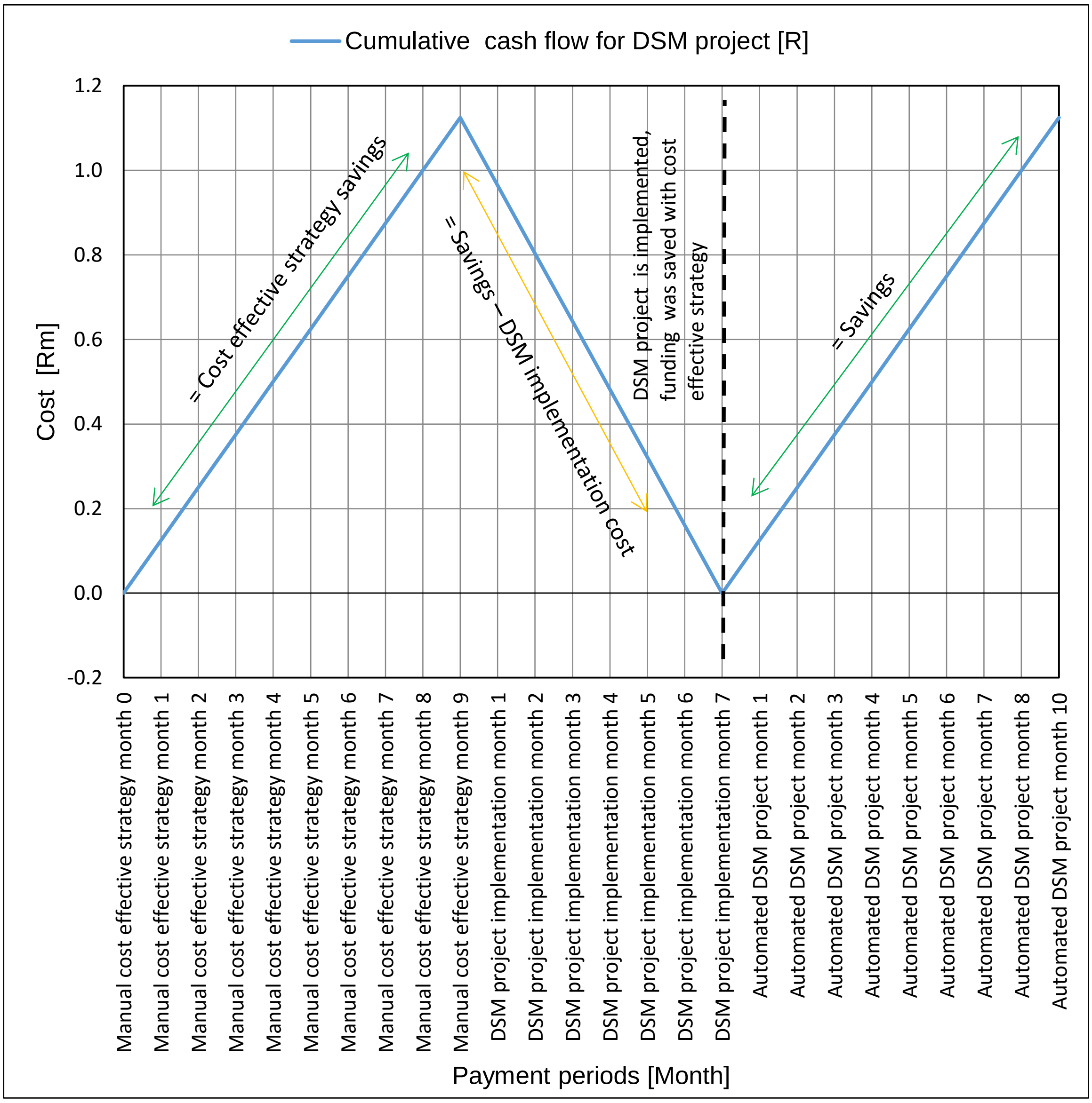


Figure 57: Potential cash flow when combining a cost effective strategy with a DSM project

# Chapter 5. Conclusion and recommendations


*The conclusion of the study and recommendations for future work*

## 5.1 Result of this study

The platinum industry faces various challenges such as decreasing platinum prices, labour strikes and escalating production cost. Electricity was identified as the fastest growing expenditure, which contributed largely towards the growing operating cost. Mine cooling systems were identified as one of the most energy intensive operations, which presented potential energy saving opportunities.

Due to the challenges that the platinum industry faces, Eskom IDM funding constraints and the new ESCo process, any intervention to reduce energy had to be cost effective without affecting underground safety limits or production. Thorough knowledge of mine refrigeration systems was collected in the literature review. The highest energy-consuming components and existing energy saving strategies on mine cooling systems were identified.

Necessary insight on unique operational limitations and requirements provided the basis to determine potential energy savings on Platinum Mine A. An estimated demand reduction range of 2 948-4 617 kW was determined based on normal operational procedures and assumed power usages of the components in the cooling system.

With the sufficient background on the cooling system of Platinum Mine A, a cost effective energy demand reduction strategy was developed. The developed strategy entailed manually switching the major energy-consuming components off from the control room using an existing SCADA control during Eskom’s evening peak period (18:00–20:00). While these components were switched off, the underground temperatures and dam levels were measured and monitored. These parameters were identified as the crucial requirements and limitations on the cooling system of platinum mines.

The strategy was then simulated to verify that the strategy was feasible. The simulation results showed that an average demand reduction of 3 685 kW could be achieved by implementing the developed strategy on Platinum Mine A. The simulation determined that the underground temperature would not exceed the limit of 27.5 °C WB and the chill dam levels would be sustained between the upper and lower limits of 100% and 20%.

With the predicted results of the simulation, the strategy was then implemented on Platinum Mine A. The strategy required no implementation cost as existing infrastructure and mine personnel already on duty were used. The strategy was then implemented as two tests on different days during the summer period. The results of Test 1 and Test 2 showed average savings of 4 048 kW and 3 774 kW were achieved distinctively while the underground temperature limits and chill dam levels were within limits.

The average demand reduction achieved between the two tests was 3 911 kW, which was 95% accurate when compared with the simulation results – this was within the estimated savings range. Thus, results of the implementation validated the estimated savings range and simulation results.

Therefore, the estimated savings range, the simulation and the implementation of the developed strategy proved that the strategy was feasible. Thus, it can be concluded that immediate savings can be achieved with no payback period. The strategy is, however, dependent on human intervention, which in the long run is less sustainable than automated control.

The ideal combination would be to implement the cost effective energy saving strategy with the aim to reduce operating cost in the short term. These savings could then be used to contribute to a more sustainable automated control such a potential DSM project, which requires substantial funding. Based on the new ESCo process, the cost effective strategy would satisfy the requirements and the mine would then have the involvement of the ESCo for three years to maintain the targeted savings.

## 5.2 Recommendation for future work

In this study, it was shown that implementing the cost effective strategy on Platinum Mine A has reduced the electricity cost thereof significantly. The following is recommended for further work regarding this study:

- Simulate the power usage of the underground fans or install power meters to determine the power usage of the underground fans. This will provide more accurate power usage results for the refrigeration system.
- This study proved the strategy for surface BACs. Further studies can be done by implementing the strategy on underground BACs.
- The investigation and maintenance cost for the cost effective strategy and potential DSM project can be included in future work.
- The potential to implement the cost effective strategy during Eskom's morning peak period can be investigated to optimise the cost saving.

The operators can improve the parameter readings during the strategy implementation by installing underground temperature sensors that can be monitored permanently and thus rectify the chill dam level sensors. This will allow the operators to switch the refrigeration system on and off for longer periods to optimise the savings.

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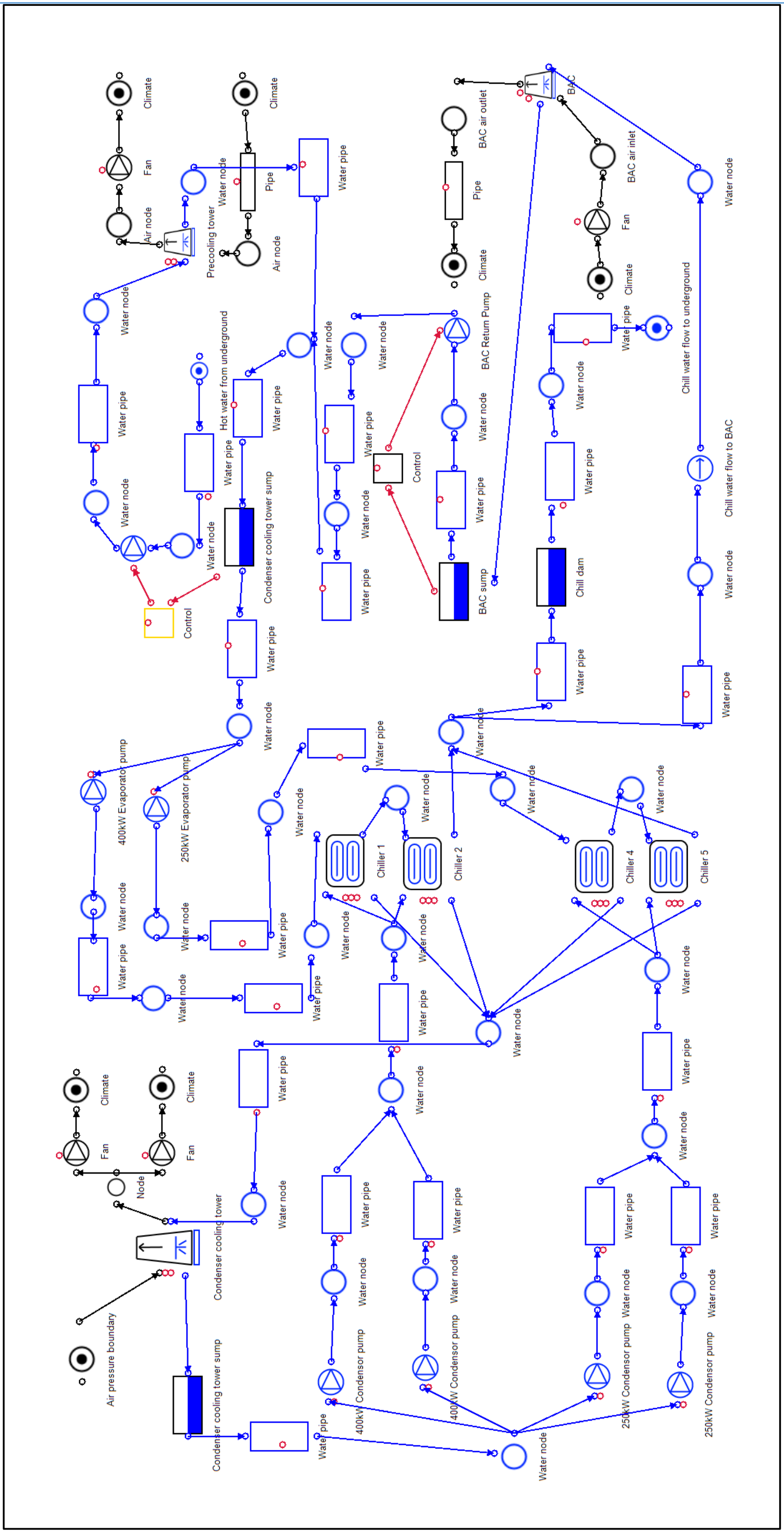


Figure 58: Simulation model layout

Table 25: Processed data for Test 1

| Hour | Baseline [kW] | Scaled Baseline for Test 1 [kW] | Measured power usage during Test 1 [kW] | Saving from Test 1 [kW] |
|---|---|---|---|---|
| 0 | 4 982 | 5 296 | 5 377 | - |
| 1 | 4 922 | 5 232 | 5 353 | - |
| 2 | 4 934 | 5 245 | 5 408 | - |
| 3 | 4 940 | 5 251 | 5 236 | - |
| 4 | 4 750 | 5 050 | 5 254 | - |
| 5 | 4 719 | 5 016 | 5 297 | - |
| 6 | 4 702 | 4 998 | 5 258 | - |
| 7 | 4 804 | 5 107 | 5 293 | - |
| 8 | 4 823 | 5 126 | 5 371 | - |
| 9 | 4 916 | 5 225 | 5 533 | - |
| 10 | 5 027 | 5 343 | 5 573 | - |
| 11 | 5 270 | 5 602 | 5 807 | - |
| 12 | 5 218 | 5 547 | 6 726 | - |
| 13 | 5 331 | 5 667 | 6 572 | - |
| 14 | 5 482 | 5 827 | 6 371 | - |
| 15 | 5 406 | 5 747 | 5 796 | - |
| 16 | 5 461 | 5 805 | 5 739 | - |
| 17 | 5 461 | 5 806 | 5 845 | - |
| 18 | 5 615 | 5 969 | 1 874 | 4 095 |
| 19 | 5 569 | 5 920 | 1 918 | 4 002 |
| 20 | 5 411 | 5 752 | 5 916 | - |
| 21 | 5 312 | 5 647 | 6 312 | - |
| 22 | 5 131 | 5 454 | 6 260 | - |
| 23 | 5 034 | 5 351 | 6 893 | - |

Table 26: Processed data for Test 2

| Hour | Baseline | Scaled Baseline for Test 2 [kW] | Measured power usage during Test 2 [kW] | Saving from Test 2 [kW] |
|---|---|---|---|---|
| 0 | 4 982 | 5 219 | 4 197 | - |
| 1 | 4 922 | 5 155 | 4 195 | - |
| 2 | 4 934 | 5 168 | 4 313 | - |
| 3 | 4 940 | 5 175 | 4 380 | - |
| 4 | 4 750 | 4 976 | 4 727 | - |
| 5 | 4 719 | 4 943 | 5 413 | - |
| 6 | 4 702 | 4 925 | 5 588 | - |
| 7 | 4 804 | 5 033 | 5 654 | - |
| 8 | 4 823 | 5 052 | 6 163 | - |
| 9 | 4 916 | 5 149 | 6 470 | - |
| 10 | 5 027 | 5 266 | 6 611 | - |
| 11 | 5 270 | 5 520 | 6 703 | - |
| 12 | 5 218 | 5 466 | 6 779 | - |
| 13 | 5 331 | 5 584 | 6 378 | - |
| 14 | 5 482 | 5 742 | 5 980 | - |
| 15 | 5 406 | 5 663 | 5 258 | - |
| 16 | 5 461 | 5 721 | 5 481 | - |
| 17 | 5 461 | 5 721 | 5 218 | - |
| 18 | 5 615 | 5 882 | 2 019 | 3 863 |
| 19 | 5 569 | 5 834 | 2 148 | 3 686 |
| 20 | 5 411 | 5 668 | 6 164 | - |
| 21 | 5 312 | 5 565 | 6 742 | - |
| 22 | 5 131 | 5 374 | 6 570 | - |
| 23 | 5 034 | 5 273 | 5 923 | - |

Table 27: Temperature data of Test 1

| Hour | Ambient temperature for Test 1 [°C] | BAC WB outlet air temperature for Test 1 [°C] | Calculated underground WB air temperature for Test 1 [°C] |
|---|---|---|---|
| 0 | 24.4 | 5.3 | 16.3 |
| 1 | 24.8 | 5 | 16.3 |
| 2 | 23.5 | 5.2 | 16.3 |
| 3 | 21.7 | 5 | 16.1 |
| 4 | 21.7 | 5.1 | 16.1 |
| 5 | 21.4 | 5.3 | 16.2 |
| 6 | 21 | 5.4 | 16.2 |
| 7 | 21.5 | 5.5 | 16.2 |
| 8 | 22.3 | 5.9 | 16.4 |
| 9 | 24 | 5.9 | 16.5 |
| 10 | 24.5 | 5.8 | 16.5 |
| 11 | 25.1 | 5.9 | 16.5 |
| 12 | 26.6 | 6 | 16.6 |
| 13 | 28.3 | 5.5 | 16.6 |
| 14 | 29.9 | 5.7 | 16.7 |
| 15 | 30.9 | 5.9 | 16.9 |
| 16 | 30.9 | 6 | 16.9 |
| 17 | 30.5 | 6.2 | 16.9 |
| 18 | 29.1 | 9.4 | 17.6 |
| 19 | 28.3 | 11 | 18 |
| 20 | 27.6 | 9 | 17.5 |
| 21 | 27.2 | 6.9 | 16.9 |
| 22 | 26.2 | 6.4 | 16.7 |
| 23 | 25.7 | 7 | 16.8 |

Table 28: Temperature data measured during Test 2

| Hour | Ambient temperature for Test 2 [°C] | BAC WB outlet air temperature for Test 2 [°C] | Calculated underground WB air temperature Test 2 [°C] |
|---|---|---|---|
| 0 | 21.8 | 5 | 16.1 |
| 1 | 20.9 | 5 | 16 |
| 2 | 21 | 5 | 16.1 |
| 3 | 20.6 | 5 | 16 |
| 4 | 19.1 | 4.9 | 15.9 |
| 5 | 18.7 | 5 | 15.9 |
| 6 | 19.6 | 5 | 16 |
| 7 | 21.3 | 5 | 16.1 |
| 8 | 23.4 | 5.1 | 16.2 |
| 9 | 26.1 | 5 | 16.3 |
| 10 | 27.1 | 5 | 16.4 |
| 11 | 28.1 | 5 | 16.5 |
| 12 | 30 | 5 | 16.6 |
| 13 | 31.6 | 5 | 16.7 |
| 14 | 30.9 | 5 | 16.6 |
| 15 | 30.9 | 5.3 | 16.7 |
| 16 | 31.2 | 5.7 | 16.8 |
| 17 | 30.2 | 5.7 | 16.7 |
| 18 | 28.9 | 7.6 | 17.2 |
| 19 | 27 | 9.1 | 17.5 |
| 20 | 25.9 | 7.1 | 16.9 |
| 21 | 25 | 5 | 16.3 |
| 22 | 23.8 | 5 | 16.2 |
| 23 | 22.8 | 5.1 | 16.2 |