

# **Improved implementation strategies to sustain energy saving measures on mine cooling systems**

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## Abstract

<b>Title:</b>	Improved implementation strategies to sustain energy saving measures on mine cooling systems
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Reliable, efficient and cost-effective energy supply is crucial for economic and social development. Mining and industrial sectors consumed close to 37% of the total energy produced in the world during 2013. The South African power network is strained by the rapid expansion of mining, industrial and public sectors. Generation, transmission and distribution of electrical energy are in progress, but supply will not meet demand in the near future.

The South African electricity supplier needs capital for expansion. Electricity price increases have been significantly higher than increases in the gold price over the last few years. Mining companies are under pressure from government to improve their labour relations. They are obligated to spend money on local infrastructure development. Therefore, cost efficiency receives higher priority than ever before and requires an implementation strategy.

Cooling systems on mines proved to be significant electricity consumers. These systems lack integrated management and efficient and optimised control. Electricity demand can be reduced through implementation of energy saving measures on these cooling systems. Energy saving measures reduce the operational costs of mining to ensure that mines stay globally competitive. The identification of long-term challenges for energy saving measures is crucial.

Successful implementation of energy saving measures results in improved utilisation and performance of mine cooling systems. These measures must be maintained to ensure a

constant positive impact on reduced electrical energy consumption. The electrical energy savings are dependent on external factors, such as ambient conditions.

Improved implementation strategies of energy saving measures will prevent deterioration of utilisation and performance of the mine cooling systems. Monitoring and reporting of key performance indicators are crucial. Lack of integrated maintenance can lead to lost opportunities and the deterioration of equipment and machines.

The improved implementation strategies in two separate case studies proved sustainable savings of 1.73 MW and 0.66 MW respectively. The electricity cost savings for Mine A and Mine B are R8.8 million and R2.9 million respectively. These savings have been sustained for periods of seventeen and seven months respectively, indicating the value of the study.

**Keywords:** Mine cooling system; cooling auxiliaries; energy efficiency; energy management; electrical demand-side management; variable water flow; implementation strategies.

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# Nomenclature

## List of units

<b>Symbol</b>	<b>Description</b>	<b>Unit of measure</b>
°C	Measure of temperature	Degrees Celsius
G	Denotes $1 \times 10^9$	Giga
h	Measure of time	Hour
k	Denotes $1 \times 10^3$	Kilo
ℓ	Measure of volume	Litre
m	Measure of distance	Metre
M	Denotes $1 \times 10^6$	Mega
N	Rotational speed	rpm
$\eta_w$	Water-side efficiency	No unit
Q	Measure of water flow rate	$m^3/s$
s	Measure of time	Second
t	Measure of mass	Ton
W	Measure of power	Watt

**List of symbols**

<b>Symbol</b>	<b>Description</b>	<b>Unit of measure</b>
D	Diameter	m
H	Pressure head	m
P	Input power	W
$P_{ref}$	Compressor motor power	W
$Q_{evaporator}$	Energy absorbed by the evaporator	W
$T_{ai(WB)}$	Wet-bulb temperature in	°C
$T_{wi}$	Water in temperature	°C
$T_{wo}$	Water out temperature	°C
$\dot{W}_{actual\ daily}$	Daily power consumption	W
$\dot{W}_{scaled\ baseline}$	Scaled daily power consumption baseline	W
$\dot{W}_{savings}$	Power saving	W

## Abbreviations

<b>Symbol</b>	<b>Description</b>
BEP	Best Efficiency Point
CA	Cooling Auxiliary
COMRO	Chamber Of Mines Research Organisation
DSM	Demand Side Management
EEDSM	Energy Efficiency and Demand Side Management
ESCO	Energy Service Company
ESH	Environmental, Health and Safety
FIS	Field Isolator Station
IP	Intellectual Property
IPMVP	International Performance Measurement and Verification Protocol
KPI	Key Performance Indicator
LCC	Life Cycle Cost
MCC	Motor Control Centre
M&V	Measurement and Verification
MS	Main Shaft
OEM	Original Equipment Manufacturer
OPC	Open Platform Communication
PLC	Programmable Logic Controller

ROI	Return On Investment
SCADA	Supervisory Control and Data Acquisition
SMTP	Simple Mail Transfer Protocol
VS	Ventilation Shaft
VSD	Variable Speed Drive
WB	Wet Bulb
WSO	Water Supply Optimisation

# CHAPTER 1: INTRODUCTION



1

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The need for implementation of sustainable power savings on mine cooling systems is highlighted.

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<sup>1</sup> P. Maré, Personal photograph. "Abandoned mine shaft", South Africa, 2014.

## 1.1. Preamble

### The South African power network

Eskom, the primary electricity utility in South Africa, is under pressure by a growing economy, causing the margin of reserve generation capacity to reduce. The South African power grid is under strain, which is caused by significant expansion in mining, industrial and public sectors [1]. The extension of the power network requires capital and is a time-consuming endeavour [2].

Reliable, efficient and cost-effective energy supply is crucial for further economic and social development. Some argue that the lack of research on energy and power has been responsible for the electricity shortage experienced in the country [3]. The failure by government to allow independent power producers into the market also adds to cited issues [4].

The development of new facilities to expand, generate and distribute electrical energy is underway to enable supply to meet demand in the nearby future [5]. Eskom is expanding the generation capacity by the addition of two power stations, Medupi and Kusile, to their existing generation fleet [6].

Further expansion will bring the nominal generation capacity up to 58.3 GW [7]. Eskom power stations have a designed lifespan of approximately 50 years. Considering the number of years the existing power plants have been in operation, as illustrated in Figure 1, a substantial reduction in reliability can be expected [8].

The expansion of power plants is delayed due to South Africa facing unique challenges. These delays prove costly in terms of economic growth [9, 10]. Power plants take approximately 8 – 10 years to build [6]. Taking into consideration that older power plants need upgrades in order to continue operation, Eskom will be faced with significant challenges to produce sufficient electricity to keep up with demand.

An alternative strategy, called Demand Side Management (DSM), can reduce the strain on the electricity supply network. The aim of DSM is to manage electricity demand through load management and energy efficiency strategies [11].

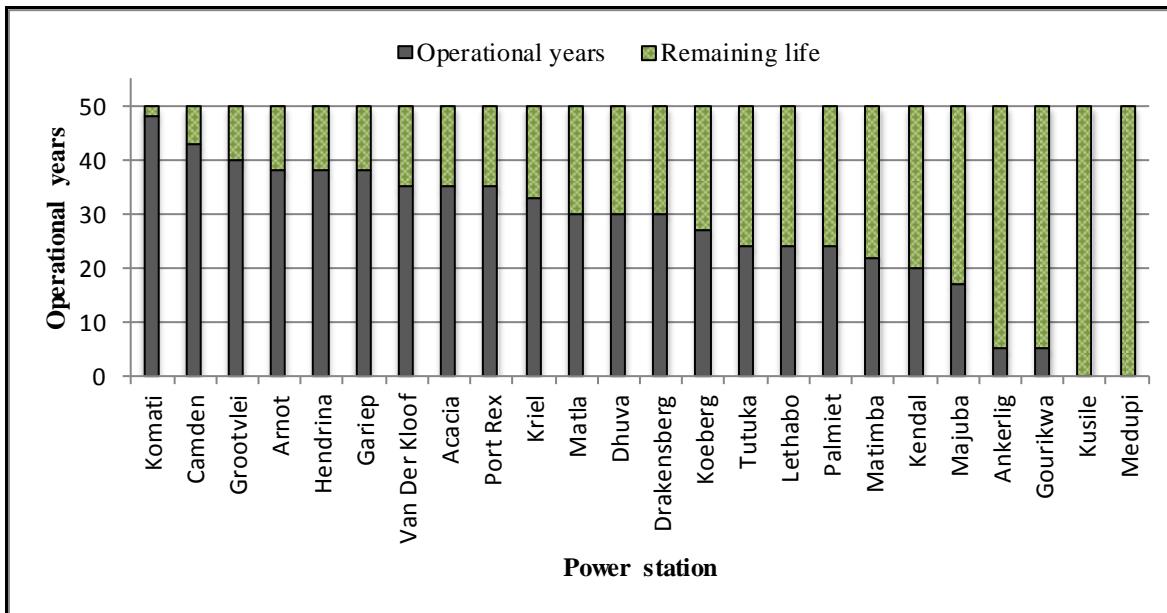


Figure 1: Average age of Eskom generation fleet

Energy efficiency, for practical purposes, can be defined as the ratio between economic outputs versus energy consumption [4]. DSM programs could enable the mining and industrial sectors to improve the energy efficiency of their systems significantly.

Eskom contributed funding to launch various energy efficiency programs with incentives for implementation to reduce strain on the supply grid. Funding allows these sectors to increase global competitiveness and reduce their carbon footprint through energy efficiency projects. From the start of the financial year in 2013, Eskom spent over R700 million on integrated demand management and energy efficiency initiatives [12].

Various strategies to relieve the impact of the power supply shortage were developed by local businesses and government. Some of the first energy efficiency strategies in the country were launched by government in 2005. The goal was to improve energy efficiency nationally with 12% by the year 2015 [13].

These strategies have proven successful reductions in electricity demand in the country [14]. Figure 2 illustrates the cumulative demand savings from 2005, as reported by Eskom [15]. Although the strategies relieved some strain, Eskom still requires substantial reductions in power usage to accommodate further economic expansion. DSM strategies are, however, the fastest way to reduce the power consumption while electricity generation expansion is underway [11].

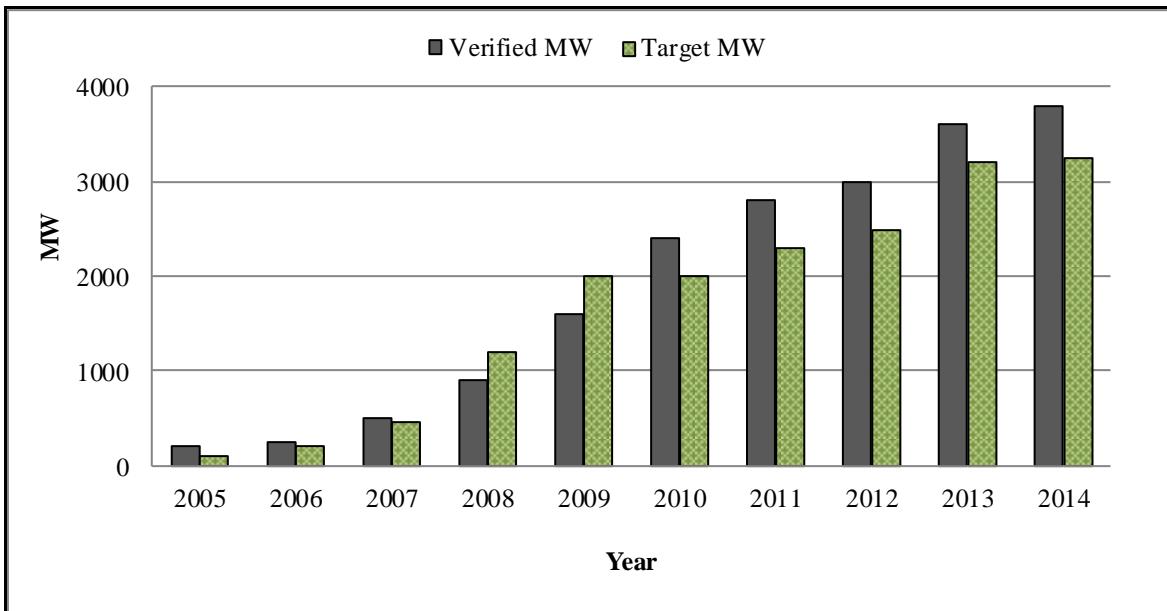


Figure 2: Cumulative DSM demand savings from 2005

Most energy intensive industries do not have the expertise or resources to undertake desired energy management or energy efficiency programs [15]. The mining and industrial sectors are some of the largest electrical energy consumers in the country [4]. These consumers suffer from utilisation of old technologies with designed safety factors, which consume unnecessary energy [16]. The introduction of modern technology and energy efficiency initiatives is fundamental. Modern technology allows for efficient management and reduction of energy consumption in the industry [17].

### Mining and industrial sectors as energy consumers

The mineral resource industry is a vital employer and economic driver for many developing countries [18]. The South African economy is largely based on mineral extraction and processing. These processes consume the highest portion of energy in the country compared to other sectors [4]. Fossil fuels are the primary source of energy supply to these industries [19]. The shortage of non-renewable resources is dawning, and a decrease in the consumption thereof is critical [20].

The South African government requires mining companies to improve their labour relations. Government looks to mining companies and miners to build local infrastructure [21]. These factors increase a mine's operational costs, and the corporate ability to sustain any of these projects is decreasing drastically. Mines are retaining reactive cost cutting as an effort to

improve return on investment (ROI). Reactive cost cutting, however, causes unwanted effects and is not sustainable [22].

The mining industry is committing to cost efficiency in many ways, but this alone will not suffice. These sectors consumed 37% of the world's total produced energy by 2013 [23]. The consumption of this amount of electrical energy restricts mining expansion and limits capital outlay due to significant escalated electricity costs.

Gold mines are some of the largest industrial electricity clients within the industry, consuming 47% of the electricity supplied by Eskom in 2014 [15]. Figure 3 illustrates the percentage gold price increase versus electricity tariff increase from 2004 to 2014. The average price increase of electricity has been significantly higher than the increase in gold price. It is clear that the economic viability of gold mining may be at risk.

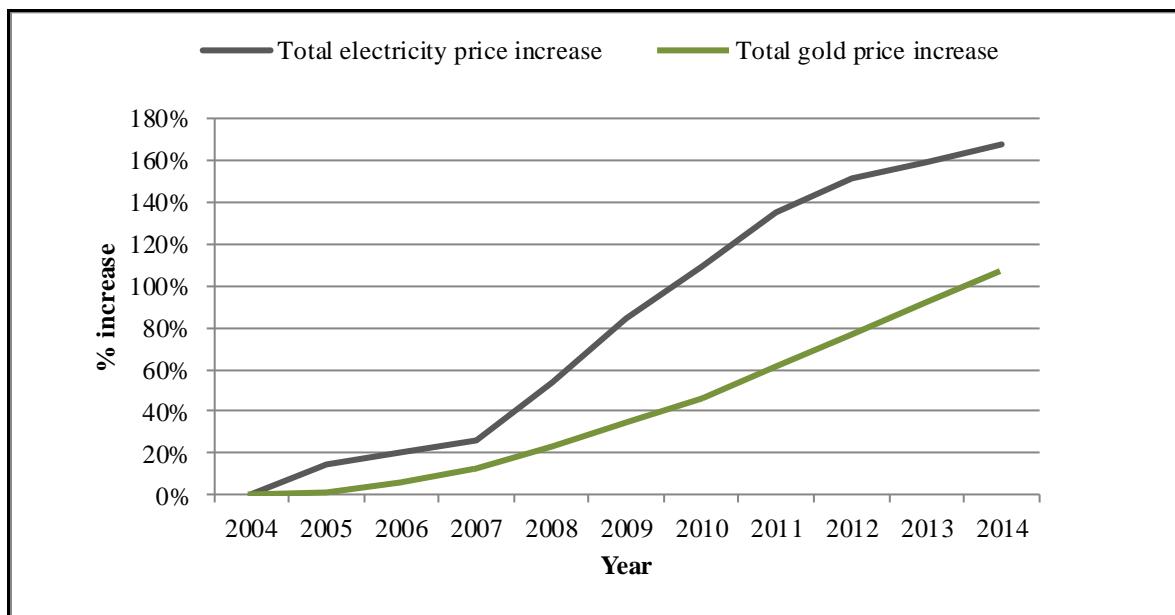


Figure 3: Comparison of gold price and electricity tariff increase from 2004 to 2014

Mines must, therefore, improve their efficiency to remain cost effective. This is done by adopting the necessary processes, technologies and mind-sets that will strengthen and ensure long-term operations. Introduction of modern technology is an important addition to DSM initiatives [23, 24].

## 1.2. Energy saving measures on mine cooling systems

Investigating the various electricity consumers on typical deep-level gold mines revealed numerous areas for implementation of DSM initiatives. DSM initiatives at deep-level mines can be implemented on systems such as cooling, compressed air, pumping, fans, processing and material handling [25].

Mine cooling systems consume approximately 25% of the total electrical energy usage of a typical deep-level mine [26]. Most mine cooling systems are over-designed and present ample opportunity for implementation of DSM projects [27]. Certain measures or strategies can be implemented on these systems to reduce energy consumption and make these sectors more efficient amongst others.

As a result, a mine's operational cost will be reduced, allowing more funds for company expansion and improved labour relations. This study will specifically be based on mine cooling systems of deep-level gold mines in South Africa. Gold mines in South Africa are some of the deepest mines in the world, mining at depths of 3 km and developing operations up to 5 km deep [28].

Mining at these depths poses various hazards, of which the most dominant is excessive heat. Mine cooling systems are used to ensure worker safety by creating a safe working environment. These systems are required to maintain working area temperatures below the legal limit of 27.5 °C wet bulb (WB) [28]. The virgin rock temperatures of deep-level gold mines in South Africa reach temperatures of up to 60 °C [29].

The energy consumption of mine cooling systems becomes a dominant factor as mines deepen and development continues. Deep-level operations require a significant amount of cooling, typically between 370 kW of refrigeration per kiloton per metre (kt/m) at a mean depth of 3 km, and 570 kW of refrigeration per kt/m at a mean depth of 3.5 km [30]. This amount of cooling is required, specifically in South Africa, due to the extreme geothermal gradient increase of between 10 °C and 20 °C/km [28].

Mine cooling systems must perform without failure for a strenuous number of hours. Malfunction of the cooling systems can prove costly in terms of lost production hours. Technology used on these systems was developed by the Chamber of Mines Research

Organisation (COMRO) [31, 32] in the 1980s. These systems operate with a lack of integrated management and inefficient control [16].

After the initial design of these systems, little has been done to improve operational design safety barriers [16]. With mine cooling systems consuming up to a quarter of a typical mine's energy consumption, it can be deducted that improving the energy efficiency of these systems would result in a significant power saving. By implementing energy efficiency strategies and adequate maintenance and operational procedures, the energy consumption of these systems can be significantly reduced.

Various energy saving measures have been implemented during the past few years in an attempt to reduce the energy consumption of different mine cooling systems [27]. Some of these projects were successful up to the point where the energy service company (ESCO) had no further contractual obligation after project implementation [33].

An energy audit was conducted on 20 large mine cooling systems to investigate the potential savings and feasibility of implementing energy saving measures. The energy audit revealed that mine cooling systems consumed 1 318 GWh/year. The review also indicated that the implementation of new technology and energy saving strategies on other deep-level mines can result in annual electricity savings of 145 GWh [23].

It can be concluded that energy saving measures on mine cooling systems is a necessity and is feasible. The implementation of energy saving measures on four of these mine cooling systems resulted in an average saving of 32.5% [27]. Further improvement of these existing energy saving measures is, however, still possible. Implemented projects tend to deteriorate over time. Deterioration of projects occurs due to various reasons, such as lack of maintenance and poor implementation strategies [17].

An improved implementation strategy is required to minimise challenges of implementing energy saving measures on future mine cooling systems and to sustain the implemented strategies.

### **1.3. Sustainability of energy saving measures**

Energy management and sustainability has become a key focus for the mining and industrial sectors. Environmentally-friendly technology is emerging in all engineering disciplines. Ensuring sustainable energy saving systems became the priority of countries worldwide [34]. Energy efficiency improvements are of the most cost-effective methods towards sustainable economic development [4].

Energy efficiency is also the most cost-effective approach in the effective reduction of energy consumption of a system [35]. There are also other beneficial factors to consider regarding implementation of energy efficiency strategies. These factors include, amongst others, the impact on environmental dynamics. Reduction of greenhouse gas emissions, SO<sub>2</sub>, NO<sub>x</sub> and smoke emissions are a direct result of efficient energy management.

Implementing energy efficiency strategies are sometimes troublesome, due to mining personnel being reluctant to undergo behavioural changes, let alone system changes. Energy usage improvements are only achieved through implementation of energy efficient equipment or behavioural changes [36].

The lack of awareness programs and historically low electricity tariffs led to extensive energy usage, which could be prevented or managed by a behaviour change towards usage. Numerous factors influencing energy management or improved energy efficiency must be taken into account; therefore energy efficiency improvement demands an analytical process [36].

The sustainability of any identified energy efficiency strategies will largely depend on maintenance and monitoring of these strategies after implementation [37]. Monitoring and reporting key performance indicators (KPIs), such as system efficiency for instance, will reveal any maintenance that must be applied to the system [38].

System changes should not interfere with production. Energy saving measures provide feasible and sustainable energy savings through implementation of new equipment, or strategic system modifications. Implementation of new equipment, or alterations of system operational procedures, should also take the original equipment manufacturer (OEM) specifications into account.

Operation of equipment outside of OEM specifications can lead to equipment malfunction or costly downtime. Automation of equipment relating to system improvements ensures further sustainability [39]. This must function in accordance to the implemented KPI monitoring systems. A control system must also be implemented with the energy saving measure to ensure that all necessary parameters are logged.

Deterioration of energy saving measures can, therefore, be prevented by implementing limits onto system controllers. Sufficient training must be provided to all involved parties, increasing the possibility of sustained energy saving measures. Implemented or altered system operational procedures tend to discourage personnel from maintaining the implemented equipment and strategies.

Existing energy saving measures can be improved if energy savings are no longer realised. The operating cost of a deteriorated system can be reduced, and energy savings can be achieved once again. The priority technologies showing the largest potential for savings should first be applied.

#### **1.4. Problem statement and objectives of this study**

The need to reduce the electricity demand in South Africa escalated drastically over the past decade. The mining sector was identified as a significant electrical energy consumer. This industry suffers with old technology and equipment that is not energy efficient.

Mine cooling systems have been classified as major electrical energy consumers. Various energy saving measures have already been implemented on a number of mine cooling systems. The implemented strategies reduced the electricity demand and proved significant cost reductions.

The implementation of energy saving strategies results in challenges and sustainability issues if a method is not defined whereby these strategies can be implemented. Long-term challenges associated with the implementation of these energy efficiency projects must be identified.

The focus of this study will be to proactively prevent and minimise the challenges in implementing energy saving measures on mine cooling systems. The identified method

should include long-term solutions to implementation of energy saving measures on mine cooling systems.

This study hypothesises that by identifying these challenges, the implementation of energy efficiency projects on other mines can be streamlined. The proposed strategy will promote the sustainability of energy saving measures with improved utilisation and performance of mine cooling systems.

A mine with implemented energy saving measures will be identified and investigated for the feasibility of improvements. Another mine cooling system with no implemented energy saving measures will be used as a case study to test the proposed implementation strategies.

The implemented energy saving measures should reduce operating cost on deep-level mines. By implementing these measures according to the proposed strategies, and by maintaining and improving existing strategies, load will be removed from the electricity grid, allowing a significant decrease in power consumption and monetary expenses.

## **1.5. Overview of dissertation**

*Chapter 1: Introduction* - An overview of the need for this study is given. The effect of the strain on the Eskom grid is discussed, as well as the need for implementation of sustainable energy savings on the mining and industrial sectors. The need for improved implementation strategies to sustain energy saving measures is also identified. Projects in this study are focused on deep-level gold mines.

*Chapter 2: Literature study* - Energy saving measures on mine cooling systems are investigated. Specific components that consume the most energy are studied in detail. The effects of implemented energy saving measures on a mine cooling system are also examined. Current implementation strategies are identified and reviewed. The factors influencing system performance is discussed.

*Chapter 3: Improved strategies for mine cooling systems* - This chapter provides more detail on energy efficiency and sustainability on existing applications of mine cooling systems. Improvements to existing energy saving measures on a mine cooling system will be discussed in detail. A method for improved implementation strategies on mine cooling systems is

developed in this chapter. The method of identifying challenges and replicating a solution for these challenges on a new energy saving project will also be discussed.

*Chapter 4: Practical application of improved strategies* - The strategies developed in Chapter 3 will be tested on a mine cooling system with no implemented energy efficiency strategies. The result of the case study is discussed and compared to the results from a Measurement & Verification (M&V) team. The verification of the results through simulation is compared with actual measured results. The validation of the study is also presented in this chapter.

*Chapter 5: Conclusions and recommendations* - This chapter summarises the key findings, limits of the study, and provides further recommendations for future studies and/or developments.

## CHAPTER 2: LITERATURE STUDY



2

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Deep-level mine cooling systems are reviewed, and optimisation techniques used in industry are identified. Implementation strategies and performance of energy saving measures are also reviewed.

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<sup>2</sup> Adapted from: Art's work [Online]. Available: <http://www.arts-work.blogspot.com>

## 2.1. Preamble

The implementation of energy saving measures as a necessity to ensure global competitiveness of deep-level gold mines in South Africa was identified in Chapter 1. The power supplier ensured that various incentives are launched to reduce the power strain on the grid and to cater for an expanding economy.

Gold mines were identified as significant electricity consumers. This increased the feasibility of implementing energy saving measures to reduce energy consumption on mines. The sustainability of these energy saving measures decrease over time, due to various reasons identified in Chapter 1.

The research problem is contextualised by addressing the hypothesis of this study, which is identifying challenges of implementing energy saving measures on mine cooling systems by improving the implementation strategies to focus on the sustainability of the energy saving measures.

Deep-level mine cooling systems and typical cooling auxiliaries are discussed in this chapter in order to simplify the understanding of the research problem. The effects of energy saving measures on mine cooling systems and subordinate systems are conveyed to analyse the scope of implementation strategies.

The performance of energy saving measures will be analysed, as well as identifying the means of sustaining these measures. The current implementation strategies are furthermore reviewed in order to gain an understanding of implementation strategies to quantify the scope of improved strategies to address the research problem.

## 2.2. Deep-level mine cooling systems

### 2.2.1. Overview

South African ore bodies are located deep below the surface [28]. Mines are continuously deepening to access ore beyond 3 km. Virgin rock temperatures at these depths can reach up to 60 °C [16]. The geothermal gradient in South African mines varies between 10 °C and 20 °C/km [28].

Apart from a significant temperature rise due to the geothermal gradient, there are other heat sources contributing to heat stress in deep mines. Primary heat sources underground include exposed rock faces, virgin rock, machinery and fissure water [40]. Another contributing heat load is caused by adiabatic compression [17].

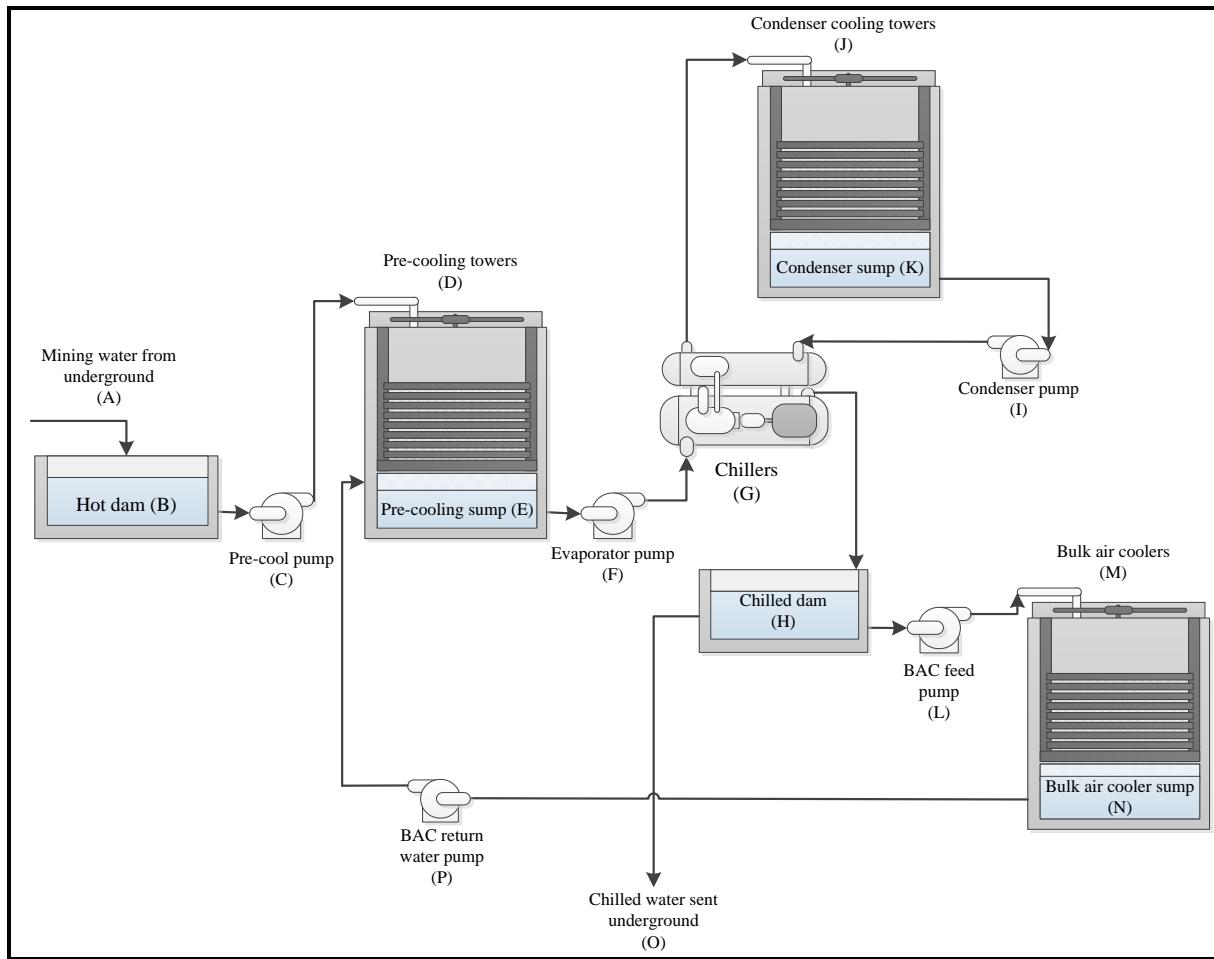
Adiabatic compression, or more accurately termed, auto-compression, also adds heat to ventilated air due to an increase in temperature and pressure of air entering and descending down the shaft. The auto-compression process is a conversion of potential energy into internal energy, due to the atmospheric air mass applying pressure to the air mass in the mine shaft [41].

Artificial cooling is required to remove heat loads to ensure safe working areas are maintained for mine workers. Artificial cooling is introduced when the average temperature of a working area exceeds 32 °C DB [28]. The underground temperature must, therefore, be regulated to not only ensure worker safety and productivity, but also to create sufficient environments for equipment to operate without unwanted heat effects [42].

Surface mine cooling systems are used to supply chilled water and cold, dehumidified air to underground workplaces. These cooling systems are, however, energy intensive, as described in Chapter 1.2. A common practice is to utilise centralised underground cooling systems (chillers, cooling towers and air coolers) to cool the underground environment [43]. Surface cooling systems are preferred due to increased heat rejection capacity [44].

Mine cooling systems can have different configurations and layouts, depending on the type and depth of a specific mine. A schematic layout of a typical surface deep-level mine cooling system is illustrated in Figure 4. A typical mine cooling system consists of pre-cooling towers, condenser cooling towers, chillers, bulk air coolers (BACs) and storage dams [26].

Used mining service water (A) is pumped from de-watering dams situated underground to a hot dam (B) on surface. The hot water is pumped (C) through spray nozzles in the pre-cooling towers (D), where after the water is collected in the pre-cooling sump (E). Evaporator pumps (F) are used to pump the pre-cooled water through the chillers (G). The water is cooled to temperatures that meet mine requirements and then stored in the chilled dam (H).



**Figure 4: Schematic layout of a typical mine cooling system**

The condenser pumps (I) are used to circulate condenser water through the condenser cooling tower (J) spray nozzles for heat rejection into the atmosphere, whereafter the water is collected in the condenser sump (K). BAC pumps (L) are used to pump water through the bulk air coolers (M), whereafter the water is collected in the bulk air cooler sump (N). The chilled water is also sent underground for mining services (O). The following sections elaborate on the functioning of each component in the system.

### 2.2.2. Storage dams

Mine cooling systems require storage capacity for hot and chilled water. Storage dams are used for this purpose [45]. Storage dams are required since chilled water demand varies daily, resulting in a variation in hot water pumped to surface also requiring storage [46].

Chillers in mine cooling systems are used to maintain a set chilled water temperature in the chilled water storage dam to provide underground operations with cold water at the required

temperature [28]. Variations in chilled water usage can also occur due to seasonal changes that allow the number of operating chillers to be reduced [47].

When the chilled water storage dam is full, recirculation of water to the pre-cooling dam is implemented. Some mines aim to avoid unnecessary cooling by throttling chilled water to control storage dams on a specified level. Controlling water flow by using valves is, however, an inefficient process [48]. Variable flow strategies are, therefore, a significant benefit to such a system [49].

Sediment build-up in storage dams are a frequent occurrence due to mines' poor water quality [50]. Sediment build-up can, however, restrict the dam level control on storage dams due to reduced capacity [38]. High water quality is not a concern in normal industrial open-circuit cooling towers, as make-up water is commonly available, such as in the petroleum and electricity generation industries [51].

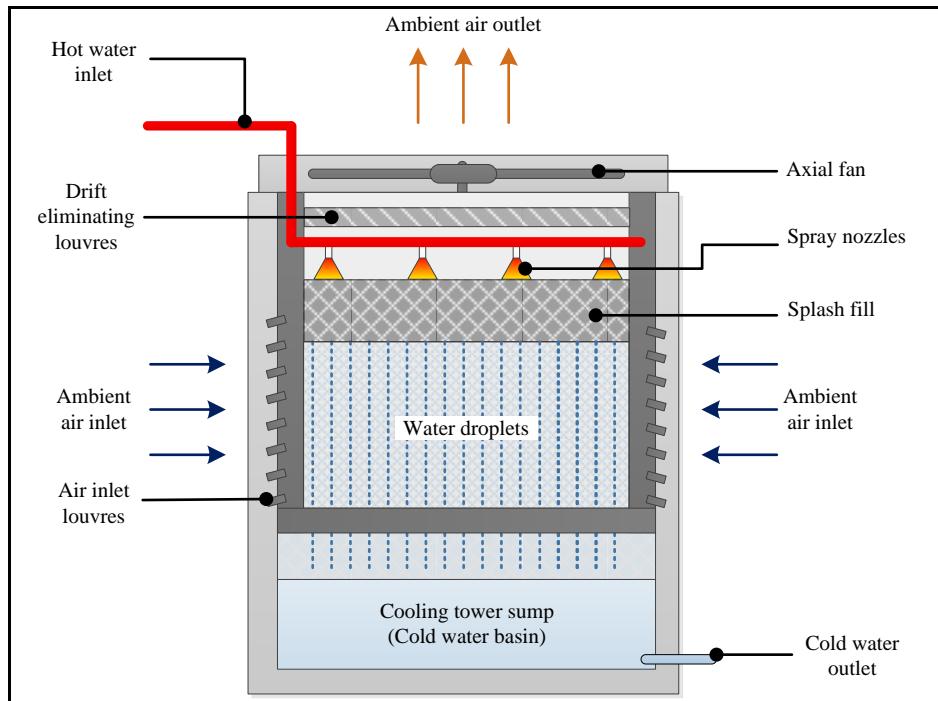
Mines, however, struggle with water quality when production surpasses the settler operating capacity [50]. In general, frequent maintenance on cooling towers, chillers and pumps are required when water quality is not up to standard. Maintenance on these systems due to poor water quality can lead to increased labour costs [38].

### **2.2.3. Cooling towers**

Mine cooling towers are categorised as direct heat exchangers. In a typical mine cooling system, cooling towers are used to pre-cool (termed pre-cooling towers) water before entering the evaporator circuit, and also to cool condenser water [52]. A combination of evaporation and convection causes heat to be removed from the water, and thus transferred to the ambient air [45].

In mechanical draft cooling towers, nozzles are used to disperse water, resulting in water droplets forming in the tower [53]. The radii of water droplets depend on the pressure drop in the nozzles and the presence of packing and fill inside the tower [45]. Water temperature and flow rate also influence the size of the water droplets [53].

Figure 5 illustrates a schematic drawing of a typical mechanical draft cooling tower. Mechanical draft cooling towers are commonly used on the surface at deep-level mines [44]. These cooling towers can cool water to within 3 – 6 °C of ambient air temperatures [27].



**Figure 5:** Schematic drawing of a cooling tower [44]

Warm water enters the cooling tower and is sprayed through the spray nozzles. The incoming air and water are mixed in the fill, where the contact area and contact time between the air and water are increased. Air velocities in these cooling towers are typically between 1.5 m/s and 3.6 m/s [38].

The cooled water is collected in the cooling tower sump, from where it is pumped through the chillers. The forced-draft fans on top of the cooling tower extract the warm air into the surrounding environment. Apart from the fans, only the pumping of reticulation water and the replacement of the evaporated water can be identified as energy consumers on cooling towers [54].

Cooling towers normally operate with a coefficient of performance (COP) of approximately 30 [38]. Changes in the operational parameters of the cooling tower can have a significant effect on the performance of the tower. Insufficient water flow and pressure will cause uneven distribution of water and therefore affect the flow distribution and pattern in the cooling tower [53]. Favourable conditions for scaling and fouling occur due to these conditions, promoting decreased efficiency.

Reductions in COP can be experienced due to evaporation in the tower, leading to an increase in dissolved solids and contaminants in the tower. These solids and impurities lead to scaling

and sedimentation build-up on tower components, such as the fill and air inlet louvres [45]. Dust and contamination build-up can also occur within the towers [54]. The treatment of water and regular maintenance on the towers can prevent the scaling, contamination and sedimentation affecting the heat-transfer capabilities in the tower [55].

### Bulk air coolers

Cooling of the entire mine is usually done by a centralised unit (either underground or on the surface) called a bulk air cooler (BAC) [16]. BACs utilise the chilled water provided by the chillers to cool ambient air to the required temperature for circulation throughout the mine. BACs are similar to cooling towers, with the main difference being the heat transfer direction [52].

The BACs are located near the shaft, with ducting that sends the cold, dehumidified air underground. Underground BACs function on the same principles as surface BACs. Dust concentration can also be reduced by the utilisation of underground BACs for mine ventilation and cooling [43].

During cooler winter months (typically between June and August in South Africa), the BACs are not required, due to the air being sufficiently cold and dry. Maintenance on the cooling systems is usually conducted during these months [38].

The water-side efficiency of a cooling tower can be calculated using Equation 1. The COP of the chillers is dependent on the performance of the BACs and cooling towers. Inefficient cooling towers and BACs cause a temperature rise throughout the system and therefore affect the cooling range of the chillers [45].

$$\eta_W = \frac{T_{wo} - T_{wi}}{T_{ai(WB)} - T_{wi}}$$
 Equation 1

Where:

$\eta_W$  = water-side efficiency (%)

$T_{wo}$  = water out temperature ( $^{\circ}\text{C}$ )

$T_{wi}$  = water inlet temperature ( $^{\circ}\text{C}$ )

$T_{ai(WB)}$  = air inlet wet-bulb (WB) temperature ( $^{\circ}\text{C}$ )

The range of the BAC is the change in temperature of the water inlet and outlet, given by  $-(T_{wo} - T_{wi})$ , and the approach is the difference of the water outflow and WB temperature of the air flow, given by  $-(T_{ai(WB)} - T_{wi})$  [17]. The performance indicators of BACs are similar to that of cooling towers [38].

#### 2.2.4. Chiller plants

Surface chillers are used to chill mining water. Underground plants are used to do the same, but heat rejection is constrained due to limited availability of exhaust air, where surface chillers use atmospheric air [38]. Chiller plants can cool water to between  $3\text{ }^{\circ}\text{C}$  and  $6\text{ }^{\circ}\text{C}$  [27].

A typical mine cooling system consists of one or more chillers. These chillers can be arranged in three different types of configurations. Figure 6 illustrates the three different chiller arrangements typically found on deep-level mines. Chillers are designed to handle variations in thermal loads. The different chiller arrangements cater for these varying loads [56].

Chillers can either be configured in a 1) parallel configuration, which is used for variable flow requirements, 2) series configuration, used for variable temperature requirements and 3) series-parallel configuration, for variable flow and temperature requirements [57].

Shell-in-tube or plate heat exchangers are used in chillers making use of screw- and centrifugal compressors [58]. The refrigeration cycles used in industry are vapour-compression and ammonia-absorption cycles. The configuration is normally dependent on the specific requirements of the mine [59].

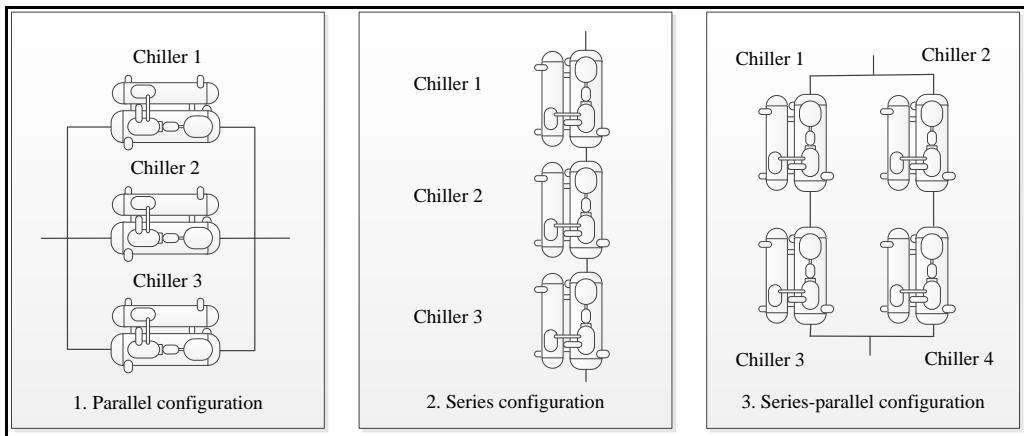


Figure 6: Various chiller configurations

A vapour-compression cycle used in mine chillers is illustrated in Figure 7. The water flows through the tubes and the refrigerant flows in the shell. Water is chilled in the evaporator by using the latent heat of evaporation in the refrigerant. Heat rejection in the process is absorbed by the condenser water [59].

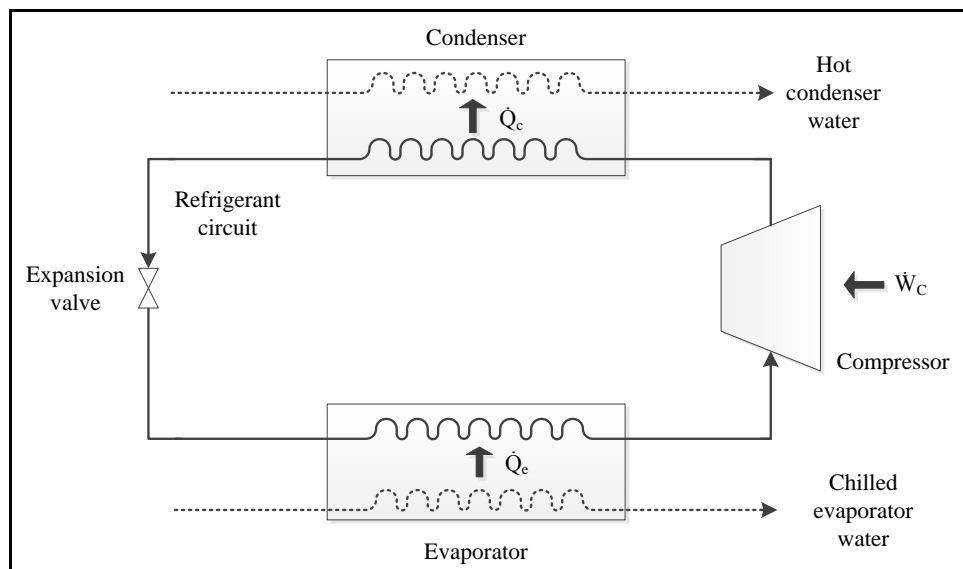


Figure 7: Vapour-compressor cycle used in mine chillers

The compressors of the chillers have guide vanes (centrifugal compressors) or slide valves (screw compressors). The cooling load is controlled by the guide vanes or slide valves, depending on the type of compressor used [60]. The type of compressor used is governed by the system-specific pressures and specific volumes required [58].

The compressor is the main power consumer on a chiller. The coefficient of performance (COP) of a chiller is the measure of the efficiency of the chiller and is largely dependent on the compressor power consumption. The COP of a chiller can be calculated with Equation 2 [56].

$$COP = \frac{Q}{P_{ref}}$$
Equation 2

Where:

COP = coefficient of performance (-)

Q = Refrigerating rate (kW)

P<sub>ref</sub> = compressor motor power (kW)

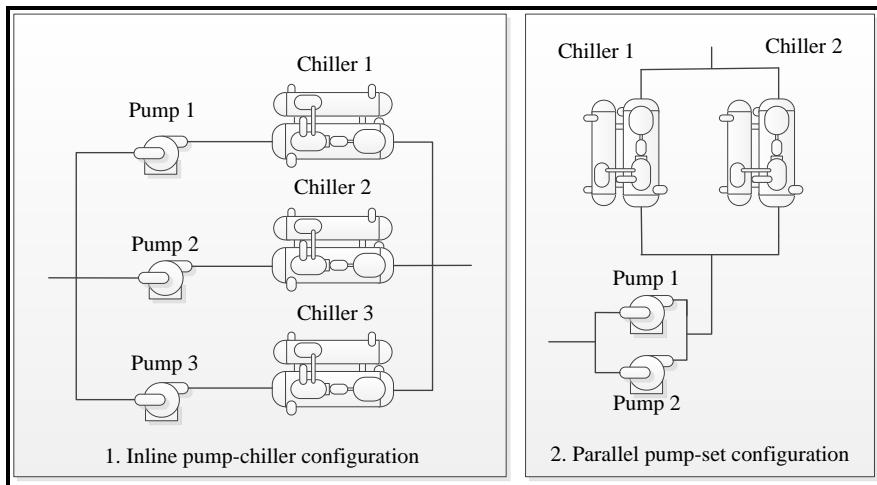
High COP values indicate efficient operation of the chillers. Compressor power input and cooling-load changes affect the COP of the chillers. Compressor-capacity control systems ensure a set water outlet temperature in the evaporator circuit. It is therefore clear from Equation 2 that a change in evaporator flow rate and temperature can affect the evaporator cooling load. Typical chillers used on a deep-level mine can have a cooling capacity to the order of 6 MW [27].

### 2.2.5. Pumps and motors

Mine cooling systems often utilise pumps to reticulate condenser and evaporator water [39]. These pumps, together with cooling tower fans, are termed auxiliary equipment, as they operate independently from the chillers. All auxiliary equipment can be separately controlled, as they are not directly part of the chillers [38].

Pumps can be configured in either parallel or direct-inline when applied to chillers. Figure 8 illustrates an inline pump-chiller configuration (1) and a parallel pump-set configuration (2). Inline pump configurations are applied to individual chillers (chillers arranged in parallel). Parallel pump-sets pump into a common manifold to supply a network of chillers (typically chillers arranged in series or series-parallel configurations).

Parallel pump-sets require valves on the inlet of chillers to control the water flow rate and pressure entering the chiller, due to pressure drops caused by the common manifold [38]. Common manifolds thus complicate the control of the auxiliary pumps. Inline pumps create a suitable configuration for controlling pump speeds, as the speed reduction only affects the individual chillers [61].



**Figure 8: Different pump-chiller configurations**

Centrifugal pumps are commonly used in mining applications due to the variety of pump sizes available [61]. Positive displacement pumps can achieve a significantly higher efficiency, but are limited in size. The pressure produced by a centrifugal pump is due to a rotating impeller accelerating the passing liquid circumferentially [38]. The impeller and casing shape design govern the efficiency of producing the required pressure.

Selecting a pump for a particular application requires matching the system curve with the characteristics curve of the pump. The characteristic curve shows the designed performance of a pump, while the system curve indicates the positive static head and the friction of the particular system [62].

Numerous factors have to be considered when controlling the speed of a centrifugal pump. Controlling pump speeds can significantly influence the efficiency of the specific pump. Controlling the pressure of a pump system is thus limited by this factor [63]. Affinity laws govern the effects that flow-rate reductions have on the characteristic curve of a pump. The affinity laws are represented by Equation 3 to Equation 6 [64].

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \quad \text{Equation 3}$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad \text{Equation 4}$$

$$\frac{H_1}{H_2} = \left( \frac{Q_1}{Q_2} \right)^2 \quad \text{Equation 5}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad \text{Equation 6}$$

Where:

Q = water-flow rate ( $\ell/s$ )

D = impeller diameter ( $m^2$ )

N = rotational speed (rpm)

H = pressure head (m)

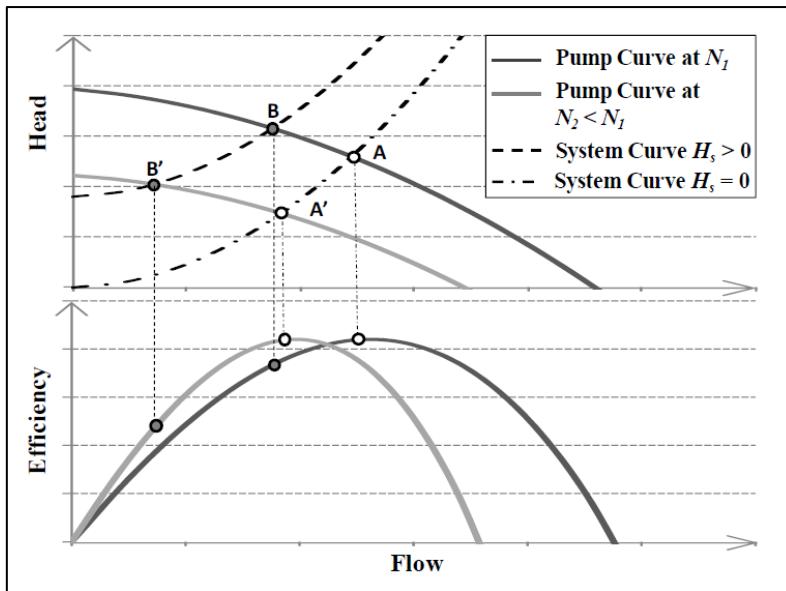
P = pump input power (kW)

Affinity laws indicate that the flow rate (Q) is directly proportional to the rotational speed (N), increase in pressure head (H) is directly proportional to the square of the flow rate, and the input power is proportional to the cube of the rotational speed [65].

When inspecting the characteristic and system curves of a pump, the region of optimal pump efficiency should correspond with the general operating point of the pump. This region is obtained by plotting the required head against system flow rate and is called the best efficiency point (BEP) [65]. Other changes to the system, such as valve adjustments, have the effect of changing system resistance, thus affecting the flow rate and delivery pressure of the pump [66].

Speed reduction of pumps by variable speed drives (VSDs) is widely used in industry [49]. From literature, it is found that systems dominated by frictional losses alone are beneficial to variable flow control. Systems characterised by a large static pressure head have a limited speed range for control, and also suffer a significant decrease in pumping efficiency [67].

The operating points and efficiencies of a system- and pump characteristics curve is illustrated in Figure 9. The pump efficiency can be maintained, while the input power required is significant [67]. This is true because speed reduction causes the pump operating point to move down an iso-efficiency line. This phenomenon is thus suitable for mine cooling system pumps with small static heads and significant friction [27].



**Figure 9: Typical system and pump characteristics curves [68]**

Inspecting Figure 9, above, clearly indicates that, for a system with no static head, the operating point A at a specific rotational speed  $N_1$  translates to A' due to speed reduction to  $N_2$ . A and A' maintain the same efficiency (iso-efficiency). For a system with a significant static head, the operating point at the reduced speed B' translates to an efficiency lower than operating point B at the nominal speed  $N_1$  [67].

From Equation 6 and the fact that the efficiency is not substantially influenced for pumps in mine cooling system applications, one can deduce that the sustainable pump efficiencies are proportional to electricity savings and prolong the operating life of the pump [63].

In cases where reduced pump efficiencies are void, unnecessary increases in wear rates and increased life-cycle costs (LCC) can be avoided. LCC include original purchase costs, electricity costs and maintenance costs. Other factors influencing LCC must also be considered [27].

Examples of other factors are the net-positive suction head (NPSH) of the pump. The NPSH must be higher than required, effectively avoiding cavitation problems. Another example is the practise of scheduling different pumps to operate to reduce stress on the parts, such as bearings and other rotating parts [66].

The motors coupled to the pumps deliver the required input power to drive the pump. Pump motor speeds can be altered, either by changing the number of poles, or by altering the incoming frequency. Altering poles require a physical change to the motor [69]. Changing the

frequency, however, can easily be achieved by the installation of a VSD. Application of VSDs results in lowered current drawn by the motor, relating to reduced power consumption at lowered speeds [70].

Electrical power savings due to the installation of VSDs are possible in industry [70]. Reductions in motor speeds cause concerns regarding operating temperatures of the motor. Electrical motors in variable torque applications can have speed reductions of up to 50% without unwanted effects due to temperature rise [70].

Pump-motor configurations, found on mine cooling systems, operate in variable torque applications. This indicates that VSDs can be applied to these applications with negligible effects on motor temperatures. Other unwanted effects of applied VSD control are harmonics and motor-bearing pitting.

VSD manufacturers have developed harmonic filters to counter the harmonics in the system. Numerous methods have been developed to counter bearing pitting, which include replacing the existing bearings with isolated bearings and installing shaft grounding brushes [70].

#### **2.2.6. Control and instrumentation**

Control and instrumentation on mine cooling systems require connections between the supervisory control- and data acquisition (SCADA) system and the programmable logic controller (PLC). Interaction among the field instrumentation, PLCs and the SCADA requires a specific connection called open-platform communications (OPC) connection. OPC connection enables the mine cooling system to be integrated with any SCADA and thus ensures an effective management tool [23].

Altering or implementing any optimisation strategies on mine cooling systems require system upgrades to components such as PLCs, field instrumentation and, in some cases, the management systems.

Control of mine cooling systems requires calibrated and accurate measuring instrumentation. Potential measuring errors can be limited with regular calibration. Equipment such as chillers are controlled with a specific PLC located at the chiller. This PLC controls all equipment on the chiller. Errors should be minimised to effectively and efficiently control equipment – accuracy and sensitivity of instrumentation is thus crucial [71].

Instrumentation installed on the mine cooling system should be efficient to allow control and monitoring of the performance of the system. System variables that are significantly important are pressures, temperatures, currents and power usages.

### **2.3. Cooling system optimisation techniques**

#### **2.3.1. Overview**

Mine cooling systems often operate under inefficient control and lack of integrated management [16]. This section investigates the strategies that are currently implemented on mine cooling systems that reduce the electricity consumption and optimise operation of the entire system. Energy efficient strategies will firstly be identified. The effects of these strategies will also be analysed in this section.

Energy efficiency in industry can be improved by three different approaches, namely 1) energy management, 2) energy saving by technologies, and 3) energy saving by policies [20]. The focus of this study will be on the energy saving by integration of energy management and technologies to sustain energy saving measures on mine cooling systems.

#### **2.3.2. Energy efficiency strategies for mine cooling systems**

Existing state-of-the-art technologies include the integration of VSDs with new control methods and also an energy management system [23]. Various energy efficiency strategies have been implemented in industry that utilise the technologies mentioned above. The application of VSDs offers significant energy savings when applied in industry [72].

VSDs control the speed of electrical motors by varying the frequency of the alternating current (AC) supplied to the motor and modulates and controls the speed, mechanical power and torque of the motor [20, 70]. From literature it is evident that VSDs and VSD compatible motors are the most efficient while operating under a given load [20, 72, 73].

It is evident that the application of VSDs is widespread. Incorporating VSD technology in various designs to optimise the energy performance of a mine cooling system proves significant energy savings.

There are a few variable flow strategies that are implemented to optimise the following circuits of a mine cooling system [17], namely:

- evaporator flow control,
- condenser flow control,
- BAC flow control, and
- pre-cooling flow control.

### Evaporator flow control

A variable flow control strategy was developed for the evaporator side of the chiller [27]. The control of the evaporator flow rate is the aim of the strategy. This can be achieved by the installation of VSDs on the evaporator pumps. The flow rate can then be controlled by using PID control logic to control the speed of the pump to maintain a specified chill dam level. The evaporator circuit flow control is indicated by the red square in Figure 10.

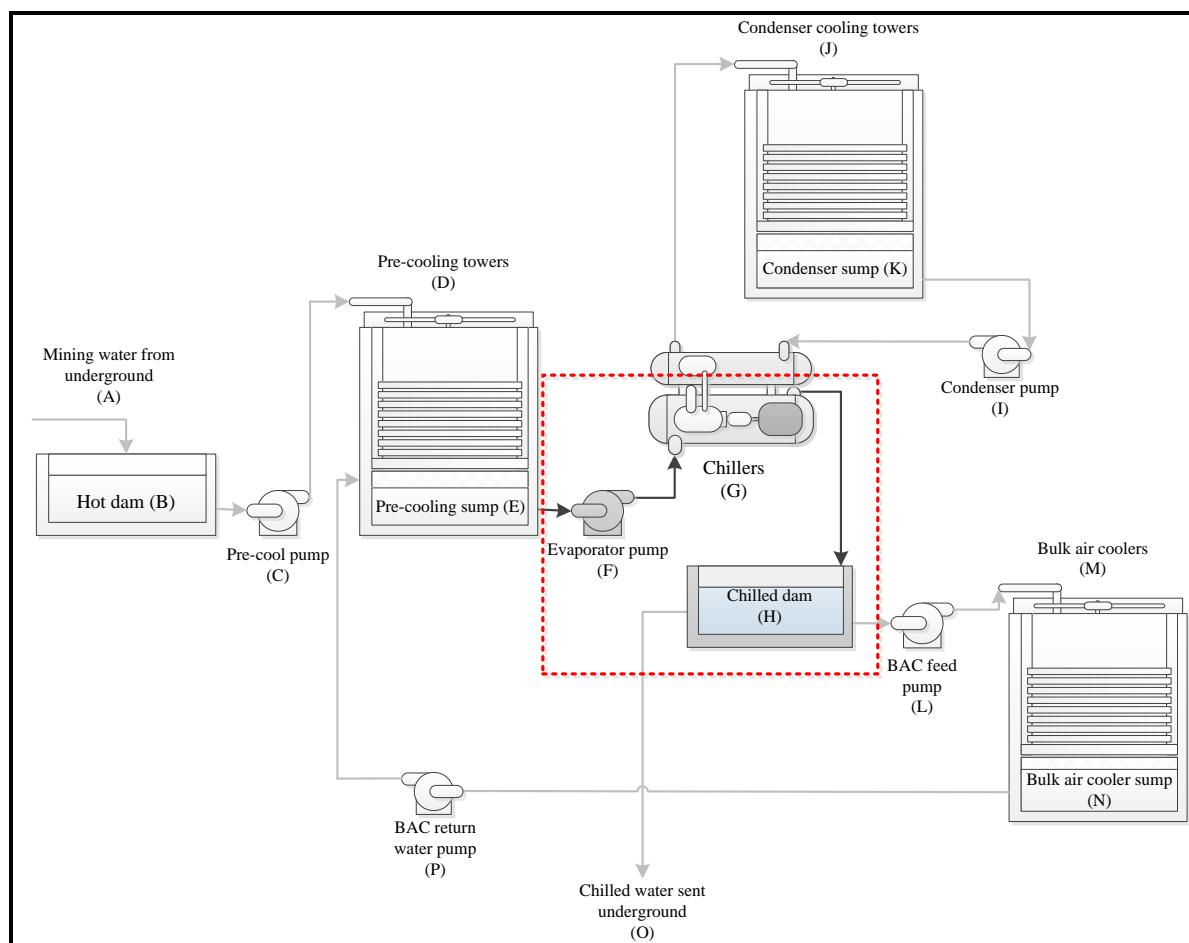


Figure 10: Evaporator circuit flow control

The chill dam is a reflection of the demand for chilled water; the control is therefore based on the chilled water dam level. The constraint of chilled water flow and temperature can be placed on the evaporator circuit [45]. The flow control on the chillers, through throttling valves, must, therefore, be eliminated, and the valves must be fully opened [26].

Controlling the pump speed by utilising a VSD ensures that the design conditions are met without compromising the requirement for chilled water, effectively using the cubic-flow relation to obtain pump power savings. The back-passing of water to the pre-cooling circuit must therefore be eliminated to reduce the high cooling loads imposed on the chillers.

The chiller compressor control is based on maintaining the evaporator outlet temperature at a set outlet value. The evaporator flow control should thus not adversely affect the outlet temperatures, due to sufficiently-low inlet temperatures. The compressor capacity control (vane control) will reduce refrigerant flow rate and the required pressure rise, which leads to power savings on the compressor.

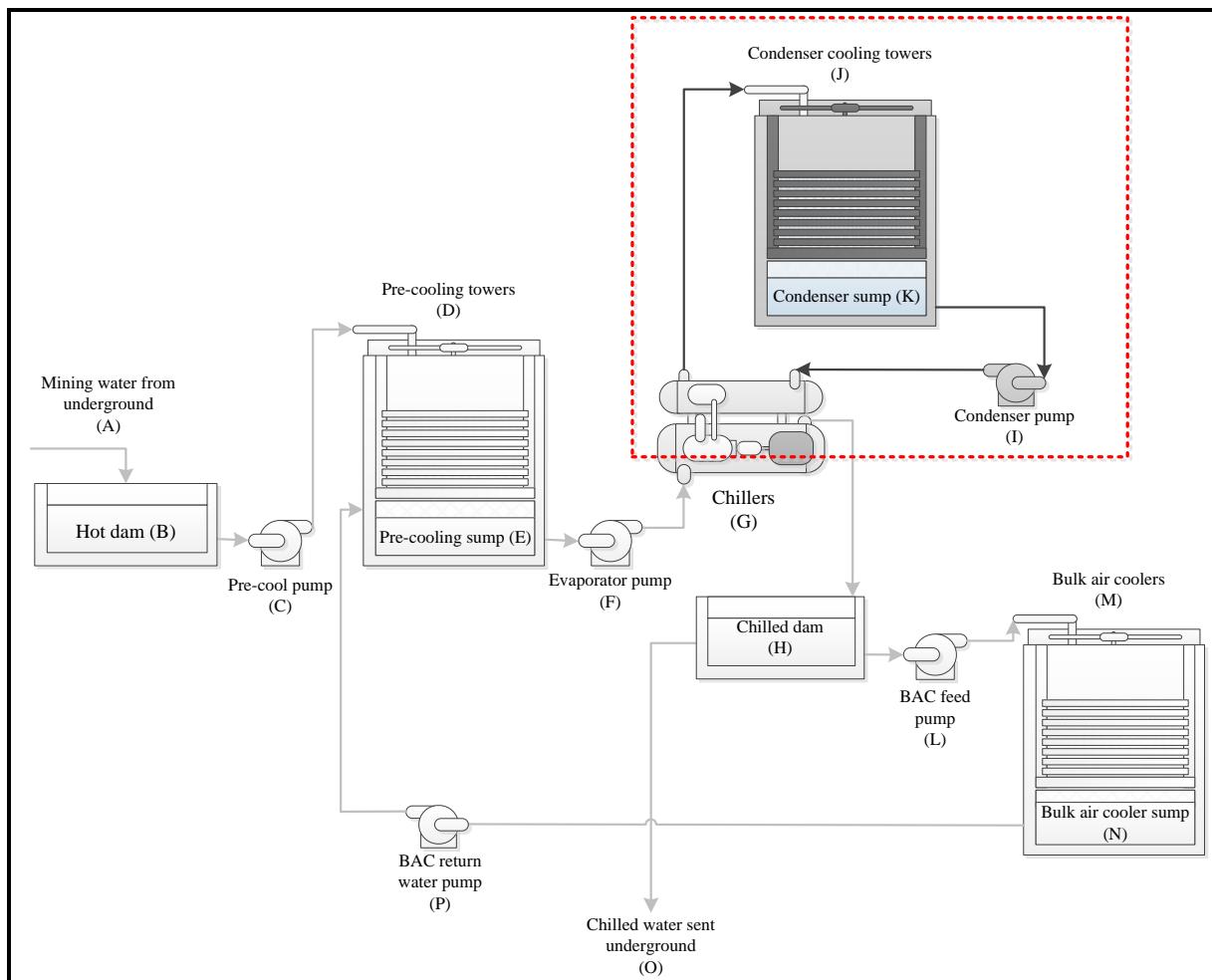
Evaporator flow rates below 60% of the OEM design specifications of a chiller must be avoided when applying evaporator flow control to a system [16]. Chiller trip conditions must also be considered by adapting the flow to control just above the minimum trip limits. This will ensure increased COPs of the chillers and avoid unwanted effects on the tubes, such as scaling/fouling [74].

### **Condenser flow control**

A variable flow control strategy was also developed for the condenser-side of the chiller [27]. The control of the condenser flow rate is the aim of the strategy. The strategy is based on the same principle as the evaporator flow control, which states that design loads are rarely reached during normal operation. The condenser circuit flow control is indicated in the red square in Figure 11.

The water flow rate must be controlled to maintain the design change (delta) in temperature across the condenser using PID control [26]. Water flow rate can be controlled by installing VSDs on the condenser pumps of the chillers. The valves, used to throttle the condenser flow rate to design flows, must be fully opened.

The condenser energy savings are based on the same principles as discussed for the evaporator flow control strategy. Condenser control should be carefully considered due to adverse effects, such as reduced COP, increased compressor power usage and the increased possibility of scaling in the condenser tubes [27].



**Figure 11: Condenser circuit flow control**

When implementing the condenser water flow control, the water flow rate must not be reduced by more than 60% of the design flow of the chiller. The condenser cooling towers are also affected by the strategy. The ambient conditions play a significant role in the increase or decrease of condenser water temperature. Implementing condenser flow control strategies can still be justified due to the significant pump energy savings [26].

The flow distribution pattern in the condenser cooling tower must be observed during commissioning to determine whether the water flow rate and delivery pressure is sufficient for optimal heat exchange in the tower [37].

## BAC circuit

A BAC flow control strategy, which is constrained by the requirement to cool and dehumidify air to 8 °C DB, was also developed [27]. The strategy is based on the fact that the temperature safety barrier must only be utilised for small portions of a typical hot day. During cooler months, over-cooling in the BACs is a result of operating at full load conditions. The BAC circuit flow control is indicated in the red square in Figure 12.

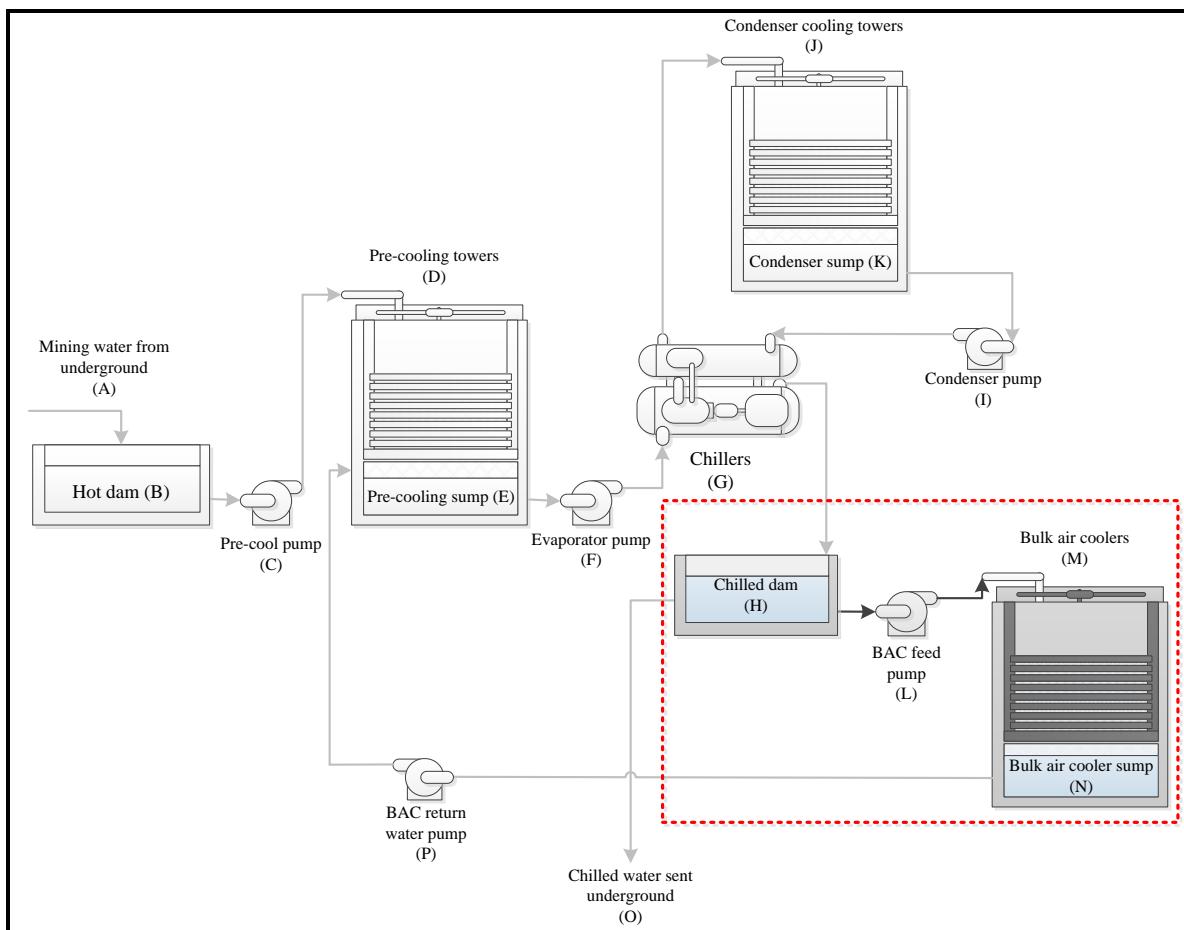


Figure 12: BAC circuit flow control

The proposed control, depending on the mine cooling system layout, is to:

- open valves that throttle BAC flow to design conditions (if valves are present),
- stop over-cooling BAC air temperatures by matching the demand for cool, dehumidified air with advantageous changes in climate,
- consider BAC sump dam levels by avoiding unnecessary pumping.

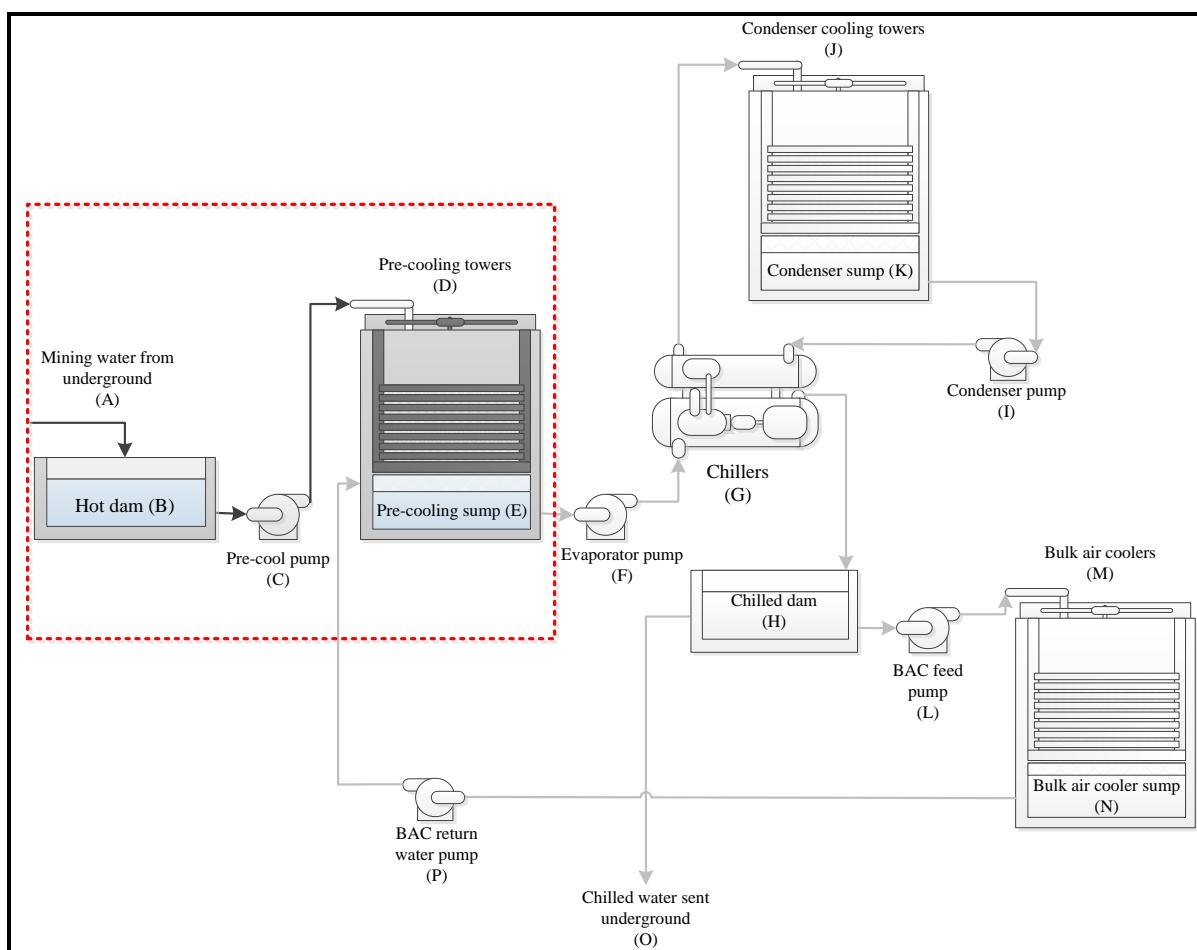
The BAC flow control strategy is applied by installing VSDs on the BAC feed pumps and controlling the speed according to the direct change in ambient conditions. The control will

ensure that the demand for ventilation air will be met without the consequences of overcooling.

BAC tower flow control must consider the flow distribution within the tower when implementing the project. Degraded BAC performance can be a result of neglecting the lower limits of BAC flow rates. VSDs can also be installed on BAC return water pumps and can be controlled with closed-loop PID control, according to a set BAC sump dam level.

### Pre-cooling flow control

Implementation of the evaporator flow control strategies results in modulation of the water feed from the pre-cooling towers. The pre-cooling tower flow control should also be included to keep all dams balanced while achieving pump energy savings [27]. The pre-cooling circuit flow control is indicated in the red square in Figure 13.



**Figure 13: Pre-cooling circuit flow control**

The valves used to throttle the flow through the pre-cooling towers should be fully opened when VSDs are installed on the pre-cooling tower feed pumps. PID control must be implemented, with the dam level as the control feedback.

The pre-cooling tower performance should be considered when implementing the pre-cooling tower flow control. The flow distribution should be established, as mentioned previously. The result of the pre-cooling flow strategy will improve pre-cooling dam temperatures and pump energy savings.

The implementation of energy saving measures discussed in this section will aim to reduce the power consumption of the system. The implementation strategy should be carefully considered and should be adapted to suit the specific application.

## **2.4. Existing implementation strategies**

### **2.4.1. Overview**

Energy saving measures are widely implemented in industry [4]. It is implemented as DSM projects, as discussed in Chapter 1. These projects aim to either reduce the pattern of energy consumption by a consumer, or reduce overall electrical energy consumption [75].

A new DSM method must be implemented successfully and cost-effectively [27]. This will support current incentives for the development of the DSM method. This dissertation only focusses on energy saving measures on mine cooling systems as part of a DSM strategy. The method developed is therefore only applicable to mine cooling systems and their specific strategies.

### **2.4.2. Preliminary implementation**

Control system optimisation of mine ventilation systems have previously been investigated [76]. These systems lack simultaneous resolutions to address operational concerns, efficiency of operation and control robustness [27]. Unreliable and impractical implementations are a result of their complexity.

An energy management system is required when implementing a DSM project. This system must control sub-systems, monitor and manage the integrated mine cooling system and all auxiliaries. The sustainability of an energy saving measure depends significantly on the integration with an energy management system (EMS).

The EMS must consider real-time interaction with other subsystems to ensure a robust and effective system. The mine cooling system in its entirety must be monitored and controlled according to an effective control philosophy, which caters for the effect of altered equipment control [17, 27].

Implementation of energy saving measures should include a detailed strategy to determine the pre-implementation conditions in order to determine the effect of a savings intervention. Comparable boundary conditions are thus required in order to measure system performance. The performance of components before intervention can thus be compared to the performance after implementation.

From the literature it was established that further development is required for the implementation of available energy saving technologies [27]. The success of load management depends on various factors, such as operation strategies, Eskom tariff rates and structures, thermal storage capacity and climate conditions [56]. An improved strategy must include these factors.

Implementation of an energy efficiency strategy requires a detailed analysis to determine the expected outcome of the strategy [17]. All equipment in the system that will undergo alterations must therefore be inspected to determine the need for protective measures to be installed on the equipment.

#### **2.4.3. Implementation and post-implementation considerations**

System limitations and constraints must be identified during initial project investigation. It is, however, impossible to identify all system limitations. The general operation of the cooling system can be identified during the investigation phase. Extensive functionality regarding system functionality and limiting constraints can only be identified during implementation of the energy saving measures [17].

Potential problems can be analysed by gaining extensive knowledge of the operation of the mine cooling system. Any interference with production should be avoided. Equipment functioning should only be altered if a sustainable operation replaces the existing ineffective operation [43].

The system delivery of the cooling system should not be adversely affected, only improved. The sustainability of the improved system is ensured by documenting changes throughout the

implementation process, and constantly updating the process documentation. The available process data should furthermore be analysed during the implementation of the project to ensure system design is still relevant and will function as expected.

Controllable operation parameters must be monitored by an energy management system (EMS), and critical plant parameters must also be logged and analysed on a frequent basis. Redundancy is another requirement during implementation. The relevant measures must be put in place to integrate the EMS and the SCADA, but to also ensure that the PLC can resume the necessary control when required. Without catering for redundancy, the system cannot be fully automated [27].

## **2.5. Performance of energy saving strategies on mine cooling systems**

### **2.5.1. Overview**

The performance of energy saving measures is significantly dependent on the strategy whereby the measures were implemented [38]. This section focusses on identifying the factors and operational parameters to consider when an energy saving measure is implemented. These factors and operational parameters must be analysed in order to, firstly determine the performance of the entire system, and secondly, to improve the sustainability of the implemented energy saving measures.

### **2.5.2. Mine cooling system requirements**

The mine cooling system requirements must be identified to determine the constraints of the control of the implemented system, as discussed previously. Comparable boundary conditions must be identified for pre- and post-project implementation. Thereafter, only comparable boundary conditions should be considered, to accord with measurement and verification procedures [16, 27].

The original design of the implementation strategies should include and compensate for mine service delivery requirements. The performance, however, must still be measured and compared to actual effects within the system. The main requirements to consider are productivity and safety of the mine and mine workers [56].

The main priority for a mine cooling system is to function reliably during the supply of chilled water underground and to the BAC, where air will be cooled to be circulated

underground [47]. Chilled water requirements (flow rate and temperature) and BAC air outlet temperatures are identified as crucial system requirements. Thus, the chilled water temperature and chilled dam level should be kept within tolerable limits [77]. These limits are determined during project commissioning.

As previously discussed, chilled water is used for various operations, which include workplace cooling, either through supplying chilled water to working areas, or through air cooling in the BAC [78]. By ensuring the requirements are kept within tolerable boundaries, the productivity and worker safety will not be compromised [42].

These requirements can also be used to determine the performance of the implemented energy saving measures on the cooling system [27]. The chilled-water temperature must be supplied according to mining demand and environmental, health and safety regulations. From the literature it is clear that chilled-water temperatures of 3 °C to 6 °C will be adequate [38, 79].

The literature also indicates that mines require the working area temperatures to be maintained at 27.5 °C (WB) to create a safe and comfortable environment for workers [80]. Cooling strategies applied to the BAC circuit should thus not adversely affect the temperatures underground. Environmental health and safety mine personnel prefer BAC air outlet temperatures of 7 °C WB.

### **2.5.3. Performance measurement strategies**

The impact of energy saving measures is commonly measured by comparing pre- and post-project energy consumption. Performance and energy consumption of mine cooling systems are, however, functions of ambient conditions and mine production schedules, and therefore frequently change.

Pre- and post-project performance and energy consumption can therefore not be compared without compensating for the effect of ambient and production influences [81]. Pre- project refers to the period before equipment installations; post- project refers to the period after the handover to the client.

The performance of mine cooling systems can be measured by using comparable boundary conditions, as stated previously [16]. The effect on energy consumption, however, requires other strategies or models to account for changes in weather and production [81].

Independent measurement and verification teams are usually contracted by Eskom to validate the savings of an energy-saving project proposed by an ESCO in industry. Measurement and verification (M&V) in industry is governed by the International Performance Measurement and Verification Protocol (IPMVP), but it was also found that M&V in industry is regarded as an inaccurate science [82].

The M&V team is responsible for auditing the pre- and post-project power data. This is normally achieved by compiling power baselines and developing a regression model to compensate for the possible changes in production or climate conditions. This regression model is then used to measure the performance of the system in terms of electrical energy consumption [83].

The method used to establish the baseline and linear regression model will be discussed in section 4.2.4. The performance measurement of the case studies that will be conducted in this dissertation will be done according to the regulations mentioned above.

#### **2.5.4. Long-term sustainability of energy savings**

Studies indicated that mine cooling system energy savings can only be sustainable when an EMS is implemented as part of the energy saving measures. Automatic control of the mine cooling systems should further be possible, with optimisation as part of the aim of implementation [84].

Monitoring and reporting of key performance indicators also serve as an approach to improve the sustainability of energy savings. Robust monitoring and reporting systems ensure effective communication among ESCOs, the client and Eskom, resulting in sustained energy savings [24].

Accurate performance measurement also promotes sustainable energy savings, as indicated in the previous section. By constantly monitoring the performance of the interventions one can gain extensive knowledge regarding the savings achieved. A cumulative decrease in power savings will be the first indicator of an inefficient system not achieving the targeted energy savings.

DSM initiatives implemented by ESCOs are already aimed at improving system performance and also achieving sustained energy savings. The maintenance of these implemented initiatives is crucial to sustain the energy saving measures [37]. The energy saving measures

identified for each specific application must be designed and altered to promote sustained energy savings [37].

Key performance indicators (KPIs) are used to monitor the performance of a mine cooling system [38]. The characteristics of each component can be used to monitor the condition or state of the equipment. These KPIs must be included in the setup of the monitoring and reporting system.

## 2.6. Conclusion

This chapter firstly focussed on the overview of a typical deep-level mine cooling system. The various components of the system were analysed. This analysis served as a knowledge base in order to identify applicable optimisation techniques to be implemented on mine cooling systems to reduce energy consumption.

The identified optimisation techniques focus on matching the evaporator flow with demand for chilled water, condenser flow with heat load, dam level control of the pre-cooling circuit, and change in ambient enthalpy control of the BAC circuit of mine cooling systems. Improved strategies for implementation can now be implemented with a broad understanding of the type of system control.

The research problem, however, stated that the method of implementation of these energy saving measures must be improved in order to sustain the proposed energy saving initiatives. Shortfalls of current implementation strategies were identified and Chapter 3 will focus on improving current strategies to satisfy the research objective.

It was identified that the performance of the energy saving measures plays a significant role in the sustainability of the implemented projects. Mine requirements must be kept in mind during initial system design and implementation. Factors that influence the long-term sustainability of energy saving measures were also identified.

A method to quantify energy savings were also discussed, with the focus largely on mine cooling system performance.

# CHAPTER 3: IMPROVED STRATEGIES FOR MINE COOLING SYSTEMS



3

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Existing energy saving measures are investigated and improved strategies for implementation are developed from the evaluation.

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<sup>3</sup> P. Maré, Personal photograph. "Hitachi chiller", South Africa, 2014.

### **3.1. Preamble**

Numerous energy saving measures have been developed and implemented on mine cooling systems on most of the South African deep-level gold mines in the past decade. The goal of the implemented measures was to improve system efficiency by reducing power consumption, without affecting production or worker environment conditions.

The feasibility of improving the existing projects increases due to the deterioration of older projects. Conducting energy audits on some mines proved that the power-savings target is no longer achieved. In some cases the implemented strategies and equipment might have deteriorated to a severe extent where utilisation of the strategies were abandoned.

System operation before the energy saving project implementation was re-implemented by mine personnel when deterioration of the implemented systems started. Engineers on some mines are proactively maintaining implemented strategies, reporting deterioration of any of their systems to relevant ESCOs as soon as concerns are raised.

Lack of integrated management, maintenance, optimal utilisation and optimised control on current energy saving projects are, however, direct causes of deterioration. Efficient and reliable systems are a result of thorough and successful project implementation. Improved implementation strategies therefore have to be developed with the focus on sustainability of the energy saving measures.

This chapter will discuss a mine, Mine A, with deteriorated energy savings. The energy saving measures will be re-implemented, with sustainability of the energy savings as the main focus, and secondary to that, the equipment utilised by the measures. By identifying challenges on typical cooling systems, the implementation of energy saving projects on other mines can be streamlined with improved implementation strategies.

### **3.2. Evaluating existing energy saving measures**

#### **3.2.1. System description**

A critical evaluation of an existing DSM project on Mine A, which is a deep-level gold mine, was conducted after deterioration of energy savings and plant performance was observed. The original project implementation was part of the IDM energy efficiency initiatives

launched by Eskom, and was implemented in 2011. The project focused on controlling and optimising the surface mine cooling system and auxiliaries.

A detailed investigation, according to the process described in Appendix II, was conducted. The investigation revealed the initial detailed objectives of the project and also the technical system integration and operation. A clear definition and understanding of the original project control philosophy needs to be established before altering any current system parameters or operational procedures.

Variable flow strategies were implemented on the surface cooling system of Mine A. The chillers at Mine A are arranged in a parallel configuration. Each chiller configuration features its own evaporator and condenser pump. The basic layout of all system components are illustrated in Figure 14.

The installed equipment related to the existing saving strategy and the initial control philosophies are indicated in Table 1. The specifications of each component in the system are listed in Table 15 in Appendix I. The installed equipment was crucial in the effective operation of the energy saving measures during initial project implementation.

Details of the original control philosophy are discussed in the sections that follow. An additional part of the investigation was to identify any feasible system improvements which primarily focus on sustainability. Various system improvement strategies were identified. System improvements can be identified by analysing the system operation and operational parameters.

The focus of the improvements on Mine A was to integrate, optimise and control the pre-cooling towers, condenser cooling towers, bulk air-cooling towers and the chiller evaporator and condenser circuits.

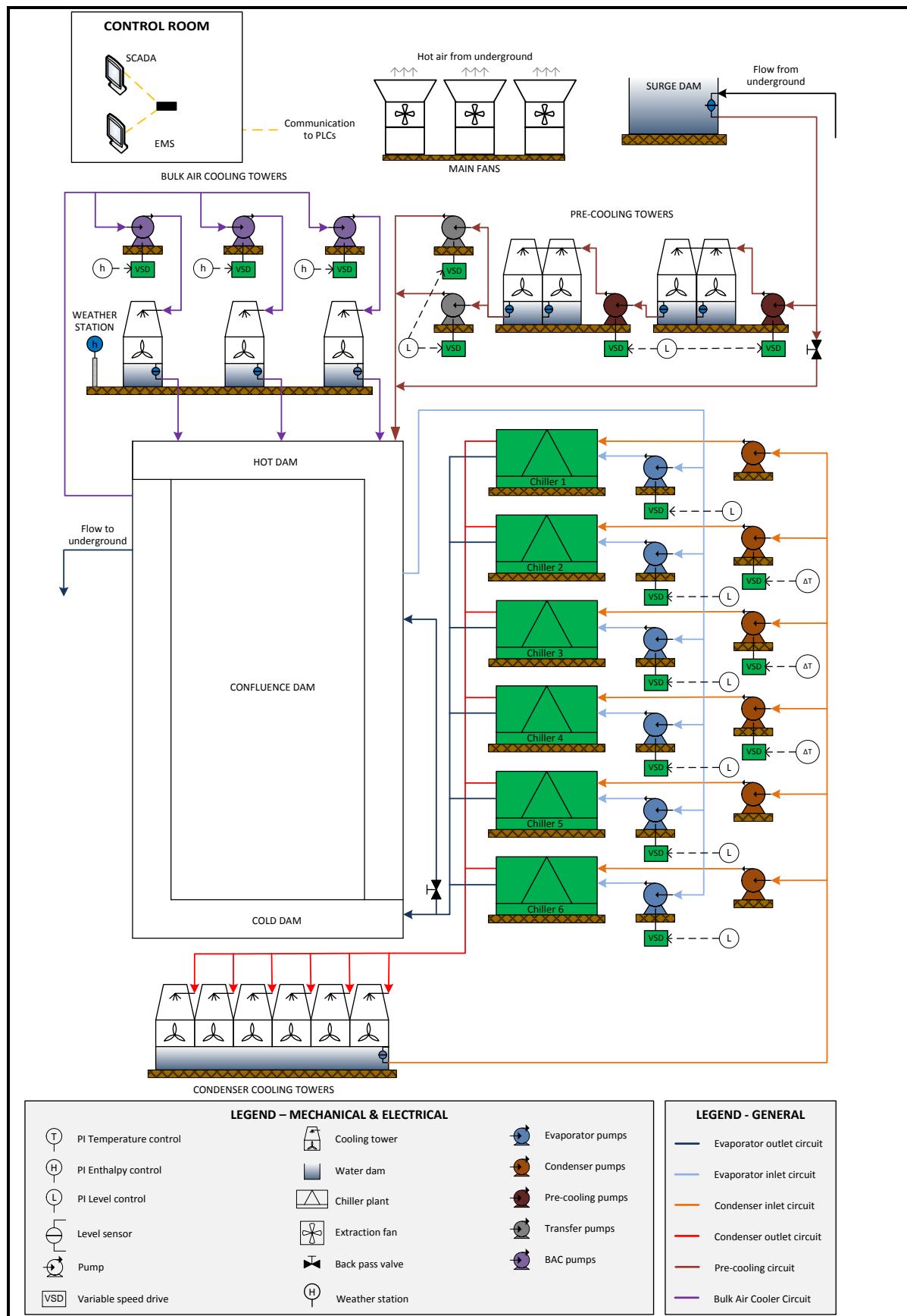


Figure 14: Cooling system layout with implemented energy saving measures at Mine A

**Table 1: Equipment and control philosophy of energy saving measures on Mine A**

<b>Implemented saving strategy</b>	<b>Installed equipment</b>	<b>Set point</b>
i. <b>Pre-cooling tower flow control</b> <ul style="list-style-type: none"> <li>- Install a VSD on each pre-cooling pump.</li> <li>- Install a VSD on each transfer pump.</li> <li>- Maintain a constant level at pre-cooling dam 1.</li> <li>- Maintain a constant level at pre-cooling dam 2.</li> <li>- Maintain a constant hot dam level.</li> </ul>	<p>2 × 70 kW VSDs (525 V/122 A, including circuit breakers, line choke and motor choke)</p> <p>2 × 40 kW VSDs (525 V/122 A, including circuit breakers, line choke and motor choke)</p> <p>-</p> <p>-</p> <p>-</p>	<p>-</p> <p>-</p> <p>80%</p> <p>80%</p> <p>80%</p>
ii. <b>BAC tower flow control</b> <ul style="list-style-type: none"> <li>- Install a VSD on each BAC return water pump.</li> <li>- Control VSDs according to change in ambient enthalpy.</li> </ul>	<p>3 × 75 kW VSDs (525 V/122 A, including circuit breakers, line choke and motor choke)</p> <p>1 × Weather station (including a probe)</p>	25 – 70 kJ/kg
iii. <b>Evaporator water flow control</b> <ul style="list-style-type: none"> <li>- Install a VSD on each evaporator pump.</li> <li>- Maintain a constant chilled water dam level (cold confluence).</li> </ul>	<p>6 × 110 kW VSDs (525 V/122 A, including circuit breakers, line choke and motor choke)</p> <p>-</p>	<p>-</p> <p>80%</p>
iv. <b>Condenser water flow control</b> <ul style="list-style-type: none"> <li>- VSDs installed on three condenser pumps</li> <li>- Maintain a constant delta temperature rise over each condenser.</li> </ul>	<p>3 × 200 kW VSDs (525 V/122 A, including circuit breakers, line choke and motor choke)</p> <p>-</p>	<p>-</p> <p>4 °C</p>

The system operation after project decommissioning was compared to the original control philosophy during initial project implementation. The energy saving project was operational for approximately two years before it was completely decommissioned. A short summary of the original control philosophy follows:

1. The pre-cooled and surge dam back-pass valves were decommissioned. The hot dam level was maintained at 80% and pre-cool dam level was maintained at 85% using VSDs to control the feed pumps.
2. Flow through the BAC was controlled using VSDs on the feed pumps. The pumps were controlled linearly according to the change in ambient enthalpy to maintain a BAC air outlet temperature of 7 °C WB.
3. Evaporator pumps were controlled to deliver the necessary flow to control the chilled dam level on 75%. Chiller trip conditions were taken into account and were avoided through PLC control.
4. Condenser pumps were controlled to deliver a flow to maintain a fixed change in temperature over the condenser at 3.5 °C. Chiller trip conditions were taken into account and were avoided through PLC control.

### **System operation**

Hot water enters the surface surge dam at a temperature of 26 °C. Water is pumped from the surge dam through the pre-cooling towers to the hot dam. The average temperature in the hot dam is approximately 9 °C. Approximately 20 Mℓ/day is pumped from the underground de-watering dam during an average working day.

The pre-cooled water (from the hot dam) is pumped through the six chillers. Water is chilled to 3 °C, which is then supplied to the cold dam. The combined nominal cooling capacity of the chillers is 36 MW, with a combined COP of 5.7 at nominal design conditions.

Approximately 675 ℓ/s is pumped through the BACs back into the hot dam. The remaining chilled water is sent underground through a turbine to a 39-level chilled dam. From here the water is used in mining operations. De-watering pumps on 75-level, pump the used water to the surface surge dam, whereafter the process is repeated.

The system operation has been explained; an evaluation of each circuit in the cooling system will now be conducted. From the evaluation, a solution to the challenges of the implemented measures will be developed.

### 3.2.2. Control system

#### Evaluation

The EMS is a crucial part of implemented energy saving measures. This system controls the operation of the energy saving measures on the mine cooling system. The original computer servers installed as part of the project had no OPC connection and operated with outdated software. These servers were used to host the EMS.

Mine A migrated to a new SCADA version after the initial energy saving project implementation. Such a system change causes numerous connectivity issues between the EMS and the SCADA. A significant amount of control data tags were moved from the old SCADA version to the new SCADA version.

The mining Control and Instrumentation department made these system changes without considering the effect on the energy saving measures. The control tags form an integral part of the energy saving project. Without the necessary control tags, the EMS could not function according to initial design. Control tags are also used in conjunction with the monitoring and reporting system to achieve optimal savings.

The monitoring and reporting system requires a live update of the control tags to report the system operational parameters and system performance. The automatic monitoring and reporting system was disabled due to loss of OPC connection. These systems were also configured to give an indication of the condition of running equipment.

The control servers were also used to log system data, and send the data to a centralised server. The data transmission applications were outdated and the SMTP address was no longer functional. System operation data was, therefore, not available to analyse exact problems. The SCADA was the only source of reliable data. SCADA data was, however, only available for three preceding months due to limited storage capacity on client servers.

Critical PLC code, programmed onto the PLCs during initial project implementation, was no longer functional. Change of procedure documentation (normally required when processes are altered on mines) was not available to inspect the altered code. Deciphering the code proved to be time-consuming. Investigation revealed that the system, including PLC control, operated according to the original mine control philosophy before project implementation.

These shortfalls had to be addressed to ensure that system control can resume. A strategy to improve sustainability and prevent control system deterioration was thus required.

## Solutions

The first step was to re-establish communication between the control server and the SCADA. Control software was updated to the latest available version. The ESCO that originally implemented the project was contracted to re-implement or develop the original project PLC code. The control server communication was re-established through OPC connection with the new SCADA version.

Reliable connection with the SCADA was ensured by using updated OPC tools and utilising watchdog tags. Watchdog tags were implemented to monitor the active OPC connection. Immediate reports of communication failure can be compiled and sent by reporting the status of the watchdog tags in real time. System administrators can therefore address communication issues as soon as they occur.

The control tags on the control server were re-implemented. This ensured that the necessary communication between the equipment and PLC can function in accordance with the original control philosophy. The automatic monitoring and reporting system was upgraded and commissioned, ensuring effective system monitoring and reporting of system operational parameters.

Data logging commenced due to all communication and control tag issues being resolved. The data was used to analyse the system and provide a baseline in order to compare the data of the re-commissioned system with the deteriorated system. The next step was to resolve the issues and address concerns raised regarding the implemented energy saving measures.

### **3.2.3. Pre-cooling tower water flow control**

#### **Evaluation**

The pre-cooling tower water flow control strategy was firstly investigated. The towers showed clear signs of maintenance on both the fill and spray nozzles. The frequency of maintenance was unclear. Supplying the towers with an adequate amount of flow prevented sediment build-up within the towers.

The fans on the cooling towers showed clear signs of regular maintenance. The air flow through the cooling tower was satisfactory, as there were no significant changes made to the operation of the fans. The fans on the cooling towers functioned as normal and were running at full load during normal operation. There was therefore no energy-saving strategy implemented on the fans.

Further investigation of system operation indicated that the pre-cooling tower pump control did not function as required. VSDs on the pre-cooling pump motors were originally programmed to control the pump speed to vary the flow in order to control the pre-cooling sump level. PI control was utilised to increase or decrease the pump frequency from 0 Hz to 50 Hz, depending on the pre-cool sump level.

Operation of pumps at these frequencies proved to be problematic. Mining personnel disabled the VSD control on the pre-cooling pumps due to various reasons. Operating the pumps at a frequency below a certain minimum-allowed frequency forced the pumps to operate below the BEP.

Rotational speeds below a minimum frequency caused the pumps to deliver a pressure well below the required pressure head. The pumps need to pump a head of approximately 10 m. An insufficient flow distribution in the tower was the result of operating below the minimum frequency.

Mine personnel raised the concern of damaged motors due to VSD control. A concern of low rotational speeds increasing the operating temperature of the motors was raised. This can result in motor winding damage. The mine personnel argued that the motor cooling fan cannot produce the same amount of cooling at low rotational speeds compared to maximum speeds.

Control server and SCADA communication issues proved to be part of the reasons provided by mine personnel that led to the decommissioning of the VSDs. The EMS control was no longer active and set points were no longer provided to the PLCs.

Some instances occurred where dams overflowed regularly due to a faulty dam level sensor. The alarm and notification capability was no longer in operation and faulty field instrumentation was no longer identified automatically. Lack of efficient dam level control was blamed and was part of the motivation to disable VSD control. Faulty field

instrumentation can cause unwanted environmental pollution due to dam flooding. However, the PLCs also have the capability of determining or indicating faulty field instrumentation.

The following list summarises the reasons for the decommissioned pre-cooling flow strategies:

- insufficient water flow (due to variable control) meant inadequate flow distribution patterns, resulting in little to no pre-cooling of process water;
- pumps and motors can be damaged due to variable control and control at low rotational speeds;
- scaling and fouling of the tower fill can occur due to reduced flow through the towers; and
- faulty field instrumentation caused conditions where environmental pollution concerns were raised.

## Solutions

### *Water flow distribution in the towers:*

The pre-cooling towers' flow distribution was found to be inadequate. Tests were conducted on the pumps to determine the required operating pressure and flow of the pumps to meet system demand. The minimum frequency whereby the pump can operate and still deliver a sufficient flow distribution had to be determined.

For these tests to be conducted, the VSD control had to be re-implemented. The PLC code and control equipment issues were resolved. The pre-cooling pump VSDs were firstly inspected to ensure no damage occurred over the project lifetime. The VSDs were switched to automatic control and the flow tests commenced.

The flow and pressure delivered at various frequencies were determined. This was achieved by manually changing the rotational speed of the pump through the VSD from the control system. The flow through the tower inlet pipeline was measured with an ultrasonic flowmeter.

The frequency was decreased until the flow distribution pattern was no longer sufficient for effective heat transfer. The minimum-allowed frequency was programmed onto the PLC. It was found that a frequency of 37 Hz allowed the pumps to deliver a pressure sufficient enough to overcome the required head.

At this frequency the water flow distribution in the tower caused the water temperature to decrease within tolerable limits. Proper air flow and water flow control results in more efficient cooling. The aim is to do as much cooling as possible before the water enters the chillers.

The minimum frequency of the transfer pumps (that transfers the water from the pre-cooling dams to the hot dam) was changed to 20 Hz through similar tests. This ensured that all the pumps in the pre-cooling circuit operate close to their respective pump curve. It was also found that the back-pass valve (pre-cool dam to chilled dam) was still decommissioned. The back-pass valve to the surge dam was still closed. This ensured that the full cooling range of the cooling tower is utilised.

*Pump- and motor damage due to variable flow control:*

The electrical efficiency of the motor is increased by applying variable speed control to the motor. This allows the motor to operate at conditions favouring the appropriate system where the motor is installed. The major concern of mine personnel was that motors are exposed to extreme thermal deterioration of stator windings due to VSD control.

In section 2.2.5 it was concluded that the motor speed in a variable torque application can be reduced to a minimum of 50% without additional forced cooling. At this speed, the motor will still operate within the designed thermal parameters. The harmonics caused by the application of VSD control can be limited by harmonic filters that are installed into the VSD enclosures. The VSDs at Mine A were all pre-fitted with harmonic filters.

As discussed in section 2.2.5, reducing the rotational speed of the pump below the allowable minimum speed can cause a significant reduction in the flow rate and efficiency of the pump. Operating the pump within this region for extended periods can potentially damage the pump and reduce the pump life, or increase LCC.

A certain threshold can be determined where the pump does not generate sufficient head to pump the water to the top of the cooling tower. This was determined when the inadequate

water flow distribution through the tower was addressed. Below this minimum frequency the pump efficiency and flow rate is zero.

Below the minimum frequency the pump can become a water heater, causing operating temperatures to exceed the designed OEM operating temperature. This effect damages the pump and reduces pump life. It is important to note that flow control through speed reduction is more efficient than control applied through a control valve.

Speed reduction poses several benefits, as discussed in section 2.2.5. Ultimately the effects on the (LCC) of the specific pump should be investigated before applying variable flow strategies. If the operational control ranges of the pumps are adjusted to control with a reduction of approximately 30%, the pumps should operate within the designed load range.

*Scaling and fouling of the tower fill:*

From the literature it was established that solid particles can attach to the surface of the fill and tower structure if the flow is not enough to carry the particles further. A simple solution to this would be to ensure that the flow through the tower is evenly distributed throughout the tower. This can be achieved by conducting physical tests and observing the flow pattern in the tower at various pump speeds. The minimum VSD frequency that was adjusted compensated for this criterion.

*Faulty field instrumentation:*

Faulty instrumentation devices need to be inspected and repaired where necessary. In the case of a faulty dam level sensor, the sensor needs to be replaced and recalibrated according to the dam specifications. Initial project implementation steps should include a thorough investigation of all field instrumentation and the instrumentation should be calibrated where required.

The necessary PLC code should include ‘broken wire’ detection through strategic coding, and calibration of instrumentation must regularly take place during winter months when the operation of the cooling system is minimal.

### 3.2.4. Bulk air cooler tower water flow control

#### Evaluation

BAC tower water flow control was investigated. The BACs are supplied with chilled water from the cold dam by the BAC feed pumps. The water quality adversely affects the cooling potential of the BAC in the same way as the pre-cooling towers. The BAC towers showed few signs of scaling or fouling.

Mine personnel claimed that the BAC outlet temperatures were not up to standard. The pumps did not operate at the required speed to produce sufficient flow. A weather station was installed as part of the BAC water flow control during initial project implementation. It was found that the weather station malfunctioned, which led to incorrect readings.

The BAC pump flow control was based on the ambient enthalpy. Incorrect measurements by the weather station compromised the energy savings of the BAC circuit flow control. The BAC delivered a change in ventilation air temperature, based on varying ambient enthalpy. This results from a constant flow of chilled water and a continuous variation of ambient conditions.

It was also found that the weather station had no radiation shield installed. Radiation shields are utilised to prevent radiation from heat sources, such as the sun, which influence physical readings measured by the resistance temperature detector.

It was found that the PLC control logic was not changed since the initial project implementation. Further inspection showed that the BAC pump control was disabled. The VSD control was locally disabled on the VSD panel through the auto/manual switch. The control tags were not available, resulting in no control of the BACs.

Lack of control caused mine personnel to disable the VSD control due to inadequate flow distribution patterns in the BACs. BAC pumps were allowed to operate at very low frequencies, resulting in the water pressure produced by the pumps to be less than that of the required static head. This implicates the heat transfer ability of the tower.

BAC tower water flow control was disabled by management due to the following concerns:

- the safety of mine workers could be compromised due to varying BAC air outlet temperatures exceeding 7 °C WB. This is especially of concern during the hottest times of the day when more cooling is required;
- insufficient water flow (due to variable control) resulted in inadequate flow distribution patterns, adversely affecting the cooling of ambient air;
- pumps and motors were assumed to be damaged due to variable flow control; and
- control based on ambient enthalpy is not accurate enough to allow the required constant BAC air outlet temperature of 7 °C WB.

## Solutions

### *Maintaining the correct BAC air outlet temperature:*

A temperature sensor was installed in the BAC outlet duct and connected to the PLC to monitor the BAC air outlet temperature. Mine personnel indicated that the air outlet temperature was never measured or monitored. Environmental health and safety requirements indicated that the BAC air outlet temperature should be 7 °C WB (8 °C DB).

The BAC air outlet temperature can be monitored by implementing a reliable monitoring method. The control was still based on the ambient air enthalpy measured close to the BAC. The weather station was re-commissioned and the control through the VSDs was enabled.

The effective control based on the ambient enthalpy allowed the water flow through the towers to be increased or decreased as the required cooling load increased or decreased. Thus, during the hottest times of the day, the BAC pumps would run at maximum frequency, allowing more cooling to be done.

### *Water flow distribution in the tower:*

The BAC tower flow control was inadequate. The same process as described in the pre-cooling tower flow control section was followed to determine the minimum required pressure and flow of the pumps. The VSD control was re-implemented. All PLC control logic was verified and the control was tested.

The VSDs were switched back to automatic control. The flow and pressure delivered at various frequencies were determined by following the same steps as discussed in the previous section. When a suitable flow distribution pattern was found, the minimum VSD frequency was programmed onto the PLC.

It was found that a frequency of 31 Hz allowed the pumps to deliver a pressure sufficient enough to overcome the head needed. The maximum flow was similarly determined (from original OEM specifications). The maximum frequency was programmed as 44 Hz. At this frequency, the BAC pumps deliver the designed flow of 225 l/s through the tower inlet pipe.

The water outlet nozzles within the BAC were resized to allow 225 l/s of flow through the tower. At the frequency stated previously, the water flow distribution in the tower caused the water temperature to decrease within tolerable limits. Proper air- and water flow control results in more efficient cooling.

*Pump- and motor damage due to variable flow control:*

Pump- and motor damage solutions regarding BAC flow control is similar to that of the pre-cooling tower flow control. The adjustment of the minimum operating frequency of the VSDs also ruled out the problem of the pumps not producing enough pressure and flow to meet the cooling demand. The pumps can now operate at the designed load when required by a certain demand.

*Control based on ambient enthalpy:*

The installation of a radiation shield on the weather station ensures accurate measurement, resulting in more accurate control. A more precise control could be achieved by programming the PLCs to control according to the direct air outlet temperature of the BACs. This type of control reduces the risk of employee safety being jeopardised, or missed energy saving opportunities.

The weather station is not a critical component, but adds value to a system that operates according to a change in ambient climate. Utilising the change in environmental conditions to control the flow through the BAC pumps is an indirect type of control. A more suitable control would be to use the BAC air outlet temperature as the direct input for the PI control loop.

### **3.2.5. Chiller evaporator water flow control**

#### **Evaluation**

Investigating the chiller evaporator water flow control revealed that the VSD control on all six of the evaporator pumps was disabled. The plant operator claimed that the evaporator flow did not exceed the required minimum flow upon chiller start-up, thus causing the machine to operate close to trip conditions. It was found that the machine would trip shortly after start-up.

As a result, all the VSDs were set to manual control, resulting in the pumps running at maximum speed during normal operation. This means that the variable demand for chilled water was never utilised. Disabled VSD control resulted in a lack of energy savings on the chiller evaporator pumps.

The isolation valves situated on the inlet of the evaporator water pipeline were used to throttle the water flow going through the machine. These valves were used to maintain a fixed flow rate instead of using VSD control. This was done to regulate flow manually to achieve the desired design flow rate of the chillers.

Maintaining this constant flow rate also ensured a chilled water temperature of 3 °C on average, overcooling the BAC air outlet temperature to a temperature well below the required 7 °C WB.

Evaporator flow control was disabled by mine personnel due to the following reasons:

- high chilled water temperatures (typically above 5 °C) compromise the safety of workers underground and cause higher downstream BAC air outlet temperatures;
- evaporator flow rates during chiller start-up were not sufficient, resulting in running conditions below-full load; and
- low evaporator flow rates cause favourable conditions for scaling of the evaporator tubes.

## Solutions

### *High chilled water temperatures:*

High chilled water temperatures are due to lowered flow rates through the chillers, as discussed in section 2.2.4. The chilled water that is supplied to the BAC must typically be between 3 °C and 5 °C for the BAC to be able to cool and dehumidify air to 7 °C WB. Allowing the system to achieve these operating parameters will ensure a 7 °C WB BAC air outlet temperature.

The evaporator flow control is based on the cold dam level. The minimum output frequency can easily be adjusted to allow more flow at lower cold dam levels. This must be tested through system improvement tests. The concern was also addressed by the changes proposed in the section of the BAC water flow control.

### *Evaporator flow rates during chiller start-up:*

The investigation revealed that the chiller evaporator control is effective immediately upon start-up. At chiller start-up (see process in section 2.2.4), the evaporator motor control was enabled immediately after the pump was started. This means the system monitors the cold dam level and adjusts the motor speed to control the evaporator flow according to the dam level.

Lowered evaporator flow rates during start-up means that the flow does not exceed the set flow rate required to operate the chiller at the required load. A simple solution would be to allow all chiller pumps (including condenser pumps), to operate at maximum speed for a certain fixed time period after start-up, whereafter normal PI control, based on the cold dam level (or condenser delta temperature in the case of condenser control), can resume. The minimum time was determined by actual tests and it proved that five minutes was sufficient.

### *Low evaporator flow rates increase probability of scaling:*

Scaling or fouling of the heat exchanger tubes in the chiller evaporator vessel can occur if favourable conditions are present. To prevent the build-up of sediment in the tubes, the flow reduction must fall within the OEM specified flow regions. This will ensure that effective heat transfer can still take place.

It is important to note that it would still be necessary to clean the evaporator tubes during yearly maintenance, even under normal original operation. Water treatment would also reduce the build-up of any particles in the evaporator tubes. The minimum-allowed frequency of operating the evaporator pumps was adjusted to 37 Hz.

### **3.2.6. Chiller condenser water flow control**

#### **Evaluation**

Investigating the chiller condenser water flow control revealed that the VSD controls on condenser pumps were disabled. The three condenser pumps, which could be controlled with VSDs, were running at full speed during normal operation. The other three condenser pumps do not have VSDs installed, due to budget constraints during the initial project implementation.

Condenser flow control was thus not possible. The fan speeds of the condenser cooling towers cannot be varied and operate at full load during normal operation. In some cases, the fans on the cooling towers can be used to ensure a fixed condenser outlet temperature from the tower.

The variable flow strategy on the condenser circuit is aimed at controlling the condenser flow at a constant change in condenser inlet- and outlet temperatures. Valves used to throttle the flow through the condenser were once again used to ensure a flow rate at design conditions. The following concerns were raised by management and resulted in the control strategy being disabled:

- the condensers are being compromised due to reduced flow rates, causing favourable conditions for scaling in the condenser tubes. This causes a significant increase in the maintenance costs related to condenser tube cleaning, due to the cost of the chemicals required for cleaning;
- VSD control on the three condenser motors causes high operating temperatures, resulting in motor damage, and then motor failure; and
- only three of the six pumps have VSDs installed;
- condenser performance is being affected by low flow conditions.

## Solutions

*Pump- and motor damage due to variable flow control:*

The pump- and motor damage solution regarding condenser flow control is similar to that of the pre-cooling tower flow control. The motor speed can be limited to a minimum threshold of within 50% of the full speed. This threshold can be determined by physical flow tests.

*Low condenser flow rates increase probability of scaling:*

The reduction in condenser flow can be solved in a similar way as described under the chiller evaporator flow section. It is important to indicate that, even under normal operation, it would still be necessary to clean the condenser tubes during yearly maintenance. Water treatment would also reduce the build-up of any particles in the condenser tubes.

The minimum-allowed frequency of operating the condenser pumps was adjusted to 36 Hz. It is also important to note that the water quality does not deteriorate as rapidly compared to the evaporator, pre-cooling and BAC circuits. The condenser circuit makes use of potable water and is completely isolated from the mining water process flow, and operates as a closed-loop system.

*Condenser performance is affected by low flow conditions:*

Investigation revealed that the chiller condenser control is effective immediately upon start-up. At chiller start-up (see process in section 2.2.4), the condenser motor control was enabled immediately after the pump was started. This means that the system monitors the delta condenser temperature and adjusts the motor speed to control the condenser flow according to delta temperature.

Lowered condenser flow rates during start-up means that the flow does not exceed the set flow rate required to operate the chiller at the required load. The same solution will be applied to the condenser pumps, as discussed in the chiller evaporator flow section.

### **3.2.7. Chiller control**

#### **Evaluation**

As a result of the implemented energy saving strategies, the feasibility of stopping a chiller increased significantly. This was due to the effective utilisation of the cooling capability of

the machines. Some machines were regularly started and stopped as the demand for chilled water and cool, dehumidified air varied. The strategies, however, ensured that one machine could be stopped entirely.

Some machines were, however, stopped and started irregularly by the chiller operators. The reliability of the measures decreased due to the reasons discussed in the previous sections, resulting in cycling of the machines to meet demand during various times of the day. Management was concerned about a possible increase in oil usage due to multiple stops and starts of the various chillers, leading to shaft seal damages.

There is therefore a risk of increased maintenance. Mine personnel were therefore prohibited from unnecessary stopping and starting of chillers.

## Solutions

The control system installed as part of the original energy saving measure did not stop and start the chillers automatically; it only proposed a running schedule that was predicted by analysing chilled water demand and BAC air outlet temperatures. The chiller operators were instructed to stop/start the machines as needed.

### **3.2.8. Monitoring and reporting**

#### Evaluation

Part of the initial project implementation was the ability to automatically monitor and report the operational parameters of the mine cooling system. Monitoring and reporting of key performance indicators (KPIs) are crucial to ensure the sustainability of energy saving projects. The specific KPIs were discussed in section 2.5.3.

The deterioration of the energy saving measures on the system under investigation could have been minimised by utilising the necessary monitoring and reporting systems. If relevant KPIs were identified and the monitoring and reporting tools were used by the ESCO or the mine, it could have addressed concerns sooner.

## Solutions

Most mining personnel only focus on production. Maintenance of auxiliary equipment is therefore not always attended to. This leads to detrimental functioning of equipment and

machinery over time. Developing the necessary criteria and implementing an automatic monitoring and reporting system ensure that mine personnel are constantly notified of system performance.

Criteria that have a direct relation to maintenance of the cooling system can be reported once a threshold has been surpassed. These types of systems can also be used to create formal maintenance schedules. Regular- and preventative maintenance can increase system performance significantly, as discussed in section 2.5. Operational procedures can be refined by the effective reporting of KPIs.

### **3.3. Developing improved implementation strategies**

#### **3.3.1. Preamble**

The objective of identifying the existing operation of energy saving measures implemented on Mine A was discussed in section 3.2. The system operation was compared to original implementation of the energy saving measures. It was found that the system was significantly altered, to the detriment of the energy saving measures.

This also had a negative impact on the capital expenditure and caused the budget for electrical power to be exceeded. An improved strategy will be developed whereby energy saving measures can be implemented and sustained on mine cooling systems. Methods to improve the existing energy saving project will be verified by the actual re-commissioning of the energy saving measures in section 3.4.2.

This section summarises the improved strategies derived from re-commissioning the energy saving measure on Mine A.

#### **3.3.2. Summary of identified solutions**

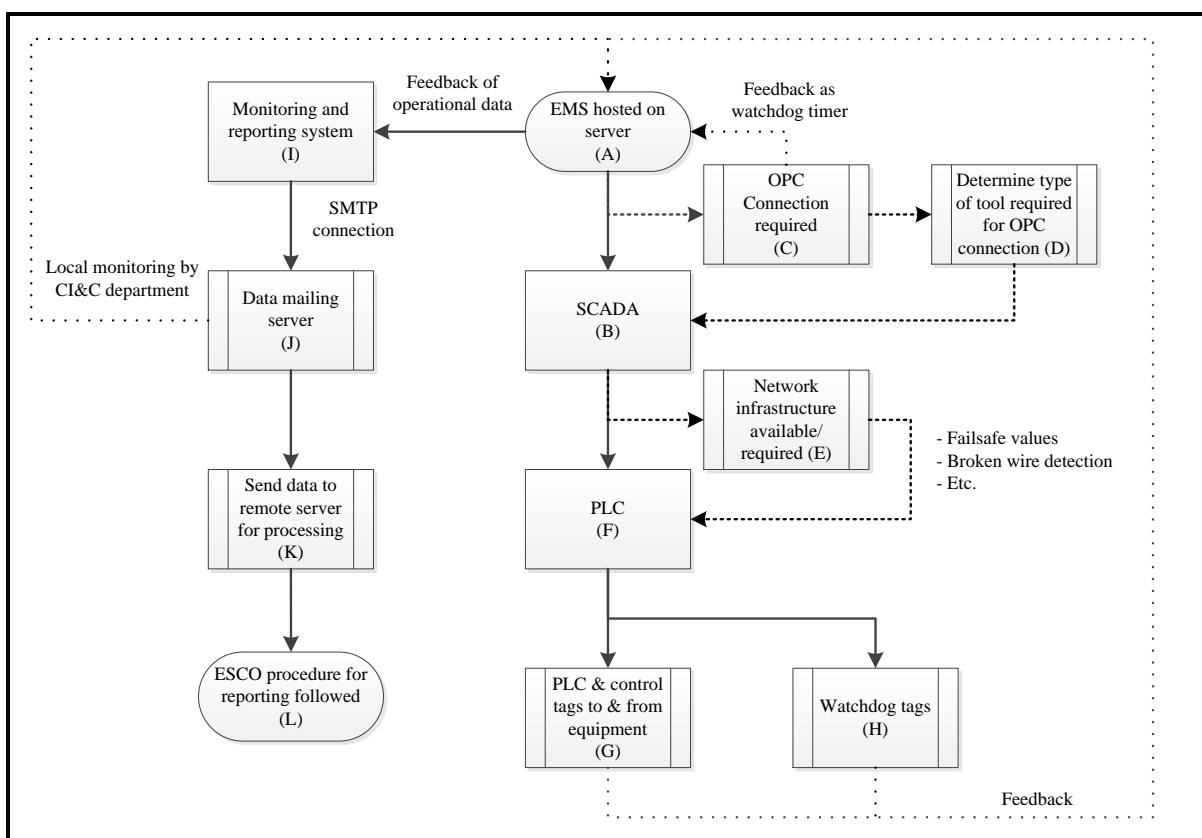
The methodology for the improved implementation strategies is summarised in different system categories in this section. The section conveys this method and informs the reader of the critical points to consider regarding energy saving project implementation on mine cooling systems.

It is important to note that most of these parameters and considerations must be identified through detailed investigations, but must also be applied during project implementation.

These parameters and considerations must be updated throughout the project to ensure effective and thorough implementation.

## Control system

The layout in Figure 15 lists the identified and summarised strategy to follow for control-system integration when implementing energy saving measures on mine cooling systems. These solutions aim to improve sustainability of the system control.



**Figure 15:** Control system strategy when implementing energy saving measures

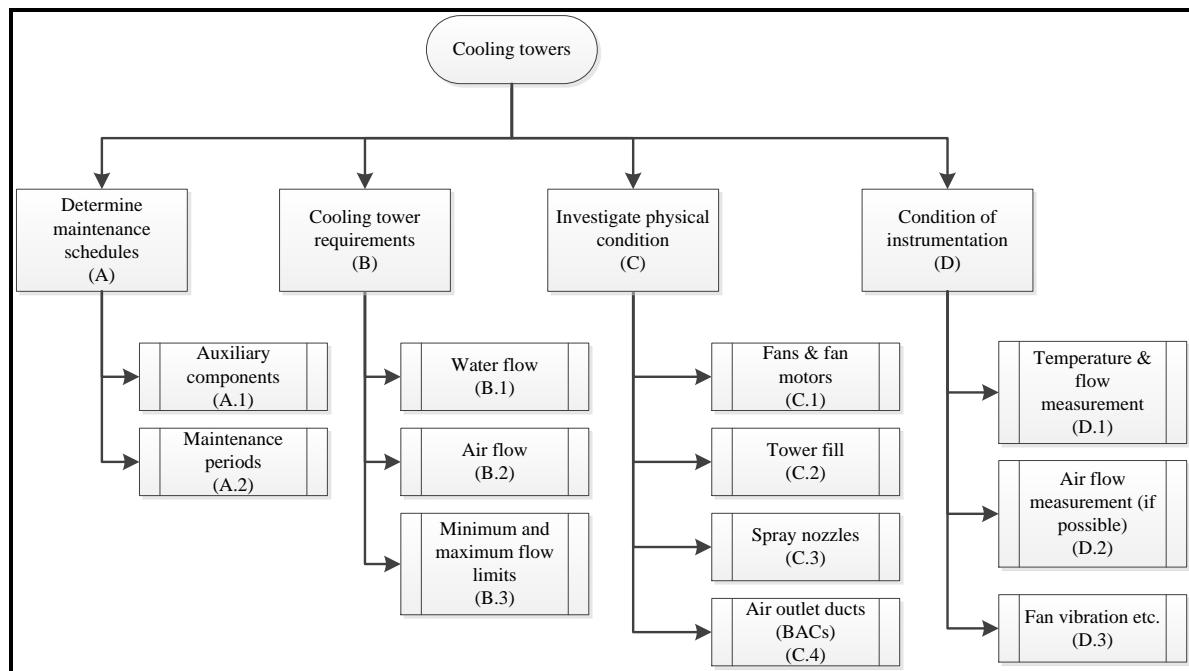
From Figure 15, it is important to note the various communication interfaces. The stability of communication interfaces (EMS with SCADA, for example), influences the sustainability of the energy saving measures. Stable connections ensure that the monitoring and reporting system reports reliable data as logged on the EMS server.

The EMS (A) connection with the SCADA (B) is established via OPC connection (C). Various OPC tools (D) are available in industry to ensure stable connections. The availability of suitable network infrastructure (E) between the SCADA and the PLC (F) must be determined upon investigation.

The necessary PLC control tags to and from equipment (G) must cater for the type of control applied to the system components. Watchdog tags (H) must be utilised to ensure that the status of system control is monitored. All tag data must be processed by the monitoring and reporting system (I). By using SMTP connection, the data will be sent through a mailing server (J) to the remote ESCO server (K) for further processing. The ESCO will follow the respective procedure for reporting (L).

## Cooling towers

The layout in Figure 16 lists the summarised strategy for cooling towers when implementing energy saving measures on mine cooling systems.



**Figure 16: Cooling tower strategy when implementing energy saving measures**

The maintenance schedules (A) for the cooling towers have to be determined upon implementation. The auxiliary equipment (A.1) of the cooling towers (pumps etc.) and the maintenance periods (A.2) have to be determined. Yearly maintenance is often scheduled during winter months.

The cooling tower requirements (B), such as the water flow (B.1) and air flow (B.2) specifications have to be determined during commissioning. The minimum and maximum flow limits (B.3) must also be determined and programmed onto the PLCs during commissioning.

The physical condition (C) of the towers must be investigated. The physical condition of the fans and fan motors (C.1), tower fill (C.2) and spray nozzles (C.3) must be determined during investigation. The air outlet ducts of BACs (C.4) must also be inspected.

The condition of instrumentation (D), such as the temperature and flow measurement (D.1), air flow measurement (D.2) and fan vibration measurement instrumentation must be in working order. It is important to document the findings throughout the strategy during implementation for future reference.

## Pumps

The layout in Figure 17 indicates the summarised strategy for pumps when implementing energy saving measures on mine cooling systems.

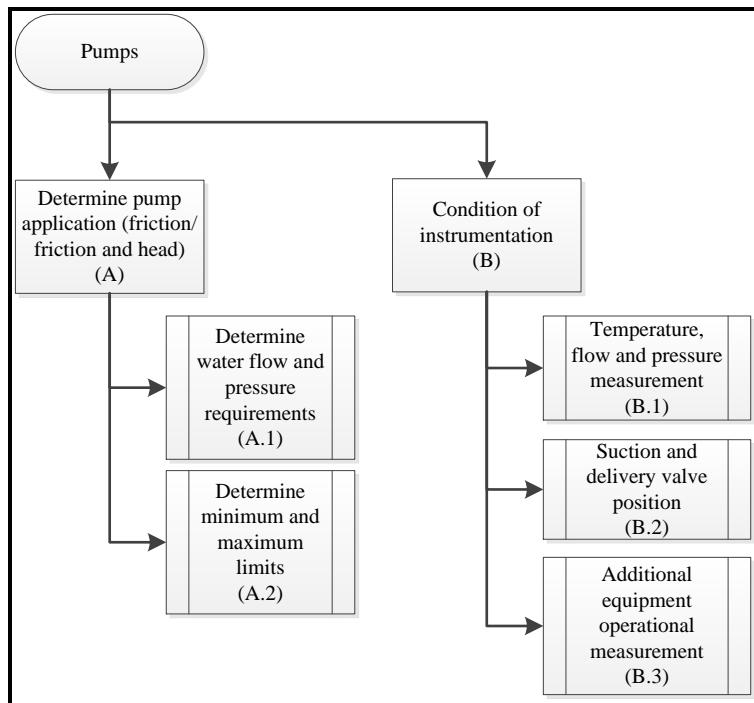


Figure 17: Pump strategy when implementing energy saving measures

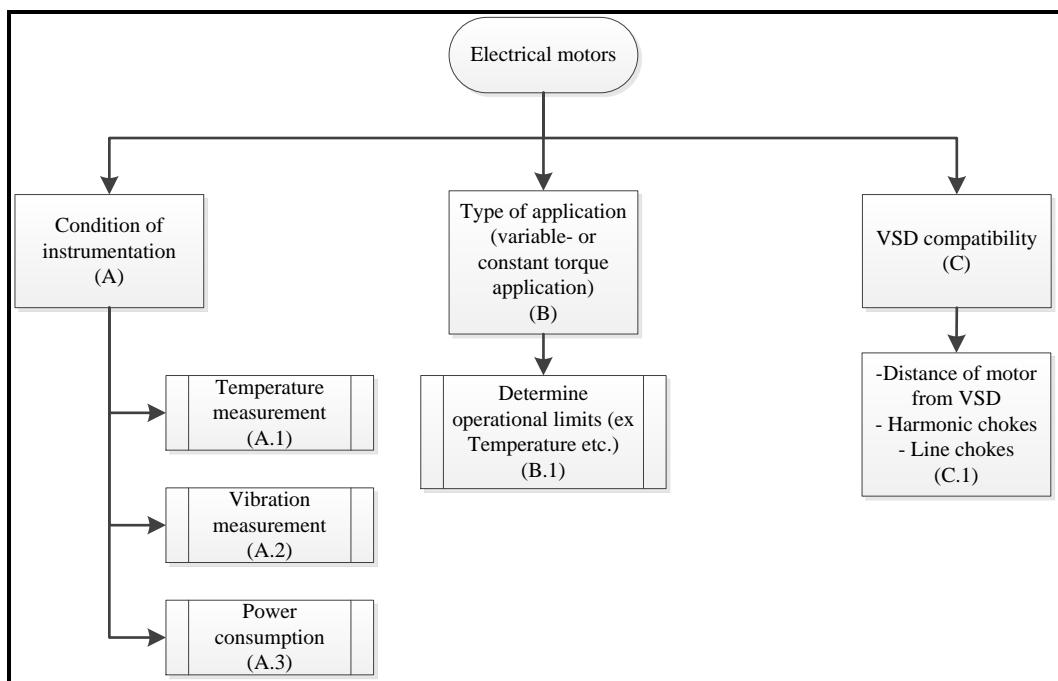
The pump application (A) is of significant importance. The application governs the feasibility of applying variable flow control to the pumps. The application, however, must be established during initial project investigation. The water flow and pressure requirements (A.1) will influence the control limits of the pump/motor combination. The minimum and maximum control limits (A.2) will be determined during project implementation.

The condition of instrumentation (B) on the pumps is crucial to ensure sustainable power savings. Temperature-, flow- and pressure measurement instrumentation (B.1) can be used to determine the physical condition of the pump, as well as the pump efficiency. Suction and delivery valve position (B.2) feedback is required to ensure optimal utilisation of the variable flow control. This is done by ensuring the valves are fully open when the pump is in operation.

Any additional equipment measurement can be included in the monitoring and reporting system for further system analysis.

### **Electrical motors**

The layout in Figure 18 indicates the summarised considerations for electrical motors when implementing energy saving measures on mine cooling systems.



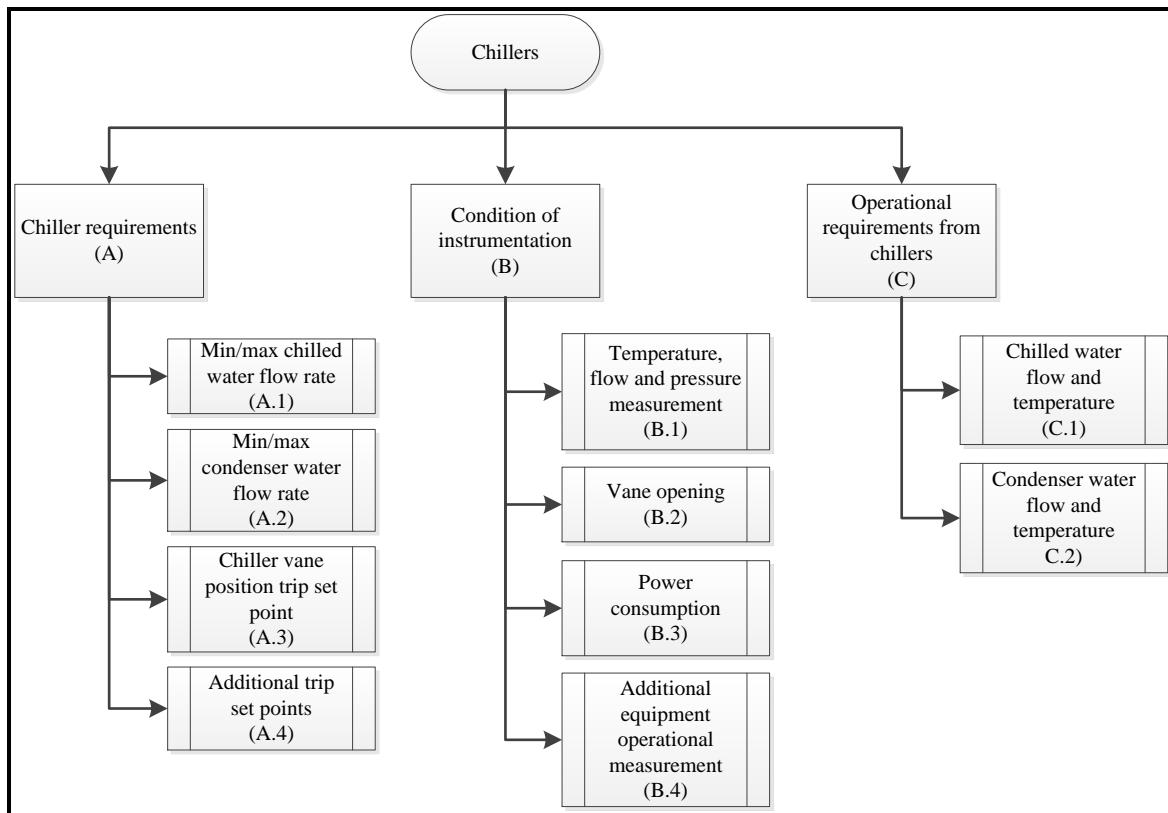
**Figure 18: Motor strategy when implementing energy saving measures**

The condition of instrumentation (A) on electrical motors must be inspected during implementation. The temperature measurement (A.1), vibration measurement (A.2) and the power consumption (A.3) are all crucial measurements.

The type of application (B) will determine the operational limits (B.1) of the electrical motor and also the allowed VSD control limits. VSD compatibility must also be determined during initial project investigation.

## Chillers

The layout in Figure 19 indicates the summarised strategy for chillers when implementing energy saving measures on mine cooling systems.



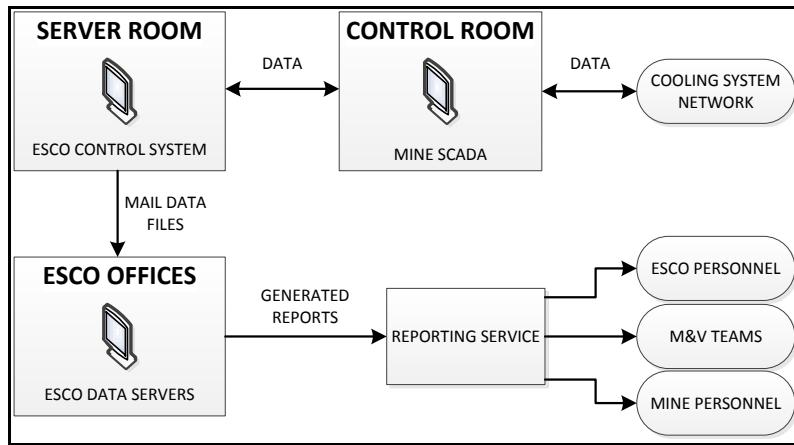
**Figure 19: Chiller strategy when implementing energy saving measures**

The chiller requirements (A) must be adhered to during project implementation. This includes the minimum and maximum evaporator and condenser water flow rates (A.1, A.2). The chiller vane position set point must also be considered when a chiller scheduler is implemented. Additional trip set points (A.4) must be documented during implementation.

The condition of instrumentation (B) on the chiller must be inspected. The required temperature, flow and pressure measurement (B.1), vane opening feedback (B.2), power consumption (B.3) and any other additional equipment operational measurement (B.4) must be in place during implementation and commissioning of the energy saving measures.

## Monitoring and reporting

The system required to ensure sustainable monitoring and reporting is indicated in Figure 20.



**Figure 20: Monitoring and reporting system layout – Mine B**

The exact functioning of the system in Figure 20 is beyond the scope of this dissertation. The system can be summarised as follows:

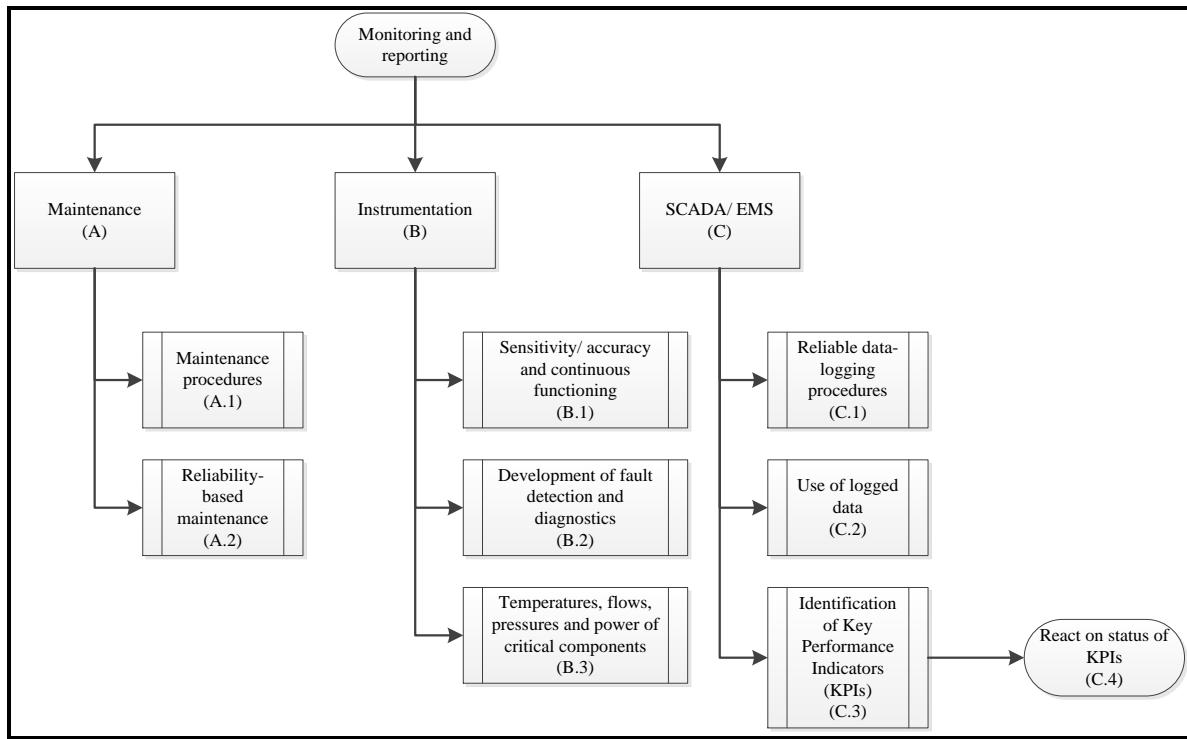
- The SCADA reads PLC tag data from the mine cooling system network and stores the data on the local SCADA host.
- Through the OPC connection, the ESCO EMS accesses these data tags and stores the values in data files.
- The data files are sent via mail servers, or by means of routers, to the ESCO offices.
- The ESCO data servers generate the reports.
- The generated reports are then sent via the reporting service to the relevant recipients.

The layout in Figure 21 indicates the summarised strategy for monitoring and reporting procedures when implementing energy saving measures on mine cooling systems.

The monitoring and reporting system strategy involves three main component considerations. Firstly, the maintenance (A) consists of documenting and enforcing maintenance procedures to be followed (A.1) on system components. The focus on reliability-based maintenance must be incorporated (A.2) into the system.

Secondly, the instrumentation of the system (B). Sensitivity and accuracy (B.1) of field instrumentation must be ensured by regular calibration. Fault detection and diagnostics must be in place (B.2). All temperature-, flow-, pressure- and power consumption thresholds must be established (B.3).

Thirdly, the SCADA/ EMS (C). Reliable data-logging procedures (C.1) must be ensured. The processing and interpretation (C.2) of logged data must be in place, as well as the identification of KPIs (C.3) and reaction on the KPIs (C.4).



**Figure 21: Monitoring and reporting strategy when implementing energy saving measures**

The strategies as illustrated in Figure 15 to Figure 21 will be used as a guideline for improved implementation strategies. The considerations will be tested by re-implementing the existing energy saving measures on Mine A accordingly. The following section consists of the verification of the developed solution and will also test the proposed improvements.

### 3.4. Verification of improved strategies

#### 3.4.1. Overview

The development and identification of improved strategies, as described in the previous section, need to be verified. This can be done by re-implementing the energy saving measures according to the developed strategies. Thereafter, actual performance tests can be conducted to determine the impact of the improved strategy.

The expected outcome of the performance tests was that a universal method can be implemented on various mine cooling systems. By implementing the energy saving measures by means of this strategy, implementation can be simplified and will lead to sustainable

energy savings. A simulation will be compiled to verify the simulation software for application on other mine cooling systems.

### **3.4.2. Actual performance tests**

A baseline was established in order to compare the impact of the developed solution and project improvements. The mine cooling system's operational parameters were reverted to the original parameters before any energy saving measures were implemented. This includes original PI control on PLC level, and flow control with manually-adjustable valves and all equipment operating at full load when in operation.

The baseline tests were conducted over a period of four consecutive days. The mine personnel were fully responsible for operating the system and all energy saving measures were disabled. The control of the pre-cooling and transfer pumps was still operational due to the implication of the pre-cooling dams overflowing if control was not enabled.

It was decided that a period of four consecutive days was sufficient to establish the system energy performance according to the mine control philosophy. The cost implications were also a decisive factor that was considered. Operating the system for longer periods under inefficient control can lead to significant operation cost penalties in terms of electricity costs. The operational parameters and system control during the baseline tests are tabulated in Table 2.

The parameters listed in Table 2 can be related to the various circuits, as indicated in Figure 14. The various VSD frequency ranges and set points for control are also indicated. The type of control (variable- or constant flow) refers to the control on the specific pumps. Variable flow control is achieved through the VSDs, where constant flow control refers to either manually throttling a valve, or fully open pipelines.

After completing the baseline tests, the improved strategies were applied by implementing energy saving measures and project improvement alterations. The improved strategies were tested for a period of four consecutive days. During this period, the mine cooling system was operated with the improvements as discussed in the previous section.

All energy saving measures were re-implemented and optimised according to the new strategy. The EMS was allowed to control the entire mine cooling system. The operational parameters and system control during the project improvement tests are tabulated in Table 2.

**Table 2: Operational parameters of Mine A and system control during performance test**

Description	Initial implementation	Baseline	Project improvements
<i>Transfer pumps</i>			
Min VSD frequency [Hz]	0	20	20
Max VSD frequency [Hz]	50	50	50
Dam level set point [%]	80	80	80
Control	Variable flow	Constant	Variable flow
<i>Pre-cooling pumps</i>			
Min VSD frequency [Hz]	0	37	37
Max VSD frequency [Hz]	50	50	50
Dam level set point [%]	85	85	85
Control	Variable flow	Constant	Variable flow
<i>BAC pumps</i>			
Min VSD frequency [Hz]	0	44	31
Max VSD frequency [Hz]	50	44	44
Min water flow [ℓ/s]	0	255	30
Max water flow [ℓ/s]	250	255	225
BAC air outlet temperature [°C WB]	5	< 7	< 7
Control			
<i>Evaporator pumps</i>			
Min VSD frequency [Hz]	34	50	37
Max VSD frequency [Hz]	43	50	45
Min water flow [ℓ/s]	180	253	190
Max water flow [ℓ/s]	250	253	253
Cold dam level set point	75	None	75
Control	Variable flow	Constant flow	Variable flow
<i>Condenser pumps</i>			
Min VSD frequency [Hz]	38	50	36
Max VSD frequency	50	50	45
Min water flow [ℓ/s]	360	435	350
Max water flow [ℓ/s]	450	435	435
Condenser temp difference set-point [°C]	3.5	None	3.5
Control (3 pumps only)	Variable flow	Constant flow	Variable flow
<i>Refrigeration plants</i>			
Chilled water temperature [°C]	< 7	< 4	< 4

After completing both tests, the operational data had to be compared. The electrical data was obtained from an independent company that logged the mine cooling system feeder power data. The system data for both tests were captured on the EMS and the SCADA. It is important to note that, during the baseline tests, the EMS server was only used for monitoring and data capturing, due to control measures being disabled.

Using the system and power data, the performance of the system during each test was determined. The performance tests required comparable boundary conditions to be identified. These conditions aided in successfully measuring the impact of the implementation of the

new improved strategies. The comparable conditions that were identified are listed in Table 3. The electrical power demand is a function of these parameters.

**Table 3: Comparable boundary conditions**

Nr.	Parameter
1	Ambient air enthalpy [kJ/kg]
2	Chilled water temperature to underground [°C]
3	Chilled water flow to underground [ℓ/s]

System boundary conditions were monitored before the implementation of system improvements in order to establish a baseline. The ambient enthalpy is of importance, due to the BAC circuit directly controlling the change in ambient enthalpy. The ambient air enthalpy should thus be approximately the same for one or more days during the two different tests.

The chilled water flow and temperature are reflections of the demand for chilled water to be sent underground. The demand also indicates the required power consumption to cool the mining water to the required temperature. The boundary conditions are also system constraints, which can be used to effectively compare the operating parameters of the respective days. The parameters at initial project implementation in Table 2 are only displayed as reference to the changes throughout the project lifetime.

As discussed previously, it was crucial to compare boundary conditions that are similar during the two different test periods. After the two weeks of tests, the data was analysed in order to draw a conclusion regarding the suggested improvements and the improved strategies. The mine assisted with verification of the data.

The tests spanned a total of eight mine-production days. Analysis of the data proved that not all of the days can be compared, due to a significant variance in the boundary conditions. It was decided that the two days with the most similar boundary conditions must be compared. This was day three and day eight.

### **Interpretation of results**

Table 4 provides a summary of the most crucial test results. The two different test periods (baseline and improved strategies) were compared. The two days with the same service delivery at comparable boundary conditions were extracted. The boundary conditions for

these two days were approximately the same and it was therefore possible to compare the data of the different scenarios of control.

**Table 4: Summary of the performance test results**

Nr.	Description	Baseline	Improved strategies	Difference (%)
1	Total system power [kW]	6380	4651	27%
2	Chiller compressor power [kW]	3986	3020	24%
3	Auxiliary power [kW]	2395	1631	32%
4	Ambient air enthalpy [kJ/kg]	38.7	37	4%
5	Chilled-water temperature to underground [°C]	3.4	3.4	0%
6	Chilled-water flow to underground [ℓ/s]	228.4	230.7	-1%
7	BAC air outlet temperature [°C DB]	5.9	8	-36%
8	Evaporator water inlet temperature [°C]	7.7	9.8	-27%
9	Evaporator water outlet temperature [°C]	2.9	3	-3%
10	Evaporator water flow [ℓ/s]	252.4	197.4	22%
11	Condenser water delta temperature with VSDs [°C]	2.5	2.6	-4%
12	Condenser water delta temperature without VSDs [°C]	2.5	3.1	-24%
13	Condenser water flow with VSDs [ℓ/s]	439.8	426.6	3%
14	Condenser water flow without VSDs [ℓ/s]	454.5	452.6	0%
15	Chiller vane position [%]	49.9	65.8	-32%
16	Chiller status	4.6	3.1	33%
17	Amount of refrigeration plant starts	5	0	100%
18	38L Turbine stops	3	0	100%
19	Combined COP	5.3	5.7	8%
20	Thermal power [kW]	34136.9	26767.3	22%

It should be kept in mind that mine cooling systems vary seasonally; therefore, a comparison period should typically include different days from different seasons. The electrical power demand and system performance of the two days were compared. Various factors were analysed in order to determine the effect of improved strategies of the energy saving measures on the system. The interpretation of the results will be described in relation to Table 4.

*Item 1:* The total cooling system's average electrical power demand on the two selected days is 1.73 MW (27% reduction). A comparison between the total system power during the two tests is illustrated in Figure 22. By inspecting the curve representing the power during the baseline tests, it can be seen that there is a large reduction in power consumption between 11:00 and 15:00.

This is due to a number of chiller trips due to, firstly, use of turbines underground and secondly, inadequate control by machine operators. A comparison of the power profiles indicates that the control with project improvements is more stable than the control during the baseline tests.

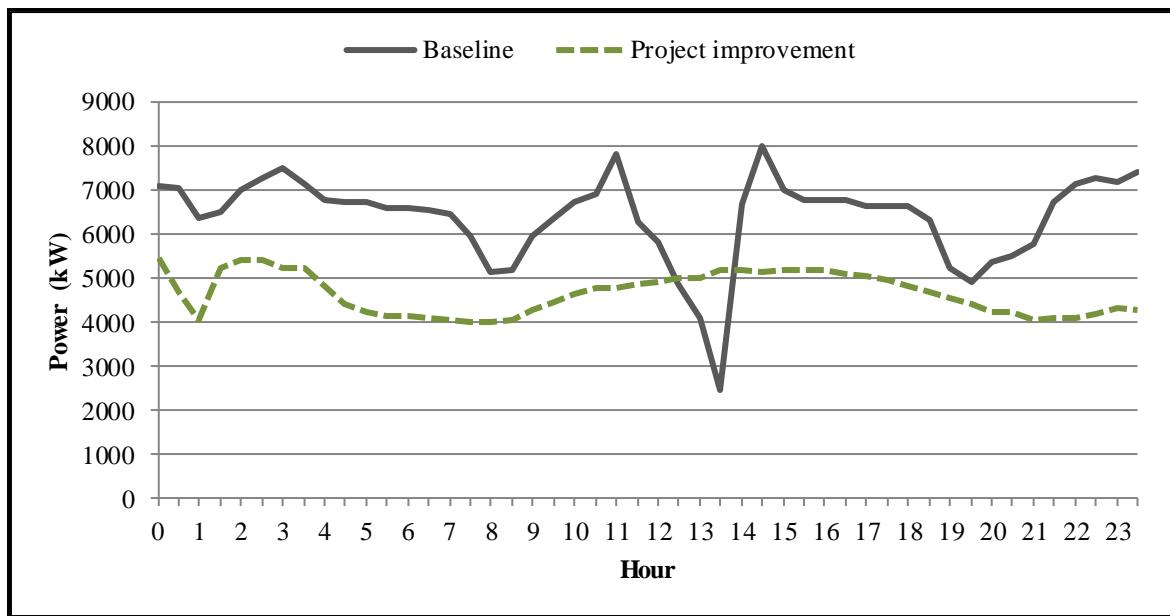


Figure 22: Total system power – Mine A

The total system power is also used to calculate the total power demand saving achieved by implementing and sustaining the energy saving measures. This will be analysed in the sections that follow.

*Item 2:* An average chiller compressor electrical power demand saving of 0.96 MW was achieved. The average of the chiller compressor power is illustrated in Figure 23. The machine trips can also be seen between 11:00 and 15:00. A thorough comparison of the chiller stops and starts was required in order to establish the sustainability of the applicable control strategies.

The chiller starts/trips were therefore analysed for the other days of the performance tests. The results are summarised in Table 16 in Appendix I. Analysis of the results indicated that there were approximately 50% more machine trips during the entire baseline test period, compared to the improved strategies' test period. There were also approximately 56% more machine starts during the entire baseline test period, compared to the project improvement test period.

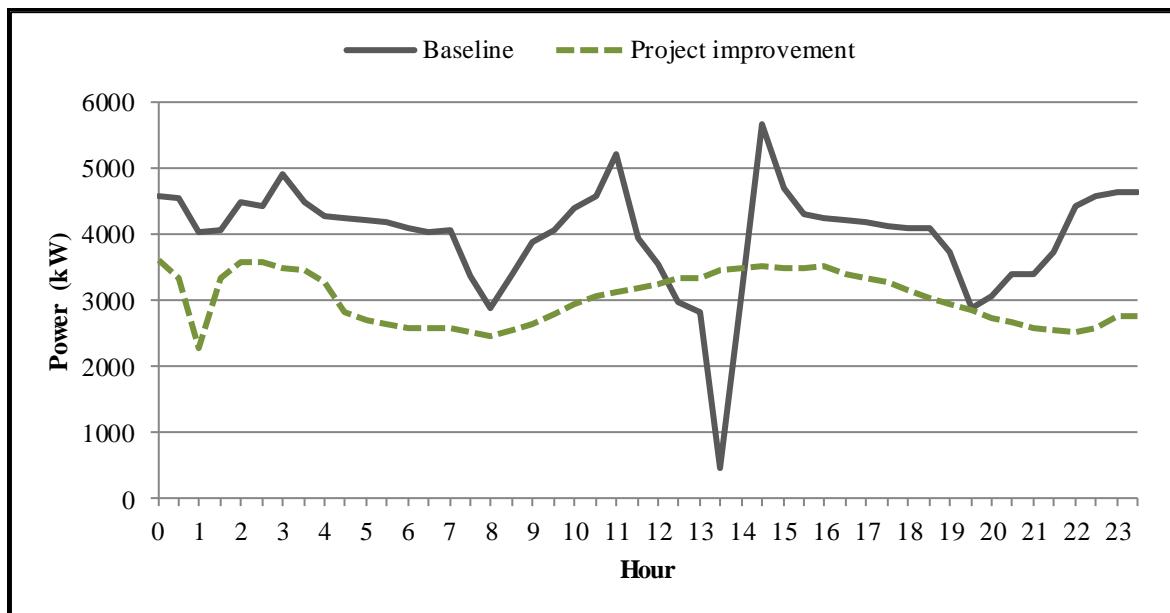


Figure 23: Total compressor power of chillers – Mine A

The trips/start were therefore reduced through the project improvements by applying effective control, not only directly on the auxiliaries, but also indirectly through effective utilisation of the chillers. A clear reduction in the baseline compressor power can be seen in Figure 23. The chillers' running status for the two selected days is displayed in Figure 24.

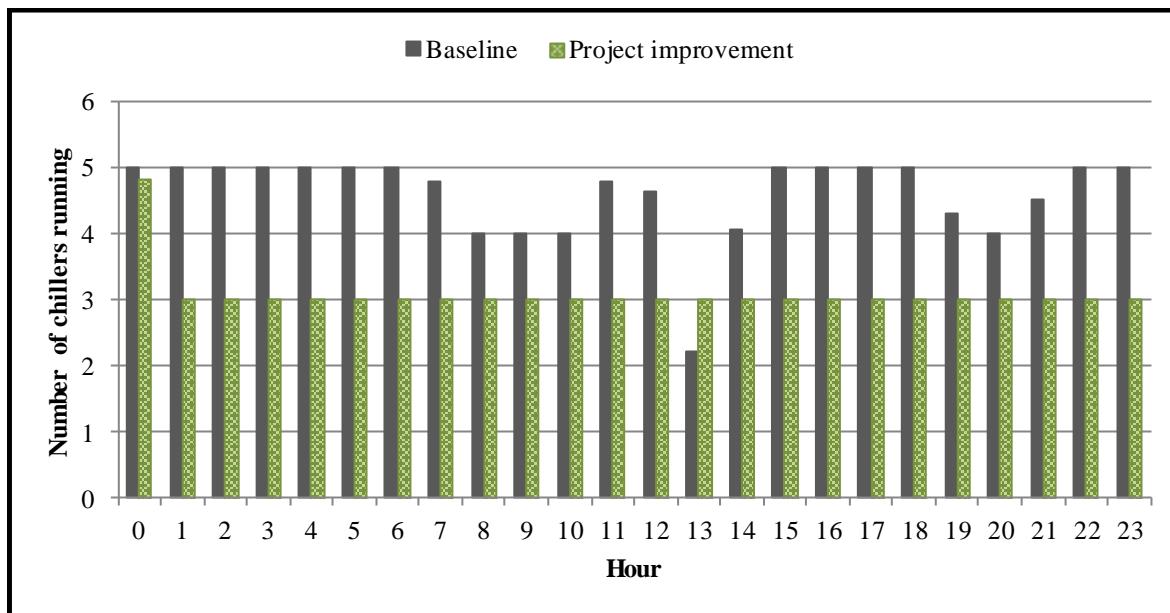


Figure 24: Number of chillers running – Mine A

*Item 3:* The average auxiliary electrical power demand saving is 0.76 MW. The auxiliary equipment includes the cooling tower fans and water pumps.

*Item 4:* The ambient air enthalpy was identified as a constant boundary condition. The flow of the BAC pumps is modulated in proportion to the change in enthalpy. The enthalpy is measured close to the BAC towers. The change in ambient enthalpy for the two days that are compared is illustrated in Figure 25. The average ambient enthalpy difference is 1.7 kJ/kg.

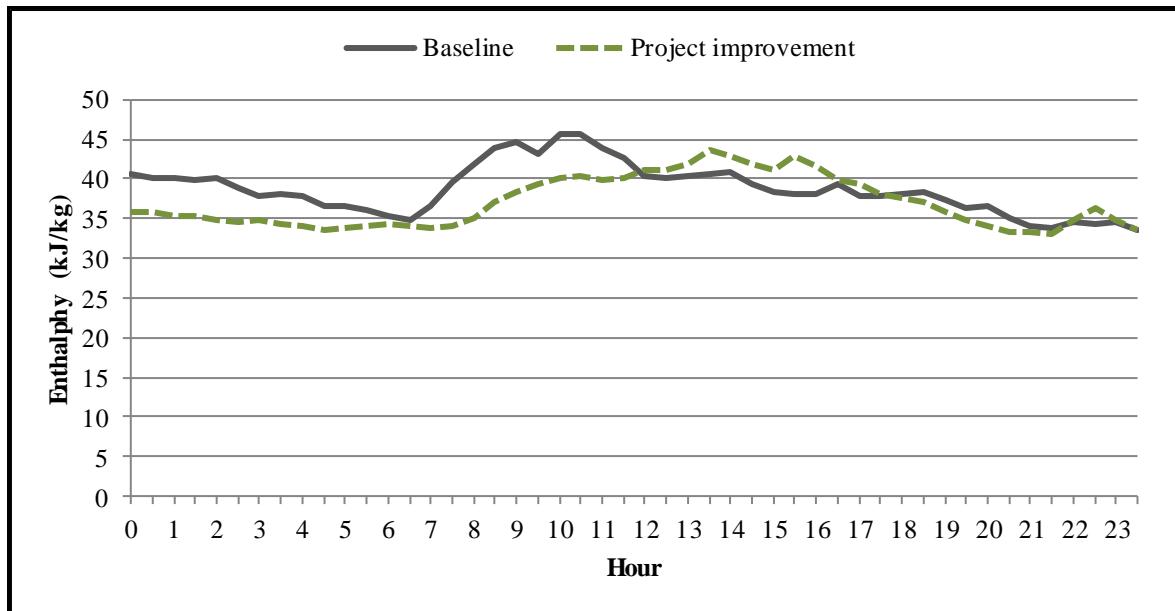


Figure 25: Ambient air enthalpy of performance tests – Mine A

*Item 5:* The average chilled water temperature difference sent underground is 0 °C and is within the requirements. Figure 26 illustrates the average chilled water temperatures throughout the day for both tests.

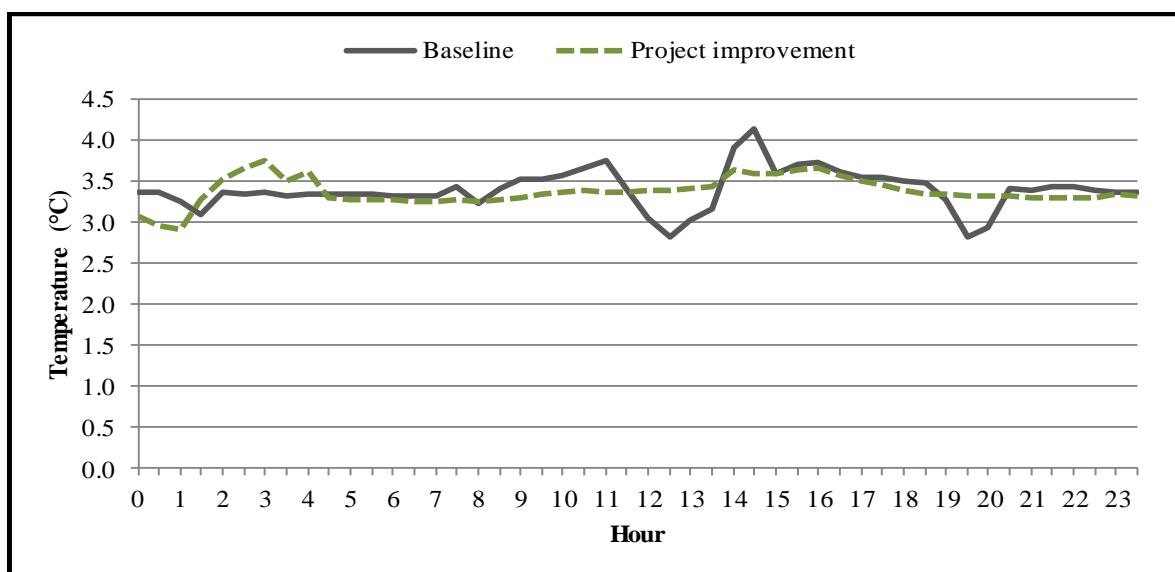


Figure 26: Chilled water temperature to underground – Mine A

The chilled water demand varies extensively throughout the day; this variation is used to reduce chilled water flow through the chillers when the demand lowers. It is crucial to keep the chilled water temperature of the required set point for operations, as discussed in section 2.5.2.

*Item 6:* The difference in the chilled water flow to underground is only 2.3 l/s. Chilled water flow to underground was the third comparable boundary condition. The average chilled water flow throughout the day is illustrated in Figure 27. The average flow is approximately the same for both tests. It is important to remember that the chilled water demand varies throughout the day due to mining activities and schedules.

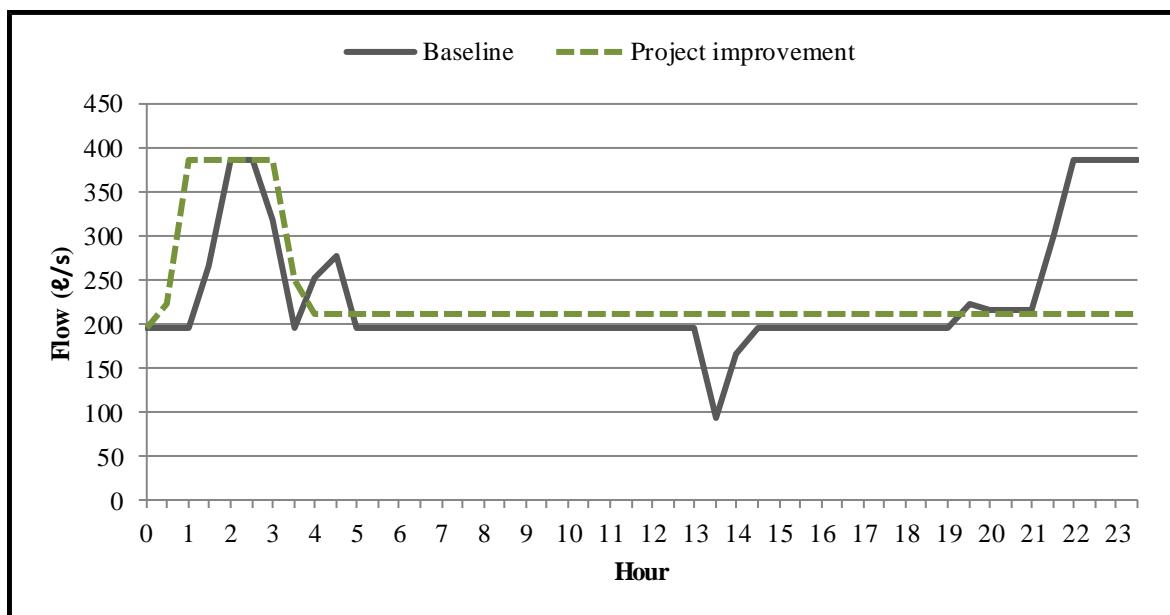


Figure 27: Chilled water flow to underground – Mine A

*Item 7:* With the implementation of the system improvements, the BAC air outlet temperature average satisfies the required maximum value of 7°C WB. The BAC cooling demand was approximately the same for both days, due to the ambient air enthalpy being approximately the same (average difference of 4%). The BAC circuit energy savings are a result of the reduction in supply water flow due to the change in ambient enthalpy.

The average BAC water flows and VSD frequencies of the BAC pumps during the baseline performance tests are illustrated in Figure 28. The significant reduction in water flow and a decrease in VSD frequency are due to the machine trips. It is also clear that the pumps were running at full design flow throughout the tests, resulting in inefficient use of electrical energy.

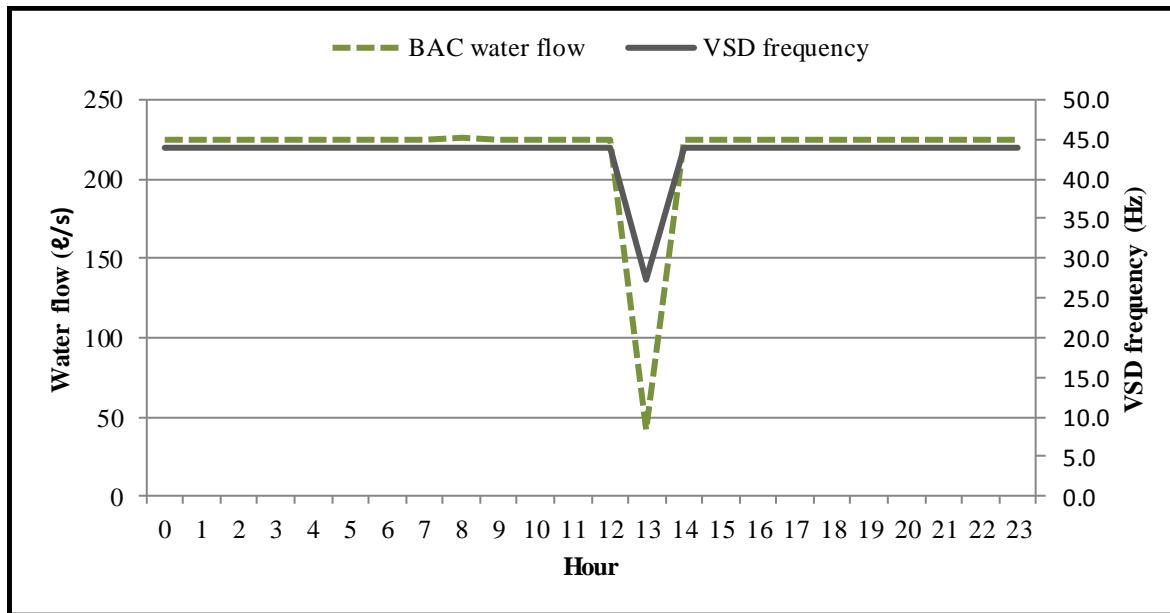


Figure 28: Average BAC water flow vs. VSD frequency – baseline period – Mine A

The average BAC water flows and VSD frequencies of the BAC pumps during the improved strategies performance tests are illustrated in Figure 29. For a decrease in ambient enthalpy, the system alters the VSD frequency linearly, as discussed previously. The reduction in motor speed reduces the water flow rates accordingly.

The energy saving of the BAC circuit is thus achieved by the flow reduction, as indicated in Figure 29. The speed variation directly influences the power consumption of the electrical motor.

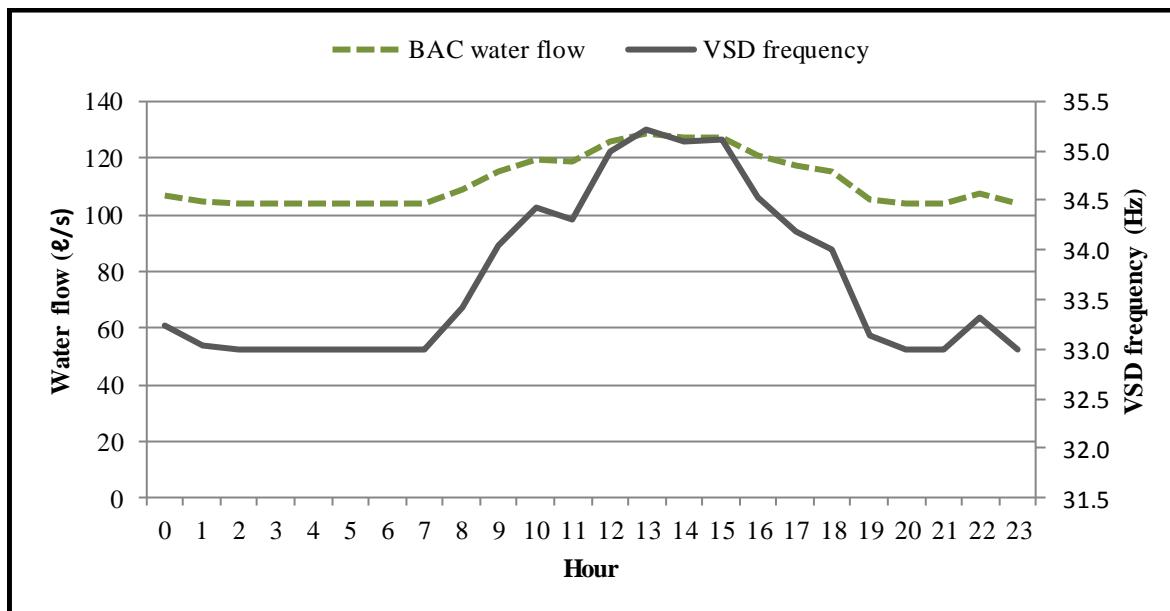


Figure 29: Average BAC water flow vs. VSD frequency – project improvements – Mine A

The average BAC air outlet temperature is illustrated in Figure 30. The improved strategy's test temperature is on average 2.1 °C higher than the baseline temperature. The chiller machines' compressor electrical demand savings (cooling demand savings) and pumping (BAC and evaporator pumps) electrical demand savings are a result of the lowered demand for cooling.

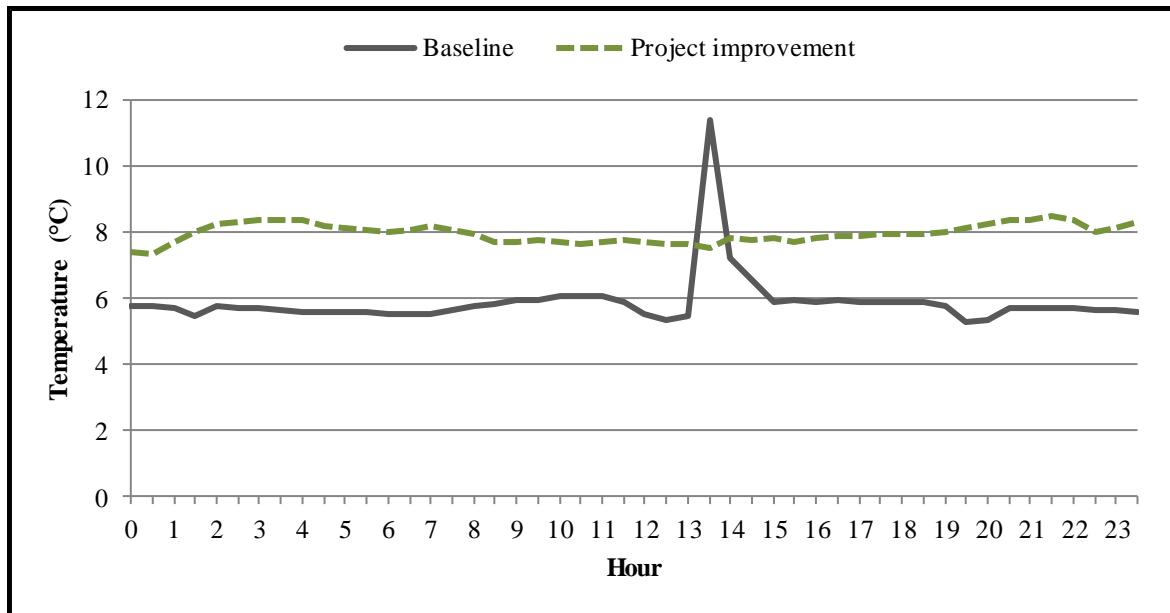


Figure 30: BAC air outlet temperature (DB) – Mine A

The temperature safety barrier is fully utilised, which ensures effective cooling when necessary. The air outlet temperature is still within the required limits. The environmental department requires an average air outlet temperature of 7 °C WB (8 °C DB). The temperature spike during the baseline tests is due chiller trips.

During a machine trip, the water is no longer cooled to the required 3 – 4 °C, therefore affecting the BAC air outlet temperature. The trips also have a direct impact on the BAC circuit, as can be seen in Figure 28. Sustainable and effective control is thus applied through the improved strategies. The system improvements aided in maintaining the BAC outlet temperature at the required set point.

*Item 8:* The evaporator inlet temperature average of performance tests is 2.2 °C higher than the baseline. This results in higher chiller COPs, due to a higher potential for heat transfer in the evaporator heat exchanger. The energy saving measures on the evaporator and condenser circuits ensure effective utilisation of the chiller cooling power. The chiller efficiency can be

seen by analysing the COP achieved by the various machines that were in operation. The combined COP of the machines is illustrated in Figure 31.

A clear increase of COP between the different tests can be seen by applying a linear trend line to the data points. There was an average increase of approximately 9% for the days in comparison. The combined average of the baseline COP for all test days is 8% lower than the days of the project improvement tests.

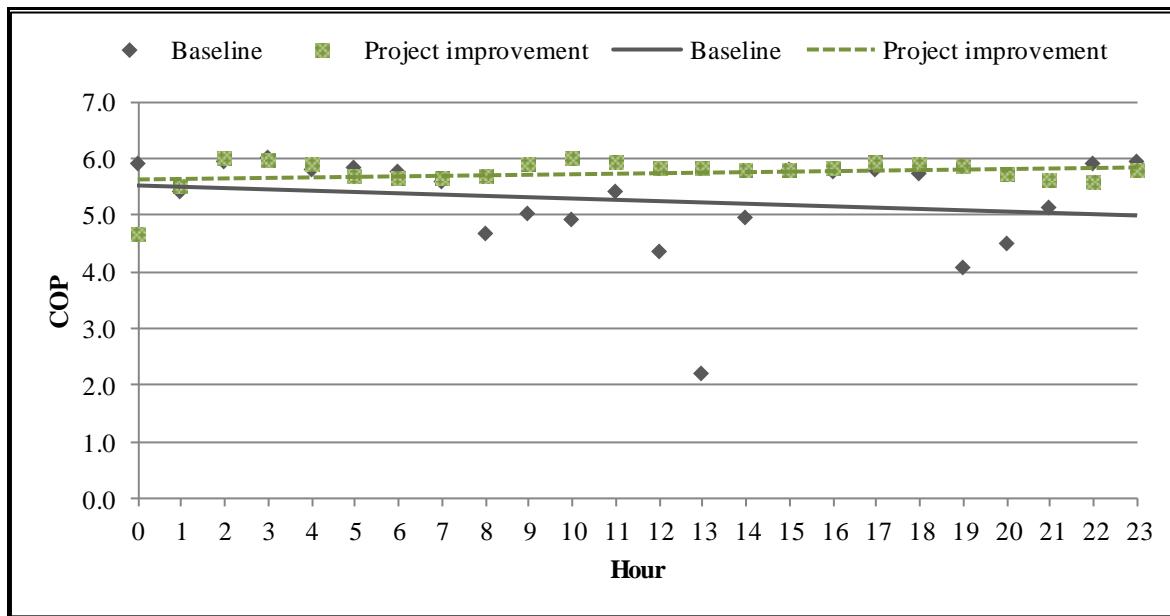


Figure 31: Combined COP of performance test – Mine A

*Item 9:* The evaporator outlet temperatures differ with only 0.1 °C.

*Item 10:* The flow rate during system improvements tests is 55 ℓ/s lower than the baseline, resulting in evaporator pump electrical demand savings. These flows are within the required flow limits.

*Item 11:* The change in condenser water temperature average of the condenser pumps with VSDs differs with 0.1 °C. Due to budget constraints during initial project implementation, only three VSDs were installed in the condenser water circuit. Condenser pumps that were operational during the baseline test were pumps 1, 3, 4, 5 and 6 (not all running at the same time). There are VSDs on pumps 2, 3, and 4 only.

The control based on the delta condenser temperature ensures that overcooling does not occur in the condenser cycle. The condenser water flow without VSDs for the baseline tests are

approximately the same and constant when the pump is in operation. The condenser water flow with VSD control for the project improvement tests are illustrated in Figure 32.

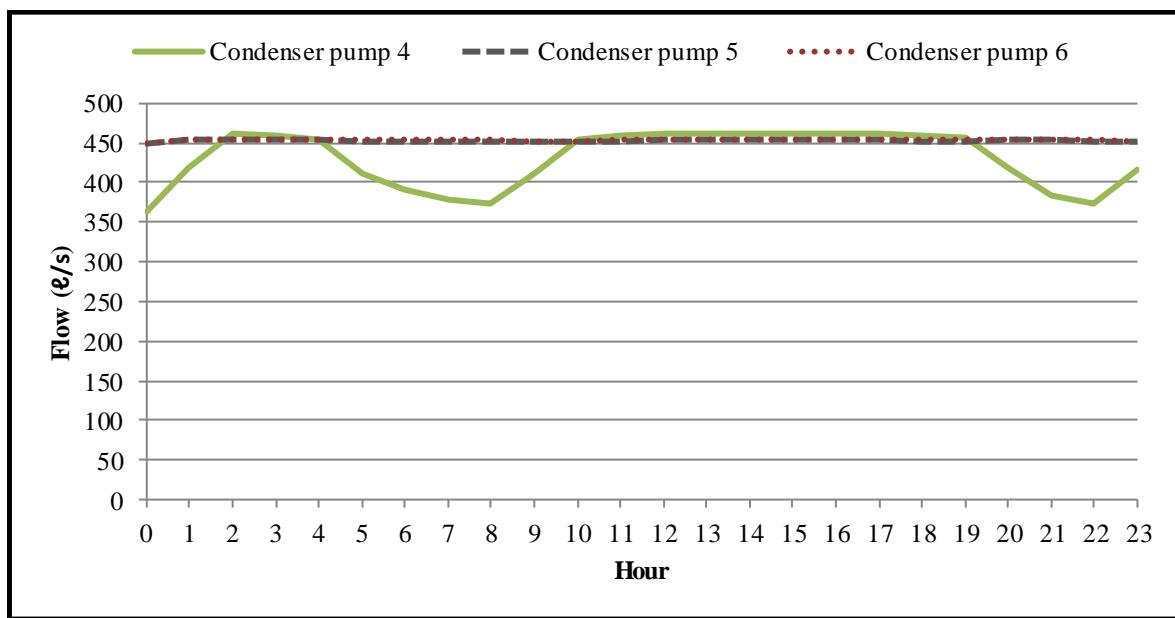


Figure 32: Condenser water flow during project improvement tests – Mine A

Figure 32 clearly indicates that the condenser pumps without installed VSDs (pump 4 and 6) operate at the design flow rates. The throttling valves on the condenser inlet pipelines were used to throttle the flow to deliver the required 450 l/s. This configuration is usually used on most mines, similar to the evaporator flows.

This creates ample opportunity to implement a sustainable flow control system to utilise the rarely imposed design thermal loads of the condensers to present an energy saving. Condenser pump 6 was operated with VSD control according to the specifications and control parameters previously mentioned.

Condenser pump 1, 2 and 3 was not used during these tests. The reduction in motor speed causes a reduction in flow. This, in turn, results in a power demand saving on the condenser pumps.

*Item 12:* The change in condenser water temperature average of the condenser pumps without VSDs differs with 0.5 °C.

*Item 13:* The condenser water flow average of the condensers with VSDs on the pumps differs with 13.2 l/s. This small difference in flow is due to only chiller number 4 running with a VSD on its condenser pump for this specific day. Chiller number 4 was running at full

load most of the time, resulting in almost maximum condenser water flow throughout the day. The condenser water control strategy did therefore not result in any significant condenser pump energy savings for this day.

*Item 14:* The condenser water flow average of the condensers without VSDs on the pumps differs with 1.9 ℓ/s.

*Item 15:* The vane openings of the chillers differ by 19.5%. Through the implementation of the system improvements, the chillers operated at higher vane openings, resulting in higher COPs. The flow control strategies on the evaporator and condenser circuits have a direct impact on the vane openings of the chillers. The average combined vane opening of the chillers is illustrated in Figure 33. The cooling load is effectively controlled by using the guide vanes of the chillers.

During the baseline tests, the average chiller status was approximately four machines, compared to the project improvement test, which was approximately three machines. Reducing the number of machines running causes the vanes to open more due to the distributed load of running fewer machines.

Using the chiller scheduler, which schedules the number of machines to run by monitoring the vane opening, one can effectively reduce the system power demand by running fewer chillers.

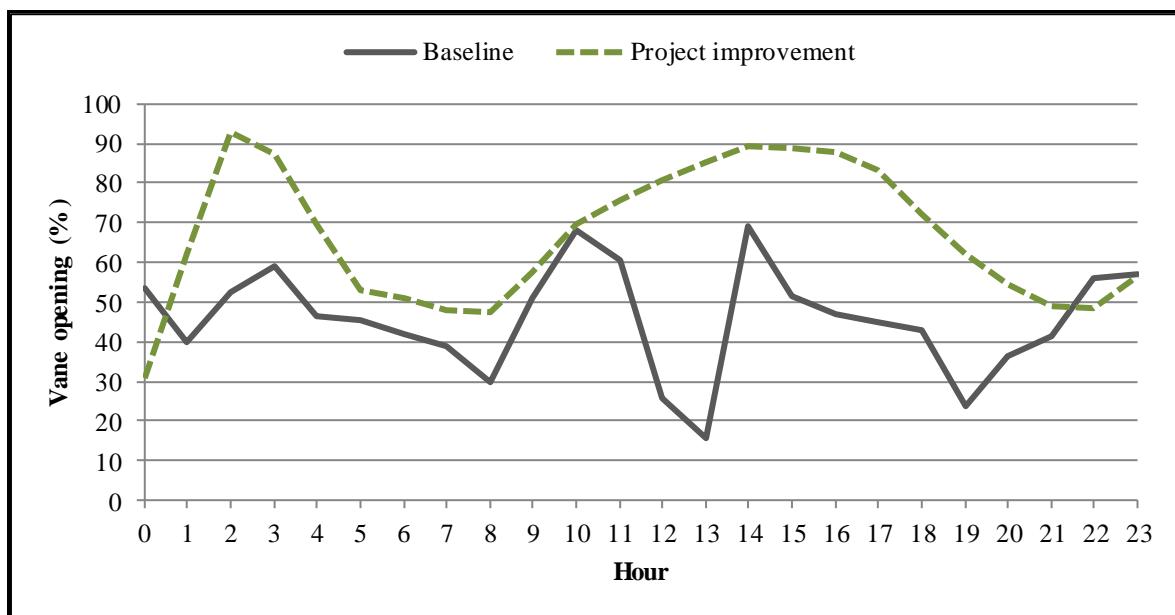


Figure 33: Combined average of the chiller vane openings – Mine A performance tests

*Item 16:* The average number of chillers running during the project improvement day is 1.5 lower than the baseline.

*Item 17:* There were seven chiller starts during the baseline day. Three of the seven starts were caused by the starts/trips of the turbine underground.

*Item 18:* There were three turbine stops during the baseline day and zero during the project improvements day.

It is apparent that the project improvement with the improved strategies ensures improved operation of the cooling system. This is concluded from the fact that there were no chiller trips during the project improvement tests.

### **Cost implications**

Comparing the two performance test days resulted in a power demand saving of 1.73 MW. The original target demand power savings was 1.50 MW. Re-implementing the energy saving measures according to the improved strategies aimed to sustain the 1.50 MW power demand saving over the long term.

Cost implications for allowing such a beneficial system to deteriorate can amount to approximately R4 million per annum. The added benefits of sustaining the power demand saving can be divided into various sections, which can potentially reflect additional cost savings.

It was previously stated that the energy saving project was implemented as part of the Eskom EEDSM initiative. The client was therefore obligated to maintain the savings for as long as possible, firstly to reduce electrical energy consumption, and secondly to aid Eskom in their endeavour to reduce the strain on the national supply grid.

During initial implementation, the client indicated a budget reduction due to decreased energy usage, thus adapting the energy usage forecast to adequately compensate for a significant reduction in electricity costs. Successful implementation of sustainable projects can easily surpass the expected payback period and can continue to remove strain from the Eskom grid.

The project improvements efficiently utilise every component of the mine cooling system and increase system performance. This results in a reduction of the life-cycle costs of the machinery and equipment operating in the system if OEM specifications are adhered to. The recommissioned system parameters and operational data show that, when the system is operating within the correct control parameters, all operational requirements are satisfied.

### **3.4.3. Simulation**

A simulation model and procedure is required in order to accurately predict the effect of implementation strategies on various other mine cooling systems. By using an accurate simulation model, one can predict the monetary saving due to reduced electricity consumption of other mine cooling systems. The effect of implementing energy saving measures can also be determined.

This section aims to verify the simulation software called Process Toolbox (PTB) by comparing simulated results with the actual performance tests. The comparison will give an indication of the degree of accuracy of the simulation software. PTB is a component-based simulation package. This implies that all physical components that a mine cooling system consists of can be simulated.

The simulation model allows the user to design, analyse and optimise the performance of a mine cooling system. Process flow paths similar to site layouts can be constructed. Mine cooling system energy saving projects require large capital investment to implement. The potential investment and expected return in terms of payback period can be determined by using the simulation software.

#### **Simulation procedure**

The simulation procedure can be summarised under the following steps adapted from [24]:

1. Identify and understand the system dynamics.
2. Collect the relevant system data.
3. Formulate and construct the simulation model.
4. Validate, execute and interpret the simulation model (discussed in this section).

The first step was to identify and understand the dynamics of the mine cooling system. The various components of the mine cooling system, together with the typical operation, were

described in the literature study. It is crucial to have background knowledge of the mine cooling system to be simulated in order to construct an accurate simulation model.

In section 3.2 and 3.3, existing energy saving measures were evaluated on mine cooling systems and a proposed solutions and project improvements were implemented. The required system dynamics is clearly described by the various equations used in the simulation model. The most important equations are listed in Appendix III.

The equations used give an indication of the required data to be collected and used in the simulation model. All the necessary data was already logged by the EMS, as described in the previous sections. The data was readily available from the automatic reporting system. The power data was retrieved from an independent company that uses power meters to automatically report the power consumption of the system to the mine.

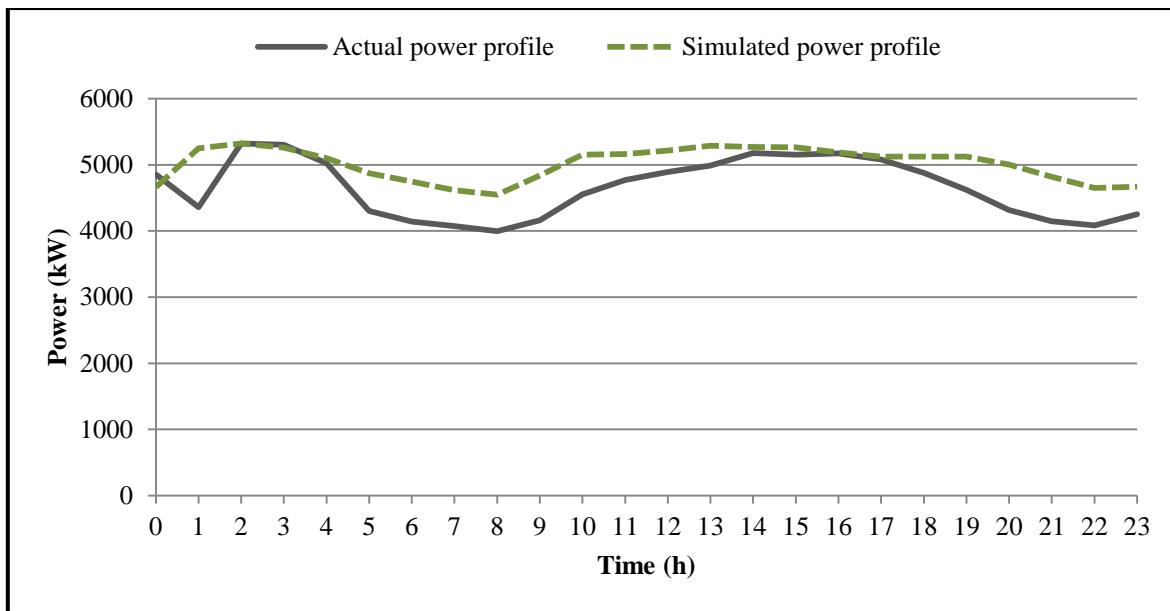
The cooling system of Mine A was modelled in the PTB simulation software. The expected savings that could be achieved was determined through the simulation model. Various cooling system specifications are required as input. These specifications are used to predict and determine the operational parameters of the cooling system over a defined period.

System operational parameters, as measured, can also be inserted into the simulation model to ensure accurate calculation and to predict system reaction to the various constraints and specifications. The simulation software has the capability to simulate the cooling system over various seasons. This function is used to determine the project operation in various seasons and the change in operational parameters due to seasonal changes.

### **Simulation verification**

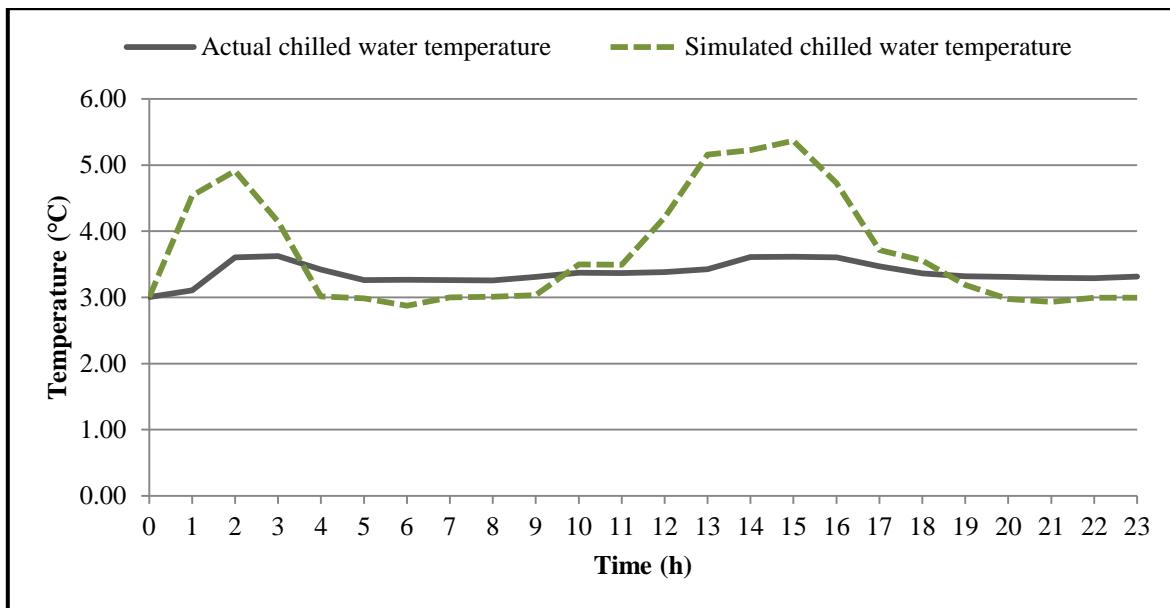
Power usage of the system, temperatures and flows from the simulation model were compared to the simulation model. The accuracy of, firstly, the simulation procedure and, secondly, the simulation model can be verified with this process. The actual logged data was entered into the model as input variables.

The actual vs. simulated power profiles for a typical production day are illustrated in Figure 34. The average percentage difference between the actual and simulated profiles is 7%.



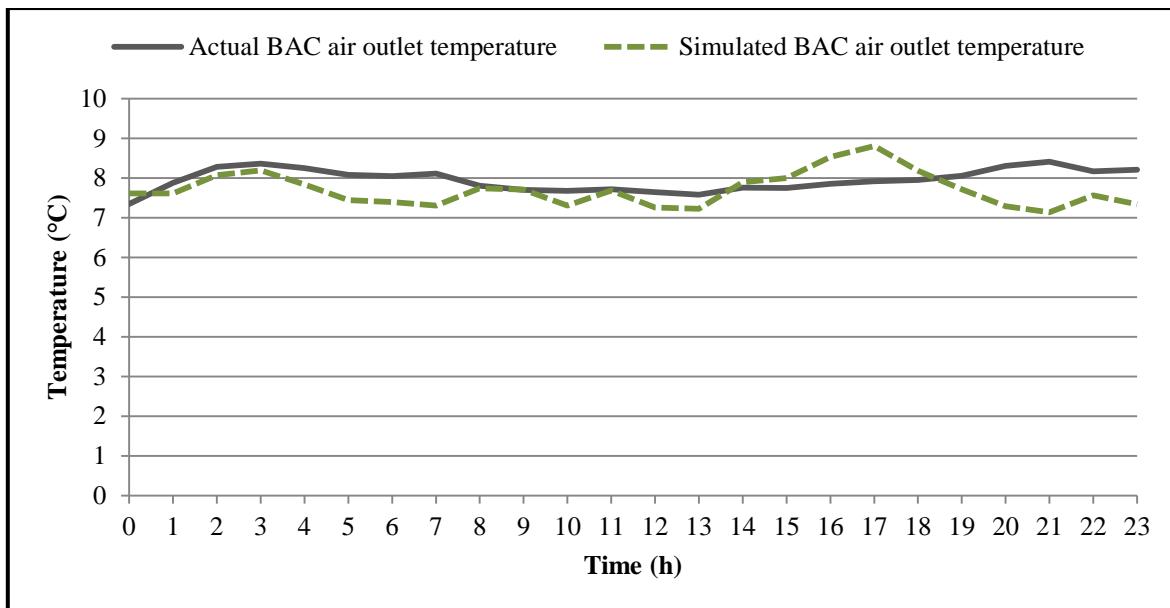
**Figure 34: Actual vs. simulated power profiles verification – Mine A**

The chilled water flow rate was used as an input to simulate the chilled water demand from the cooling system. The demand for chilled water at a required temperature and BAC air outlet temperature was thus simulated. The actual vs. simulated chilled water temperatures are illustrated in Figure 35.



**Figure 35: Actual vs. simulated chilled water temperature – Mine A**

The simulated chilled water temperature differs with an average of 8.7% from the actual results. The actual vs. simulated BAC air outlet temperatures are illustrated in Figure 36.

**Figure 36: Actual vs. simulated BAC air outlet temperature – Mine A**

The simulated BAC temperature differs from the actual results with an average of 3.3%. It can be concluded that the service delivery requirements are satisfied by inspecting the simulation results, as indicated and illustrated in Figure 34 to Figure 36 above. Service delivery requirements are the main concern when changing or altering the mine cooling system.

The simulation model with implemented energy saving measures can be used to determine the optimum control philosophy of a mine cooling system. This simulation model can thus be used to predict/identify possible potential for energy savings on mine cooling systems. The summary of the service delivery requirements are indicated in Table 5.

**Table 5: Summary of the actual vs. simulated service delivery requirements – Mine A**

System component/requirement	Simulated results	Actual results	Difference (%)
<b>Power profile (kW)</b>	5011	4651	7.2%
<b>Chilled water temperature (°C)</b>	3.7	3.4	8.7%
<b>BAC air outlet temperature (°C)</b>	7.7	8.0	3.3%
		<b>Average (+/-)</b>	6.4%

Table 5 shows that the daily average of the simulated (5011 kW) vs actual (4651 kW) power usage differs by 7.2 %. The purpose of the simulation is to predict the energy saving impact of energy saving measures. Considering this type of application, it can be concluded that an accuracy of 7.2% is sufficient.

The feasibility of the implementation of energy saving measures is also governed by the effect on the service delivery of the cooling system after implementation. The simulation model also accurately predicts this effect when considering the difference between the simulated and actual results of the chilled water (8.7%) and the BAC air outlet temperature (3.3%).

It can be concluded that PTB can accurately predict the expected energy saving impact for proposed energy saving measures. The minor discrepancy in the power usage of the simulated vs actual daily averages introduces a safety factor in the model. The overall average difference between the simulated and actual results is 6.4%.

#### **3.4.4. Potential for replicating**

Various mines in South Africa have the same type of configuration as Mine A. The feasibility for replicating improved implementation strategies must be established. Although [27] conducted a pilot study for implementing variable flow strategies on numerous mine cooling systems, it is difficult to predict the exact outcome of implementation.

Improved implementation strategies can ensure that target electrical power savings are achieved with minimal effect on the system components. The energy analysis of 20 large mine cooling systems creates valid grounds where the feasibility of implementation can be increased.

Potentially, it is possible to replicate the improved implementation strategies, as discussed in the previous sections, with the main focus on sustainability of energy savings. These identified methods will be tested on a mine as a case study in Chapter 4.2.

Limitations do, however, exist. Some mines utilise underground refrigeration techniques, which can entail technical difficulties that have not been identified in this study. PTB can also be used to determine the feasibility of implementation of energy saving measures.

### **3.5. Conclusion**

A surface refrigeration and cooling system with implemented, but deteriorated, energy saving measures was identified at Mine A. The energy saving project was implemented at Mine A during 2011. The system was not maintained and deteriorated up to the point where the original implemented energy saving strategies were disabled.

The opportunity to re-commission, optimise and improve the entire mine cooling system was identified with the help of mine personnel. Analysis of key performance indicators of the system was crucial. This enabled the identification of problem areas in the system. Re-commissioning of the energy saving project was required and performance tests had to be conducted.

Previous sections of this chapter focused on evaluating existing energy saving measures on a mine cooling system. It was found that numerous factors contributed to the de-commissioning of the energy saving measures. A solution to the challenges of implementing the measures was identified and all concerns were addressed. The solution was implemented with project improvements and actual performance tests were conducted.

A simulation model for the mine cooling system of Mine A was constructed in PTB. This simulation conservatively predicted the electrical power usage of the system. The simulation vs. actual results had an average difference of 6.4% when compared. The simulation was deemed accurate enough for the purpose of determining the feasibility of implementing energy saving measures on mine cooling systems.

The potential for replicating the methods discussed in this chapter was also discussed. The method identified will be replicated to a surface mine cooling system as a case study, in effect determining the potential for replicating. It was evident from the literature that numerous mine cooling system projects have been implemented in the country. These projects might lack efficient control and maintenance, and scope for improved implementation strategies exists, which can lead to system improvements, increasing and sustaining the energy saving impact.

# CHAPTER 4: PRACTICAL APPLICATION OF IMPROVED STRATEGIES



4

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Application of improved implementation strategies on a deep-level gold mine cooling system as a case study.

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<sup>4</sup>P. Maré, Personal photograph. “Hitachi chiller”, South Africa, 2014.

## **4.1. Preamble**

An improved implementation strategy to sustain energy saving measures on mine cooling systems was developed in the previous chapter. The feasibility of the strategy was determined by implementing the strategy with project improvements. It was clear that the proposed energy savings with the energy saving measures was quantifiable.

Implementation was done on Mine A in order to prove the viability of the strategy on similar cooling systems. Mine A already had existing energy saving measures installed, which improved the viability of successful implementation. The following chapter will discuss the implementation of the strategy on Mine B as a case study.

The proposed energy saving measures will be discussed and the simulated impact will be determined by using PTB. This will give a clear indication of the feasibility of implementing the strategy on Mine B. The methods applied to measure and verify the energy savings achieved will also be presented.

This chapter will consider the entire implementation, including simulations, equipment installation, energy management and control- system integration, and finally results verification and discussion. The mine cooling system of Mine B will firstly be described and clearly defined.

The implementation of the energy saving measures, according to the improved strategies, will aim to efficiently utilise the surface cooling system at Mine B.

## **4.2. Implementation of improved strategy**

### **4.2.1. System description**

The surface cooling system at Mine B is only used for ventilation and cooling purposes. A simplified layout of the surface mine cooling system is displayed in Figure 37. Chilled water at 3 °C is supplied by two parallel sets of chillers, each set consisting of two chillers in series. The chilled water is supplied to five BACs (four BACs located at the main shaft (MS) and one BAC located at the ventilation shaft (VS)). The system operates in a closed-loop configuration.

The chilled water leaves the BACs at approximately 11 °C. The MS BAC water is pumped back to the evaporator dams, situated close to the VS. The evaporator dams are two separate tanks that equalise through gravity feed. The VS BAC sump also equalise with the two evaporator tanks.

From the evaporator dams, the water is pumped through the chillers for the process to be repeated. The four MS BACs supply cold, dehumidified air to the underground working areas, whereas the one VS BAC supplies cold dehumidified air to 30-level only. The air is then extracted from the mine by the main shaft fans. The BACs cool ambient surface air down to about 7 °C WB (8 °C DB).

The fans, situated on top of the BACs, operate at full capacity under normal operating conditions. The four chillers have a total nominal cooling capacity of 26 MW and a COP of 5.3 under nominal design conditions. The condenser water inlet temperature is approximately 27 °C.

### **Normal system operation**

The entire mine cooling system is fully operational during summer, autumn and spring months (September – May). During these months, all BACs and chillers are in operation. The demand for cooled air increases during these months. The chillers and BACs are stopped during winter months (May to August).

Due to a significant reduction in ambient temperature, the demand for chilled water and cooled air allows the complete stoppage of the surface cooling system. The WB temperature of the ambient air is sufficiently cold and dry during the winter months and meets the requirements as stipulated by the ESH department.

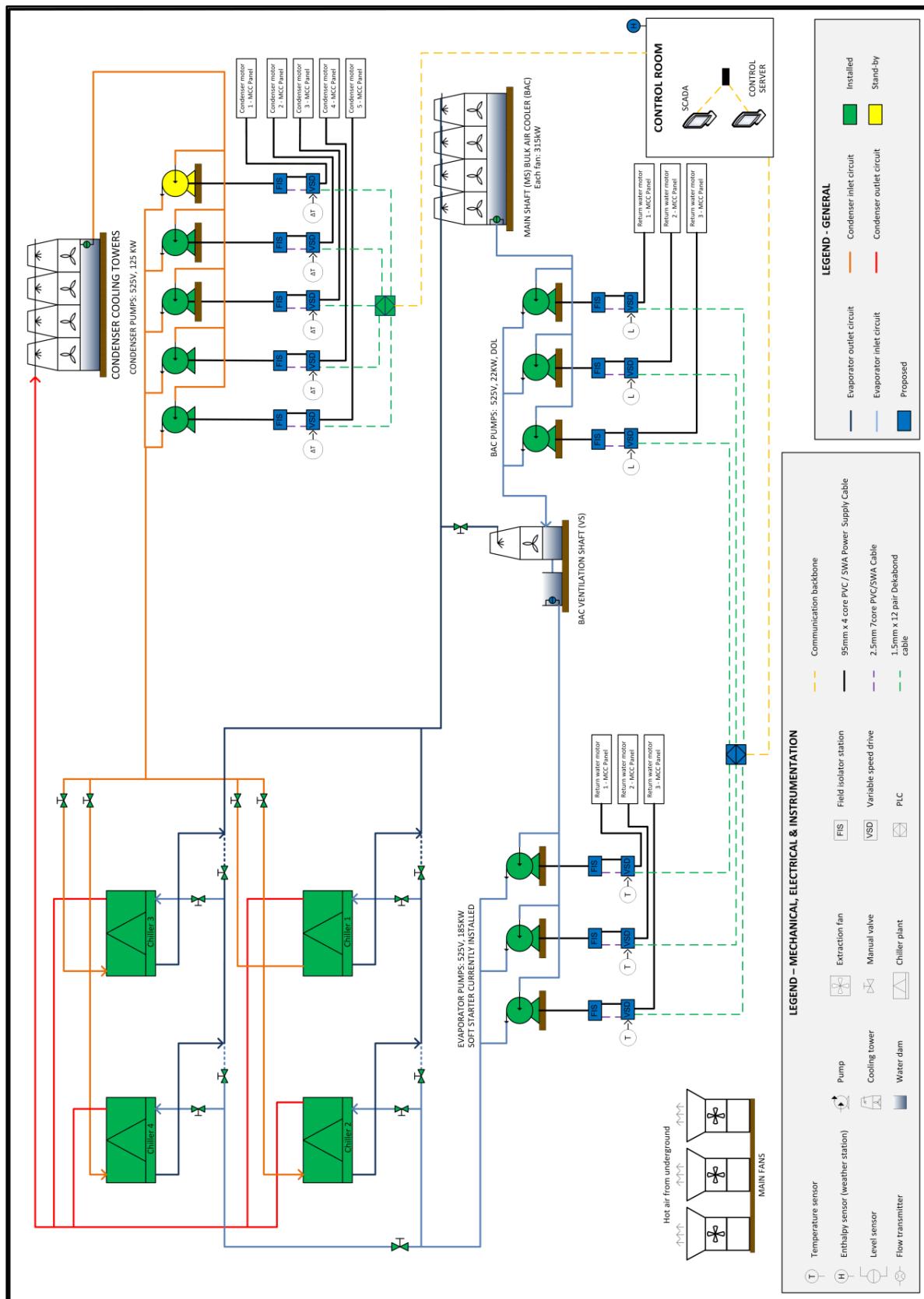


Figure 37: General layout and proposed energy saving strategies of Mine B

## System specifications

The surface cooling system specifications of Mine B are listed in Table 6.

**Table 6: Surface cooling system specifications - Mine B**

<b>Chillers (individual)</b>	
Evaporator outlet temperature [°C]	3
Evaporator water flow rate [l/s]	250
Condenser inlet temperature [°C]	24
Condenser water flow rate [l/s]	315
Cooling capacity [kW]	6600
COP lead machines [-]	5.5
COP lag machines [-]	5.3
Refrigerant [-]	R12
Compressor power [kW]	1350
Compressor type [-]	Centrifugal
<b>Water pumps</b>	
Number of evaporator pumps [-]	3
Evaporator pump motor rating [kW]	185
Number of condenser pumps [-]	5
Condenser pump motor rating [kW]	125
Number of BAC return water pumps [-]	3
BAC return water pump motor rating [kW]	22
<b>Cooling towers</b>	
<i>BACs towers</i>	
Number of towers [-]	5
Water inlet temperature [°C]	3
Water outlet temperature [°C]	10
Water flow rate per tower [l/s]	147
Air outlet temperature (wet-bulb) [°C]	7
Air inlet temperature (wet-bulb) [°C]	22
Airflow rate per tower [kg/s]	300
<i>Condenser towers</i>	
Number of towers [-]	4
Water outlet temperature [°C]	27.5
Water inlet temperature [°C]	32
Water flow rate per tower [l/s]	315
Air inlet temperature (wet-bulb) [°C]	22
Airflow rate per tower [kg/s]	300
<b>Combined plant</b>	
Combined COP [-]	5.5
Combined cooling capacity [MW]	26
Volume of water sent underground [Ml/day]	-

### 4.2.2. Proposed energy saving measures

The energy saving project investigation methodology, as described in Appendix II, was primarily conducted to determine the feasibility of implementing energy saving measures on the cooling system of Mine B.

The proposed energy saving measures that can be implemented on Mine B is discussed in the following section. The energy saving measures installed on Mine A was altered and modified to increase the feasibility of implementation on Mine B. The proposed equipment installations are indicated in Figure 37.

Control and instrumentation upgrades are normally required on older mine cooling systems. The advanced energy saving measures requires improved system control and monitoring. The sustainability of these measures depends on strategic upgrades with minimal costs. Control and instrumentation upgrades also increase the sustainability, due to the vast range of monitoring and reporting capabilities that accompany such upgrades.

There are primarily three different water reticulation circuits on Mine B that present ample opportunity for increased energy performance. The optimisation of these circuits can potentially result in reduced energy consumption. The circuits with energy saving measures are listed in the sections that follow.

### **Evaporator water flow control**

The proposed control of the chiller evaporator flow entails fully opening the evaporator inlet valves on the chiller inlet pipeline, normally used to throttle the desired flow through the chillers. VSDs must be installed on all three evaporator pumps. The flow must now be controlled by the VSDs only. The control logic feedback signal will be the MS BAC air outlet temperature, measured by a temperature probe that is situated in the air outlet duct of the MS BACs. The temperature probe can only measure the DB temperature of the air.

The control system (which will be installed as part of the project) must provide an air outlet temperature set point to the SCADA and PLC, allowing VSD control. The frequency of the VSDs should be increased if the temperature is above the set point, and the VSD frequency should be decreased if the temperature is below the set point.

Figure 64, Appendix III, represents the evaporator flow control strategy and elaborates on the exact proposed control of the evaporator pumps. The pumps must operate between the minimum and maximum speed.

### **BAC water flow control**

The proposed control of the BAC water flow entails installation of VSDs on all three BAC return pumps. The control of the VSDs will be primarily based on dam level control of the MS BAC dams. The control system must supply dam level set points to the SCADA and PLC.

During normal operation, the VSDs must control two of the BAC pumps to maintain the specified MS BAC dam level set point, utilising PI control on the PLC. PI control logic must be used to decrease pump speeds when the ventilation shaft BAC sump level exceeds the level set point, and increase pump speeds when the ventilation shaft BAC sump level drops below the level set point. The pumps must operate between the minimum and maximum speed.

### **Condenser flow control**

The proposed condenser water flow control entails installation of VSDs on all five condenser pumps. The control of the VSDs will be based on the change (delta) in condenser inlet and outlet temperature. The control system will supply a delta temperature set point of 5 °C to the SCADA and PLC. The manual isolation valves used for throttling the condenser on the condenser inlet pipelines must be adjusted to allow control.

The condenser pump speed must be increased when the condenser water temperature difference exceeds the temperature set point. Similarly, the pump speed must be decreased when the temperature difference drops below the temperature set point, utilising closed-loop PI control logic. The pumps must operate between the minimum and maximum speed.

### **Chiller scheduling**

Due to the change in ambient conditions, the surface chiller machines can be switched off once the cooling demand reduces. The temperature safety barrier will be further utilised to obtain the power demand saving when possible. A chiller scheduler will be programmed onto the control system, which will schedule the machine statuses required to maintain the BAC air outlet temperature at 8 °C DB.

The schedule will be sent to the SCADA to allow the operators to stop and start the chillers as required. It is important to note that the control system does not have the control privileges to

automatically stop and start the chillers. The stopping and starting of chillers at Mine B require the closing/opening of inlet pipeline valves once the chillers are stopped/started to avoid unnecessary circulation of water.

The operators at Mine B were trained to stop/start the chillers according to the correct procedure. This, however, is not a sustainable solution, as operators are not reliable and neglect following the procedures, which leads to damage or failure of equipment and machinery.

### **Energy saving potential – Mine B**

The simulation software (discussed in section 3.4.3) was used to predict the amount of monetary savings due to reduced power consumption. The system reaction due to the implementation of the energy saving measures and altered control philosophy can also be predicted to an acceptable degree of accuracy.

The reaction of the system can also influence the sustainability of the energy saving measures, as described in Chapter 3. The mine cooling system was compiled in PTB by using Figure 37 as reference. The annual baseline surface cooling simulation model was configured to be used as reference for energy savings during the energy saving investigation. The baseline simulation boundaries for the simulation are displayed in Table 7.

**Table 7: Baseline simulation boundaries – Mine B**

Description	Dec – Feb (Summer)	Mar – May (Autumn)	Jun – Aug (Winter)	Sep – Nov (Spring)
ESKOM Electricity Tariff	2014/2015	2014/2015	2014/2015	2014/2015
Hourly climate data	2013	2013	2013	2013
Chilled water supply temperature (°C)	3.0	3.0	N/A	3.0
Average evaporator flow (l/s)	440	440	0	440
Chillers in operation	4	2	0	2
Condenser cooling towers in operation	4	4	0	4
BACs in operation	4	4	0	4

The time periods reflect the different seasons of the year (summer, autumn, winter and spring) as inputs into the simulation. Daily 24-hour averages will be simulated as different seasons. The climate data relating to the specific months were used as environmental inputs.

The Eskom electricity tariff is the most recent available tariff structure upon publication of this dissertation. The hourly climate data was available from a weather station situated close to Mine B. The chilled water supply temperature and evaporator flow are specified as crucial inputs of the simulation model.

The chillers, condenser cooling towers and BACs were also adapted to reflect the operation, as found during various site investigations. The additional inputs that were used to formulate and construct the simulation model were obtained from the mine during the investigation phase. The physical layouts of the simulation model are displayed in Figure 60 to Figure 63 in Appendix III.

### Simulation results

From the baseline simulation model, a simulated power saving impact was also simulated. The results of the simulation model are illustrated in Table 8.

**Table 8: Energy saving potential – simulation results for Mine B per annum**

System component/requirement	Simulated baseline	Simulated impact	Difference (%)
Power profile average p.a (kW)	3236	2854	12
Chilled water temperature (°C)	4.22	3.57	15
BAC air outlet temperature (°C)	6.0	6.8	12
		Average (+/-)	13

The average demand power saving potential was determined as 382 kW (saving of 12%) for normal weekdays per annum (thus including the four seasonal effects). The saving differs for each season and will be discussed in later sections.

The chilled water temperature and BAC air outlet conditions must not be adversely affected, as discussed in Chapter 2. The chilled water temperature was cooled to approximately 15% lower than the simulated baseline average.

The simulated impact on the BAC air outlet temperature is on average 12% higher than the simulated baseline temperature. The BAC air temperature is not concerning, due to the temperature being below the required 8 °C DB temperature.

## Cost-benefit analysis

The simulation model, as discussed, indicated a potential saving of 12% if energy saving measures are implemented on Mine B. The economic feasibility must, however, be considered in order to determine the feasibility of project implementation. The improved implementation strategies aim to reduce the challenges before project implementation.

Conducting a cost-benefit analysis will ensure that all financial risks related to project improvement, will be taken into account. Firstly, the electricity cost due to the 12% saving will be calculated.

### *Electricity cost savings*

The electricity cost savings of the proposed implementation strategies can be calculated by using the Eskom Megaflex tariff structure. The tariff structure and demand period definitions were used for calculation purposes (Table 17, Appendix IV). The cost saving of a typical summer day was calculated and is illustrated in Table 9.

The average electricity tariff for a typical summer day is 0.52 c/kWh. The average power saving during a normal summer weekday is predicted as 893 kW, with a cost saving of R11 551 per day. The autumn and spring savings were calculated using a similar approach. Calculation resulted in a 329 kW power saving during a normal autumn weekday, and a 305 kW power saving for a normal spring weekday. This saving equates to R3952 for an autumn weekday and R4200 for a spring weekday.

The surface cooling system on Mine B is not operational during winter months, resulting in no impact on electricity savings during these months.

**Table 9: Typical summer day electricity cost saving**

Potential summer savings							
Hour	Electricity tariff (c/kWh)	Baseline electricity (kW)	Project electricity (kW)	Baseline electricity cost (R)	Project electricity cost (R)	Cost saving (R)	Cost saving (%)
0	35.31	5666	4922	2001	1738	262	13%
1	35.31	5598	4859	1977	1716	261	13%
2	35.31	5537	4800	1955	1695	260	13%
3	35.31	5488	4747	1938	1676	262	14%
4	35.31	5449	4698	1924	1659	265	14%
5	35.31	5418	4655	1913	1644	270	14%
6	55.65	5428	4624	3021	2573	448	15%
7	80.86	5533	4612	4474	3729	745	17%
8	80.86	5767	4624	4663	3739	924	20%
9	80.86	5988	4659	4842	3767	1075	22%
10	55.65	5995	4795	3336	2668	668	20%
11	55.65	5993	4903	3335	2729	607	18%
12	55.65	5992	4984	3335	2773	561	17%
13	55.65	5990	5028	3334	2798	536	16%
14	55.65	5991	5091	3334	2833	500	15%
15	55.65	5991	5129	3334	2854	480	14%
16	55.65	5992	5170	3335	2877	458	14%
17	55.65	5994	5196	3335	2891	444	13%
18	80.86	5996	5210	4849	4213	636	13%
19	80.86	5998	5195	4850	4201	649	13%
20	35.31	6000	5157	2118	1821	297	14%
21	35.31	6000	5107	2118	1803	315	15%
22	35.31	6000	5047	2119	1782	336	16%
23	35.31	5812	4983	2052	1759	293	14%
Average	<b>52.43</b>	<b>5817</b>	<b>4925</b>	<b>3062</b>	<b>2581</b>	<b>11551</b>	<b>15%</b>

#### *Estimated project costs*

The implementation of an energy saving project requires various types of equipment, time-consuming labour and specialised skills. The costs related to implementing the proposed energy saving project must therefore be evaluated. The initial capital required to implement the project on Mine B was determined by conducting numerous site visits with contractors to obtain quotes to complete the scope of work.

After various considerations and requirement analysis, subcontractors were selected and the quotes were compiled in a bill of quantities. The total estimated project cost is R3.4 million. The sustainability of the energy saving measures relies significantly on the design life of the

equipment supplied to achieve the variable flow control. The most expensive component included in the cost estimation is the VSDs.

From the literature, it was established that the typical design lifespan of a VSD is 20 years under normal running conditions. For the purpose of this study, the assumption is made that the costs to maintain additional physical hardware is negligible in comparison to the initial costs incurred, and the accumulative electricity cost saving exceeds the expected maintenance costs.

#### *Project payback period*

The project payback period governs the feasibility of implementing energy saving measures on most industrial sites. The relevant mine personnel involved with approving the capital outlay requires a guarantee of short periods for return on investment.

The project payback period can be calculated by comparing the amount of initial costs incurred with the potential electricity cost saving. Table 10 illustrates the simulated seasonal electricity cost saving potential for the implementation of the energy saving measures on Mine B.

**Table 10: Simulated electricity cost saving potential – Mine B**

Season	Electricity cost savings
<b>Summer</b>	R 1 039 557
<b>Autumn</b>	R 363 567
<b>Winter</b>	R -
<b>Spring</b>	R 382 202
<b>Total</b>	<b>R 1 785 326</b>

The total yearly savings equate to approximately R1 785 326. Comparing the expected yearly cost savings with the budgeted implementation costs, which amount to R3.4 million, results in a payback period of approximately 23 months.

Payback periods of one to three years, with energy efficiency strategies implemented on large motors in industry, have been achieved [85]. The payback period of 23 months (1.9 years) falls tolerably within the acceptable expected payback periods according to the literature. The payback period is crucial for the sustainability of the energy saving measures. It is important to have a short payback period in order to justify the maintenance costs of ESCOs to maintain

the implemented energy saving measures. The mine approves projects with a payback period of less than 24 months.

With the potential payback of 23 months, it was decided to continue with the implementation of the proposed energy saving measures on Mine B. The equipment installations and control and integration are discussed in the following section.

#### **4.2.3. Equipment installations and control and integration**

After the feasibility of energy saving measures on Mine B was established, the implementation of the project commenced. Each energy saving measure required different equipment to be installed. The energy saving measures with required equipment and proposed control is listed in Table 11.

The necessary equipment was ordered from the relevant suppliers after comparing quotes from various suppliers. The equipment delivery and installations were part of the ESCO's project management process. The ordering, delivery, installation and commissioning of the equipment and system took place over a period of 11 months. The control system was also commissioned by the relevant ESCO.

#### **Implementation considerations**

The improved implementation strategies identified in Chapter 3 indicated that, for an energy saving project to be implemented, certain implementation and control considerations must be analysed and established. The identified and developed energy saving measures are indicated in Table 11. The type of control and control set points are also indicated. The control considerations are discussed in the following section.

**Table 11: Equipment installed for energy saving measures on Mine B**

<b>Implemented saving strategy</b>	<b>Installed equipment</b>	<b>Set point</b>
i. <b>BAC tower flow control</b> <ul style="list-style-type: none"> <li>- Install a VSD on each BAC return water pump</li> <li>- Control VSDs according to evaporator dam level</li> </ul>	3 × 22 kW Yaskawa VSDs (525 V, including circuit breakers, line choke and motor choke) -	- 70 %
ii. <b>Evaporator water flow control</b> <ul style="list-style-type: none"> <li>- Install a VSD on each evaporator pump</li> <li>- Control VSDs according to direct BAC air outlet temperature.</li> </ul>	3 × 185 kW Yaskawa VSDs (525 V, including circuit breakers, line choke and motor choke) 1 × weather station, including all probes (measuring ambient pressure, temperature and enthalpy)	- 7 °C (WB)
iii. <b>Condenser water flow control</b> <ul style="list-style-type: none"> <li>- VSDs installed on three condenser pumps</li> <li>- Maintain a constant delta temperature rise over each condenser.</li> </ul>	5 × 160 kW Yaskawa VSDs (525 V, including circuit breakers, line choke and motor choke) -	- 5 °C

### **BAC tower flow control**

Figure 38 shows the group of BAC pumps. The BAC pump system alterations included the installation of field isolator stations (FIS) close to each pump. Isolator stations are required to locally isolate the pumps independently for maintenance or equipment replacement purposes.



Figure 38: BAC pumps – Mine B

The water levels of the MS BAC and VS BAC sumps are balanced by the BAC pumps. The BAC pumps are used to transfer the water to the VS BAC sump in order to make the water available to repeat the cooling cycle. Figure 39 illustrates the VSDs installed on the BAC pump motors.



Figure 39: 22 kW VSDs installed on the BAC pump motors – Mine B

### Evaporator water flow control

Figure 40 illustrates the group of evaporator pumps. The pump system alterations are similar to that of the BAC pumps, which included the installation of FIS close to each pump. Figure 40 also indicates the VS BAC sump from where the water is pumped.



Figure 40: Evaporator pumps – Mine B

Figure 41 illustrates one of the four chiller machines on Mine B. The performance of the chillers will be influenced by the implementation of the evaporator flow control strategy. The effects on the chillers are discussed in section 4.3.



Figure 41: One of the four chillers at Mine B

### Condenser water flow control

Figure 42 shows the group of condenser pumps. The pump system alterations are similar to that of the BAC and evaporator pump stations, which included the installation of FIS close to each pump.



**Figure 42: Five condenser pumps at Mine B**

Figure 43 indicates the condenser cooling towers and dam from where the water is pumped.



**Figure 43: Condenser cooling towers at Mine B**

The VSDs were installed in each relevant pump station – therefore close to the motor control centre (MCC) panels. The MCC panels were all outdated and needed to be upgraded to accommodate the installation of VSDs in the system.

A new PLC was supplied, as there were not sufficient input- and output ports on the existing PLCs. The PLC panel was commissioned by mine personnel. The PLC panel also allowed for additional future expansion of the instrumentation and communication network.

During commissioning, each VSD was calibrated by means of flow tests. The allowable flow ranges were determined and programmed onto the PLCs. The high- and low-level trips were also programmed onto the PLCs where dam level control was relevant.

The minimum and maximum allowable flows were calibrated to correspond with the minimum and maximum VSD frequencies of each pump individually. The commissioned VSD parameters are listed in Table 12.

**Table 12: Programmed PLC parameters during commissioning – Mine B**

VSD control	Parameter of control
i. <b>BAC pumps</b>	<ul style="list-style-type: none"> <li>- Control</li> <li>- Feedback signal</li> <li>- Set point</li> <li>- VS BAC high level stop limit 1, 2, 3</li> <li>- VS BAC low level start limit 1, 2, 3</li> <li>- MS BAC low level stop limit 1, 2</li> <li>- MS BAC low level stop limit 3</li> <li>- MS BAC low level start limit 1, 2</li> <li>- MS BAC low level start limit 3</li> <li>- Maximum motor frequency</li> <li>- Minimum motor frequency</li> </ul>
ii. <b>Evaporator pumps</b>	<ul style="list-style-type: none"> <li>- Control</li> <li>- Feedback signal</li> <li>- Set point</li> <li>- Maximum evaporator flow</li> <li>- Minimum evaporator flow</li> <li>- Low evaporator flow alarm</li> <li>- Low evaporator flow trip</li> <li>- Maximum motor frequency</li> <li>- Minimum motor frequency</li> <li>- MS BAC dam high level trip</li> <li>- VS BAC dam low level trip</li> </ul>
iii. <b>Condenser pumps</b>	<ul style="list-style-type: none"> <li>- Control</li> <li>- Feedback signal</li> <li>- Set point</li> <li>- Maximum condenser flow</li> <li>- Minimum condenser flow</li> <li>- Low condenser flow alarm</li> <li>- Low condenser flow trip</li> <li>- Maximum motor frequency</li> <li>- Minimum motor frequency</li> </ul>

Apart from the control applied directly on the water reticulation, the status of the main shaft BAC fans must be monitored at all times. An alarm must be displayed on the SCADA and on the control system if one or more of the main shaft BAC fans should trip. This procedure will minimise the effect of wasted energy due to reduced cooling.

### Practical problems during implementation

Various practical problems were encountered during project implementation. Firstly, only two of the four PLCs of the chillers were functioning correctly. The remaining PLCs had communication issues, which resulted in loss of data due to frequent communication failure. The issue was resolved by linking the important parameters (such as evaporator and condenser flows and temperatures) to the two functioning PLCs. The status of the respective chillers was also linked to the functioning PLCs.

Secondly, a method of verifying the energy saving impact was needed that could predict the impact even after an increase/decrease in the overall production of the mine. The measurement and verification process, as described in the following section, derived an accurate scaling method that could be applied to the measured baseline to indicate the performance of the cooling system.

Thirdly, the operators are reluctant to change, which implicates the operation of the system with the implemented strategies. The operators on these mine cooling systems are used to operating the system according to a control philosophy that was used since the original installation of the equipment. Operator training required time-consuming demonstrations of new control philosophies. Operator training is crucial to ensure sustainability of energy savings.

#### 4.2.4. Measurement and verification of results

To measure the performance of a cooling auxiliary project, a baseline must be compiled, as discussed in Chapter 3. The electricity demand in kW for three months before project implementation was used to develop the load profile of the surface mine cooling system. The baseline demand profiles have referenced daily energy consumption in kWh that represents the daily service level.

The operational data for three months before project implementation was used to establish an operational data baseline. System data was obtained from the SCADA. Due to the nature of mine cooling systems, a baseline scaling methodology must also be developed. This scaling methodology allows accurate measurement of the system performance during every month of the year, and typically includes effects due to seasonal changes.

The measurement and verification (M&V) of energy saving projects are normally done by a third party to verify if the proposed electrical saving target was achieved. The performance of the system with implemented saving strategies is assessed for a consecutive three months after implementation. This period is referred to as the performance assessment period.

The electrical power baseline is scaled daily, which is referred to as the scaled baseline. The electrical energy saving performance of the system is therefore obtained by comparing the scaled baseline with the average daily electrical demand profile. The average daily referenced baseline consumption, as determined by an M&V team, is 90,574 kWh/day.

The data obtained from the SCADA consisted of the chilled water flow, evaporator inlet temperature and evaporator outlet temperature. This was the combined flows and temperatures for all the surface chillers. These operational parameters, with the electricity demand, were used to obtain Equation 7. The equation mathematically describes the relation between the delta evaporator temperature (average per day) and the electrical energy consumption (kWh/day).

$$y = 9706.3x + 30032$$

**Equation 7**

Where:

y = electrical energy consumption per day,

x = average evaporator temperature out – average evaporator temperature in.

Power data from three consecutive summer months was used to develop the baseline. The inclusion of winter months was not considered, due to the baseline scaling according to evaporator delta temperature. This scaling method accurately reflects the cooling demand required and therefore compensates for ambient effects on the cooling system [86].

The average weekday baseline as measured and established by the M&V team is illustrated in Figure 44. The power demand savings achieved by the implementation of the energy saving measures can be calculated by using Equation 8.

$$\dot{W}_{Savings} = \dot{W}_{Scaled\ baseline} - \dot{W}_{Actual\ daily}$$

**Equation 8**

Where:

$$\dot{W}_{\text{savings}} = \text{power savings (kW)}$$

$$\dot{W}_{\text{scaled baseline}} = \text{scaled power consumption baseline (kW)}$$

$$\dot{W}_{\text{actual daily}} = \text{actual daily power consumption (kW)}$$

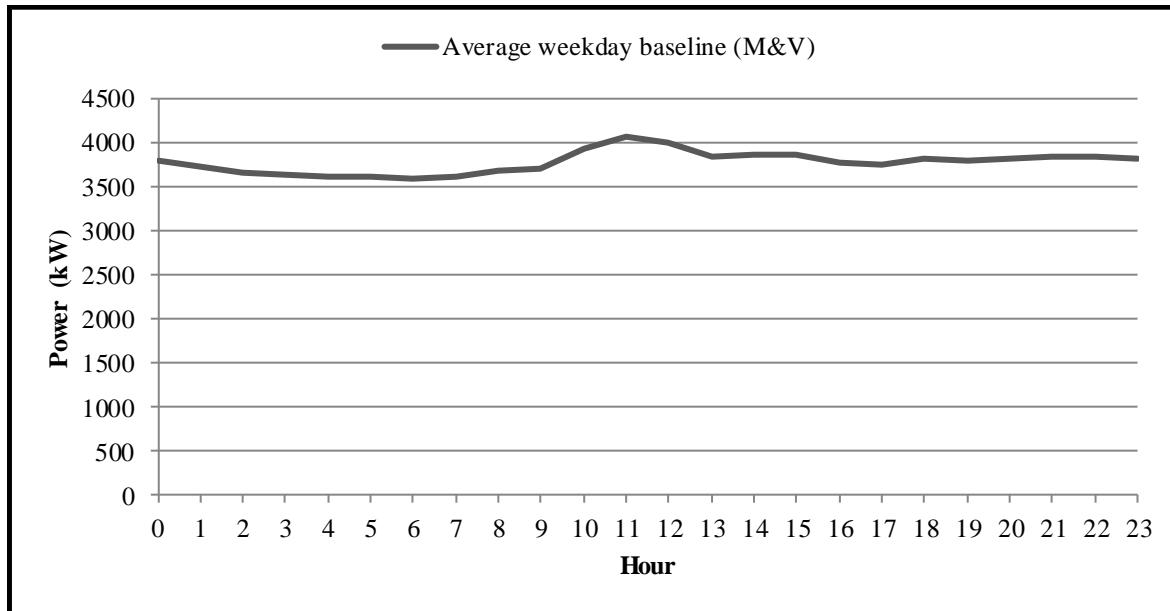


Figure 44: Average weekday M&V baseline – Mine B

After the baseline is established, performance measurement can commence. The baseline scaling method was developed to allow accurate comparison of the pre- and post-implementation power demand profiles. The energy saving impact is determined in the following section by using this developed baseline and scaling methodology.

### 4.3. Energy saving impact

#### 4.3.1. Overview

The success of the implemented DSM energy saving measures can be determined by analysing the power saving impact on the cooling system. The power savings achieved on the BAC, evaporator and condenser pumps are determined, whereafter the entire auxiliary system is analysed.

It is important to consider the service delivery after the implementation of the energy saving measures, to determine the effect on efficiency, performance and operation of the system.

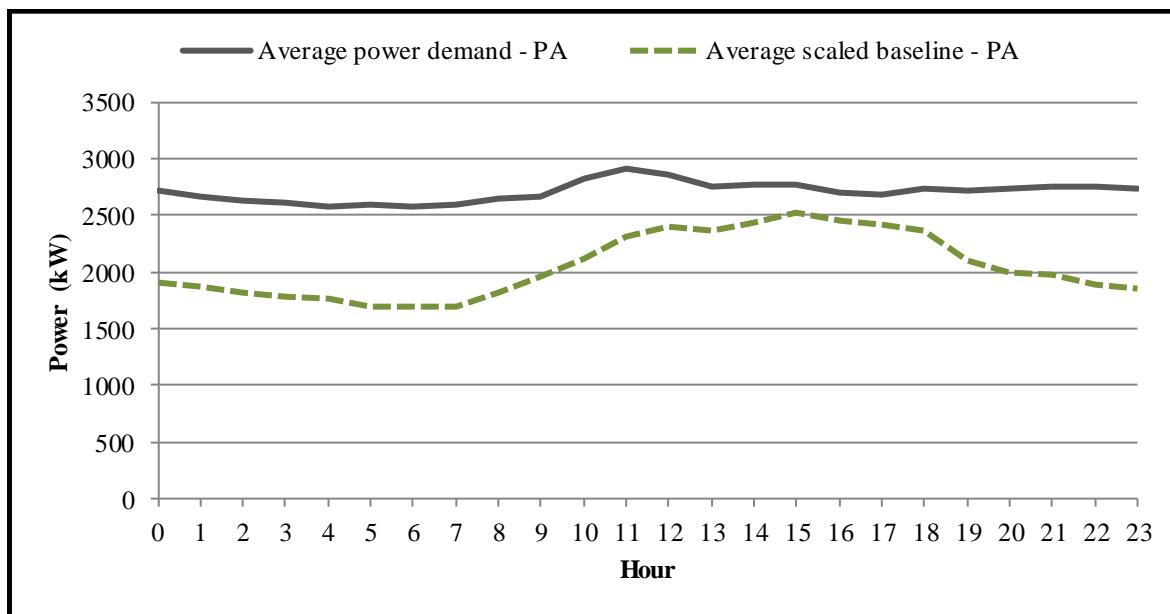
The expected outcome is that there will be an increase in efficiency and performance in the operation of system components, due to the installation of sustainable measures.

The simulated impact of the implemented power saving measures determined in section 4.2.2 for an annual average target power saving was 382 kW. The actual energy savings achieved during the performance assessment of this project will be determined and compared to the simulated impact.

#### **4.3.2. Combined cooling system**

The combined cooling systems' power usage was monitored on four power feeders supplying electricity to the plant. The power saving thus includes the savings achieved by the evaporator, BAC and condenser strategies. The average power profile of the combined cooling system during the three consecutive months of performance assessment is illustrated in Figure 45.

The average reduction, as seen in Figure 45, (calculated with Equation 8) during the performance assessment (PA) period was calculated as a daily average of 656 kW, or 15 736 kWh. This equates to an average reduction of 34% in the power demand (compared to the scaled baseline) of the cooling system over the three consecutive months of performance assessment.



**Figure 45: Average weekday performance during PA – Mine B**

The saving achieved is calculated by using Equation 7 and Equation 8. The average weekday baseline, as measured by the independent M&V team, is scaled by the average daily change in evaporator inlet and outlet temperature. The average daily change in evaporator temperature is illustrated in Figure 46.

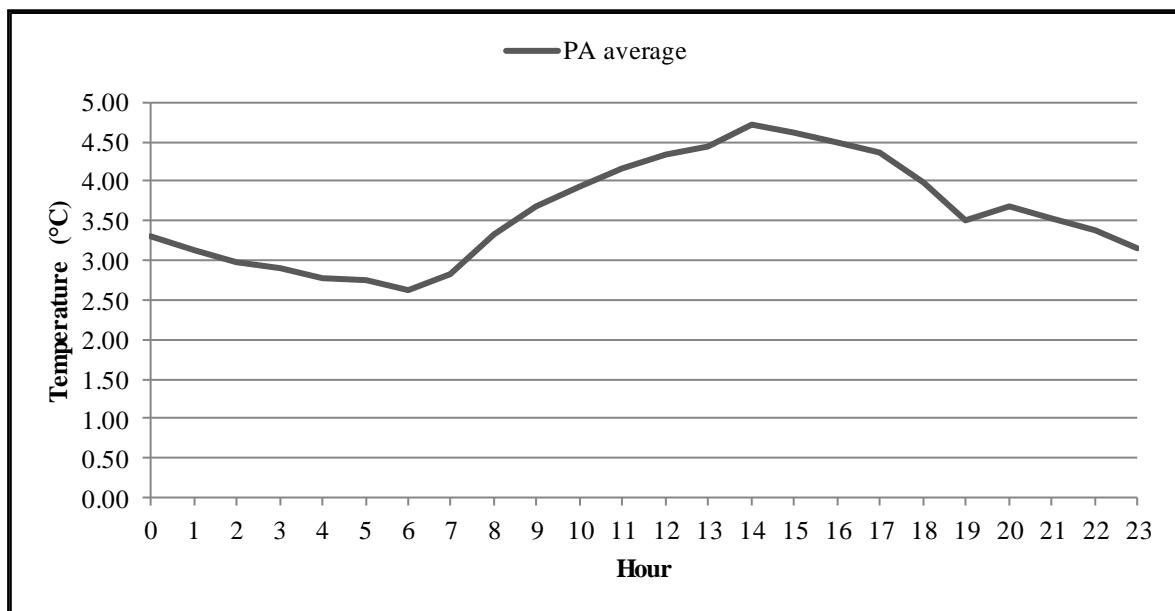


Figure 46: Average evaporator delta temperature during PA – Mine B

Inspecting the average power demand profile during PA indicates two important sections throughout the 24-hour profile. Firstly, the peak between the 8<sup>th</sup> and 19<sup>th</sup> hours can be defined as the full-load offset. The full-load offset is due to two contributing factors:

1. The reduced amount of pumping and optimal energy usage due to the BAC, evaporator and condenser flow control strategies; and
2. Cooling load in the chillers was reduced, due to less water being cooled.

The reduced amount of pumping and optimal energy utilisation is due to the flow reduction strategies on the mentioned circuits. The water valves used to throttle the flow was opened, thus allowing the energy input into the system to be efficiently utilised by the application of the VSDs.

The reduction in flow resulted in a reduced amount of cooling required. The chillers were efficiently utilised by only cooling the required amount of chilled water to feed the BACs. The BAC air outlet temperature was maintained at the required set point (discussed in the sections to follow). The full-load offset is about 450 kW during the period mentioned previously.

The second observation in Figure 45 indicates the section of the partial-load variation. The partial-load offset is primarily the result of the evaporator and condenser flow control strategies. The smaller pump capacities of the BAC pumps are not noticeable, due to the scale of the cooling system power consumption.

The average change in evaporator temperature (as seen in Figure 46) is significantly reduced due to the effect of ambient conditions. The winter seasonal impact is significantly reduced due to no required demand for cooling. The ambient air is sufficiently cold and dry for the purpose of cooling the equipment and workplaces. This is achieved by allowing the ventilation and extraction fans to operate as normal during winter months.

## Summary

A summary of the actual energy savings achieved are indicated in Table 13.

**Table 13: Combined mine cooling system energy saving summary – Mine B**

	<b>Baseline (kW)</b>	<b>Actual (kW)</b>	<b>Saving (kW)</b>	<b>Saving % of baseline</b>
<b>PA 1</b>	3833	3706	127	3
<b>PA 2</b>	2767	2067	700	25
<b>PA 3</b>	1530	390	1140	75
<b>Average</b>	<b>2710</b>	<b>2054</b>	<b>656</b>	<b>34</b>

The simulated savings potential for a normal autumn weekday was 329 kW, as discussed in section 4.2.2. The potential impact was approximately 9 % during the autumn season. The average summer saving potential was simulated as 15% of the power baseline. The reason for actual over-performance can be accounted to the various operational configurations of the chillers.

### 4.3.3. Service delivery

The implemented measures must not interfere with the mining procedures, or create adverse effects on worker safety. The mine cooling system at Mine B is only used for cooling underground areas, as described previously.

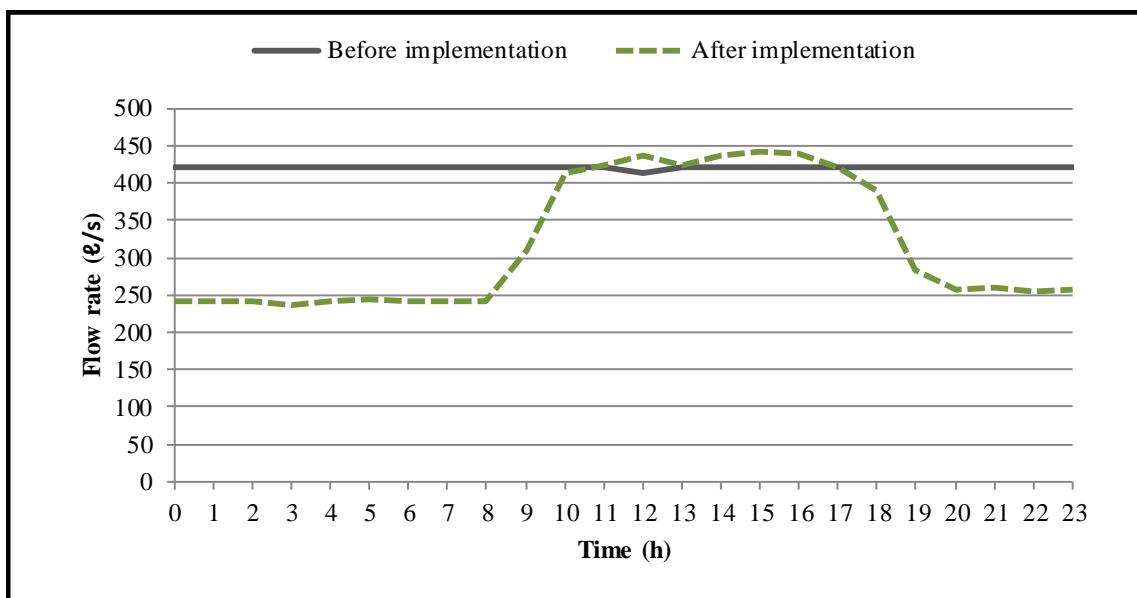
It is important to investigate the effect of the implementation strategies on the mine cooling system after project completion. The effects on the system must be beneficial to the mine in order to enhance sustainable energy saving measures. Any alteration to the system that does not add benefit will soon be reverted by mine personnel.

The service delivery can be specified under the three main parameters that will primarily affect mine production and safety of workers, namely chilled water flow and temperature and the BAC air outlet temperature. The BAC air outlet temperature can be seen as the crucial parameter of the surface cooling system that must not be affected detrimentally.

### **Chilled water flow and temperature**

The chilled water flow will firstly be investigated. Comparable data sets must be considered when analysing the effect of the evaporator water flow control strategy on the chilled water temperature.

The reduced flow rate can be accounted for by two factors. Firstly, the implemented strategies increased the feasibility to switch off one of the two running machines, due to improved utilisation of the chiller compressor (guide vane 100% open) and not overcooling. This creates the opportunity to switch off an evaporator and condenser pump. This contribution is visible in the time period between hour 0 and hour 8.

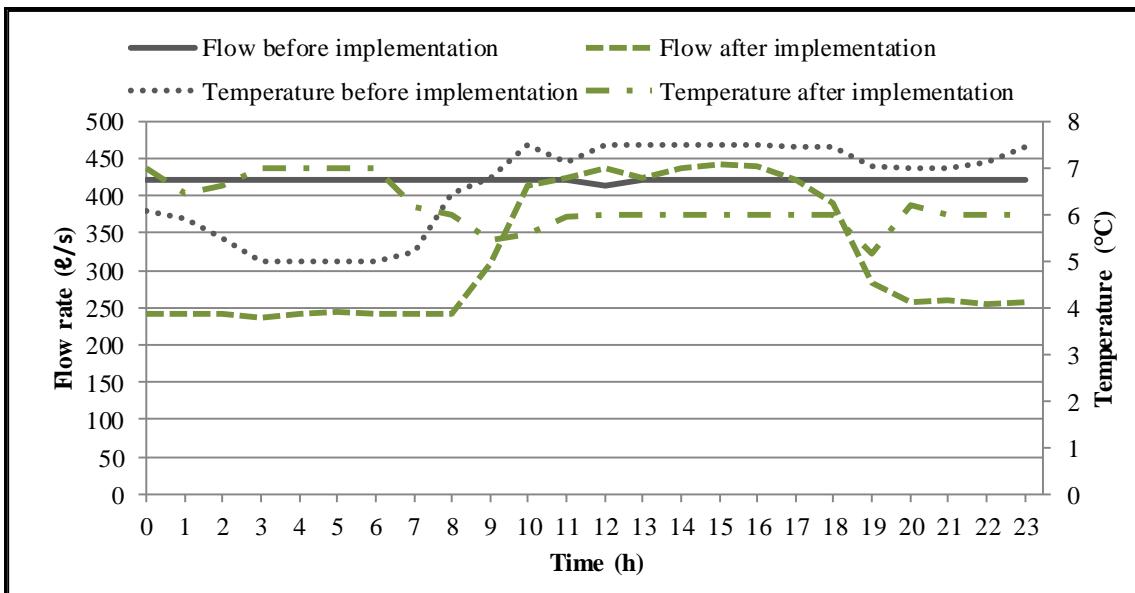


**Figure 47: Chilled water flow rate before and after project implementation – Mine B**

Secondly, the flow reduction is due to the flow control strategies as a result of the installation of a VSD on each evaporator pump. It is important to note that the machines still receive the required design flow during the hotter periods of the day (between hour 10 and 17).

By stopping the additional machines that are not required, the lifespan of equipment can be increased due to reduced running hours. Figure 48 illustrates the chilled water flow vs. chilled water temperature before and after project implementation.

It can be concluded that the service delivery of chilled water was positively affected by the addition of variable flow strategies to the system. The chilled water temperature after implementation was 8% lower on average throughout the day compared to before implementation. Thus, stopping the additional chiller did not adversely influence the chilled water service delivery.



**Figure 48: Chilled water flow vs. temperature before and after implementation – Mine B**

The chilled water delta temperature before and after implementation is illustrated in Figure 49. There was an average difference of 6% throughout the day when comparing the chilled water delta temperature before and after implementation.

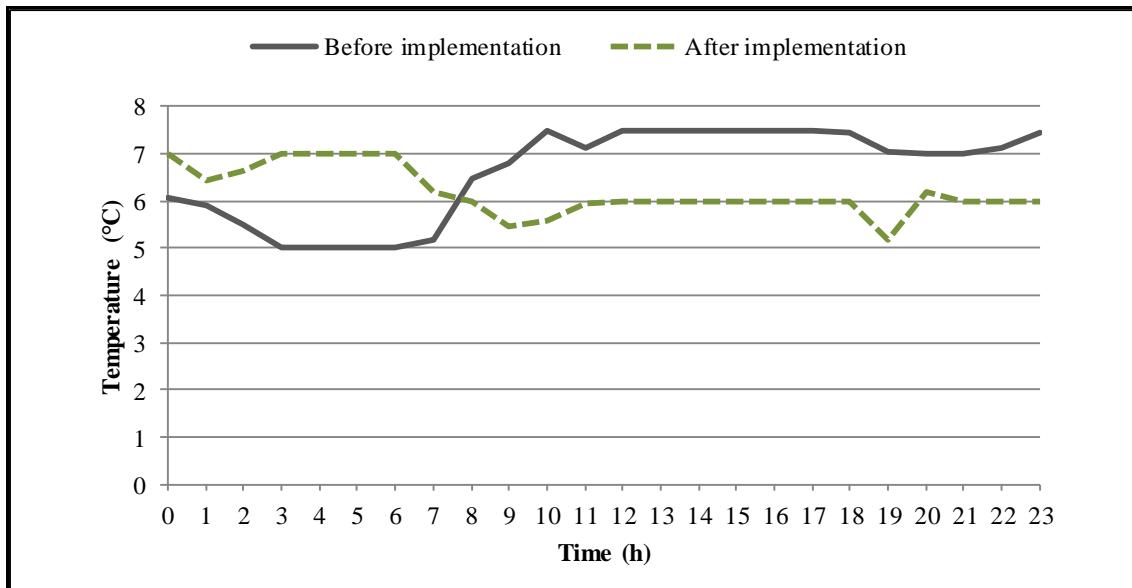


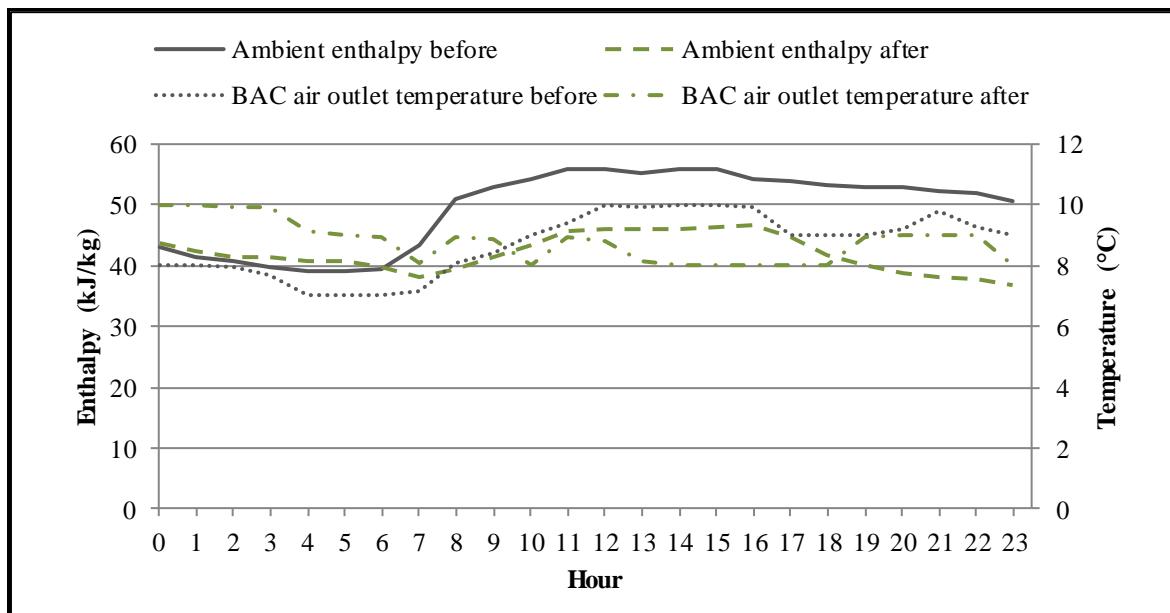
Figure 49: Chilled water delta temperature before and after implementation – Mine B

### BAC air outlet temperature

The effect of the implemented energy saving strategy on BACs is also considered. Firstly, the control based on the average air outlet temperature must be evaluated and compared to the change in ambient enthalpy. The control of the BAC water flow is normally based on the change in ambient enthalpy, such as the BAC flow control on Mine A.

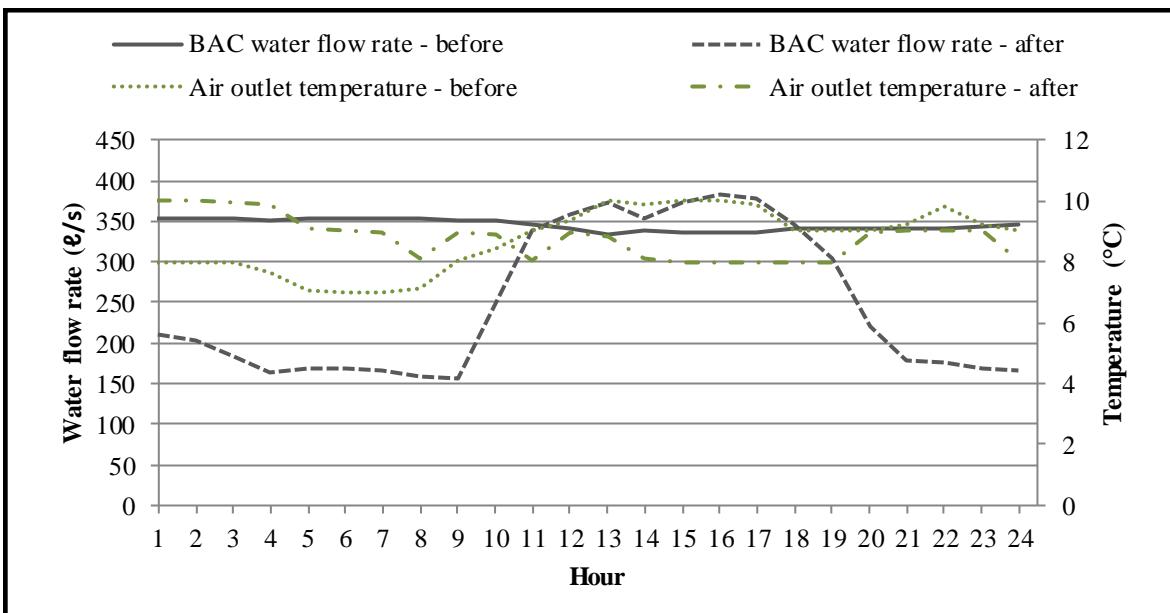
The ambient enthalpy vs. BAC air outlet temperature before and after project implementation is illustrated in Figure 50. The difference in ambient enthalpy before and after implementation was 15%. The BAC air outlet temperature difference was 1% throughout the day.

The service delivery of the BAC was thus not affected by the project implementation. The performance of the BAC depends significantly on the water and air inlet temperatures. The ambient DB and RH conditions before and after project implementation is illustrated in Figure 67, Appendix III, for comparison.



**Figure 50: Ambient enthalpy vs. BAC air temperature – Mine B**

The BAC operational parameters before and after project implementation are illustrated in Figure 51. The relation between the chilled water flows can clearly be seen in Figure 51. The MS BAC water flow rate is similar to the chilled water flow rate, except for the fraction of chilled water flowing to the VS BAC.



**Figure 51: MS BAC operational parameters before and after implementation – Mine B**

## Summary

The essential service delivery requirements before and after project implementation of the mine cooling system is illustrated in Table 14. The values in Table 14 are absolute values.

**Table 14: Summary of effects on service delivery of Mine B after project implementation**

<b>Energy saving measure</b>	<b>Before implementation</b>	<b>After implementation</b>	<b>Change (%)</b>
Chilled water temperature delta (°C)	6.6	6.2	6
Chilled water flow (l/s)	421.0	191.6	54
BAC air outlet temperature (°C WB)	8.7	8.8	1
Ambient enthalpy as comparable boundary condition (kJ/kg)	49.4	42	15

From the results listed in Table 14 above, it can be concluded that no major implications were caused regarding the service delivery of the system. The energy saving impact can therefore be sustained to the guarantee that the mine personnel approved the control of the system. The necessary post-project implementation documents were completed and signed off by both the ESCO and the client.

#### **4.3.4. System performance**

From the previous section it is clear that the implemented strategies resulted in reduced power consumption of the mine cooling system without causing adverse effects on the service delivery of the plant. However, the improved implementation strategy must sustain the energy saving measures without creating long-term challenges due to increased maintenance or life cycle costs.

The control strategies must firstly be analysed to inspect the performance and the effect on the system performance. Secondly, the effect of the implemented energy saving measures on the combined cooling system will be analysed to inspect or measure the aspect of sustainability of the energy savings.

#### **Control strategies**

The control of the evaporator pumps will firstly be analysed. For analytical purposes, a typical daily profile of the evaporator control strategy will be analysed. A typical daily profile will indicate the average fluctuation in frequency to a relative degree of accuracy.

A typical daily evaporator pump VSD frequency is illustrated in Figure 52. It is important to note that this is the average combined evaporator frequencies for the relevant day. The

frequencies of the evaporator pumps switching on and off are not considered. The strategies are based on real-time control, and therefore the system responds to changes in real time.

The evaporator pumps are controlled according to the BAC air outlet temperature. The measured BAC air outlet temperature and set point is also illustrated in Figure 52. By comparing the combined evaporator pump VSD frequency profile to the BAC air outlet profile, the accuracy of control and effect of control can be observed. The detailed evaporator flow control diagram is illustrated in Figure 64, in Appendix III.

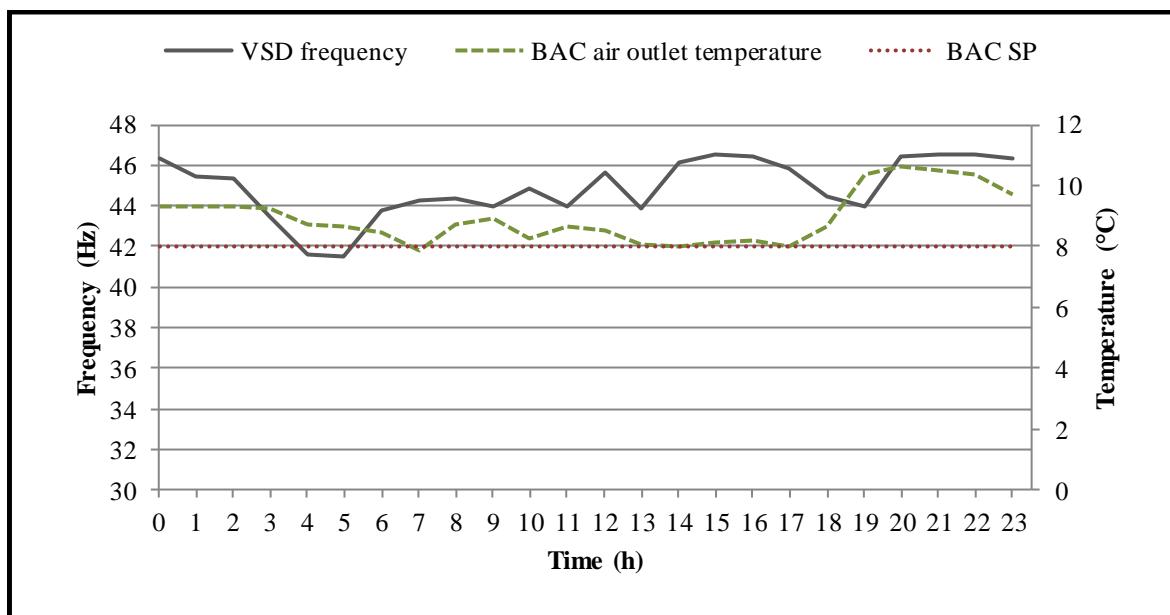


Figure 52: Combined evaporator pump VSD frequency vs. BAC air outlet temperature

From Figure 52 it is clear that the VSDs were controlled to fluctuate between the programmed limits of 40 Hz and 47 Hz. The control reacted as expected; for an increase in BAC air outlet temperature, the speed of the motor increased to allow additional cooling to be done.

The BAC set point, indicated in Figure 52, gives an indication of the control accuracy. The BAC air outlet temperature was, on average, 12% higher than the set point throughout the relevant day. The average BAC air outlet temperature was 8.9 °C (DB) on average. BAC air outlet temperatures must be between 8 °C and 9 °C (DB) according to the environmental department specification. Therefore, the actual average temperature throughout the day falls within these limits.

It is important to note that the control of the surface cooling systems is based on a reactive response. The mine engineer typically adjusts the control of the systems when complaints of

hot workplaces are brought forth by the Environmental department. In cases where the temperature limits are borderline, the BAC control set point can be adjusted to ensure that cooler air is delivered by the BACs. This will, however, have a negative impact on the energy saving impact of the evaporator flow control.

A typical daily profile of the combined evaporator pump VSD frequency and MS dam level is illustrated in Figure 53.

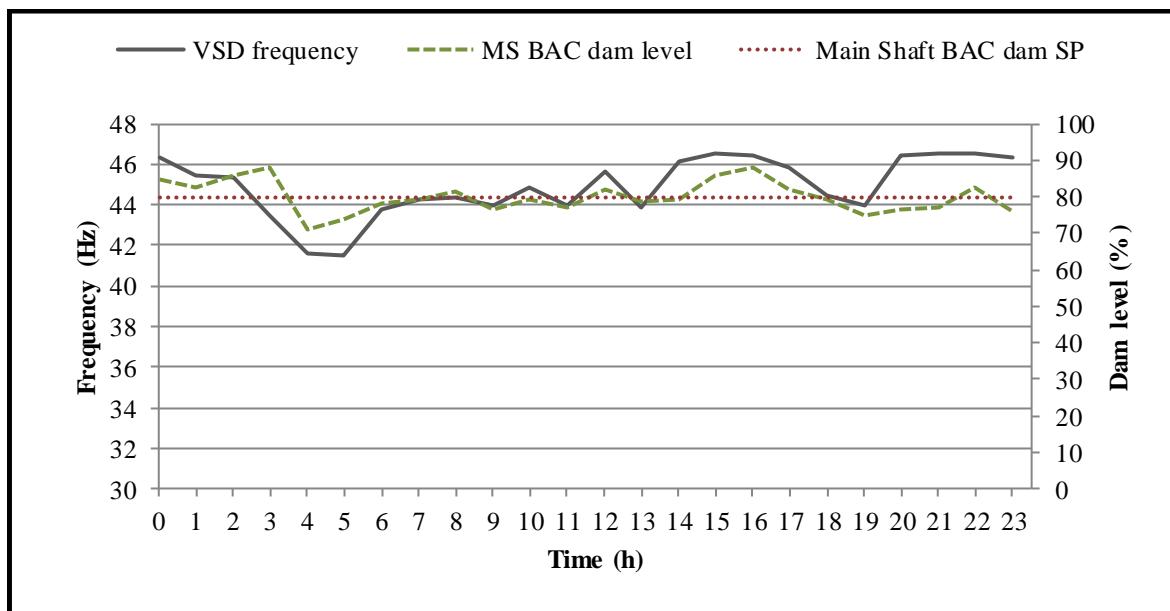


Figure 53: Combined evaporator pump VSD frequency vs. MS dam level

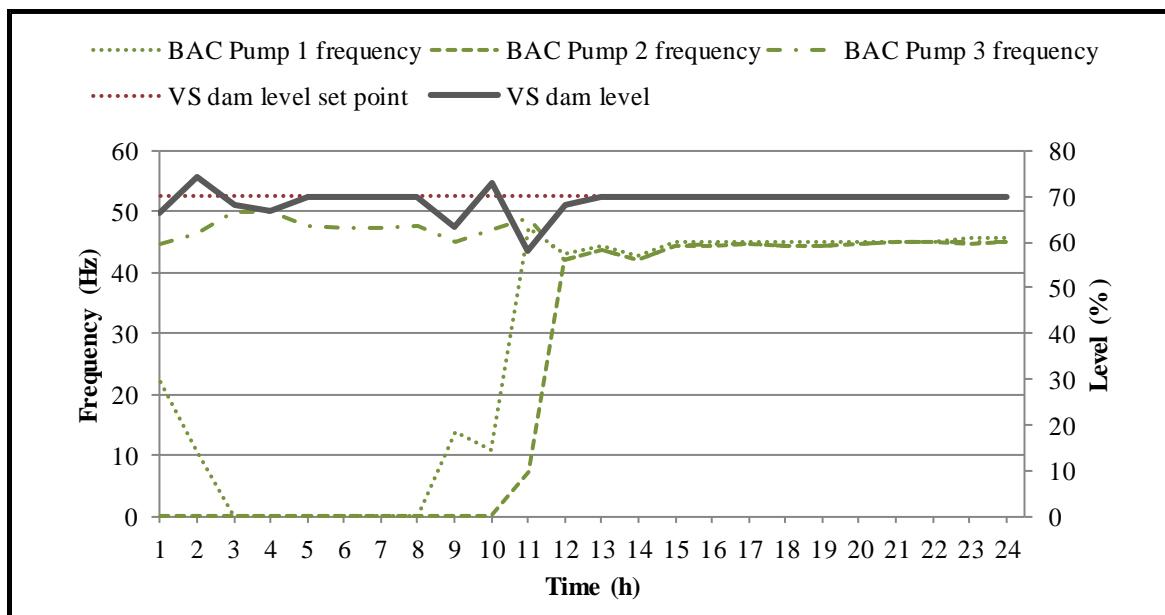
Figure 53 shows that the dam level was within the required limits of 35% and 90%. The unwanted effect of dam flooding is avoided through effective control of the upstream (evaporator) and downstream (BAC) pumps. There was a maximum deviation of 13% between the set point and actual dam level throughout the day, with an average of 0% throughout the day in comparison.

From the typical daily results it is clear that the evaporator flow control functioned according to the proposed control indicated in Figure 64. There is, however, still potential for additional savings by automating the evaporator flow circuit. Automating the evaporator circuit involves installing actuated valves on the chiller inlet pipeline. The actuated valves involve more accurate control.

When the chiller is running, the actuated valve would be in the fully-open position. The benefit lies with the automatic closing of the valve when the chiller stops. The unnecessary

water circulation would thus be eliminated. The control on the evaporator pumps can also be adjusted to match the running status of the pumps with the running status of the chillers.

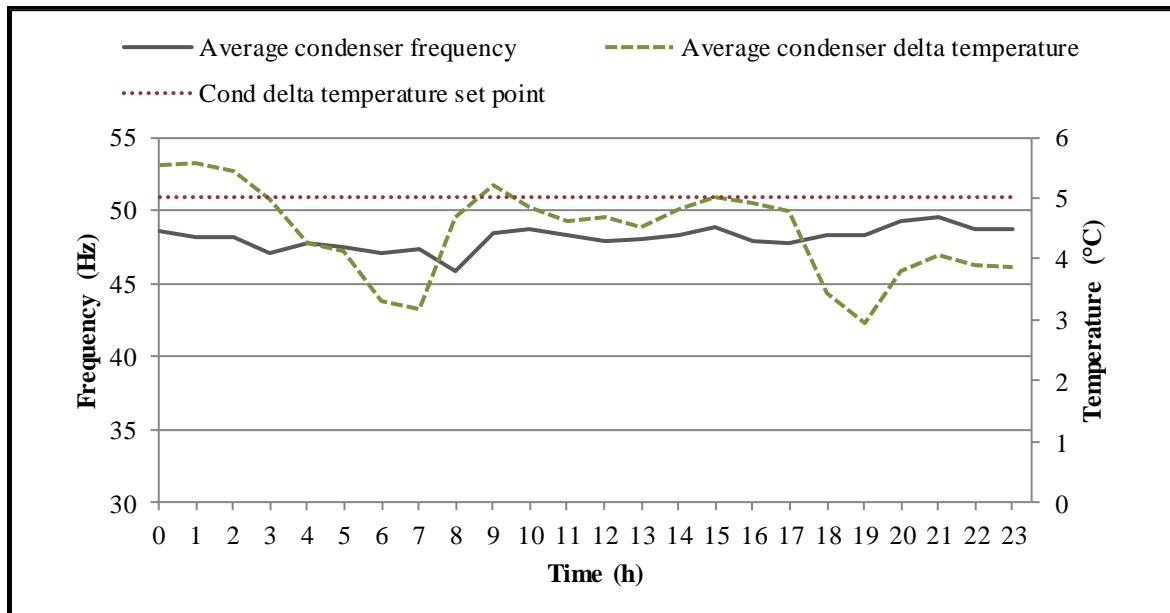
Figure 54 illustrates a typical daily profile of the BAC pump VSD frequencies compared to the VS dam level. The BAC pump VSDs were programmed to be controlled between 40 Hz and 50 Hz. If the VS dam level is below the set point, some of the BAC pumps will switch off until the level is below the specified level set point. The specific control between the relevant limits is indicated in Table 12. The control flow diagram of the BAC pumps is illustrated in Figure 65, Appendix III.



**Figure 54: Combined BAC pump VSD frequencies vs. VS dam level control on set point**

Figure 54 clearly indicates the control of the BAC pumps. The VSDs control the VS dam level at 70%. As the level drops below the set point of 70%, the VSD of pump 3 increases to bring the level back on set point. The reason for more than one pump running after hour 12 is due to the evaporator pumps running on maximum speed on the specific day, requiring more water to be transferred from the MS dam to the VS dam.

The condenser flow strategy involved the control of the condenser VSDs, based on the change in condenser temperature of all the running plants at any given time. Figure 55 illustrates the typical daily profile of the combined condenser pump VSD frequency compared to the change in overall condenser temperature. The control flow diagram of the condenser pumps is illustrated in Figure 66, Appendix III.



**Figure 55: Combined condenser pump VSD frequencies vs. condenser delta temperature**

The condenser VSDs were programmed to only control between 45 Hz and 50 Hz. The reason for this small band of control is due to the physical condenser pipeline setup. The condenser pipeline is a common manifold, resulting in divided flow to each of the four chillers. Allowing the VSD to control lower than 45 Hz results in flow rates below the low condenser flow alarm on the chillers.

Figure 55 clearly indicates that the VSD frequency was controlled between the limits of 45 Hz and 50 Hz. The control ensured flow rates between 300 l/s (minimum) and 380 l/s (maximum). For an increase in condenser delta temperature above the set point of 5 °C, the VSD frequency will increase, causing the delta temperature to drop to the set point. For a decrease in condenser delta temperature below the set point, the VSD frequency will decrease to the minimum frequency.

The average condenser delta temperature throughout the day varied by 2%, compared to the set point. From Figure 66 it is clear that the condenser flow control strategy functioned accordingly.

### Combined cooling system

The combined cooling system must also be analysed to determine the effect of the implemented energy savings strategies. The COP of the entire cooling system is analysed by using Equation 2. The combined cooling system COP before and after project implementation is illustrated in Figure 56.

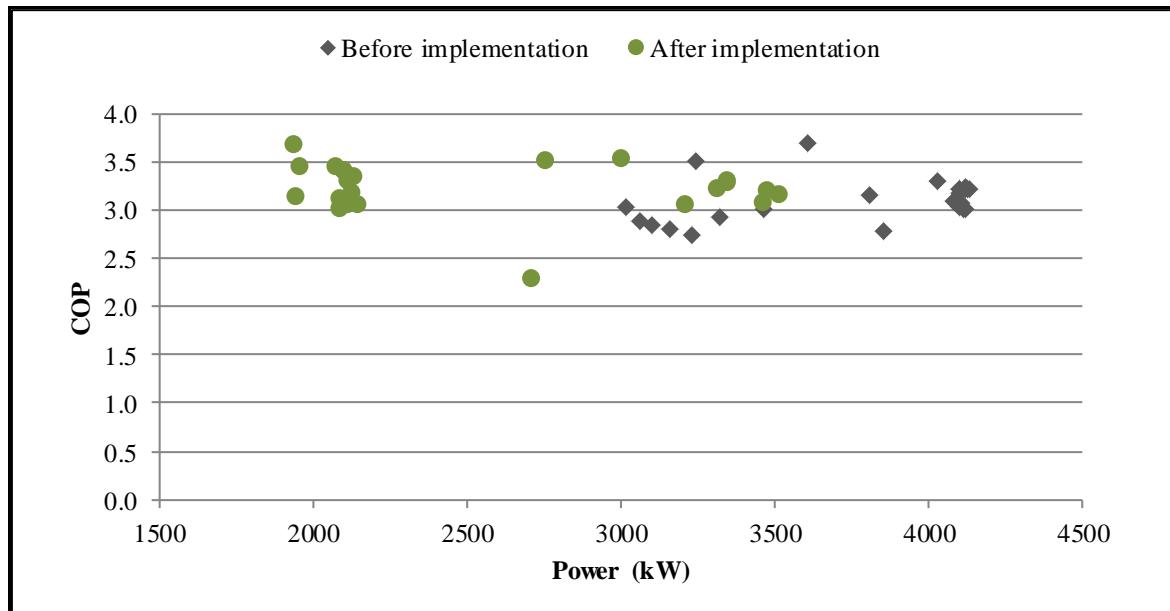


Figure 56: Combined cooling system COP before and after implementation – Mine B

Analysing the COP after project implementation revealed an average increase of approximately 4% throughout the day in comparison. It can be concluded that the proposed energy saving measures realised a saving of 656 kW throughout the three months of performance assessment. The implementation strategies that were followed resulted in optimised and efficient control of the mine cooling system.

The sustainability of the system is a function of the performance of the implemented flow control strategies by maintaining these systems; the energy saving impact can be maintained. The improved implementation strategies can be beneficial to other projects that must be implemented on mine cooling systems. The measures to improve sustainability are discussed in the section that follows.

#### 4.3.5. Validation of results

The need for the study commenced in Chapter 1 with a clear problem statement of: identifying challenges of implementing energy saving measures on mine cooling systems by improving the implementation strategies to focus on the sustainability of the energy saving measures.

In this dissertation, Mine A was identified for developing the improved implementation strategies. This involved the re-commissioning of a deteriorated energy saving project. These strategies were used to streamline the implementation of a similar project on Mine B.

The re-commissioning of energy saving measures on Mine A, according to the improved implementation strategies, brought about daily sustainable savings of 1.73 MW during weekdays for a period of 17 months. The implementation of energy saving measures on Mine B, according to the improved strategies, resulted in sustained daily savings of 0.66 MW for a period of 7 months. These results indicate the validity of this study.

The average weekday power savings achieved on Mine A and Mine B resulted in a cost saving of R8.8 million and R2.9 million respectively.

#### **4.4. Measures to improve sustainability**

##### **4.4.1. Overview**

The sustainability of a project can be dependent on various stages in the implementation of a project. The aim is to identify the challenges that can lead to reduced energy savings during the investigation phase. After this phase, the sustainability is dependent on the strategy followed to implement the project. The final dependency will be during the post-project implementation phase.

Post-implementation requires maintenance and reporting procedures to be put in place. Engineers can utilise maintenance and reporting tools to indicate equipment maintenance schedules, or to report on the inadequate operation of equipment. This section will focus on the measures that can be implemented to improve sustainability of energy savings.

It is important to note that all parties involved must react on the reports compiled by this system. Preventative actions can minimise the effect on both system components and the energy saving impact.

##### **4.4.2. Monitoring and reporting**

Monitoring and reporting requires various system components to function in unison. The equipment installed as part of the energy saving measures must be utilised to sustain the energy savings. The monitoring and reporting of KPIs were identified as methods to proactively prevent and minimise challenges with maintenance and sustainability issues.

One of the strategies identified in this dissertation involved the identification of maintenance procedures on all equipment in the cooling system. These procedures should be incorporated

into the monitoring and reporting system that reports on the KPIs. These reports should be generated on a daily, basis or as required by the various personnel maintaining each system.

The users and user requirements for the monitoring and reporting system can be identified as ESCO personnel, M&V teams and the client (mine personnel).

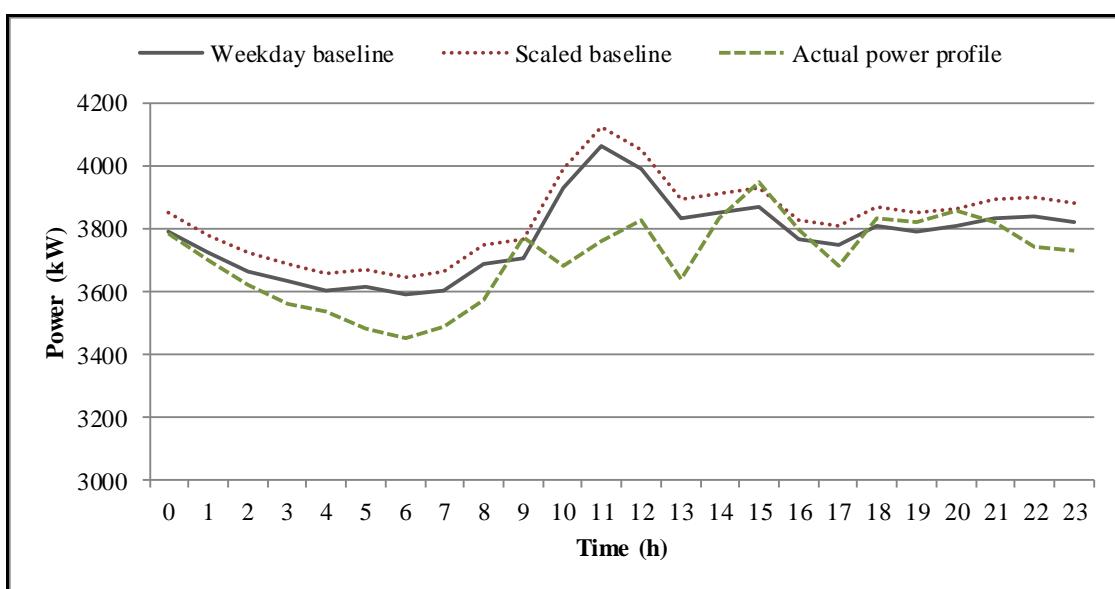
### **ESCO personnel**

ESCOs are normally contracted to maintain the energy saving measures on Mine A and Mine B. The maintenance contracts are in place in order to further improve the sustainability of the energy saving measures. The requirements of the monitoring and reporting system differ significantly from the ESCO's perspective, due to the detail required from the processes.

The reporting system can be configured to generate reports of KPIs that are identified on the mine cooling system. These KPIs typically include:

- system power consumption;
- system or equipment COP; and
- service delivery requirements.

Typical reporting on power consumption can take place on a daily basis. A typical power profile used for daily reporting is illustrated in Figure 57. The average weekday baseline, scaled baseline and actual power profiles are indicated. Power profiles are monitored daily and are also reported on a monthly basis.



**Figure 57: Typical power profiles used for reporting on system performance –Mine B**

Figure 57 clearly indicates a typical day when the targeted electrical energy savings are not achieved. Although a portion of savings are still achieved, the optimal power saving can still be achieved through detailed system performance investigation. The ESCO can now investigate the equipment statuses, service delivery and performance of the system on the previous day.

The relevance of such a report relies on the action taken by the relevant ESCO. The saving achieved for the day under inspection was only 127 kW. The potential saving is, however, is 656 kW. This has a significant impact on the monthly performance of the project and can potentially reduce sustainability over a certain period of time.

Figure 58 illustrates typical COP profiles used for reporting on systems or equipment in the system performance. The COP of three chillers is illustrated in Figure 58. The daily reports of system or equipment COP can be useful to identify any equipment not performing according to specifications.

From Figure 58 it is clear that the COP of chiller 3 is significantly lower than the COP of chillers 1 and 2. Using this as a KPI, the ESCO personnel can instruct the mine to investigate the equipment such as the evaporator pump, or the chiller in the relevant water reticulation circuit.

The flow requirements for chiller 3 in Figure 58 was not sufficient, which can potentially indicate maintenance concerns for the evaporator circuit of chiller 3.

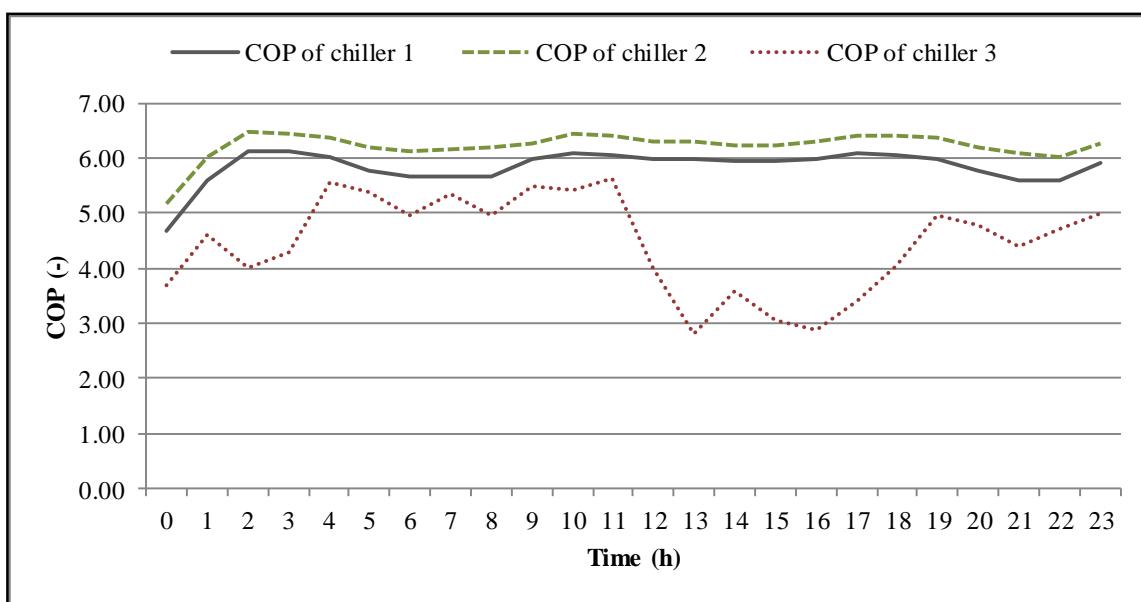


Figure 58: Typical COP profiles used for reporting on system performance –Mine B

Chilled water requirements such as flow and temperature can also be reported on a daily basis. The chilled water flow and temperature influences the BAC air outlet temperature of Mine B, as indicated in the previous section. The BAC air outlet temperature can be used and compared to the percentage difference from the set point. A threshold can be determined whereby concerning temperatures can be identified and flagged on.

### **M&V teams**

The requirements from the M&V teams for Mine B consist of the following:

- system power consumption;
- evaporator delta temperatures.

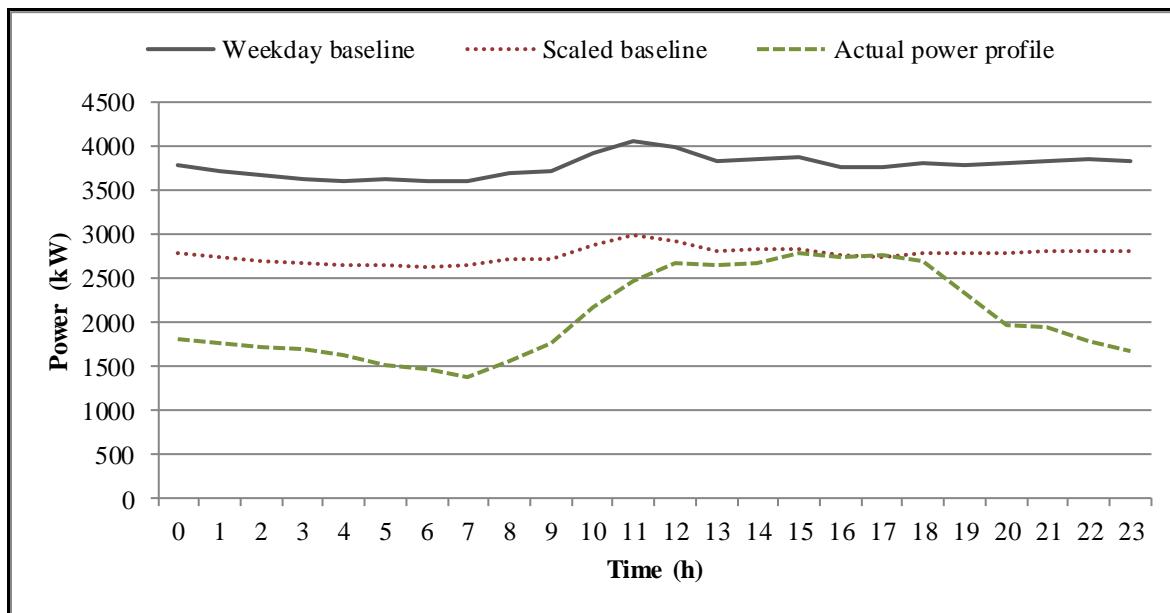
It is important to note that the M&V team only uses these data sets to verify the performance reporting of the project to Eskom, as they do not have their own reporting system in place to collect system data. The raw data sets are also sent to the M&V team.

### **Mine personnel**

Mine personnel require daily reports that only include an overview of the total system power consumption. These personnel typically include the engineers and the foremen. Daily system power consumption can be used by the engineers to update actual and budgeted kWh.

The reporting on actual power consumption is crucial due to the sustainability impact. The engineer will typically assist the ESCOs with additional maintenance costs and further control philosophy optimisation when there is daily proof of savings achieved. A typical monthly report can include the power consumption for the month, as indicated in Figure 59.

The monitoring and reporting of system KPIs are crucial to sustain energy saving measures implemented on mine cooling systems. The methods and reports indicated in this section can be utilised to maintain system components and to sustain the energy saving measures by improving the process as a whole.



**Figure 59:** Power profiles of a typical month for mine personnel reports – Mine B

Further studies into the development of a more detailed monitoring and reporting system with increased capabilities should be conducted.

#### 4.5. Conclusion

Improved implementation strategies to sustain energy saving measures on mine cooling systems were used to implement an energy saving project on a mine. The project implementation process was described and equipment installations indicated. The measurement and verification process was identified as a crucial part of sustaining the energy savings.

The energy savings achieved with the project was quantified after a simulation was used to determine the feasibility of the project. An average weekday saving of 656 kW was achieved during a performance assessment period of three consecutive months. The impact of implementing the measures on Mine B was investigated to determine the effect on sustainability.

It was found that the implemented energy saving measures with the installed equipment enable the client and ESCOs to sustainably achieve the target energy savings. Measures to improve the sustainability of the project through monitoring and reporting tools were also identified.

## CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS



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This chapter summarises the key findings and provides further recommendations.

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<sup>5</sup> P. Maré, Personal photograph. "Mine shaft", 2014.

## 5.1. Conclusions

The mining sector was identified as a significant electricity consumer in South Africa. Mine cooling systems, specifically, consume approximately 25% of the total electricity of a typical deep-level mine. Various energy saving initiatives have been implemented on most mines in the country to reduce the overall power consumption on the Eskom power grid.

The implementation of these projects is, however, not always achieved with the sustainability of energy savings in mind. An overview of literature indicated that there is currently no documented framework whereby energy saving measures on mine cooling systems, with the focus on sustainability, can be implemented. The integration of state-of-the-art technologies such as an EMS and VSDs with optimal control philosophies showed great potential for achieving power savings.

A mine, Mine A, with deteriorated energy saving measures was identified. An implementation strategy was developed during the re-commissioning of energy saving measures on Mine A. Actual performance tests resulted in sustainable savings of 1.73 MW during weekdays. A simulation model was constructed using a simulation tool, PTB, to determine the feasibility of predicting energy saving potential on other mine cooling systems.

The simulation model provided reasonable accuracy. The potential for energy saving measures on another mine, Mine B, was investigated. It was found that a potential power saving of 382 kW is achievable during normal weekdays. Energy saving measures were implemented on Mine B using the developed implementation strategies as a case study on the surface cooling system of Mine B.

The implemented measures realised a daily average saving of 0.66 MW, as verified by an independent M&V team. Various system operational parameters and components were investigated to determine the impact of the implemented measures. It was concluded that the energy efficiency improvements resulted in optimisation of the entire plant, with negligible effects on equipment LCC.

Various monitoring and reporting strategies enable all stakeholders to stay informed regarding the performance of the combined plant. Measures to improve sustainability were also addressed. The sustainability of the energy saving measures was based on the accumulative period of savings. It was found that the case study on Mine A showed sustained

power savings of 1.73 MW for 17 months, and the case study on Mine B showed sustained savings of 0.66 MW for 7 months.

The electricity cost savings for Mine A and Mine B are R8.8 million and R2.9 million respectively. The study was validated with these results, with no compromised savings since the implementation of the projects.

Decreased energy consumption enables the mines used as a case study to stay globally competitive. The need for improved implementation strategies was addressed by validation of the results achieved.

## **5.2. Limits of this study**

This study did not investigate or analyse the challenges of implementing and sustaining energy savings measures on mine cooling systems situated underground. Deep-level mines often utilise underground cooling systems. These systems usually operate independently from those installed on surface. Operating costs and electricity consumption can possibly be reduced by implementing similar energy saving measures on these systems.

## **5.3. Recommendations**

Automation of chillers have been implemented in industry; the automation of the cooling auxiliaries and integration to match the running status of evaporator and condenser circuits with series-parallel configured chillers can be investigated for further power savings. The automation of chillers can result in integrated control and management of the chilled water reticulation circuit.

The integration of various energy saving measures, apart from those applied on cooling systems, were not investigated in this study. The integration of the water reticulation, refrigeration and demand of chilled water can present significant energy savings to deep-level mines.

It is recommended that mines take the opportunity to evolve by adopting these processes, technologies and mind sets required to strengthen long-term operations, in effect increasing the sustainability of future projects. The strategies and measures discussed in this study can possibly be implemented in other industries with a significant energy saving potential.

## CHAPTER 6: REFERENCES



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List of references.

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<sup>6</sup> Adapted from: Art's work [Online]. Available: <http://www.arts-work.blogspot.com>

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# APPENDIX I

**Table 15: Surface cooling system specifications – Mine A**

<b>Chillers (individual)</b>	
Evaporator outlet temperature [°C]	3
Evaporator water flow rate [ℓ/s]	250
Condenser inlet temperature [°C]	27
Condenser water flow rate [ℓ/s]	450
Cooling capacity [kW]	6500
COP [-]	5.5
Refrigerant [-]	R134a
Compressor type [-]	Centrifugal
<b>Water pumps</b>	
Number of evaporator pumps [-]	6
Evaporator pump motor rating [kW]	110
Number of condenser pumps [-]	6
Condenser pump motor rating [kW]	160
Number of BAC return water pumps [-]	3
BAC return water pump motor rating [kW]	75
Number of pre-cooling pumps [-]	2
Pre-cooling pump motor rating [kW]	70
Number of transfer pumps [-]	2
Transfer pump motor rating [kW]	40
<b>Cooling towers</b>	
<i>BACs towers</i>	
Number of towers [-]	3
Water inlet temperature [°C]	3
Water outlet temperature [°C]	9
Water flow rate per tower [ℓ/s]	250
Air outlet temperature (wet-bulb) [°C]	7
Air inlet temperature (wet-bulb) [°C]	22
Air flow rate per tower [kg/s]	250
<i>Condenser towers</i>	
Number of towers [-]	6
Water outlet temperature [°C]	27.5
Water inlet temperature [°C]	31
Water flow rate per tower [ℓ/s]	450
Air inlet temperature (wet-bulb) [°C]	22
Air flow rate per tower [kg/s]	266
<i>Pre-cooling towers</i>	
Number of towers [-]	2
Water outlet temperature [°C]	24
Water inlet temperature [°C]	30
Water flow rate per tower [ℓ/s]	360
Air inlet temperature (wet-bulb) [°C]	22
Air flow rate per cell (2 cells per tower) [kg/s]	298
<b>Combined plant</b>	
Hot dam temperature [°C]	26
Chilled dam temperature [°C]	3
Combined COP [-]	5.5
Combined cooling capacity	39 000

## MINE A RESULTS AND CALCULATIONS

**Table 16: Performance tests – chiller trips and starts – Mine A**

Test	Baseline								Project improvements								
	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		
	Hour	Status	Trips	Status	Trips	Status	Trips	Status	Trips	Status	Trips	Status	Trips	Status	Trips	Status	Trips
0	4	0	0	0	0	5	0	4	0	4	0	4	0	4	0	5	0
1	4	0	0	0	0	5	0	3	-2	4	0	4	0	4	-1	3	0
2	4	0	0	0	0	5	0	1	0	4	0	4	-1	5	0	3	0
3	4	0	0	0	0	5	0	2	0	4	0	5	0	5	0	3	0
4	4	0	0	0	0	5	0	3	0	4	0	4	0	4	0	3	0
5	4	0	0	0	0	5	0	3	0	4	0	4	0	3	0	3	0
6	4	-1	0	0	0	5	0	4	0	4	0	4	0	3	0	3	0
7	3	0	0	0	0	5	-1	4	0	4	0	4	0	3	0	3	0
8	5	0	3	0	0	4	0	4	0	4	0	4	0	3	-2	3	0
9	5	0	5	0	0	4	0	4	0	4	0	4	0	5	0	3	0
10	5	0	5	0	0	4	0	4	0	5	0	4	0	4	0	3	0
11	5	0	5	0	0	5	0	5	0	5	0	4	0	4	0	3	0
12	5	0	5	0	0	5	-2	5	0	5	0	4	0	4	0	3	0
13	5	0	5	0	0	2	0	5	0	5	0	4	0	4	0	3	0
14	5	0	5	0	0	4	0	5	0	5	0	4	0	4	0	3	0
15	5	0	5	0	0	5	0	5	0	5	-1	4	0	1	0	3	0
16	5	0	5	0	0	5	0	5	-1	4	0	4	0	0	0	3	0
17	5	0	5	0	0	5	0	4	0	4	0	4	0	0	0	3	0
18	5	-1	5	0	0	5	-1	4	0	4	0	4	0	0	0	3	0
19	4	-1	5	0	0	4	0	4	0	4	0	4	-1	4	0	3	0
20	3	0	5	0	0	4	0	4	0	3	0	4	0	0	0	3	0
21	3	0	5	0	0	5	0	4	0	3	-1	4	0	0	0	3	0
22	3	-3	5	0	0	5	0	4	0	2	0	4	0	0	0	3	0
23	0	0	5	0	0	5	0	4	0	4	0	4	0	0	0	3	0
Total			-6		0		-5		-3		-4		-1		-3		0
Test	Baseline								Project improvements								
	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		
	Hour	Status	Starts	Status	Starts	Status	Starts	Status	Starts	Status	Starts	Status	Starts	Status	Starts	Status	Starts
0	4	0	0	0	5	0	4	0	4	0	4	0	4	0	5	0	
1	4	0	0	0	5	0	3	0	4	0	4	0	4	1	3	0	
2	4	0	0	0	5	0	1	1	4	0	4	1	5	0	3	0	
3	4	0	0	0	5	0	2	1	4	0	5	0	5	0	3	0	
4	4	0	0	0	5	0	3	0	4	0	4	0	4	0	3	0	
5	4	0	0	0	5	0	3	1	4	0	4	0	3	0	3	0	
6	4	0	0	0	5	0	4	0	4	0	4	0	3	0	3	0	
7	3	2	0	3	5	0	4	0	4	0	4	0	3	0	3	0	
8	5	0	3	2	4	0	4	0	4	0	4	0	3	2	3	0	
9	5	0	5	0	4	0	4	0	4	1	4	0	5	0	3	0	
10	5	0	5	0	4	1	4	1	5	0	4	0	4	0	3	0	
11	5	0	5	0	5	0	5	0	5	0	4	0	4	0	3	0	
12	5	0	5	0	5	0	5	0	5	0	4	0	4	0	3	0	
13	5	0	5	0	2	2	5	0	5	0	4	0	4	0	3	0	
14	5	0	5	0	4	1	5	0	5	0	4	0	4	0	3	0	
15	5	0	5	0	5	0	5	0	5	0	4	0	1	0	3	0	
16	5	0	5	0	5	0	5	0	4	0	4	0	0	0	3	0	
17	5	0	5	0	5	0	4	0	4	0	4	0	0	0	3	0	
18	5	0	5	0	5	0	4	0	4	0	4	0	0	0	3	0	
19	4	0	5	0	4	0	4	0	4	0	4	0	0	0	3	0	
20	3	0	5	0	4	1	4	0	3	0	4	0	0	0	3	0	
21	3	0	5	0	5	1	4	0	3	0	4	0	0	0	3	0	
22	3	0	5	0	5	0	4	0	2	2	4	0	0	0	3	0	
23	0	0	5	0	5	0	4	0	4	0	4	0	0	0	3	0	
Total			2		5		5		4		4		1		3		0
		Starts	Stops														
	Baseline	16	14														
	Project improvements	7	7														

---

## APPENDIX II

### Investigation methodology

The typical investigation methodology firstly requires the cooling system layout and data collection:

The cooling system layout, configuration and data collection involves the following:

- 1) Obtaining system schematic layouts to understand process flow and interaction between the different components in the system.
- 2) Detailed system specifications is measured on site to ensure the accurate development of the system baseline.
- 3) Logging operational trends to obtain system control strategies to develop a relevant baseline as reference to measure energy savings.

Process flow diagrams may include information regarding process piping, major equipment symbols, names and identification numbers, valves that affect system operation, interconnection with subordinate systems, major bypass and circulation lines, operational flow values such as minimum, maximum and normal flow conditions, and fluid compositions. The abovementioned information is critical when developing an energy saving measure.

Baseline simulation model:

An accurate baseline simulation model must be configured as energy saving reference.

This process involves the following:

- 1) Energy and mass balances of the system must be configured for a set timeline.
- 2) Models must be configured to 24-hour profiles to ensure correct daily system response.
- 3) Baseline simulations are then executed by simulating a typical year to serve as reference to future energy savings.

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The investigation process can also be summarised as follows:

1. Project investigation:
  - a. Client approval.
  - b. Obtain system layouts, operational data, system specifications and constraints.
  - c. Identify possible improvement strategies.
  - d. Obtain project baseline.
  - e. Compile simulation models.
  - f. Verify simulation models.
  - g. Simulate project impact for proposed strategies.
2. Compile preliminary scope of work:
  - a. Compile concept design.
  - b. Determine equipment upgrades required.
  - c. Costing analysis.
  - d. Compile preliminary project plan.

### **Energy saving simulations:**

Energy efficient equipment, improvements and replacements must be researched, identified and developed to reduce system energy consumption. Execution of the energy saving simulations allows the calculation of the potential for energy savings. This is possible by identifying the energy saving measure and implementing the relevant measures in the baseline model. Control and operating strategies are developed and simulated to determine the reduction in energy consumption.

### Installation cost calculations:

Cost calculations regarding installation of equipment and machinery involve the following:

- 1) Preliminary installation specifications were developed for the relevant energy saving measures.
- 2) Installation specifications were identified and budget cost for purchasing, delivery and installations are developed.

---

## Simulation model

The process that follows summarises the simulation models required for an investigation process, and also indicates the functioning of the simulation tool that is used in this dissertation. Simulation models can be compiled by using the software described in this dissertation (section 3.4.3).

### *General*

PTB is a transient thermal hydraulic system flow solver. The user can design, analyse and optimise system performance of a required system.

### *Equations used in simulations:*

Direct contact heat exchangers (BACs, pre-cooling and condenser cooling towers):

$$h_{ao} = \frac{(1-r)}{(\tau-r)} h_{ai} + \frac{(\tau-1)}{(\tau-r)} \varphi T_{wi}$$

$$T_{wo} = \left[ \frac{(\tau-1)r}{(\tau-r)} h_{ai} \right] / \varphi + \frac{(1-r)\tau}{(\tau-r)} T_{wi}$$

$$r = \frac{C_a}{C_w}$$

$$\tau = \exp[-UA(\frac{1}{C_w} - \frac{1}{C_a})]$$

$$C_a = m_a$$

$$C_w = \frac{c_{pw}m_w}{\varphi}$$

Where:

$h_{ai}$	Inlet air enthalpy
$h_{ao}$	Air outlet enthalpy
$T_{wi}$	Inlet water temperature
$T_{wo}$	Outlet water temperature
$m_a$	Air mass flow rate

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$m_w$	Water mass flow rate
$c_{pw}$	Water specific heat
$\Phi$	Saturation enthalpy/water temperature ratio
UA	Heat transfer coefficient

Water cooled chillers:

The following equation calculates the chiller cooling capacity:

$$C = C_{ref}[(T_{evap} - T_{evap}^{ref})(0.03) + 1][(T_{cond}^{ref} - T_{cond})(0.03) + 1]$$

Where:

C	Cooling capacity
$C_{ref}$	Full load cooling capacity at design conditions
$T_{evap}$	Average evaporator temperature
$T_{evap}^{ref}$	Average evaporator temperature at design conditions
$T_{cond}$	Average condenser temperature
$T_{cond}^{ref}$	Average condenser temperature at design conditions

The following equation calculates the chiller electrical power:

$$P_{wtr} = \frac{C}{COP}$$

Where:

C	<i>Cooling load</i>
<i>COP</i>	<i>Coefficient of performance</i>

Pumps:

The following equation calculates variable pump pressure difference:

$$P = \frac{F^2}{\rho A}$$

Where:

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P	Pump pressure difference
F	Pump mass flow
$\rho$	Water density
A	Flow admittance

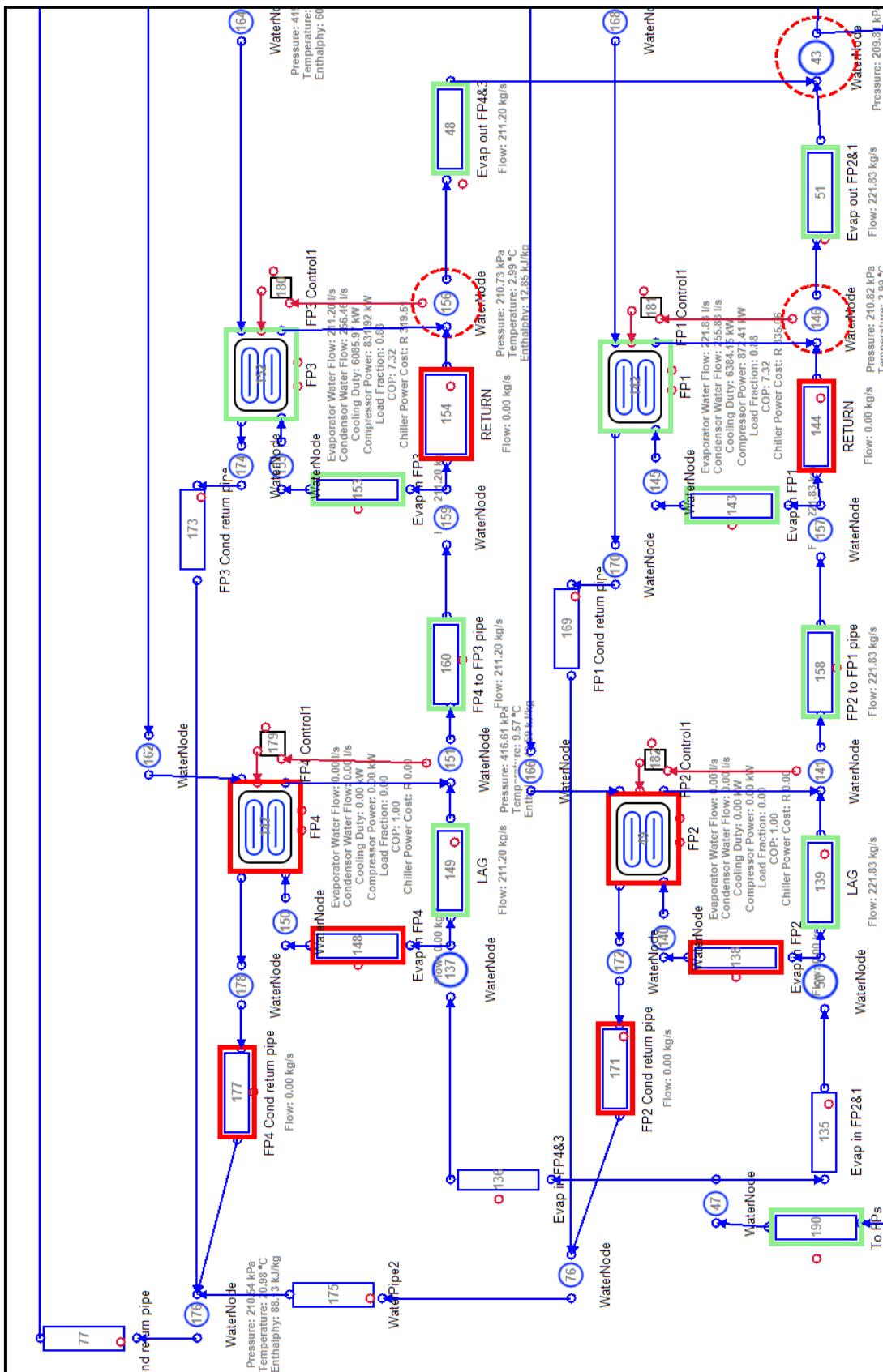
The following equation calculates the pump electrical power:

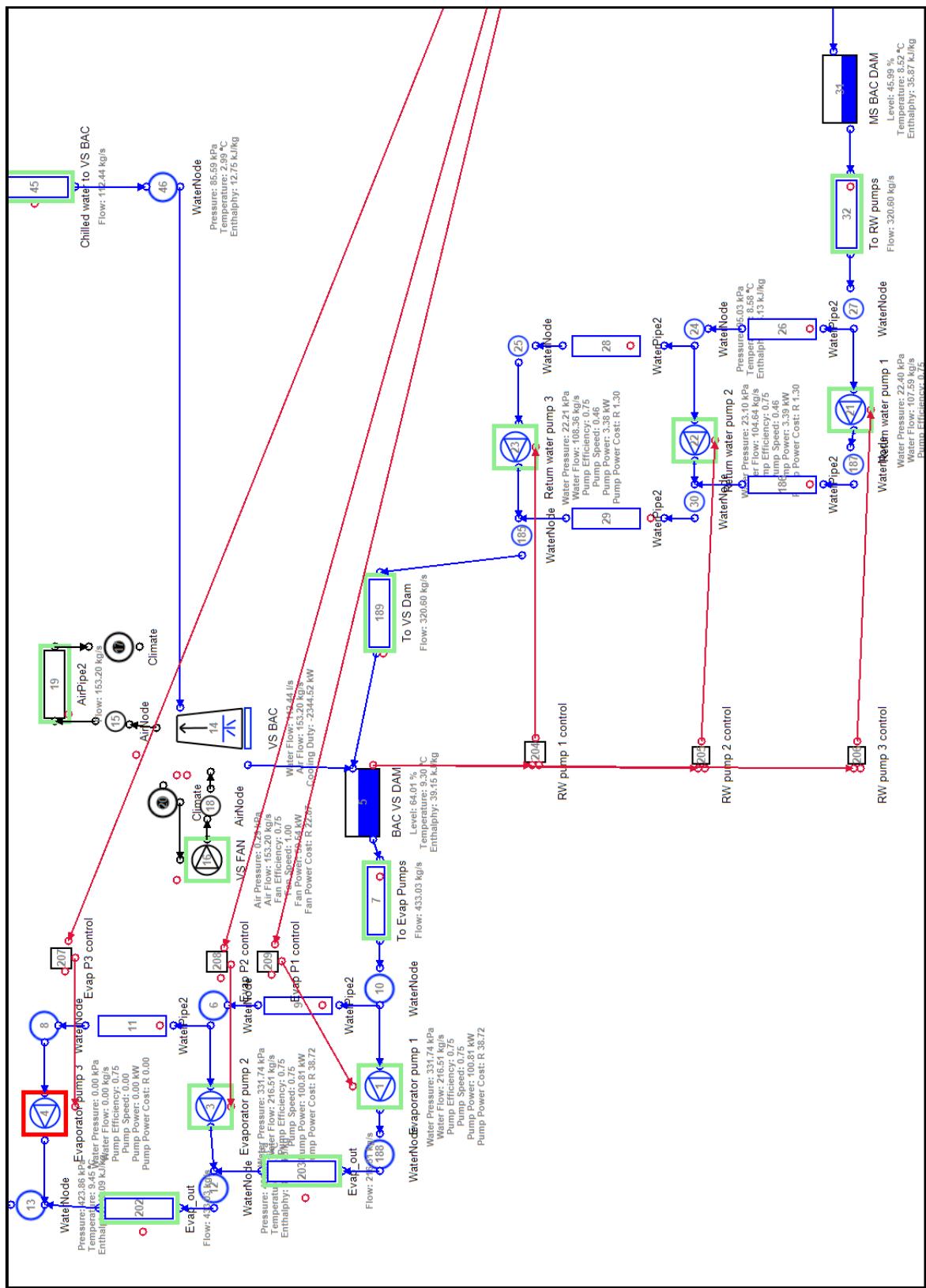
$$P_{wr} = \frac{PF}{\rho\eta}$$

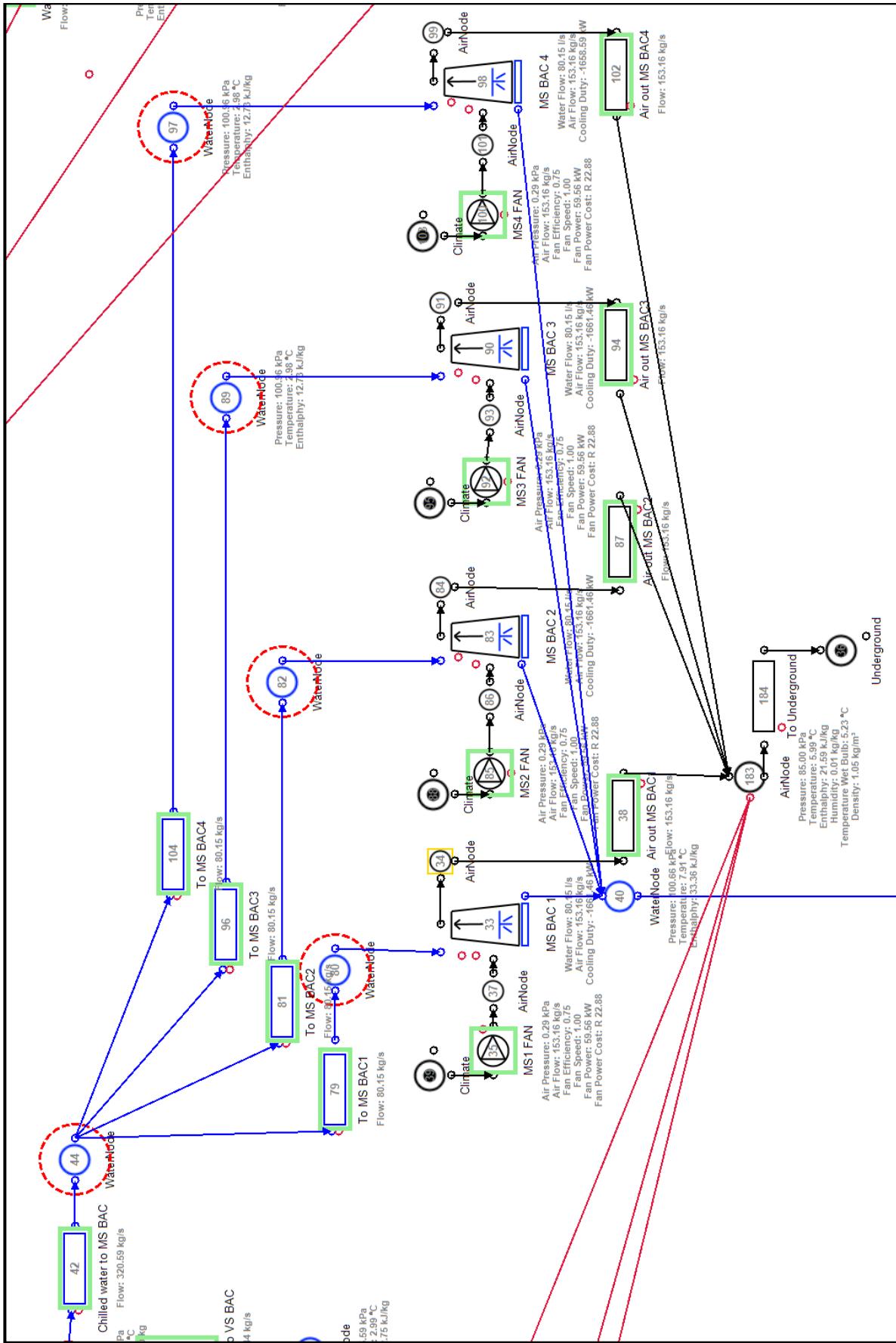
With

P	Pump pressure difference
F	Pump mass flow
$\rho$	Water density
$\eta$	Pump and motor efficiency

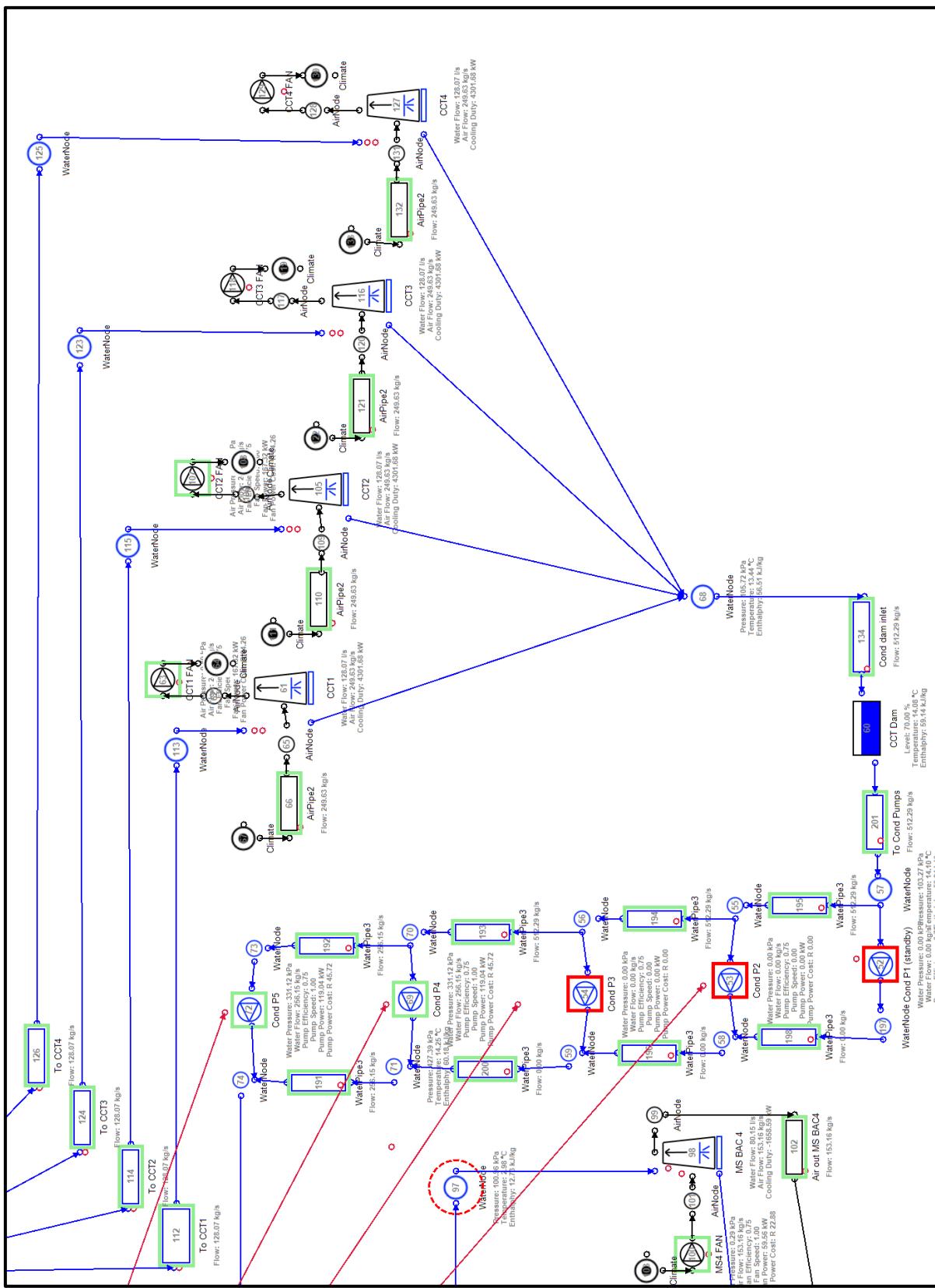
### APPENDIX III







**Figure 62: Main shaft BACs in simulation model – Mine B**



**Figure 63: Condenser pumps and cooling towers in simulation model – Mine B**

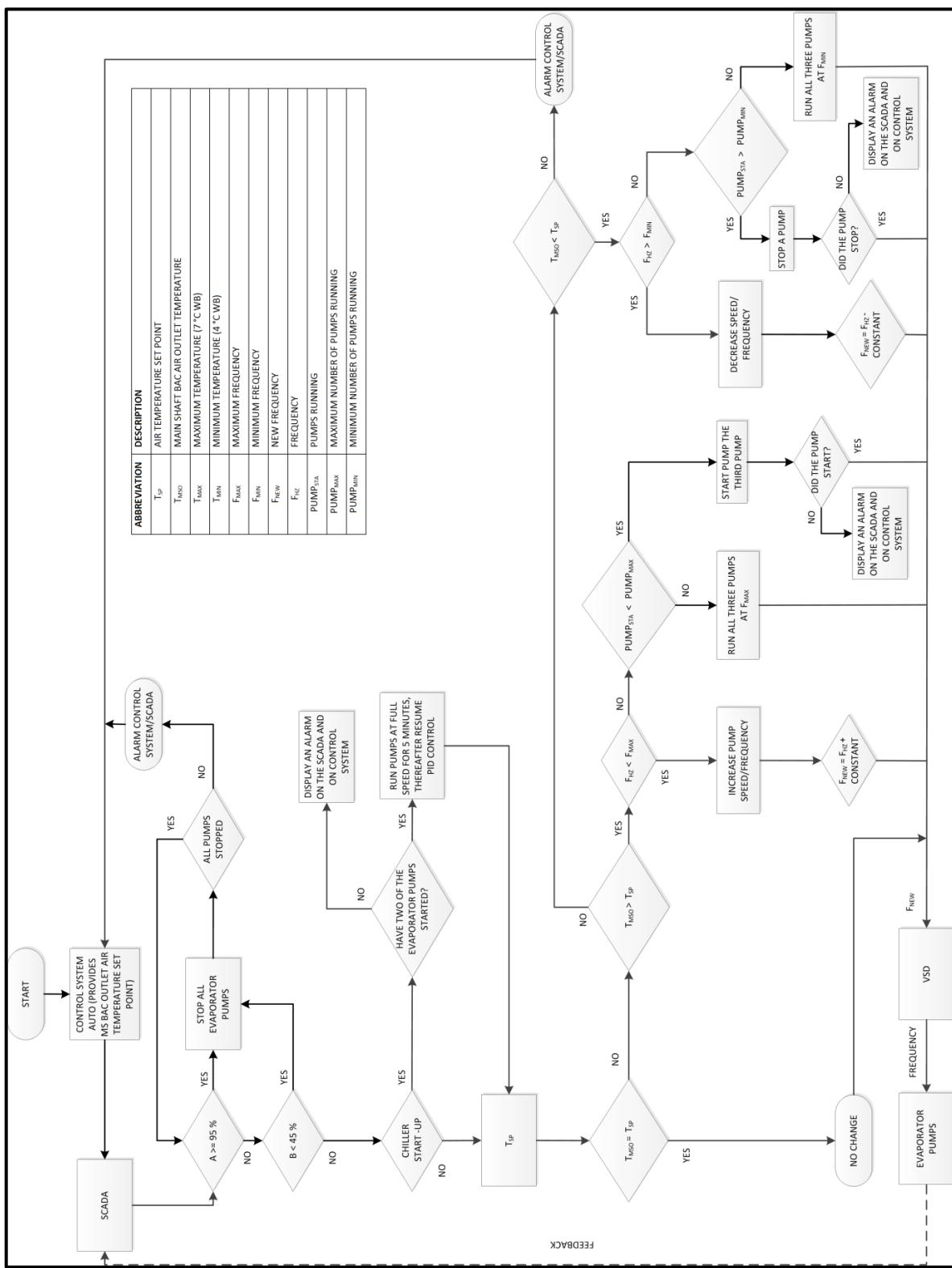
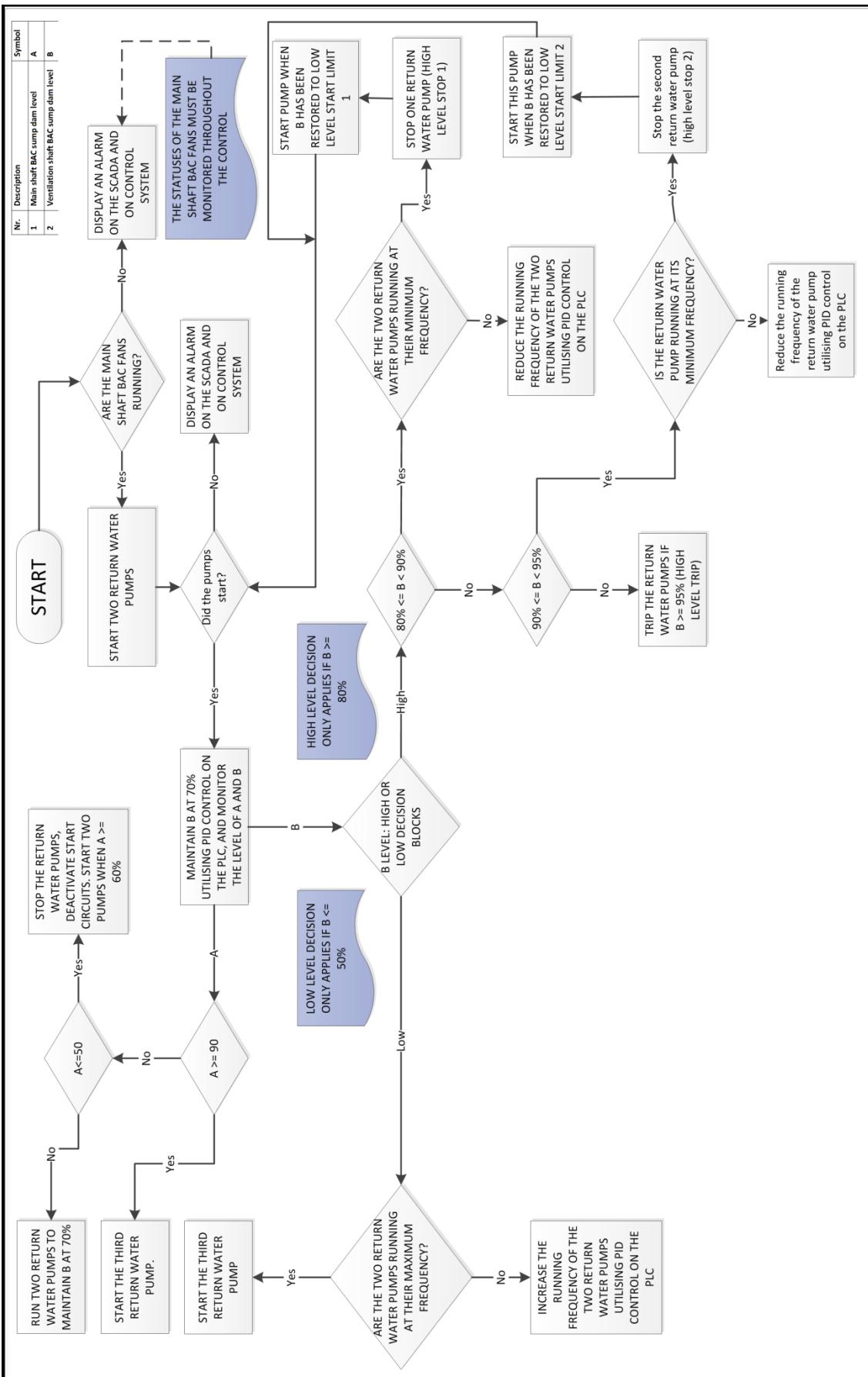


Figure 64: Evaporator flow control diagram – Mine B



**Figure 65: BAC water flow control diagram – Mine B**

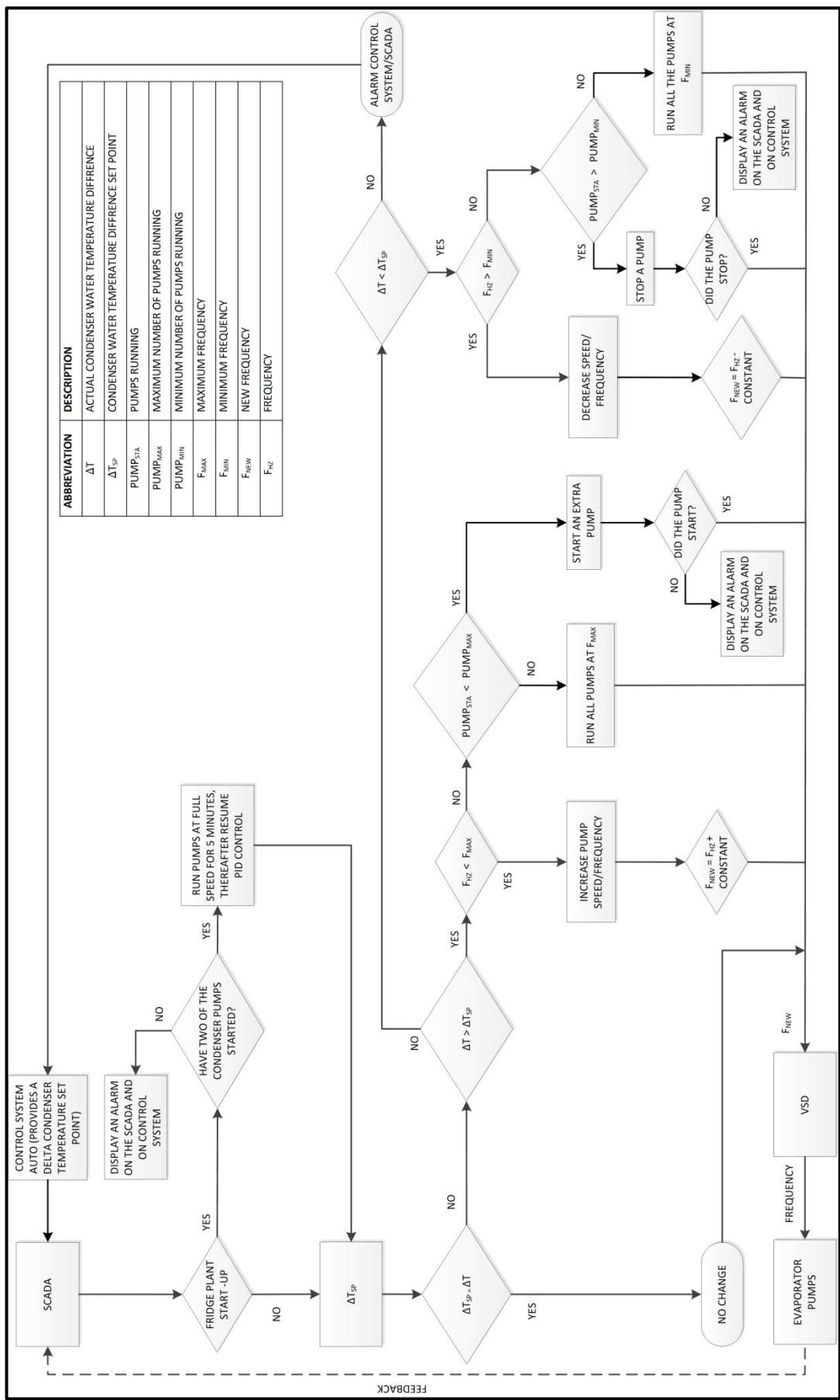
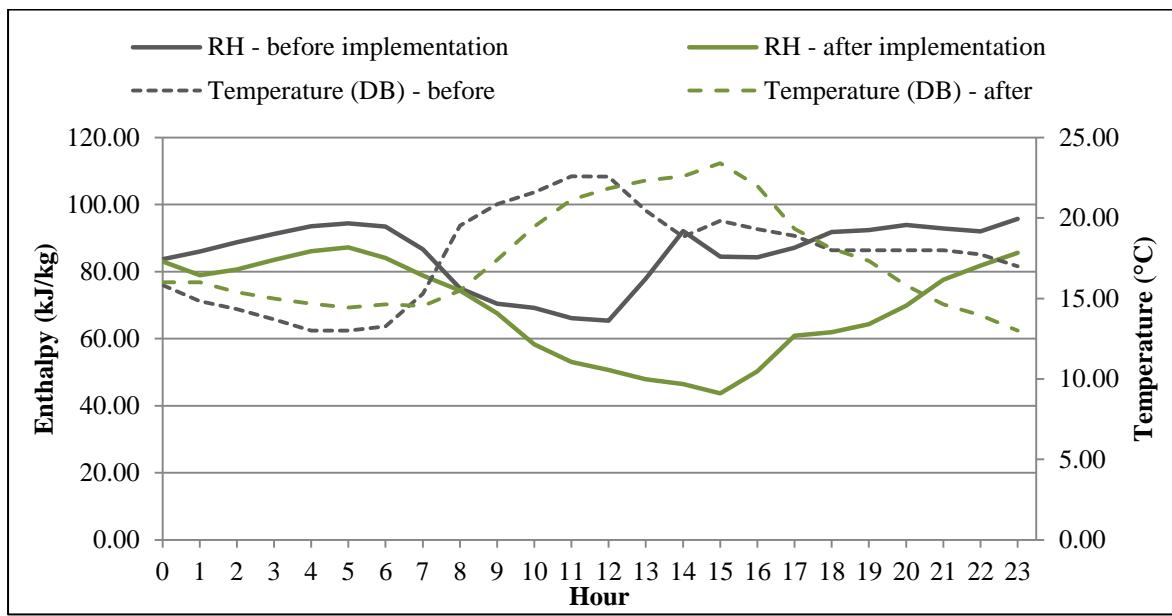


Figure 66: Condenser water flow control diagram – Mine B

Figure 67 illustrates the RH and DB temperatures before and after implementation at Mine B.



**Figure 67: Ambient DB and RH conditions before and after implementation – Mine B**

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## APPENDIX IV

Table 17 below lists the Eskom 2014/2015 MegaFlex tariff structure used to calculate the electricity cost saving of the implemented energy saving measures discussed in this dissertation. The tariff structure is based on the distance of the transmission zone from the closest substation (< 300 km) and, the voltage (>500 V & < 66kV) [87].

**Table 17: Eskom 2014/2015 MegaFlex tariff structure and time of use**

Hour	Summer tariffs (c/kWh)	Winter tariffs (c/kWh)	Time of day
1	35.31	40.78	Off-peak
2	35.31	40.78	Off-peak
3	35.31	40.78	Off-peak
4	35.31	40.78	Off-peak
5	35.31	40.78	Off-peak
6	35.31	40.78	Off-peak
7	55.65	75.09	Standard
8	80.86	247.88	Peak
9	80.86	247.88	Peak
10	80.86	247.88	Peak
11	55.65	75.09	Standard
12	55.65	75.09	Standard
13	55.65	75.09	Standard
14	55.65	75.09	Standard
15	55.65	75.09	Standard
16	55.65	75.09	Standard
17	55.65	75.09	Standard
18	55.65	75.09	Standard
19	80.86	247.88	Peak
20	80.86	247.88	Peak
21	35.31	40.78	Off-peak
22	35.31	40.78	Off-peak
23	35.31	40.78	Off-peak
24	35.31	40.78	Off-peak