



OPTIMISING THE REFRIGERATION AND COOLING SYSTEM OF A PLATINUM MINE

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ABSTRACT

Title: Optimising the refrigeration and cooling system of a platinum mine

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The platinum mining sector of South Africa (SA) has been hit by the combined impacts of falling Platinum Group Metals (PGM) prices, labour strikes and escalating production cost. The main contributor pertaining to production cost rises is the increasing electricity tariffs. In order for mines in the platinum sector to remain competitive, they need to reduce the energy consumption of electrical intensive mining equipment.

Platinum mines in SA require large surface refrigeration systems due to the high underground Virgin Rock Temperatures (VRT) gradients. Due to these high demands, refrigeration and cooling systems are identified as one of the most intensive electricity consumers in the mining process.

The need, therefore, exists to investigate optimisation strategies that can improve the Energy Efficiency (EE) of platinum mines refrigeration and cooling system. The availability of Eskom's Energy Efficiency Demand-Side Management (EEDSM) incentives provides the opportunity to optimise the electricity consumption with cost-effective strategies. The incentive will not only reduce the demand of electricity, but also assist platinum mines on managing their production cost increases more cost-effectively.

In this study, optimisation strategies were investigated that can be implemented on platinum mines surface refrigeration and cooling system, along with underground water reticulation systems. It was shown that through optimising both the service deliveries supply and demand, larger saving can be realised.

Optimising strategies were identified to address possible inefficiencies in the refrigeration and cooling system of platinum mines. The strategies entail water flow control to match the cooling supply with the demand by means of implementing Variable Speed Drives (VSDs), and equipment that will reduce the underground chilled water wastage of secondary spot coolers.

After implementation of proposed optimisation strategies on a case study, an average annual power saving of R12.5-million was realised, without affecting the service deliveries thereof. Potential results indicated that an additional annual saving of R0.8-million could be realised by implementing the proposed optimising equipment on the underground spot coolers.

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ABBREVIATIONS

BAC	Bulk Air Cooler
BIC	Bushveld Igneous Complex
CC	Cooling Car
CEP	Capital Expansion Programme
COP	Coefficient of Performance
DB	Dry-Bulb
DSM	Demand-Side Management
EE	Energy Efficiency
EEDSM	Energy Efficiency Demand-Side Management
EMS	Energy Management System
ESCO	Energy Service Company
GDP	Gross Domestic Product
IDM	Integrated Demand Management
M&V	Measurement and Verification
MCU	Mobile Cooling Unit
PBP	Payback Period
PGM	Platinum Group Metals
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PTB	Process Toolbox
RPM	Revolutions per Minute
SA	South Africa
SCADA	Supervisory Control and Data Acquisition
TOU	Time of Use
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive
WB	Wet-Bulb

NOMENCLATURE

Symbol	Description	Unit
°C	Degrees Celsius	(°C)
%	Percentage	(%)
Approach	Temperature approach of contact heat exchanger	(°C)
AEU	Annual energy used	(kWh)
CS	Cost saving	(R)
C _p	Specific heat constant	(kJ/kg.K)
ES	Energy saving	(kWh)
ET	Electrical tariff	(c/kWh)
g	Gravity acceleration	(m/s ²)
GW	Gigawatt	(GW)
h	Height	(m)
hr	Hour	(hrs)
Hz	Hertz	(Hz)
kg	Kilogram	(kg)
kPa	Kilo Pascal	(kPa)
kW	Kilowatt	(kW)
kW _A	Actual capacity of an electrical motor	(kW)
kW _R	Rated capacity of an electrical motor	(kW)
L	Load factor	(%)
ℓ	Litre	(ℓ)
m	Meter	(m)
$\dot{m}$	Mass flow	(kg/s)
Mℓ	Mega litre	(Mℓ)
MW	Megawatt	(MW)
P	Power	(kW)
PBP	Payback period	(years)
Q	Flow rate	(ℓ/s)
$\dot{Q}$	Thermal Energy	(kJ)
Range	Temperature range of contact heat exchanger	(°C)
RFB	Running feedback	(-)
RH	Relative Humidity	(%)
S	Motor speed reduction energy saving	(%)

T, Temp, temp.	Temperature	(°C)
W	Electrical energy	(kJ)
x	Ambient dry-bulb temperature	(°C)
y	Electricity consumption per day	kWh/day)
Δ	Change	(-)
η	Efficiency	(%)
ρ	Density	(kg/m ³)

CHAPTER 1. INTRODUCTION



Ever increasing production costs and fragile labour relations are crippling the platinum mining industry.

1.1. FRAGILE ECONOMY ON SOUTH AFRICAN PLATINUM MINES

Mining companies around the world have been hit by slowing global demands, price decreases and rapid escalations in domestic production costs. The mining industry has played a key role in SA's economic development for many years. SA's mining industry is the fifth largest in the world and accounts for 8.3% of SA's Gross Domestic Product (GDP) on a direct basis (Chamber of Mines of South Africa, 2013).

SA dominates the global production of PGM due to the large deposits located in the Bushveld Igneous Complex (BIC) (Glaister & Mudd, 2010; Mudd, 2012; Cawthorn, 2010). SA holds over 80% of the world's known PGM resources and reserves. Consequently, the country's mining industry accounted for 53.4% of global platinum supplies in 2013 (Baxter, 2014).

The impacts of global dynamics, despite the significant role and contribution of this sector to the economy in SA, caused major crises for the industry. The platinum industry has been hit by the combined impacts of falling PGM prices, escalating production cost and labour strikes (Baxter, 2014).

Figure 1 depicts the downward trend of the total factor productivity of the platinum mining industry from 1990 to 2012. Figure 1 illustrates how the labour costs increased through this period and the productivity decreased for each worker per kilogram produced indexed. The productivity, kilograms per worker indexed, in 2012 and 22 years back is almost identical, although more efficient mining techniques are being used to date (Chamber of Mines of South Africa, 2013).

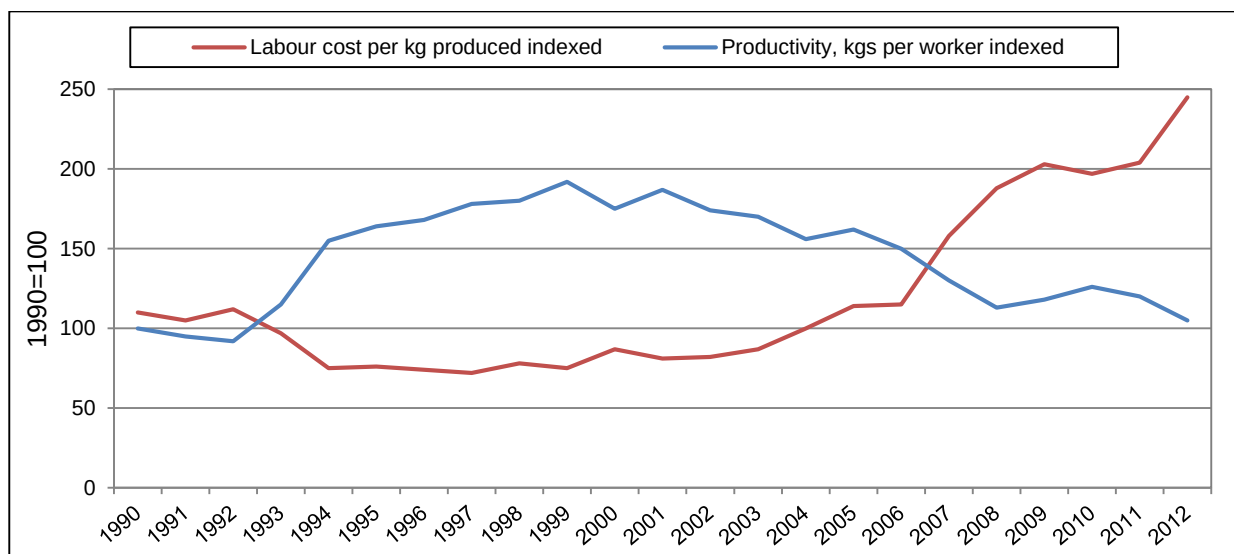


Figure 1: South African platinum mining labour productivity (kg produced per employee) and real labour costs per kilogram of PGM produced, based indexed to 1990 (Chamber of Mines of South Africa, 2013)

Figure 1 shows that the industry nearly produced 40% less platinum output per worker in the past 12 years presented. This while labour cost per kg produced indexed in 2012 is more than double it was in 1990. The production costs have risen by a composite annual growth rate of about 14% for the same period – contributing to the overall cost inflation mines experienced, as shown in Figure 2 (Chamber of Mines of South Africa, 2013).

In Figure 2, the average annual inflation affecting the SA mining sector from 2007 to 2012 is shown. It can be seen in Figure 2 why the production costs have increased so rapidly, with electricity being the largest overall contributor to the production cost increases.

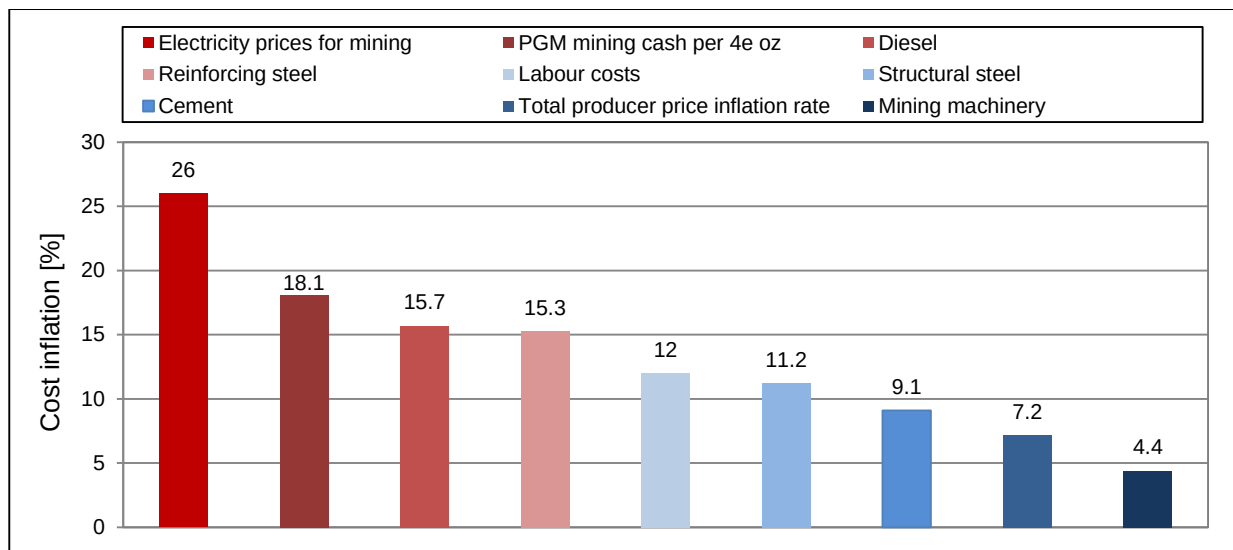


Figure 2: Cost inflation affecting the South African mining sector, average annual for 2007 – 2012 (Chamber of Mines of South Africa, 2013).

The wage-related labour strikes the platinum sector experienced in SA caused a 60% decrease in PGM supply, which affected 45% of the global platinum supply. The strikes experienced in 2014 alone caused more than a 30% loss in the annual production of PGMs. The employers have forfeited about R24 billion in revenue and employees around R10.6 billion in wages and benefits for the five-month strike period (Russell, 2014).

When mines experience strikes there are still critical equipment, like dewatering and ventilation systems, that need to operate continuously. An analysis was done on three mines by Wannenburg et al. (2009), which indicated that 80% of the total monthly power consumption was consumed by these base load systems (constant power consumers).

This means that roughly 20% of a mine's monthly power consumption is production related (Wannenburg et al., 2009). This contributes to the production losses platinum mines experience during strikes, due to the constant high consumption of electricity.

It can be concluded that there is a proven need for platinum mines to manage their production costs more effectively, to reduce costs where possible. With electricity price increases being one of the largest contributor to production cost increases experienced in the past. The focus will be to improve the EE on electrical energy intensive mining equipment, through the implementation of optimisation strategies.

This will not only improve the rate at which production costs increases, but the success of managing the energy consumption more effectively according to production demands as well.

1.2. PLATINUM MINE REFRIGERATION AND COOLING SYSTEMS

Studies have shown that there is still significant scope for widespread EE improvements (Inglesi-Lotz & Blignaut, 2011). This is especially true when focusing on high-demand sectors (Du Plessis, 2013). In SA, the industrial and mining sectors combined use 38.4% of the national electricity delivered, which makes it one of the largest electricity consumers in SA (Eskom, 2013).

This large percentage can be expected from a country like SA, since the majority of its economy relies on mineral extraction and processing (Schutte, 2007). Gold and platinum mines lead the energy consumption in the industry with both consuming 47% and 33% respectively (Eskom Demand Side Management Department, 2010).

SA deep level mines have unique refrigeration demands when considering the cooling requirements that need to be satisfied. Most underground mines make use of chilled water and cold ventilation air to satisfy these needs, generally defined as the underground service deliveries. These cooling services ensure safe underground working conditions for both employees and mining equipment at all times during mine production shifts (Du Plessis *et al.*, 2013). These energy intensive systems are shown to consume up to 25% of the total electricity used on mines, depending on the depth of the mine (Schutte, 2007).

In Figure 3, it can be seen how the underground VRT increases with mining depth increases for various mining areas in SA (Nixon *et al.*, 1992). Platinum mines in SA are found in the BIC due to the large PGM deposits (Mudd, 2012). Although platinum mines are not as deep as gold mines, which relate to the remaining three regions shown in Figure 3, they definitely require large refrigeration and cooling systems. Pertaining to platinum mines experiencing underground VRTs most gold mines experience at almost double the depth than that of platinum mines.

With these increasing VRTs, underground heat loads experienced are increasing in relation to ever-increasing mining depths. Which actually causes refrigeration and cooling systems to become more energy intensive (Zehir & Bagriyanik, 2012). As a result of the large and deep areas, which need to be cooled, large cooling systems are essential on most deep mines in SA (Du Plessis, 2013).

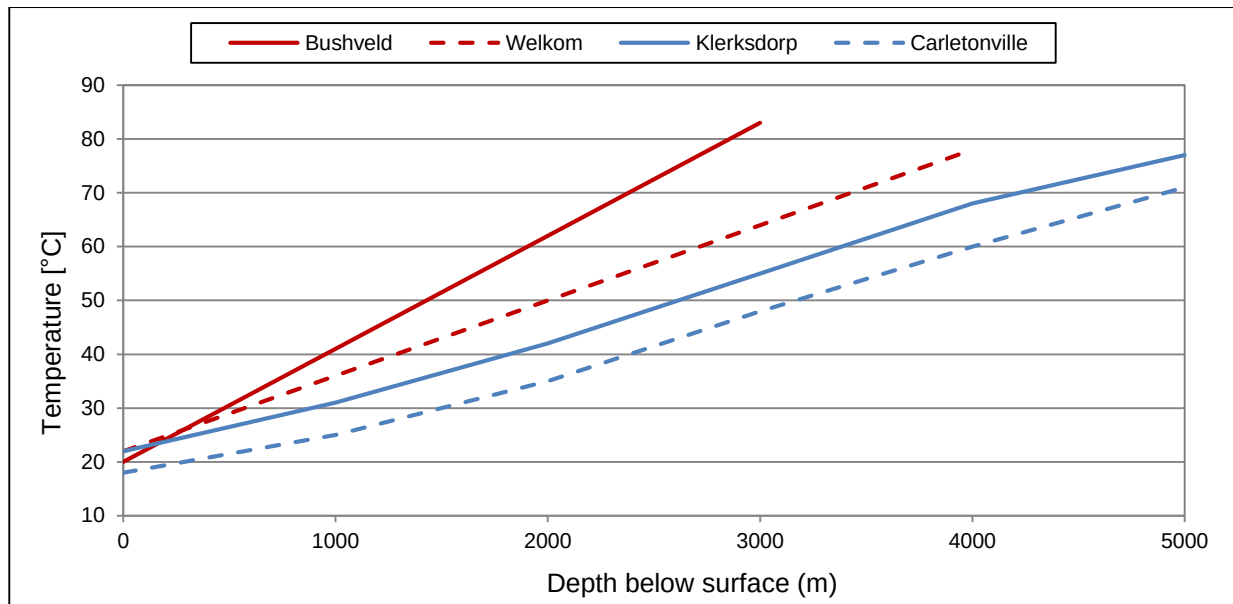


Figure 3: Virgin underground rock temperatures – for South African regions (Nixon et al., 1992).

Additionally, refrigeration and cooling systems only form part of the overall mine water reticulation system (Du Plessis *et al.*, 2012; Vosloo *et al.*, 2012). It is stated that greater efficiencies can be obtained when the distribution system of service water is integrated with the water reticulation system (Vosloo *et al.*, 2012). When optimising both, the supply and demand of the chilled services water – improving the EE potential of platinum mine refrigeration and cooling systems, when considering both surface and underground inefficient equipment.

This can potentially reduce the largest contributor to production cost increases experienced by mines in general. It is shown that the unit cost for extracting platinum can be managed more effectively when introducing optimisation strategies and equipment. The future of the deep level mining for that reason increasingly depends on the industry's ability to contend, in an acceptable and cost-effective manner, to satisfy ventilation and cooling demands more efficiently (Marx, 1990).

Figure 4 indicates the performance of underground mine workers in relation to the underground WB temperature. From Figure 4 it is eminent that when the WB temperature exceeds 31°C the worker performance drastically deteriorates. This shows the importance for adequate supply of cooling and ventilation underground. Reduced production rates are likely if the underground conditions exceed the approved limit. To ensure the productivity and safety for all workers and machinery, the mining industry defined that the underground Wet-Bulb (WB) temperature may not exceed 27.5°C (Vosloo *et al.*, 2012).

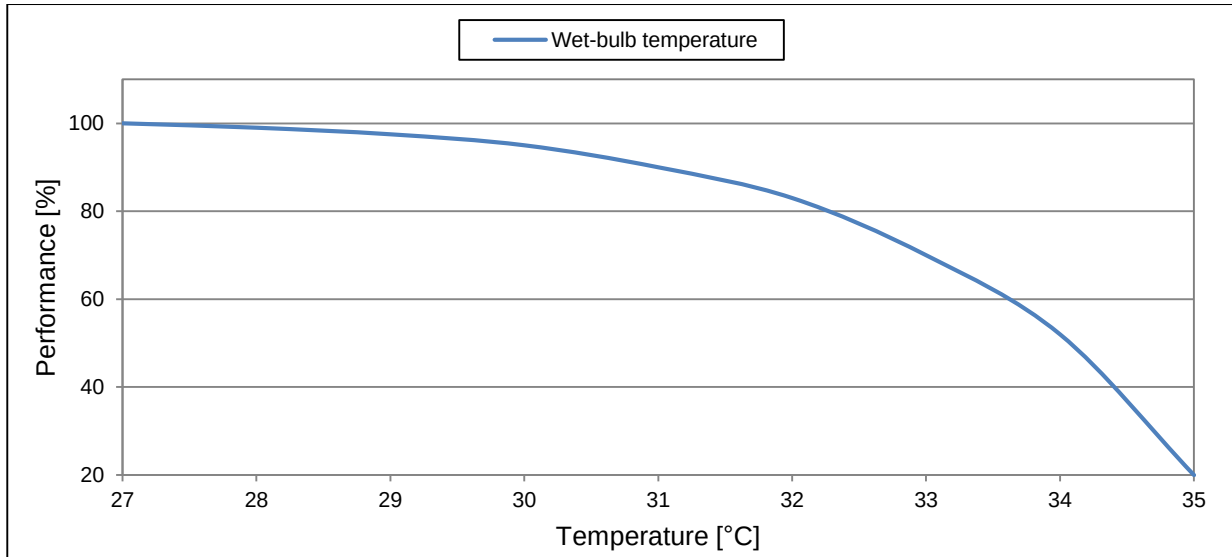


Figure 4: Underground worker performance as a function of environmental conditions (Le Roux, 1990).

Platinum mines use surface refrigeration systems, as they are suitable for the depths at which they operate. The cooling load of surface refrigeration systems are directly proportional to the ambient temperature and service delivery requirements of underground mining operations (Schutte, 2007). The power consumption of surface refrigeration systems, therefore, varies according to the cooling demand, which fluctuates daily and seasonally.

Mine drilling, blasting and sweeping shifts cause daily cooling load fluctuations by the intermittent usage of chilled service water underground (Vosloo *et al.*, 2012). Ambient weather variations cause daily and seasonally cooling load variances. Pertaining to the low WB temperature experienced during nights and winter months.

The daily and seasonal cooling demand fluctuations present substantial potential for partial load conditions (Du Plessis *et al.*, 2013; Vosloo *et al.*, 2012). With most refrigeration systems constructed before the electricity price escalations experienced in SA, it can be assumed that there was little incentive to develop energy efficient partial load conditions (Du Plessis *et al.*, 2013).

The only available control mines use at present to accommodate these cooling load fluctuations is by varying the number of active refrigeration machines (Vosloo *et al.*, 2012). It is found that some mines use manual valve-control to accommodate partial load conditions. Valve control can increase frictional resistance and pressure drops in the piping network (Du Plessis *et al.*, 2013). This can be eliminated or significantly reduced when opening a valve fully and controlling the flow by means of VSDs installed on pump electrical motors (Du Plessis *et al.*, 2012).

In addition to the part-load conditions, most mine cooling systems in SA make use of oversized and old equipment, which are poorly maintained, along with outdated control systems and inefficient control strategies. These inefficient system operations make them ideally suited for implementing new DSM projects (Du Plessis, 2013). In Chapter 2 of this dissertation mine refrigeration systems, cooling strategies and inefficient equipment will be discussed in more detail.

To summarise, the energy intensive refrigeration and cooling was identified as one of the largest electrical energy consumers found on platinum mines. These systems greatly contribute to the production costs increases through high electricity usage. It is found that typical part-load conditions, inefficient operational methods and general lack of awareness of EE technologies are prominent. Consequently, these systems present considerable potential to optimise the electrical energy usage by introducing more efficient equipment and control strategies (Grein & Pehnt, 2011).

1.3. DSM SUPPORTS BOTH ESKOM AND MINES

The rising electricity tariffs and increasing pressure for mines to manage the electrical energy consumption are leading mines to reconsider their stance for electricity saving initiatives, to stay competitive. The difficulty platinum mines face is that there are little funds if any available to implement EE projects themselves – pertaining to the volatile platinum prices, labour strikes and production cost increases previously shown (Chamber of Mines of South Africa, 2013).

Eskom, as the main electricity supply utility of SA, manages both the supply and demand to allow them to address the rising demands in electricity more efficiently. Despite this fact, margins between demand and supply remain slim (Du Plessis, 2013; Eskom, 2013). Due to the growing electricity demand, Eskom launched the Capital Expansion Programme (CEP) in 2005 to manage the supply of electricity (Eskom, 2013). With the CEP in place, Eskom attempts to manage the supply of electricity by increasing the electricity generating capacity.

The construction of additional generation capacity/plants is extremely expensive and a lengthy process, thus Eskom launched a national DSM programme (Singh, 2008). DSM can be described as action taken to change the pattern or quantity of energy used by the consumers (Pelzer *et al.*, 2007). This approach involves implementing a combination of EE measures and load management strategies (Schutte, 2007; Singh, 2008). This will assist Eskom in postponing the predicted date when the electricity demand will reach the supply capacity (Sebitosi, 2008).

DSM programmes have been used partially to fund EE projects on mines (Sebitosi, 2008). This dramatically improves the financial aspect for all consumers, making DSM projects more attractive and plausible for consumers to consider (Energy Research Centre: University of Cape Town, 2004). DSM will not only benefit Eskom to reduce the demand of electricity, but assist mines on managing their production cost increases too. The biggest contributor identified for the production cost increases experienced by platinum mines are the electricity costs.

Eskom's Integrated Demand Management (IDM) business unit make use of several funding opportunities to attract business owners to develop EE improvement programs (De la Rue du Can *et al.*, 2013). Eskom uses Energy Services Companies (ESCO) to implement DSM projects (De la Rue du Can *et al.*, 2013). The Time of Use (TOU) pricing structures was introduced by Eskom, as one of the important approaches for DSM in SA.

The goal of this strategy is to persuade large industries to reduce their electricity usage during Eskom peak demand periods (Vosloo *et al.*, 2012). This is achieved by shifting load into off-

peak periods, installing energy-efficient equipment and optimising strategies (Pelzer *et al.*, 2007). Most mines use the Megaflex tariff structure as shown in Figure 5. The energy tariff structure for the different time periods and seasons are shown.

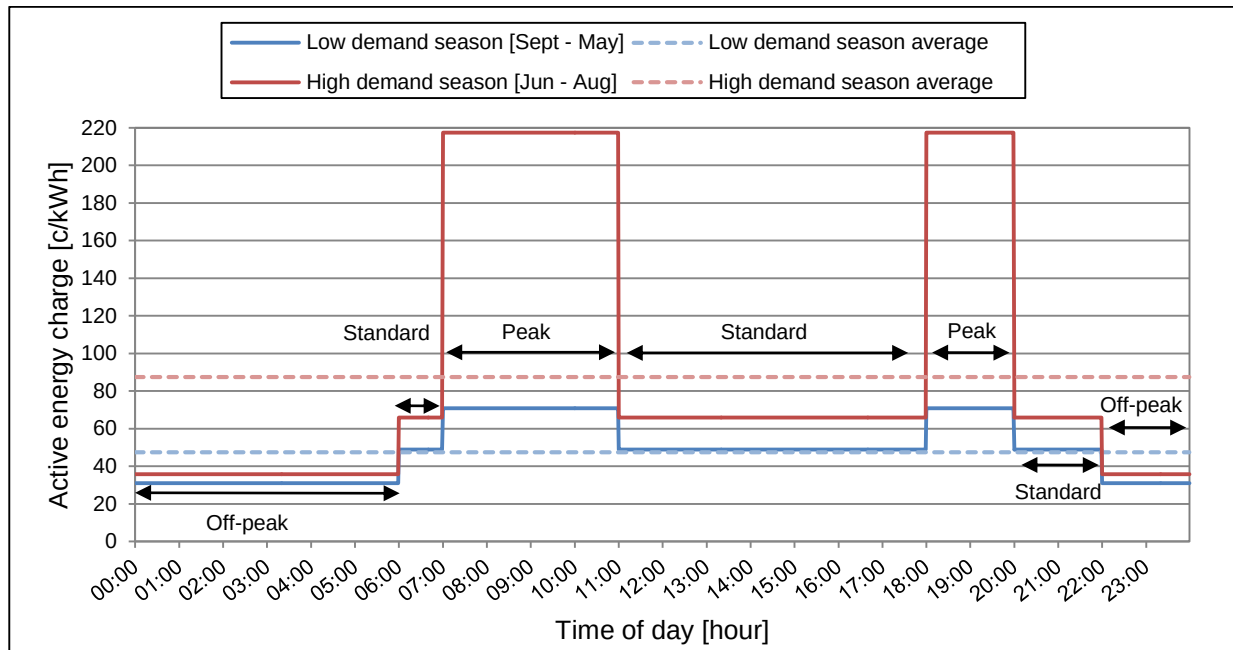


Figure 5: Megaflex weekday tariff structure (Transmission zone <300 km and voltage >500V & < 66kV) (Eskom schedule of standard prices, 2014).

DSM is a feasible solution, which will, assist mines by reducing their electricity consumption. The past success of DSM projects and increasing electricity tariffs provide enough suggestion to justify further investigations for future EE projects (Eskom, 2013). As a result, Payback Periods (PBPs) for implementing EEDSM projects are much shorter and the costs related towards implementing these projects are significantly lower for the consumer than in the past.

1.4. OBJECTIVE OF THIS STUDY

From the preceding discussion, it is clear that a need exists for platinum mines in SA to reduce production costs where possible, due to the increasing electricity costs, volatile platinum prices and wage-related labour strikes. The EEDSM initiative from Eskom makes it more attractive and feasible for consumers to reduce their demand through implementing EE initiatives. This is realisable through introducing more energy efficient equipment and control strategies.

Du Plessis (2013) developed variable-flow optimisation strategies for large mine cooling systems by introducing more efficient equipment. Du Plessis (2013) proved the effectiveness and versatility of the variable water flow strategy, by implementing it on various large gold mine cooling systems. By controlling the cooling supply to satisfy the demand accordingly, electrical cost savings were realised. Large cost savings were obtained with the optimised strategies, without adversely affecting the service delivery and system performances, with the development of an energy management system that integrates these strategies in real-time (Du Plessis *et al.*, 2012; Du Plessis *et al.*, 2013).

No results are documented to justify the feasibility and effects of adapting these strategies on refrigeration and cooling systems of platinum mines in SA. This study will contribute to Du Plessis' (2013) findings by adapting the developed strategies for platinum mines in SA.

This study will investigate the alternative EE possibilities on the energy intensive refrigeration and cooling systems of mines in SA, with the focus remaining on platinum mines. Further investigations will include the possibility of optimising a platinum mines' chilled water demand used in underground operations – showing what the impact will be of such a strategy on the surface refrigeration demand and the overall mine's water reticulation system.

To summarise, this study will focus on platinum mine's surface refrigeration and cooling systems with regards to the following:

- Identify large energy consuming equipment within the platinum mine refrigeration and cooling system that present opportunity for optimisation.
- Identify refrigeration and cooling system inefficient control and equipment.
- Investigate the possibility and feasibility of reducing underground chilled water demand and the effects, thereof, on the mine water reticulation.
- Develop and identify mathematical modelling to quantify the electricity saving achievable through the utilisation of identified optimisation strategies.

- Develop a new control philosophy and specify new parameters that can be implemented on the surface refrigeration system.
- Simulate the new control philosophy to quantify the expected result to verify the feasibility of proposed control strategies.
- Implement and verify the new optimised control philosophy with a real-time energy management system.

1.5. OVERVIEW OF THIS DISSERTATION

Chapter 1

As introduction, a general background is provided regarding the need that presents itself for platinum mines to implement DSM projects. The potential benefits of implementing DSM on a platinum mine's refrigeration and cooling system are discussed. The electricity tariff increases, ever-decreasing generation plant availability and the financial pressure the platinum sector of SA is undergoing, is identified as the research problem. The objective and scope for the study are discussed and formulated.

Chapter 2

This chapter provides an overview of mine refrigeration and cooling systems and comparison between other mining systems as found on deep level platinum mines. The overview includes a description of mine surface refrigeration and the overall cooling system as used on platinum mines. This will include detailed discussion on the subsequent system components, existing EE equipment, optimisation strategies and service delivery requirements. The advantage of implementing optimisation strategies on the water reticulation system in collaboration with optimising the surface refrigeration system is investigated.

Chapter 3

In this chapter the refrigeration and cooling system of the case study platinum mine is analysed. An energy audit is performed on the relevant system to quantify the electricity power loads. From this audit, a baseline data set is compiled and verified by an independent party to use as reference. Thereafter an optimised strategy is proposed to address identified system inefficiencies. A simulation model designed in Process Toolbox and verification calculations are used to quantify the proposed electricity savings. The feasibility of implementing the proposed strategy is discussed in terms of project PBPs.

Chapter 4

This chapter focuses on the installation and implementation of proposed equipment and resulting control strategies. A brief discussion of project management is provided with regards to contractor selection and problems encountered. The electricity savings achieved with the baseline data used as reference is presented.

Chapter 5

The overall outcome of the project is summarised with relevant findings. The accuracy of predicted potential for the implemented optimisation strategy is indicated. The overall performance of the improvements and related efficiencies are quantified. Recommendations are provided, highlighting the possibility for implementing other optimisation strategies on platinum mine refrigeration and cooling systems.

CHAPTER 2. OPTIMISING PLATINUM MINE REFRIGERATION AND COOLING SYSTEMS



Background toward identifying and customising the most appealing optimisation strategies to implement on platinum mines' refrigeration and cooling systems.

2.1. INTRODUCTION

It can be concluded from the previous section that even though SA platinum mines operate at much lower depths than gold mines, they still require large cooling systems – pertaining to the high VRTs experienced in platinum mines at much lower depths.

There is an increasing need for SA mines, especially the platinum sector, to reduce production costs where possible. This is caused by the increased awareness for optimising high electricity consuming equipment and operations, in addition to high production cost increases and labour strikes experienced.

The refrigeration and cooling systems of platinum mines are identified as worthy candidates to investigate the potential for implementing optimisation strategies. These refrigeration systems present opportunities to develop and implement DSM initiatives. This statement will be explained more comprehensively in this section, focusing on the high electricity consuming equipment.

Accordingly, a thorough literature review is necessary to understand and identify the relevant system operations, constraints and considerations in more detail. It is important that the identified factors are adhered to, when developing and implementing a new DSM strategy. Not considering these factors can lead to production losses.

This chapter will provide background and explain the workings of refrigeration and cooling systems as found on platinum mines. The focus is placed on large mine cooling systems and more specifically on surface refrigeration systems, as these systems are prominently used more on SA platinum mines. It is stated that cooling systems with one or more refrigeration plant or chiller, with a cooling capacity of more than 1.05 MW, is categorised as “large” (ASHRAE, 2001).

Background will be given on typical configurations of surface refrigeration systems and how these systems form part of the overall water reticulation system as found on most platinum mines. Attention is given to components in the refrigeration and cooling system that are high electrical energy users.

Energy optimisation strategies and equipment relevant to the identified high electrical energy consumers will be reviewed to identify possible optimisation solutions. EE initiatives on similar systems and subsystems are discussed, to investigate the possibility of adapting existing optimisation strategies.

2.2. TYPICAL LARGE MINE REFRIGERATION AND COOLING SYSTEM

Heat stress administrative and management actions need to be taken when the underground WB temperatures exceed 27.5°C (Venter, 2007). As a result large mine refrigeration and cooling systems are introduced to uphold safe environmental condition for mining to continue efficiently and safely. The three biggest sources of heat as defined by Van der Walt and Whillier (1978) in underground mines are as follows:

- Heat arising from rocks faces,
- fissure water and
- auto-compression from movement in the ventilation air down the shaft.

Further sources of heat are provided by Van der Walt and Whillier (1978). This all leads to elevated temperatures that must be reduced by introducing artificial cooling.

The mining industry's ability to stay competitive increasingly depends on its ability to maintain acceptable environmental conditions underground in ever increasing mining depths, but doing so in a cost-effective manner (Marx, 1990). Heat transfer networks used around the world are mostly driven by electrical equipment, which is the case for SA mines as well (Swart, 2003). The cooling required to maintain safe working temperatures has a direct relation to the depths at which mining occurs. Therefore, mines' electrical energy consumption increases in relation to the mining depths and operations.

The required cooling capacity of a mine's refrigeration system is depended on surface conditions and underground depth of operations. The service delivery requirements and operations of typical deep level mine cooling systems differ from that of building Heating Ventilation and Air Conditioning (HVAC) systems (Du Plessis *et al.*, 2013). Cooling systems on mines do not only supply cold ventilation air, but large volumes of chilled mine water, which is stored and then sent underground for an integrated network of end-users.

The water reticulation system on a mine is an integrated system, which comprise refrigeration plants, together with underground water supply and dewatering systems (Vosloo *et al.*, 2012). These systems are installed on the surface and underground as part of typical semi-closed loop mine water reticulation systems (Schutte, 2007). This integrated water reticulation system extracts hot water from the mine, cools it down, then uses it for surface air-cooling and returns cold service water to the various underground mining levels. This can be seen as a closed system, due to external water sources like fissure water from underground rock faces, it is described as semi-closed.

The refrigeration machine (chiller) compressors together with the auxiliaries, which consist of water pumps and air fans, are the highest electrical consumers in the refrigeration and cooling system. The configuration, layout, control sequence and operation of the refrigeration system vary according to mine-specific process constraints and distribution systems (Van der Walt & De Kock, 1984). A simplified layout of a cooling system integrated with the reticulation system is shown in Figure 6.

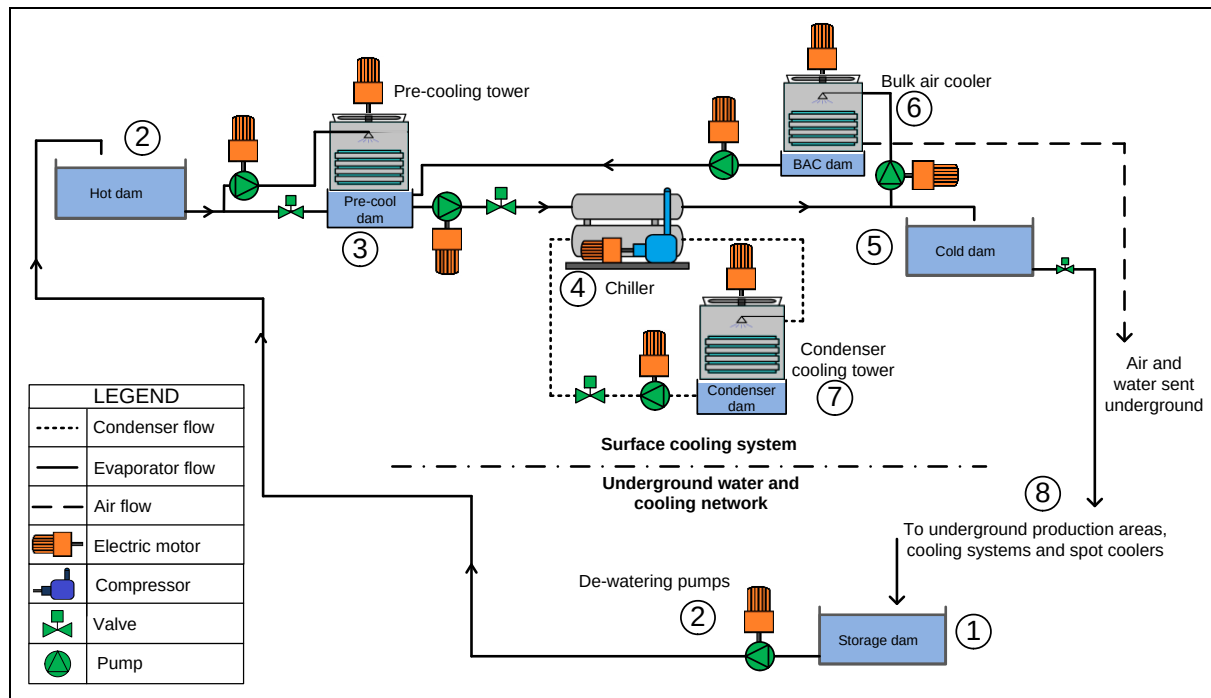


Figure 6: Simplified layout of a typical platinum mine cooling and water reticulation system.

In Figure 6 the typical subsystem interaction, water flow and electrical energy input are illustrated. The process is described briefly in the numbered items (note the numbers refer to Figure 6) that follow:

1. *Hot water storage:* All the water from mining operations (chilled water sent underground and fissure water) flows into underground hot water storage dams.
2. *Dewatering system:* Hot water from the underground dams are pumped to surface storage dams.
3. *Pre-cooling tower:* The hot water then passes through a pre-cooling tower where it accumulates in a pre-cooling dam. It is also known as the make-up water section, as this is usually the part in the cooling process where the hot water re-enters the surface cooling system. The pre-cooled water is then cooled as it is pumped through the evaporator heat exchanger of the chiller.
4. *Refrigeration machine/chiller:* Chills the water by means of vapour compression or ammonia absorption to the desired water outlet temperature. The specific layouts and

location of mine chillers and pumps depend on application and underground water requirements.

5. *Chilled water storage*: The chilled water usually flows into a surface chill dam where it is stored. From here, chilled service water is supplied underground as needed. An actuating valve that opens and closes as the demand varies throughout the day normally controls the flow required underground.
6. *Balk Air Cooler (BAC)*: The chilled water can also be supplied to a BAC that basically supplies cold dehumidified ventilation air, that is forced by various ventilation fan configurations, into the ventilation shaft. After the air is cooled, the water is returned to the pre-cooling dam.
7. *Condenser cooling tower*: Serves as a heat rejection system to dissipate heat generated in the refrigeration cycle to the atmosphere.
8. *Underground chilled service water*: After the chilled water is used for drilling, cleaning or secondary cooling operations, such as in-stope Mobile Cooling Units (MCU), it flows into underground storage dams.

Take note of the amount of electrical energy input required from electrical motors in this simplified system. In reality a combination of chillers, fans and pumps are used depending on the refrigeration requirements. The number of electrical motors usually in operation is considerably more than illustrated in Figure 6.

Table 1 summarises the typical motor ratings of pumps, fans and chillers as found on platinum mine refrigeration and cooling systems. It is shown that chiller compressor electrical motors are individually the largest electrical consumer in the refrigeration system. It is reasonable to assume that larger savings can be obtained from the chillers since they use larger electrical motors.

Table 1: Typical platinum mine electrical motor ratings.

Mine	Equipment rating [kW]					
	Pumps	Qty	Fans	Qty	Chillers	Qty
A	30 - 330	8	90 - 160	7	1800	3
B	45 - 275	4	90 - 300	6	1800	2
C	75 - 400	8	90	4	1300	5

Water pumps and fans are in the range of 30 – 400 kW as shown in Table 1. Motor ratings and quantity depends on application, air and water flow rates required for the respective systems. Pump and fan electrical motors must not be undervalued since a significant amount of this equipment are used in the refrigeration system. Therefore, savings that are possible from pumps and fans, if looked at as a combined entity, can lead to substantial electricity savings.

More detail of the above-mentioned refrigeration and cooling system components follow in Section 2.3 and 2.4, explaining each component in more detail, mentioning the different system configurations, technologies and control strategies available to reduce the electrical power consumption on these electrical motors.

2.3. BACKGROUND ON MINE REFRIGERATION AND COOLING COMPONENTS

2.3.1. Preamble

It is important to have an enhanced understanding of each component that makes up the integrated refrigeration and cooling system. This is appropriate before proceeding with present energy saving strategies implemented on similar systems. It is essential to understand the principle of operation and performance considerations of each component and its subsystems, before developing new optimisation strategies.

Refrigeration machine compressor motors are identified to be the single largest electricity consumer in the refrigeration cycle. The subsystems of the refrigeration cycle also consume considerable amounts of electrical energy if computed. It will be appropriate to investigate these components in more detail, to identify possible electrical saving strategies more effectively and safely. This will improve one's knowledge to prevent that system constraints are affected unintentionally.

Trends in SA's mining industry show that surface refrigeration systems are used in preference to similar underground systems. The main fact contributing to this trend is the poor and uncertain nature of underground heat rejection systems. Heat rejection systems condense heat from the refrigeration system to the atmosphere.

Owing to continuous mining operation advances and the nature of varying ventilation air, underground condensing temperatures fluctuate throughout the mine's life (see Section 2.3.3 and 2.3.4 for further detail). This makes it almost impossible to foresee the temperature of the air available for heat rejection. Therefore, the focus of this dissertation will revolve around surface refrigeration systems as mentioned previously.

Most platinum mines in SA use surface refrigeration installation as preference. In most cases, these platinum mines reduce the cooling load required from their refrigeration machines during winter months to reduce the electricity consumption – saving a substantial amount of money as not all chiller machines are used during the expensive electricity tariff season (Holman *et al.*, 2013).

In the next sub-section the attention will be drawn to the chiller machines as it is identified as the largest electricity consumer in the refrigeration system. Explaining the process in more detail and mentioning where there may be opportunities to optimise the equipment according to load conditions more effectively. The parameters in the refrigeration cycle that affect the cooling load for the chillers will be highlighted and explained.

2.3.2. Surface refrigeration chillers

Refrigeration machines found on mines usually operate according to the ammonia absorption or the more common vapour-compression refrigeration cycle (Borgnakke & Sonntag, 2009). The vapour-compression refrigeration cycle is used most commonly in the mining industry due to its simplicity and relatively low maintenance compared to other processes (Schutte, 2007).

The vapour-compression refrigeration cycle works on a simple principle. When a working fluid is heated to boiling point or saturation temperature (the point where the fluid turns to vapour), it will do so at constant temperature if the applied pressure remains fixed. This pressure is called the saturation pressure (Borgnakke & Sonntag, 2009). If the applied pressure increases, the saturation temperature of the fluid will raise in relation and vice versa.

The fluid can be evaporated (vaporised) by either increasing the temperature above the saturation temperature (at constant pressure) or decreasing the pressure (at constant temperature). In the same manner, condensation from vapour to fluid may occur by decreasing the temperature (at constant pressure) or increasing the pressure (at constant temperature) (McPherson, 1993).

The relationship between the saturation pressure and temperatures for any given fluid differs, refrigeration fluids are used according to these properties. Commonly used refrigerants are R134a and ammonia (R717), because the fluid properties of these refrigerants are best suited for chiller applications. Ammonia is a particularly efficient refrigerant which is ideal and only used for surface chillers application due to its toxicity (McPherson, 1993).

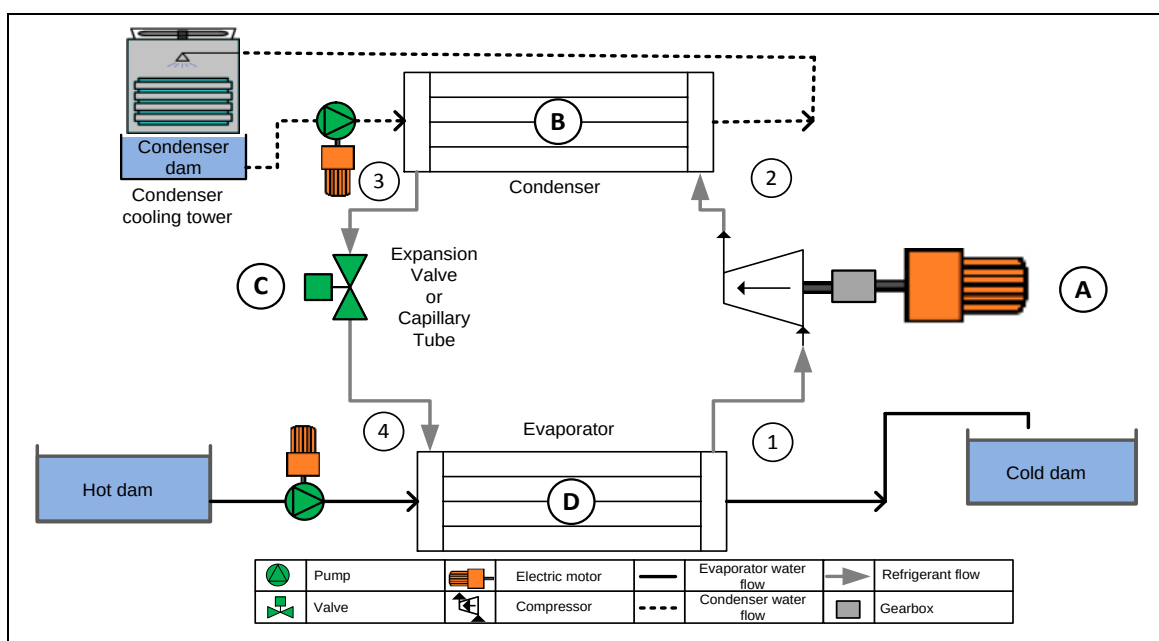


Figure 7: Ideal vapour-compression refrigeration cycle as used for mine chillers.

Figure 7 illustrates a vapour-compression refrigeration system with the essential equipment. The ideal cycle is explained briefly in the four steps that follow:

- A. *Compressor*: The refrigerant is compressed adiabatically (irreversible) from stage 1 to a superheated vapour at an elevated pressure at stage 2. When a vapour is at a temperature greater than its saturation temperature it is a superheated vapour (Borgnakke & Sonntag, 2009).
- B. *Condenser (heat rejection)*: The refrigerant is then condensed as heat is transferred to the condenser water. The heat the condenser water collected is then rejected in the condenser-cooling tower. The refrigerant leaves the condenser at stage 3 as a high-pressure liquid.
- C. *Expansion valve*: The refrigerant is flashed through an expansion valve, which reduces the pressure of the refrigerant adiabatically. As a result, some of the liquid flashes to a cold vapour. The temperature of the refrigerant decreases according to the basic principle explained earlier. This is, when reducing the pressure of a refrigerant, the saturation temperature will decrease accordingly. At stage 4, the refrigerant is now a mixture of vapour and liquid (two-phase form).
- D. *Evaporator (heat absorption)*: The refrigerant then flows through the evaporator at constant pressure, where the evaporator water in effect heats up the refrigerant, and as a result, vaporises the refrigerant and the evaporator water is cooled. The refrigerant exits the evaporative heat exchanger at stage 1, as a vapour before it re-enters the compressor, thus closing the cycle.

Figure 8 illustrates an example of a surface screw compressor refrigeration machine installation.

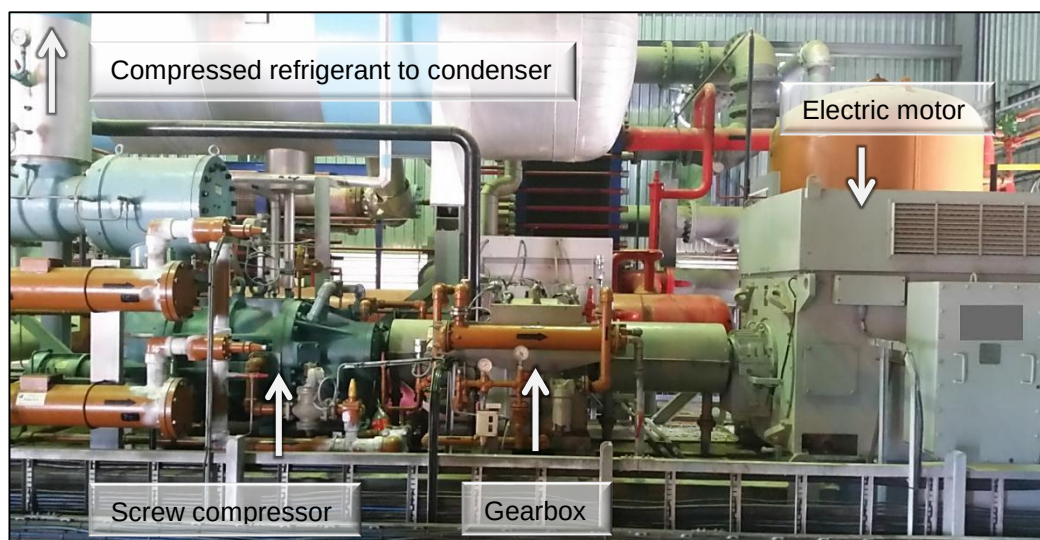


Figure 8: Illustration of a surface chiller screw compressor motor assembly.

The only significant difference between the ammonia absorption and vapour-compression cycle is in the method compression is achieved. The basic principle, described previously, remains the same to achieve the cooling affect in both refrigeration cycles. The required electrical energy input per cooling load output required to achieve compression in the ammonia absorption cycle is less than that required in the vapour-compression cycle.

The most common compressors used in the vapour-compression and ammonia absorption refrigeration cycles are centrifugal and screw types. It is important to note that centrifugal compressor machines are sensitive to changes in the compression head, which is determined by the condensing and evaporating temperatures. If these machines' operating conditions differ much from the design conditions, they became very inefficient. Screw compressors are more widely used, due to their wide-ranging condensing temperatures and as a result are less sensitive to these changes. For this reason, less electrical power is wasted if operation differs from the design (Van der Walt & De Kock, 1984).

The cooling load of refrigeration machines are controlled by guide vanes in centrifugal compressors and slide vanes in screw compressors (Widell & Eikevik, 2010). These control methods adjust the refrigerant flow accordingly, to ensure a pre-determined outlet temperature is achieved (McQuay International, 2005). The difference between the inlet and pre-set outlet water temperature, determines the amount of compression needed in the refrigerant cycle (Holman, 2013). This has a direct effect on the power consumption of the compressor's electric motor.

This can be explained with referring to Equation 2.1, which one can use to calculate the rate at which thermal energy is absorbed by a refrigeration machine at any given moment.

$$\dot{Q} = \dot{m}C_p(\Delta T) \quad (2.1)$$

where,

$\dot{Q}$ = The rate of thermal energy transfer [kJ]

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

C_p = Specific heat constant [kJ/kg.K]

ΔT = Temperature difference [K]

From Equation 2.1 it evident that for a set outlet temperature, the thermal load of a refrigeration machine will depend on the inlet temperature, or the mass flow through the

evaporator. By reducing any of the mentioned parameters, the compressor's electrical energy input can be reduced.

The efficiency of a refrigeration machine is defined by the Coefficient of Performance (COP), which can be calculated for any given moment with Equation 2.2.

$$COP = \frac{\dot{Q}}{W_{comp}} \quad (2.2)$$

where,

$\dot{Q}$ = Thermal energy [kJ]

W_{comp} = Compressor electrical energy [kJ]

The refrigeration machine's COP is a ratio between thermal energy output and electrical energy input. When the cooling load is reduced, due to lower inlet water temperatures or reduced flow rates, the compressor will reduce the refrigerant flow and pressure by closing the guide vanes or sliding valve accordingly. This will result in reduced compressor electrical power usage. The COP of a large mine refrigeration machine can be expected to be between 3 and 6, with 6 being an energy efficient system and 3 an energy inefficient system (Borgnakke & Sonntag, 2009).

Gorden et al. (2000) and Romero et al. (2011) showed that the COP of a refrigeration machine increases at reduced evaporator flow rates and decreases with reduced condenser water flow rates. When water flow rates are varied, compressor guide vanes or slide valves optimally control the power consumption to match the varying load conditions. The effect on chiller COPs, when varying the water flow, depends on the control strategy and how well the compressor control manages the changing cooling load conditions (Bahnfleth & Peyer, 2004).

It is important to remember that the cooling load and consequently the electricity consumption of surface refrigeration plants are directly related to ambient weather conditions, chilled water temperatures and volumes required thereof.

Hence, mines implement different types of chiller machine configurations to accommodate these changes. Each configuration working more efficiently to accommodate the varying ambient and water temperatures, water flow required or even both. The following sub-section will describe each of these configurations briefly by means of a visual illustration.

2.3.3. Process layouts of mine refrigeration and cooling system

Before the discussion of the different refrigeration systems process design commences, a brief background on back-pass valve control is necessary. Most of the refrigeration system process designs described below make use of back-pass control to achieve improved chiller COPs.

Chiller back-pass valve control

Refrigeration systems on mines make use of this simple and cost effective control method to operate the refrigeration machines at the highest level of efficiency. The back-pass valve system consists of a pipe and control valve connection between the evaporator discharge and inlet flow. The prime function of the back-pass valve control is to maintain a pre-determined temperature for the water entering the evaporators. This ensures that the refrigeration machine is operated near the design conditions and thereby, ensuring the least electrical power is consumed for the most cooling, resulting in higher chiller COPs (Van der Walt & De Kock, 1984).

A particular valued feature is that the bypass can be used to match the hydraulic characteristic of the refrigeration installation with that of the cold water distribution system, enabling daily temperature fluctuations to be accommodated accordingly (Van der Walt, 1979; Bailey-McEwan & Penman, 1987). Meaning that the discharge water can be recirculated and in effect reduce the overall system temperature and as a result reduce the workload of the refrigeration machines.

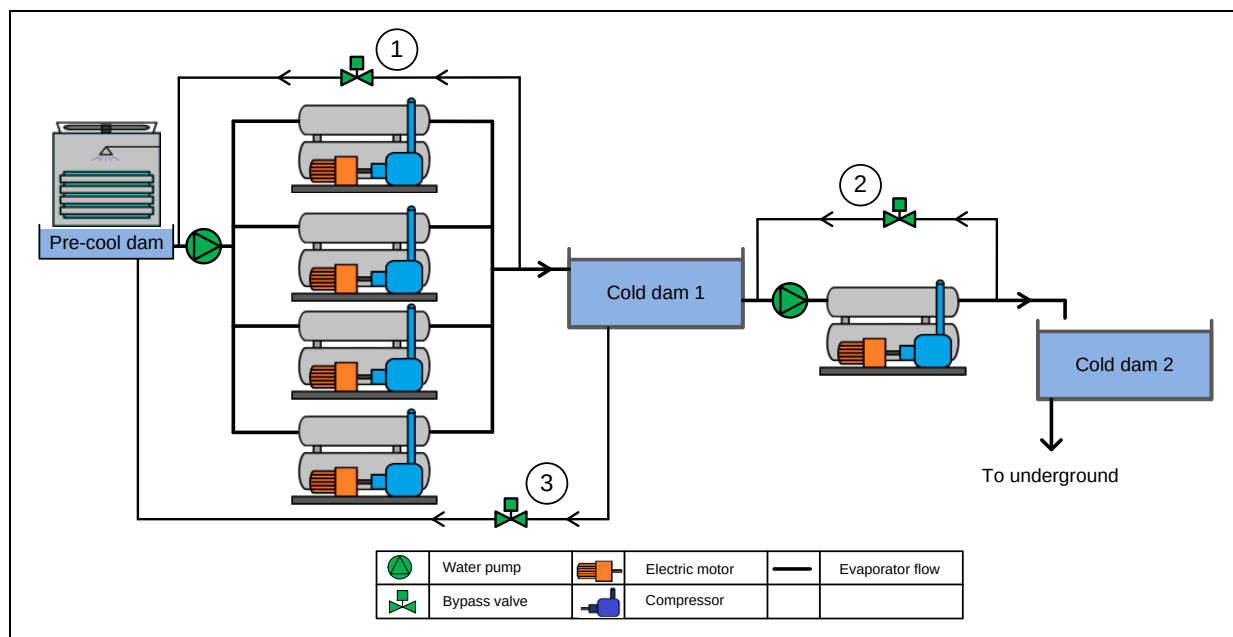


Figure 9: Multi-stage surface refrigeration system with back-pass valve control.

Figure 9 illustrates a simplified model of a multi-stage surface refrigeration system as installed on a gold mine near Westonaria. Four vapour-compression cycle machines installed in parallel are coupled in series to an ammonia absorption refrigeration machine. Water is pumped from the surface hot dam to the pre-cooling tower and then to the first stage refrigeration before it enters Cold dam 1. Thereafter, the water is cooled further before re-entering Cold dam 2 and supplied to underground mining operations.

This gold mine refrigeration system is used as illustration to exemplify the means in which back-pass valves can be implemented to optimise the overall system. Bypass valve 1 and 2 as shown in Figure 9 is used, as explained earlier, to control the discharge evaporator water temperature to a pre-determined set value. This will ensure that the machines operate more efficiently. Bypass valve 3 is used in this case to control the overall system temperature and reduce the system temperature.

Refrigeration process layouts

Major changes in water flow rates and temperatures are a result of the following:

- Seasonal temperature changes caused by ambient WB temperatures fluctuations.
- Daily ambient temperature variances.
- Changes in underground chilled water requirements daily and seasonally.

As mentioned, these varying factors have an effect on the cooling load of the refrigeration and cooling system. Different refrigeration layouts are used, each with a specific design to accommodate site-specific variances as efficiently possible. This is performed with the existing outdated equipment and control techniques. In the figures that follow, the basics of the different process designs are given, clarifying the preferred application of each.

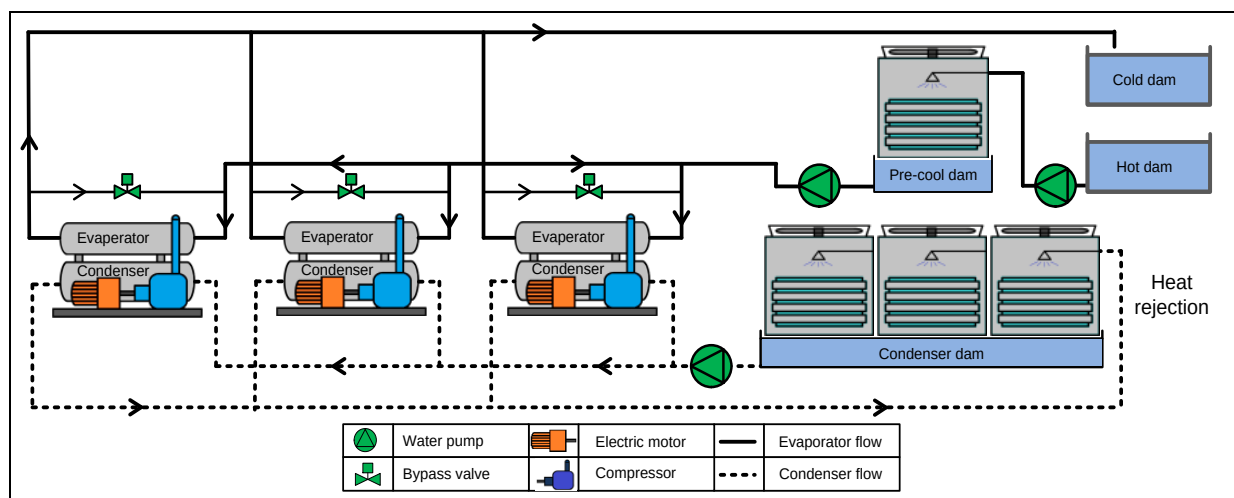


Figure 10: Variable flow process design (Van der Walt & De Kock, 1984).

The variable flow process as shown in Figure 10 is appropriate when the cooling load is primarily determined by changes in average chilled water demand requirements. The design is typically used when underground chillers are linked to stope air coolers (MCU), which are placed close to production areas and cools the surrounding air. The variable flow process supplies chilled water at a relative constant temperature by varying the number of active chillers according to water flow demands (Van der Walt & De Kock, 1984).

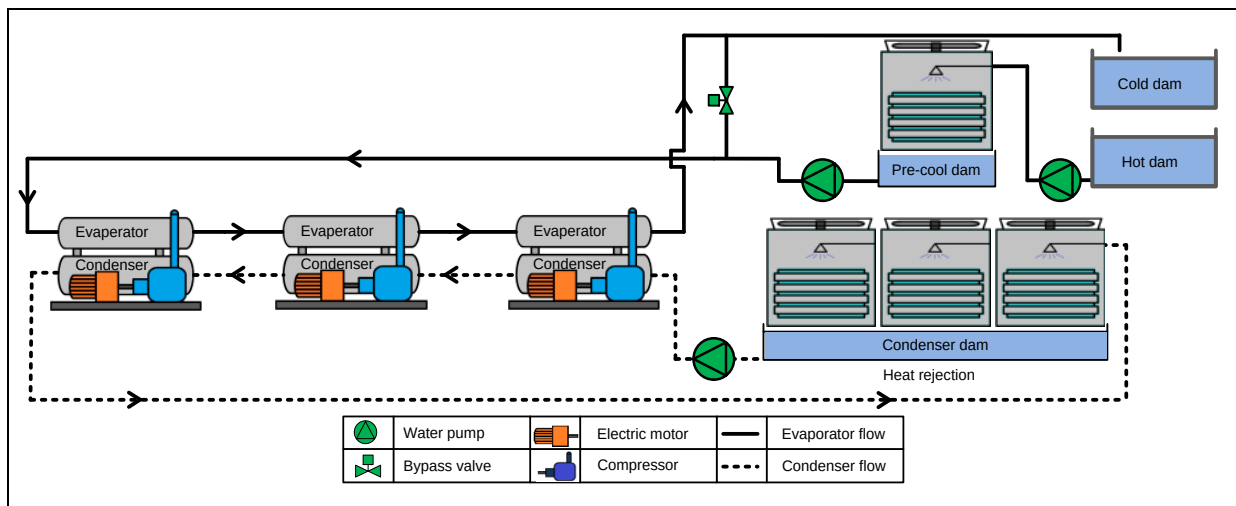


Figure 11: Variable temperature process design for centrifugal compressor refrigeration machines (Van der Walt & De Kock, 1984).

The variable temperature process shown in Figure 11 and Figure 12 is primarily suitable for a relative constant chilled water demand throughout the year. For this process the temperature at which the water returns, determines the cooling load for the refrigeration machines (Van der Walt & Whillier, 1978). The change in temperature is coupled to the varying ambient WB temperature experienced because of fluctuating ambient conditions.

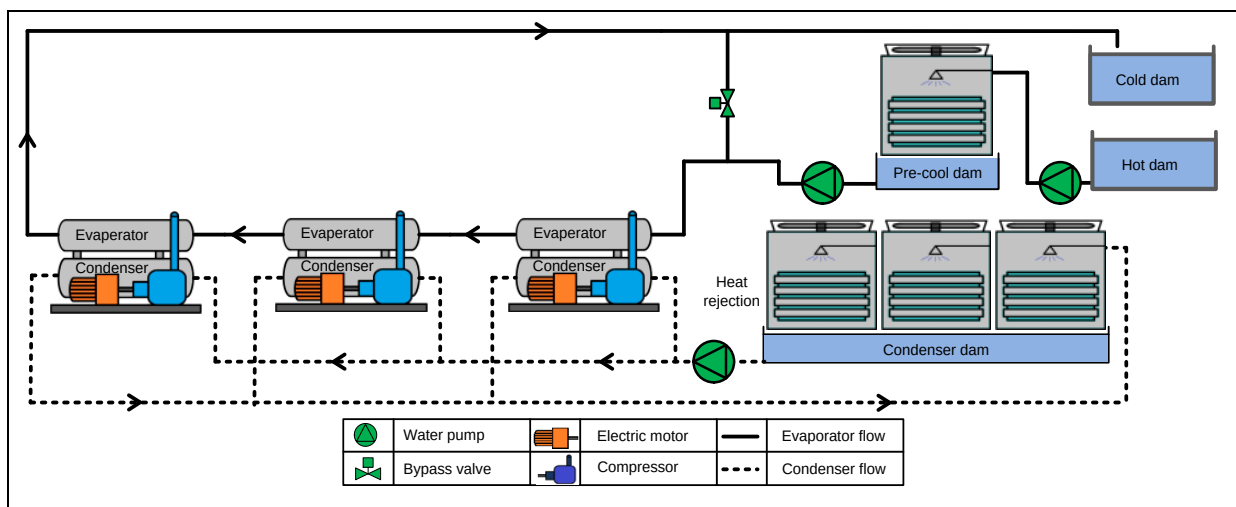


Figure 12: Variable temperature process design for screw compressor refrigeration machines (Van der Walt & De Kock, 1984).

In the variable flow process, the evaporators of multiple chillers are placed in series. When significant cooling load variances are experienced, a result of inlet water temperature changes, chillers can be switched in or out of the system, doing so without affecting the water flow through the evaporators. The variable temperature process designs are typically used for surface refrigeration plants where pre-cooling is only used to cool service water.

The only significant difference between the process shown in Figure 11 and Figure 12 is the condenser heat exchanger configuration. The condenser water circuit is coupled in parallel as shown in Figure 12 when a screw compressor is used in the refrigeration cycle. For a refrigeration cycle using a centrifugal compressor, the condenser circuit is connected in a counter flow series configuration as shown in Figure 11.

Most mines experience the need for both variable flow and temperature control. This is typical when the refrigeration plant installations provide chilled service water for underground mining operations and bulk cooling of air on the surface. This is achieved by implementing a design that combines both previously mentioned processes as shown in Figure 13.

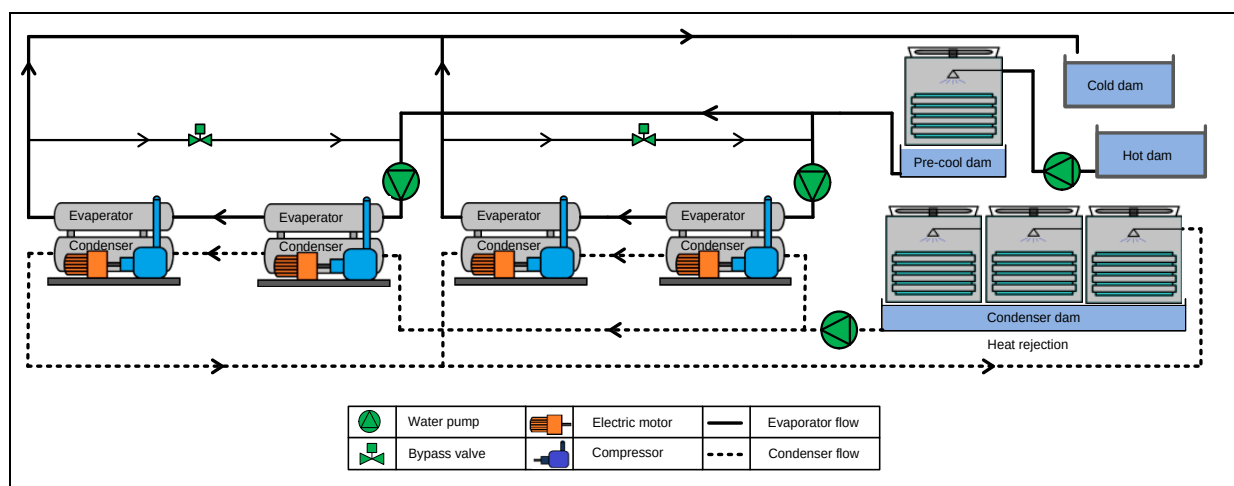


Figure 13: Variable flow and temperature process design (Van der Walt & De Kock, 1984).

It is found that most platinum mines in SA make use of the variable temperature process configuration. Even though the last mentioned process design can accommodate more system design changes. This can be a result pertaining to the initial capital needed for installing a refrigeration plant, as the variable temperature process will require fewer control, piping and pumping equipment.

Further, the variable flow process will be best suited for platinum mine in SA due to the large ambient temperature differences experienced seasonally and daily in that region. Chillers can be switched in or out of the system easily as needed during the varying ambient WB temperatures without affecting the chilled water supply. It can be anticipated that process

designs where the evaporative heat exchanger is coupled in series and pre-cooling only used for cooling service water are used on platinum mines.

Table 2 indicates what energy reducing strategy can preferably be used on the various refrigeration system process designs to achieve reduced electricity costs. It is important to note that this only suggests what strategy can allegedly be implemented more effectively on the different process designs. With few alterations, EE can most likely also be achieved on the variable flow process and the same for the variable temperature design.

Table 2: Summary of refrigeration system process design proposed optimising strategy.

Process design	Load shift	Energy efficiency
Variable flow	x	
Variable temperature		x
Variable flow & temperature	x	x

In the refrigeration system as found on mines, they use wet heat rejection or absorption cooling towers or chambers. Both of these methods make use of pumps to displace water through the tower or chamber and fans to draw or force air through at the same time. The motors electrical consumption has the potential to be reduced, to improve the overall running cost of the refrigeration and cooling system. The following two sections will focus on whether this can be achieved and if probable.

2.3.4. Heat rejection systems

Mines use heat rejection cooling towers to pre-cool underground return service water before it re-enters the refrigeration system. An example thereof is shown in Figure 14. Heat rejection cooling towers are also used to dissipate heat from the condensers of the refrigeration machines to the atmosphere. Mines typically make use of induced draft cooling towers with counter flowing water and air streams as shown in Figure 15.



Figure 14: Mine pre-cooling tower used to pre-cool hot water from underground.

Pre-cooling and condenser towers use evaporative cooling and convection to realise the available cooling from the ambient air, assuming that the ambient WB temperature is lower than the temperature of the water (McPherson, 1993). In this case, evaporative cooling is the effect when a portion of the water is evaporated into the atmosphere, because the moisture content of the air is less. The evaporation process requires energy to change from liquid to vapour, as a result the remaining water is cooled (Kröger, 1998).

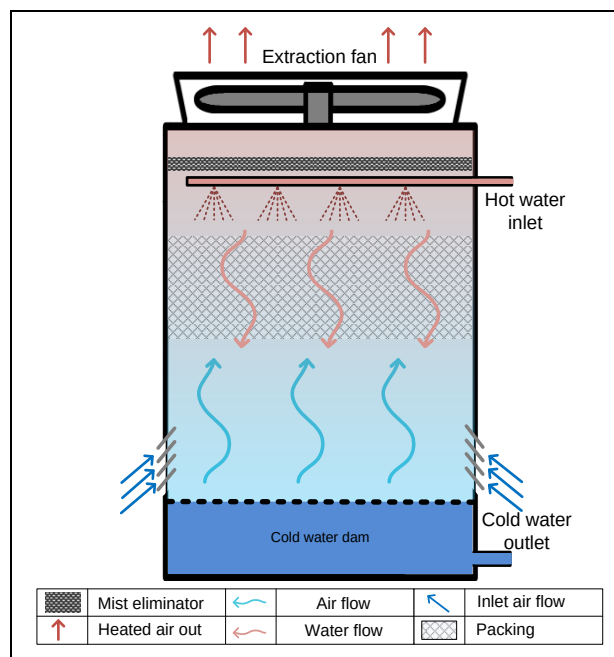


Figure 15: Typical heat rejection cooling tower layout.

A schematic layout of a condenser and pre-cool tower is shown in Figure 15 as used for surface refrigeration systems. Condenser cooling towers are usually placed next to each other as shown in Figure 16 to increase the cooling capacity. Warm water is sprayed from the top of the tower, as the water is sprayed downward a mechanical fan draws air upwards. As warm air is extracted from the tower, cold water is stored in a sump below the tower. The amount of cooling depends on the contact time between the air and water (Holman, 2013).



Figure 16: Mine condenser cooling towers staged next to each other.

Factors that influence the amount of heat exchange that can occur in a cooling tower are the counterflow velocities of the air and water, concentration and size of the water droplets. Smaller water droplets expose a larger surface to the air, improving the rate of heat exchange. These factors are influenced by changing the water supply pressure and flow, the size and arrangement of spray nozzles or by increasing the exposure of the water surface to the air by introducing splash bars, packing or fill in the heat exchanger (McPherson, 1993; Kröger, 1998).

The performance of a mine refrigeration heat exchanger can be calculated by using Equation 2.1 and 2.2. The COP of pre-cooling towers is significantly higher than mine refrigeration machines due to the low work input required (Van der Walt & De Kock, 1984). The COP of heat exchangers is directly related to the ambient WB temperature and performs very well in the colder season (lower WB temperature).

Cooling towers are designed on the average ambient temperature, water flow rates and water temperature expected for the system. When lower WB temperatures are experienced during operation than that of the design, over cooling can occur. The overall performance experienced can result in unnecessary over cooling of the water. This presents the opportunity to reduce the water flow and even air flow through the cooling tower by reducing pump and fan speeds. Resulting in the potential energy reductions as mentioned possible earlier.

2.3.5. Heat absorption systems

Mines typically make use of the following heat absorption systems to provide the necessary artificial cooling to sustain a productive working environment underground:

- Surface or underground BACs depending on mine depths (direct contact system).
- Mobile cooling units like Cooling Cars (CC).
- Spray chambers (direct contact system).

The advantage of direct contact systems is that high thermal efficiencies can be reached, but a significant amount of pumping is required. Close circuit systems require less pumping however lower thermal efficiencies can be expected (Mackay *et al.*, 2010).

Mines use BACs installed on surface or underground to provide cold dehumidified air for underground ventilation. It is said that surface BACs is the least expensive method of cooling air for underground mining operations and can reduce the amount of water to be circulated underground (Van der Walt & De Kock, 1984).

Additionally, the water used for secondary cooling, such as CC and spot coolers, can also contribute in reducing the electrical power consumption of mine refrigeration and dewatering systems (Vosloo *et al.*, 2012).

BACs, also known as evaporative spray chamber are the same as a heat rejecting cooling tower, however the transfer of heat is directly opposite. The air is cooled to a lower WB temperature while the water is heated when sprayed through the tower/camber.

Mines use either vertical towers or horizontal chambers, where the air draft through the tower/chamber is mechanically forced. Hence called mechanical forced draft towers/chambers (Kröger, 1998). Forced draft towers/chambers use fans to force air through the tower whilst induced draft towers use fans to draw the air through the tower, see Figure 15 and Figure 17.

Vertical forced draft tower

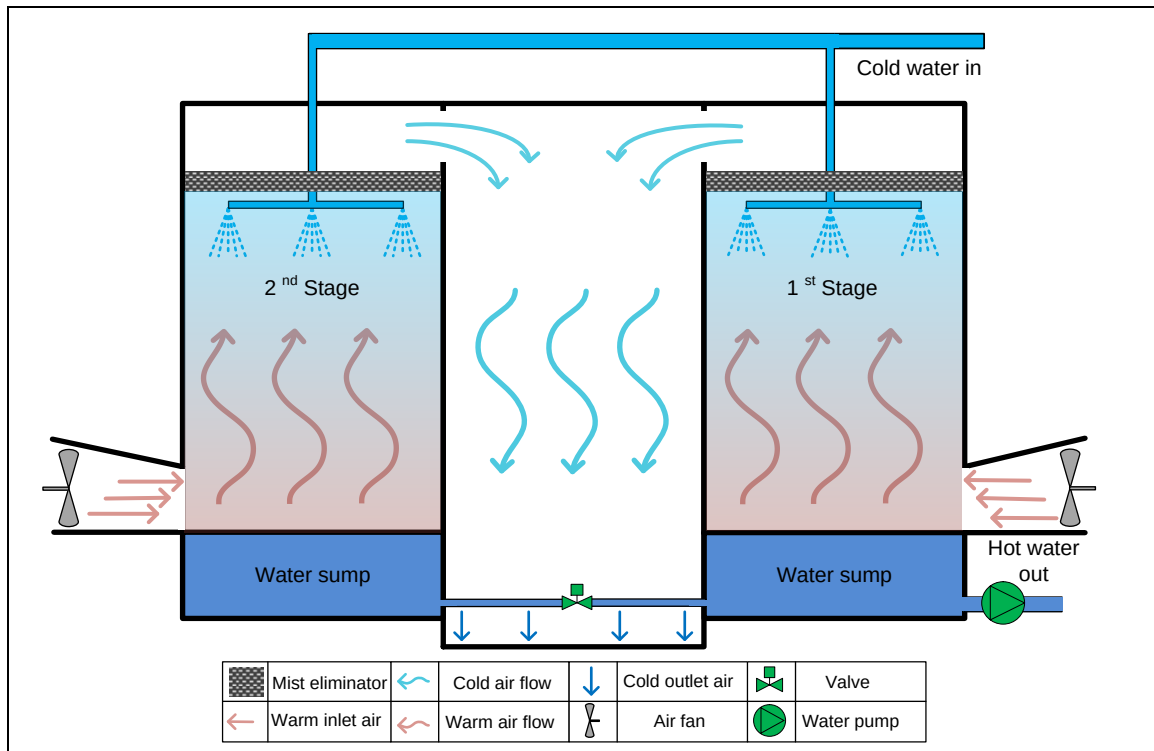


Figure 17: Schematic illustration of a vertical forced draft, counterflow BAC.

Figure 17 illustrates a multi-stage vertical forced draft cooling tower (multi-stage vertical BAC) schematically. Chilled water at a temperature lower than the ambient WB temperature is supplied to the spray nozzles situated at the top of the spray chambers. Ambient air is forced through the spray chamber and chilled water supplied from the chillers cools the air before it is forced to underground ventilations systems. In Figure 18 an example of an installed multi-stage vertical BAC is shown – that is used to cool the ventilation air of mines on surface.



Figure 18: A multi-stage vertical BAC used on a platinum mine near Northam.

Horizontal forced draft chamber

Horizontal BACs have limiting cooling capacities to that of vertical BACs (Holman, 2013). Horizontal BACs can, however, be more easily used for underground cooling of ventilation air, as it will not require extensive excavations (McPherson, 1993).

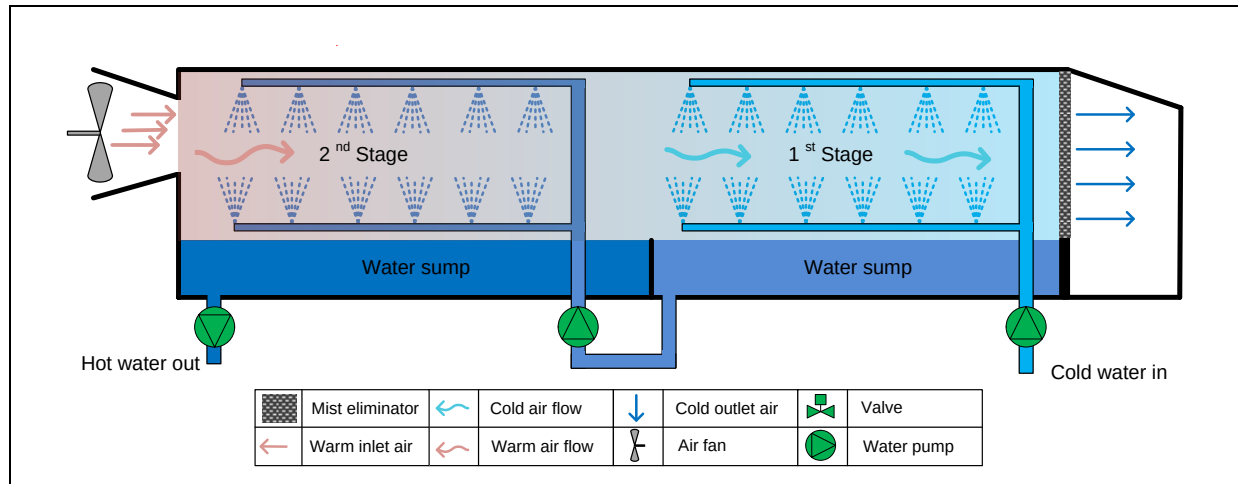


Figure 19: Schematic illustration of a horizontal multi-stage forced draft, cross flow BAC.

Figure 19 illustrates a horizontal multi-stage BAC. Ambient air is forced in to the spray chamber as it flows across the spray water. The spray of the chilled water can be directed either into or across the airflow. It is critical that the water spray and airflow is distributed uniformly across the chamber – therefore, the position of the nozzles and fans need to be accurate to ensure optimal performance (McPherson, 1993). Figure 20 shows a multi-stage horizontal BAC used to cool the ventilation air for a platinum mine on surface.



Figure 20: A multi-stage horizontal BAC used on a platinum mine near Thabazimbi.

Mine cooling towers as mentioned are designed according to the average ambient WB temperature, as is the BAC system. The only difference is that BACs are designed to deliver a certain air outlet temperature as well. The performance of BACs depend on the ambient WB temperature, thus with a lower WB temperature over cooling of the air can occur. BACs also present opportunity for partial load conditions by reducing pump and fan motor speeds.

Direct heat exchanger performance

Both rejection and absorption heat systems are categorised as direct heat rejection systems because the air is brought into contact with water surfaces. The same theoretical analysis can be used for direct heat exchangers regardless of the direction of heat transfer (McPherson, 1993). The formulas used to calculate the performance for a heat rejecting system are explained by means of condenser cooling towers.

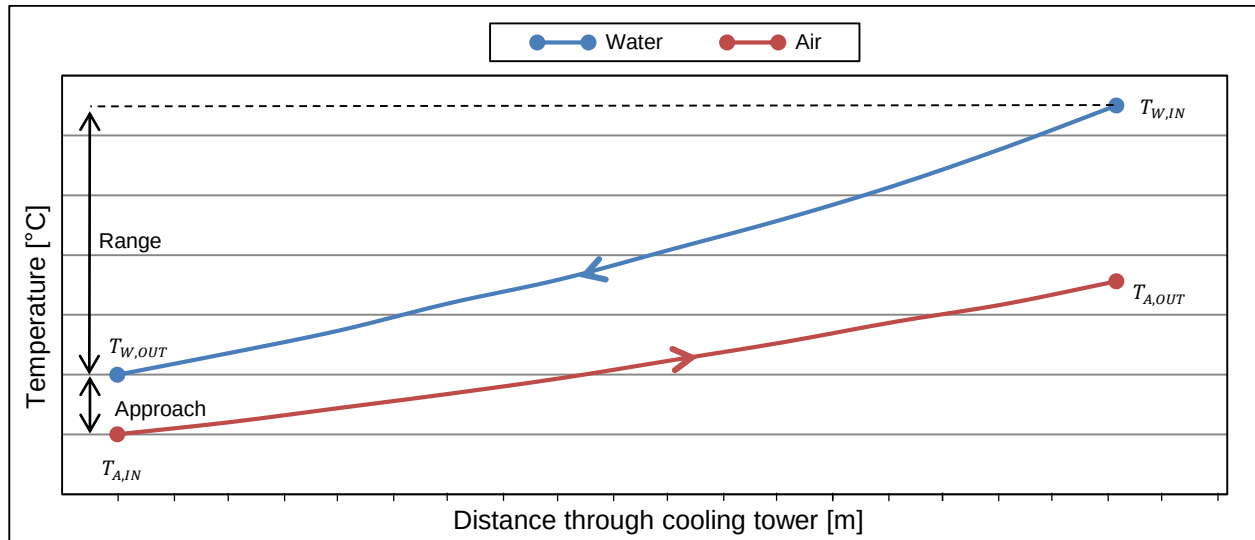


Figure 21: Variation of water and air temperature through a cooling tower.

Figure 21 demonstrates the water temperature drop as it falls through the cooling tower and the corresponding increase in WB air temperature as it is drawn through the tower. The range of a cooling tower is defined by the change between the inlet and outlet water temperature (McPherson, 1993).

$$Range = T_{W,IN} - T_{W,OUT} \quad (2.3)$$

where,

$Range$ = Change in water temperature [°C]

$T_{W,IN}$ = Inlet water temperature [°C]

$T_{W,OUT}$ = Outlet water temperature [°C]

A cooling tower's approach is defined by the difference between the outlet water temperature and inlet airflow WB temperature.

$$Approach = T_{A,IN} - T_{A,OUT} \quad (2.4)$$

where,

$Approach$ = Change in water temperature [°C]

$T_{A,IN}$ = Inlet WB air temperature [°C]

$T_{A,OUT}$ = Outlet WB air temperature [°C]

Theoretically for a perfect cooling tower the two curves in Figure 21 representing the water and air temperature would coincide. This means that the approach of the cooling tower will be zero and the range will be equal to the difference in air inlet and outlet WB temperatures.

In practice, the inlet and outlet water temperature and ambient air temperature (inlet temperature) conditions are available, thus meaning the simplest manner in which the efficiency can be measure is by considering the range, approach and water-side efficiency (McPherson, 1993).

$$\eta_w = \frac{\dot{Q}_{actual}}{\dot{Q}_{theoretical}} \quad (2.5)$$

$$\eta_w = \frac{Range}{(Range + Approach)} \quad (2.6)$$

where,

η_w = Water-side efficiency [%]

$\dot{Q}_{actual}$ = Actual heat lost from the water [kJ]

$\dot{Q}_{theoretical}$ = Theoretical maximum heat that can be gained by the air [kJ]

It is important to note that the performance of a cooling tower is indicated by a low approach value and thus high water-side efficiency as well (Du Plessis, 2013).

Mine secondary heat exchangers

Mining development is usually the activity with the highest heat loads relative to the amount of ventilation air available. This often results in worksite temperatures being significantly higher than that found with other mining activities in the same mine. Where the reach of cool surface ventilation air is a borderline issue for a mine, secondary air-cooled heat exchangers can specifically target development areas to supply adequate cool ventilation air (Howes, 1998).

Air-cooled heat exchangers (radiators) usually transfer heat from the process fluid to a cooling air stream via surface or finned tubes (Kröger, 1998). In the case of mine secondary coolers heat transfer is opposite to that of conventional air coolers. Mine secondary coolers transfer heat from the air stream, via surface or finned tubes, to the process fluid (chilled water). The cooling method of CC is based on the conduction and convection heat transfer between the cold water and warm ventilation air (Van Eldik, 2006).

The performance of wet-cooling towers (BACs, condenser and pre-cooling cooling towers) is primarily dependent on ambient WB temperatures. The performances of air-cooled heat exchangers depend primarily on Dry-Bulb (DB) temperatures of air, which is usually higher than the WB temperature (Kröger, 1998). The temperature of chilled service water determines the base for the quantity of cooling that can be realised. Passing air cannot be cooled to a lower DB temperature than that of the cooling water temperature.

For most platinum mines, the use of CC is subjected to seasonal changes, as cooler WB temperatures are experienced through winter months less artificial cooling is required. Basically two types of air coolers are used, in-line and spray types, to further reduce the cooling load near mining stopes (Gunderson, 1990).

A. Secondary in-line cooler

Figure 22 shows a typical in-line secondary heat exchanger used for underground air cooling in mines. Warm air from the surroundings is forced through the coils of a compact heat exchanger (radiator) situated inside the CC using an electrical fan. The cold service water is heated as it flows through the inside of the tubes, while the air is cooled as it flows over the fin-tube assembly of the radiator. The warm water that exits the cooling car is then dumped into mine trenches, which is a small channel that runs adjacent to the network tunnels that returns hot fissure and service water to underground storage dams (Thein, 2007).

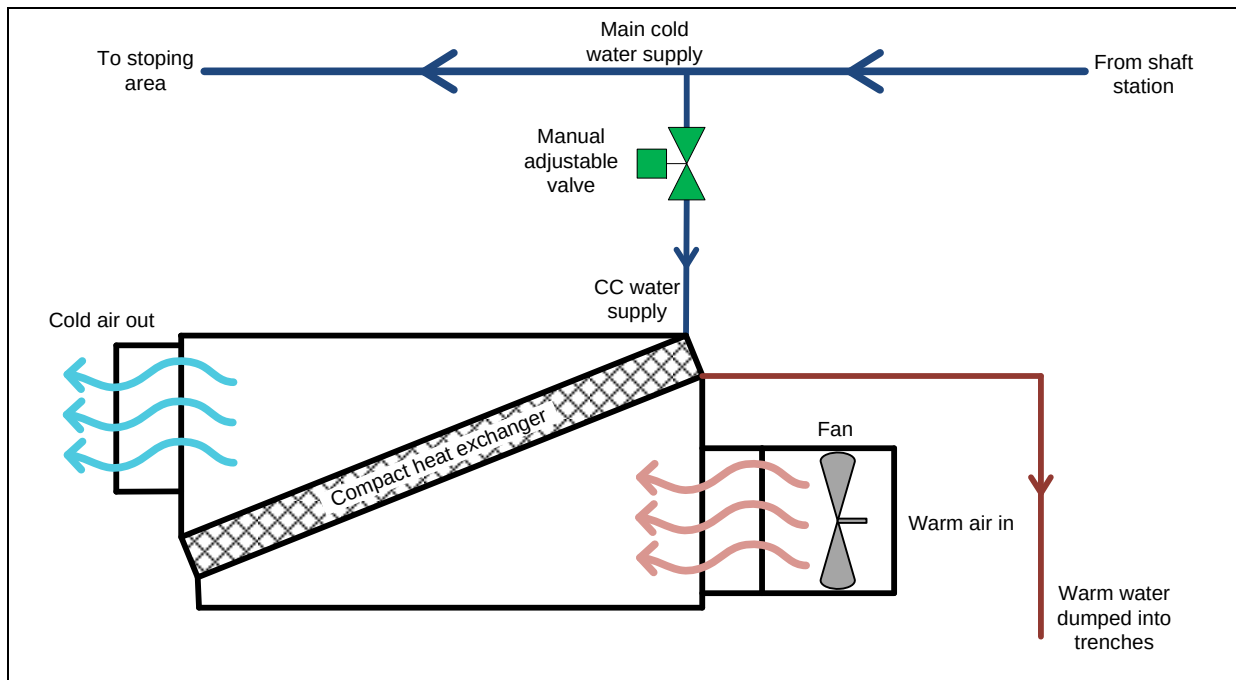


Figure 22: Schematic diagram of an in-line secondary heat exchanger used in underground mines.

An example of the most commonly used CC is shown in Figure 23 with the air inlet at the left and outlet to the right.



Figure 23: In-line type secondary ventilation air cooling car ¹.

Figure 24 displays the inside of the CC shown in Figure 23, with the air inlet shown at the left picture and outlet to the right. The pipes in the left picture are used to spray water into the radiator to wash off any impurities, like mine dust. This is performed regularly to ensure that the heat exchange rate between the air and water is not influenced.

¹ Manos Engineering (Pty.) Ltd. 2013 Gallery. <http://www.manos.co.za/gallery>. (Date of access: 12 July. 2014).

With the uses of CC being subjected to seasonal changes, winter months are ideally used to do scheduled maintenance. It is required that CC is refurbished yearly to remove all impurities, rust, fouling or any other reaction between the fluid and the wall material, to insure optimal performance.



Figure 24: Secondary ventilation cooler compact heat exchanger.

Another in-line air cooler used in mines is place directly into ventilation ducts as shown by Figure 25. The advantage with these air coolers, also known as spot coolers, is that the cooled air can be focused to areas where cooling is needed with minimal heat gain.



Figure 25: In-line type secondary ventilation air spot cooler ².

² Manos Engineering (Pty.) Ltd. 2013. Gallery. <http://www.manos.co.za/gallery>. (Date of access: 12 July. 2014).

B. Secondary spray chamber

Spray type secondary cooling equipment works on the same principle as BACs. Cold water is sprayed in a chamber, while warm air is cooled as it passes through. Usually mine tunnels are used as spray chambers as illustrated in Figure 26 below. The draft of the air flow through the chamber is produced by extraction fans or secondary fans. In BACs water losses is kept to a minimum with mist eliminators, but this is not the case with spray coolers. This is not the best method for secondary cooling due to the high water wastage.

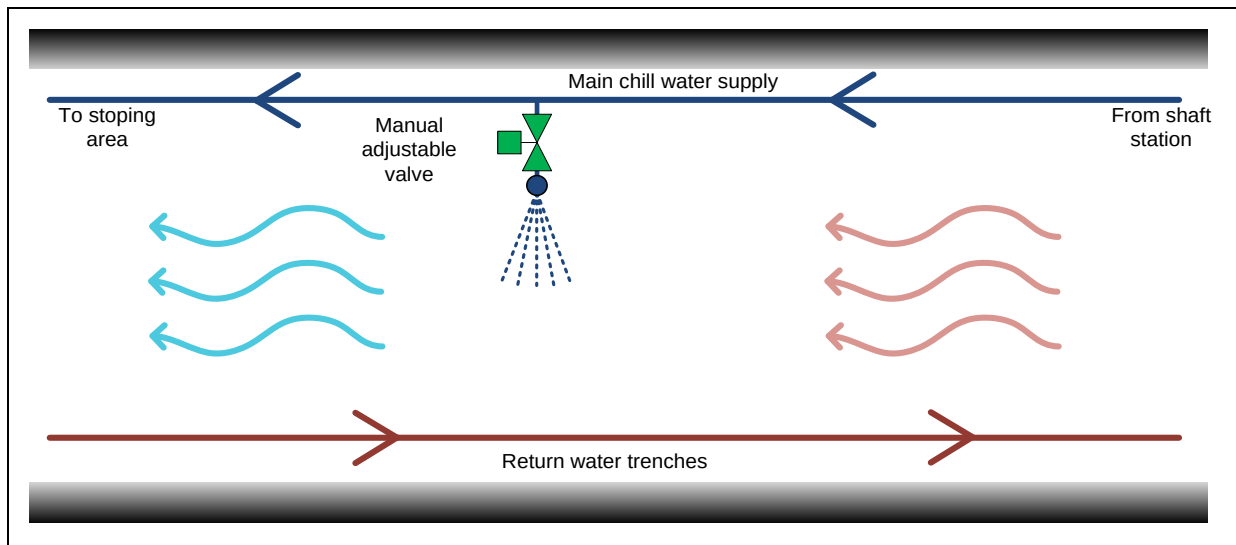


Figure 26: Secondary air cooling spray chamber.

2.3.6. Water storage dams

Water is not only used as a working fluid in mines, but serves as thermal storage (hot or cold) to provide a buffer in capacity (Schutte *et al.*, 2008). The refrigeration and cooling system of a mine is designed to deliver a constant supply of chilled water throughout the day (Vosloo *et al.*, 2012). The service water demand is intermittent as a result of the complex network of end users and production shifts (Du Plessis *et al.*, 2013). The primary purpose of storage dams, temperatures and control bypass lines is to ensure that all safety regulations are fulfilled, so that mining production can proceed with minimal disruptions (Bailey-McEwan & Penman, 1987; Jansen van Vuuren, 1983)

The varying chilled water demand of each mine has a direct effect on the size and location of surface chilled water storage dams (Van der Walt & Whillier, 1978). Mine refrigeration systems and storage dams are usually installed close to mineshafts, as shown in Figure 27. Chill dams are closed off, all to keep temperature losses to the atmosphere at a minimum.



Figure 27: Surface chilled and hot water storage dams installed on a platinum mine near Thabazimbi.

As mentioned, mine refrigeration systems supply a constant flow of chilled water to storage dams. The storage dams then absorb the fluctuating chilled water demand experienced throughout the day. If the refrigeration system, including the storage dams, is controlled optimally according to Eskom's TOU tariff structure, large savings can be achieved as shown by Calitz (2006), Schutte (2007) and Van der Bijl (2007).

2.3.7. Water pumps and electric motors

Two types of water pumps commonly used are centrifugal and axial flow types. Both pump designs work on the basic principle that energy of a liquid is increased by imparting acceleration to it as it flows through the pump impeller. The impeller of a pump supplies the energy (velocity) to the liquid, which in turn is driven by an electric motor. To recover the high fluid discharge velocity (kinetic energy) it is converted to pressure energy. This energy conversion efficiency depends largely on the impeller blade, diffuser and volute (casing) design (Sayers, 1990).



Figure 28: Typical centrifugal water pump and electric motor configuration.

Figure 28 illustrate a typical centrifugal pump driven by fixed speed electric motor to distribute water in the evaporator, condenser and BAC water circuits. Electrical motor size and pump arrangements depend on the pressure and flow required for each different application. Table 1 shows typical motor ratings used in the refrigeration and cooling system. The designed performance of a given pump or pump system is shown by a characteristic curve (Sayers, 1990). This curve usually illustrates delivered pump head, efficiency, power and required net positive suction head as function of liquid flow rates. The operating point of the pumps should be selected at the region of optimal pumping efficiency (BPMA, 2004).

It is important to note that pump impeller speed alterations will cause pump characteristic curves to change (Sayers, 1990). Despite the fact, pumps should theoretically be well suited for speed reduction (BPMA, 2004; Du Plessis, 2013). It remains eminent that all variables are considered since reduced pump efficiencies can lead to increased breakdowns. Therefore, energy savings achieved should be evaluated against pump deficiencies experienced from reduced flow rates to ensure pumping efficiencies remain adequate.

2.4. STRATEGIES AND TECHNOLOGIES FOR OPTIMISING REFRIGERATION AND COOLING SYSTEMS

Understanding the function and working of refrigeration and cooling system components will not result in optimisation strategies, but contribute to the knowledge and expertise for implementing possible EE strategies more effectively and accurately. It is essential to understand each component in the cooling systems to ensure that mine constraints are not influenced negatively, all systems run efficiently and perform according to system requirements.

Various studies have investigated the possibility of improving the energy and cost efficiency of mine cooling systems. The following section will describe possible strategies that can be adopted for optimising platinum mine refrigeration and cooling systems.

2.4.1. Variable flow control with VSDs

Overview

The term VSD can either refer to electrical or mechanical equipment that control the speed of electrical motors or the equipment connected to the motors (Carrier, 2005). Electrical VSDs have become very popular devices to regulate the speed and rotational forces of mechanical equipment (Van Greunen, 2014; Saidur *et al.*, 2012). Industrial and commercial applications range from chillers used for HVAC purposes in large buildings to process plants. On mines, their application varies across conveyors, hoists, draglines and shovels, grinding mills, electrical motor driven pumps, fans and compressors (Yu & Chan, 2008). The wide use of VSDs is proof enough to exemplify the reliability and effectiveness thereof.

Basically, VSDs operate by varying the frequency of the AC voltage supplied to the motor using solid state electronic devices. The frequency range is anything between 1 and 50 Hertz (Hz). VSDs control frequency and voltage simultaneously to maintain a constant ratio between the volts (V) and hertz (Hz). When this Volts/Hertz (V/Hz) ratio is kept constant, the current flow remains similar to full speed conditions and the torque delivered by the motor remains unchanged. Motor torque is changed when the V/Hz ratio is not kept constant through the frequency range (Saidur *et al.*, 2012).

There are currently many motor applications that can be retrofitted to allow for VSD control, as these systems are currently very inefficient. VSD technologies are being introduced in a wide range of industries to reduce losses of mechanical equipment. Equipment is used more efficiently by allowing for optimal speed control and motors to operate at ideal speeds for every

load condition. Further advantages compared to other types of variable speed controls include (Saidur *et al.*, 2010):

- Energy saving,
- improved process control,
- reduced voltage starting (smoother motor start-ups),
- lower system maintenance (build-in diagnostics),
- by-pass capability,
- multi-motor control and
- remote condition monitoring capabilities.

Methods for varying mechanical equipment rotational speeds

Many applications in the industry require the speed of a motor or its drive chain be varied to enable a more efficient process and equipment control. Prior to the advent of electrical VSDs, many technologies have been used to achieve variable speed control. Mechanical and hydraulic VSDs have been used for many years, adapting to modernisation of technology and need therefor. These include (Saidur *et al.*, 2012):

- Control valves, dampers and vanes,
- fossil fuel engines,
- hydraulic clutches,
- belt or chain drives and
- gearboxes.

VSDs can be used to save significant amounts of energy in process operations compared to traditional control methods where the load or speed of the operation varies, adding to system inefficiencies. When considering motor-pump assembly with flow control by means of an actuating valve, throttling always occurs at full motor speeds resulting in full motor power usage throughout the speed ranges. VSDs increase electrical efficiency by allowing motors to run at ideal speeds with a benefit of reducing the electricity consumption while achieving the reduced speeds.

Saidur *et al.* (2012) established that the simplicity and low costs mechanical VSDs are still preferred. Variable speed controls through mechanical VSDs all exhibit similar characteristics. Motors operate at constant speeds while the mechanical coupling ratio alters to achieve varying speeds. The torque load on the coupling device output increase and as a result, the motor torque load will increase in relation thereto (Saidur *et al.*, 2012).

Therefore, electrical VSD control still has a massive market to penetrate. Pertaining to the general lack of awareness on this technology in the industry, the energy saving accompanied thereby, the simplicity and proven effectiveness thereof.

Varying water flow with VSDs

Studies have shown that implementing VSDs to control electrical motors is one of the most efficient and promising control methods to utilise partial load conditions (Mecrow & Jack, 2008).

Seasonal weather changes and daily temperature fluctuations have shown to have an effect on mine refrigeration systems cooling demand and as a result partial load conditions exist as explained earlier. Several studies found that cooling water and air is oversupplied during these periods without considering the potential for optimising refrigeration and cooling components accordingly (Du Plessis, 2013; Vosloo, 2008).

A solution would be to match the water and air temperature supply of the refrigeration and cooling system according to demand requirements (Yu & Chan, 2013). The water flow through each circuit (evaporator, condenser and BAC) within the refrigeration system can be varied to achieve this (Du Plessis, 2013).

A generic variable flow control strategy was developed by Du Plessis (2013) to achieve the desired variable control on mine surface refrigeration systems. This strategy was adjusted and applied on gold mines' surface refrigeration systems. It resulted in an average daily system electrical energy consumption reduction of 35.4% during a three-month period.

Costs saving related toward implementing VSDs

Figure 29 is a visual representation of the theoretical cubic power-flow Affinity Law. This shows that large electrical energy savings can be achieved with relatively small motor speed and flow variations (Saidur *et al.*, 2010). Figure 29 illustrates the relationship between speed reduction and power consumption of an electric motor.

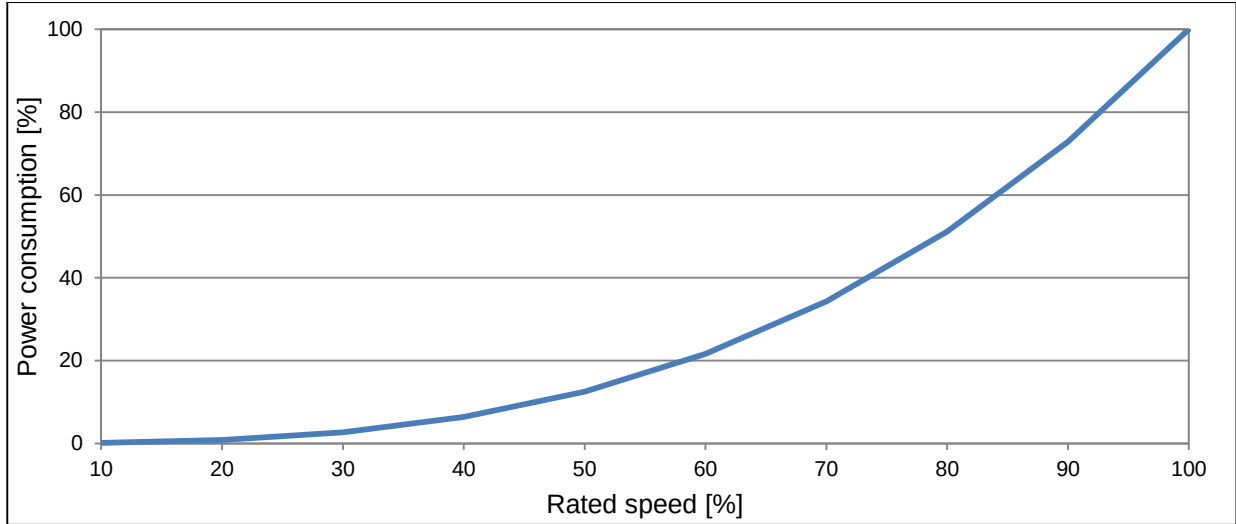


Figure 29: Electric motor power consumption as a function of rated motor speed (Saidur et al., 2010)

For example when applying Equation 2.7, a 25% reduction in motor speed will result in a 42.2% motor power consumption of the full load $(0.75)^3$ (Saidur et al., 2012). Therefore, the power consumption of the motor will be reduced by 57.8%.

$$S_{SR} = (1 - ES_{VSD})^3 \quad (2.7)$$

where,

S_{SR} = New motor power usage with reduced speed [% of full load power]

ES_{VSD} = VSD speed reduction [% of speed reduced]

The motor electrical energy usage and saving can be estimated with the following equations (Thirugnanasambandam et al., 2011):

Electrical motor energy usage:

$$AEU = \eta \times P \times L \times hr \quad (2.8)$$

where,

AEU = Annual energy used [kWh]

η = Motor efficiency [%]

P = Power rating [kW]

hr = Operating hours [hrs]

L = Load factor [-]

and

$$L = \frac{kW_A}{kW_R} \quad (2.9)$$

where,

kW_A = Electrical motor actual capacity [kW]

kW_R = Electric motor rated capacity [kW]

Now the VSD energy saving can be calculated by using Equation 2.10:

$$AEU_{VSD} = AEU \times S_{SR} \quad (2.10)$$

The cost-effectiveness is commonly indicated by the PBP, which can be calculated by Equation 2.11 (Saidur *et al.*, 2012):

$$PBP = \frac{C_{VSD}}{CS_{VSD}} \quad (2.11)$$

where,

C_{VSD} = Cost of installing VSDs [kW]

CS_{VSD} = Cost saving with VSDs [kW]

The cost saving of a VSD can be calculated with Equation 2.12 (Abdelaziz *et al.*, 2011):

$$CS_{VSD} = ES_{VSD} \times ET \quad (2.12)$$

where,

ET = Electricity tariff [c/kWh]

The following simplified equation can be used during the investigation process to identify possible pump electric motors for implementation of VSDs. An equation was developed to estimate the potential VSD savings achievable from a flow reduction of between 0% and 30% (Saidur, 2010). It is said that the condenser and evaporator flow rates will rarely be reduced below 30% of the design flow during variable flow interventions (Van der Zee, 2013).

$$VSD_{saving} = (1 - \frac{m_{reduced}}{m_{measured}})P_{pump} \times 2 \quad (2.13)$$

where,

VSD_{saving} = Savings resulting VSD flow reduction [kW]

$m_{measured}$ = Measure flow before VSD implementation [l/s]

$m_{reduced}$ = Reduced flow with VSD implementation [l/s]

P_{pump} = Measure power usage of pump with $m_{measured}$ [kW]

Control strategies implemented on mines

VSDs installed on chillier compressor motors alone can lead to a 12 – 24% energy saving (Qureshi & Tassou, 1996). Implementing VSDs on chiller compressor electric motors have shown to have poor PBP, pertaining to the high costs of medium-voltage VSDs in SA. A potential PBP of 4.2 years exists when chiller loads can be reduces substantially. However, a PBP of only 15.5 years with typical reduced loads can be achieved, due to the large cooling requirements on mines (Du Plessis *et al.*, 2013). From an economical view, this would not be feasible pertaining to the long return on investment.

PBPs of less than one third of the expected electric motor life should be considered viable (Abdelaziz *et al.*, 2011). When considering low-voltage electrical motors instead where typical feasible PBPs have been reported to be less than two years (Ozdemir, 2004). Pump and fan motors are considered more viable with reported PBP of 1.3 years and less (Crowther & Furlong, 2004; Du Plessis *et al.*, 2013). Crowther and Furlong (2004) confirmed that energy savings can be realised with variable speed control on cooling fans.

A 16.3% to 21% annual electricity consumption reduction was achieved on a case study with air-cooled centrifugal chillers through optimised condensing temperature control and varied evaporator chilled water flow. The ambient temperatures and chiller load conditions were used to adjust the condensing temperatures accordingly (Yu & Chan, 2008). During this exercise, it was noted that a minimum water flow rate should be set to prevent water from freezing in the evaporator tubes and scale building up in both evaporator and condenser tubes.

Du Plessis *et al.* (2012, 2013) specifically developed a new variable-flow control strategy that is versatile enough to implement on all large mine cooling systems. Table 3 is a short summary of the generic variable-flow strategy developed that can be altered for site-specific applications.

Table 3: Generic variable-flow control philosophy developed (Du Plessis, 2013).

Pump set	Variable water flow control philosophy
Evaporator pumps	Modulate flow to maintain set chilled water dam level
Condenser pumps	Modulate flow to maintain design condenser water temperature rise
BAC pumps	Modulate supply flow in proportion to ambient enthalpy Modulate return flow to maintain set BAC drainage dam level
Pre-cooling pumps	Modulate supply flow to maintain set pre-cooling dam level

During this study the effects of the variable-flow strategy was analysed with a case study gold mine used to verify the reported tendency of COP variances. It was shown that chiller COP will increase at decreased evaporator water flow rates and decrease at decreased condenser water flow rates (Yu & Chan, 2012; Navarro-Esbrí *et al.*, 2010; Gordon *et al.*, 2000).

A COP variance within 1.5% was maintained of the original value. It is important that both evaporator and condenser water flow strategies are implemented simultaneously (Du Plessis *et al.*, 2012). After implementation, the combined cooling load remained the same, although the combined plant COP increased by 33%.

This strategy was implemented on numerous gold mine refrigeration and cooling systems as shown in Table 4 (Du Plessis, 2013; Van Greunen, 2014). The variable-flow strategy resulted in an average daily power saving of 1 540 kW for the numerous gold mines. In other words, the refrigeration systems electrical energy consumption was reduced by 35% on average. This proved that the variable-flow strategy and energy management system could effectively be customised for a diversity of cooling systems to realise cost-effective energy savings. This was achieved without affecting critical service delivery requirements (Du Plessis, 2013).

Table 4: Average savings achieved with the variable-flow strategy implemented on various gold mines (2012/2013 Eskom tariffs) (Du Plessis, 2013; Van Greunen, 2014).

Gold mine	Average power saving [kW]	Measured saving [% of baseline]	Annual cost saving [R]	Implementation costs [R]	PBP [Months]
A	1 471	47	5 456 415	1 633 910	2.3
B	2 609	35	9 669 996	5 241 322	7.0
C	1 865	32	6 919 997	5 360 000	10.0
D	606	29	2 250 000	3 193 838	17.0
E	1 149	34	4 259 998	1 927 837	5.0
Average	1 540	35	5 711 281	3 471 381	8.3

Implementation costs on platinum mine refrigeration systems

It is important to consider related costs when evaluating the feasibility of optimisation strategies. These include capital expenditure required, return on investment and cost per saving achievable with project implementation. Data obtained from Mine A, B and C is shown in Table 5 and Table 6 respectively. Table 5 shows typical costs of low-voltage VSDs applicable for most pumps in the refrigeration system on platinum mines in SA.

Supply and installation cost per VSD increase with decreasing pump motor power ratings (Du Plessis, 2013). The benefit of pumps with smaller motor rating should be carefully considered before purchase. A result caused by the decreasing motor electricity saving possible and the increased cost per kW to implement (R/kW). Installation costs demonstrated in Table 5 include typical cabling, harmonic protection units, Programmable Logic Controller (PLC) programming, communication network equipment and the commissioning thereof.

Table 5: Typical VSD costs in South Africa (in South African Rand, November 2013 exchange rates).

Description	Voltage [V]	400 kW [R]	330 kW [R]	275 kW [R]	250 kW [R]	132 kW [R]
Company A	525	318 483	231 552	223 900	190 516	134 300
Company B	525	540 080	471 310	405 124	340 564	236 761
Average [R/kW]		1 073	1 065	1 144	1 062	1 406
Installation cost	525	20 929	49 744	48 469	40 415	28 033
VSD R/kW cost		52	151	176	162	212
Total R/kW cost		1 126	1 216	1 320	1 224	1 618

Table 6 reflects the costs pertaining to the implementation of an optimisation strategy with the installation of VSDs on refrigeration system auxiliary equipment. The proposed savings that can be achieved is based on an energy audit that was done by an ESCO. The total project cost is mostly related to pumping infrastructure installed on the mines, as more VSDs are required to achieve variable-flow control. The required VSDs that need to be installed on existing pumps to attain variable flow control are site-specific.

Table 6: VSD implementation on typical platinum mine refrigeration systems.

Mine	Cooling duty [MW]	Proposed saving [kW]	Evaporator pumps [kW]	Condenser pumps [kW]	BAC pumps [kW]	Project costs (Excl VAT)
A	19	1150	2 x 300	4 x 275	3 x 132	R3 093 801
B	10	700	3 x 250	3 x 275	-	R1 991 470
C	27	1440	2 x 400 1 x 200	5 x 400 2 x 250	-	R3 443 816

2.4.2. Chilled water demand management

Overview

There are various methods to improve water consumption and consequently the energy consumption on mine water reticulation, dewatering and refrigeration systems (Vosloo *et al.*, 2010; Vosloo *et al.*, 2012). Whilst most optimisation strategies focus on reducing the system's energy consumption, this section will focus on the factors causing the high-energy consumption.

Improving water system design and practise are key strategic requirements in moving towards a more sustainable mining industry (Gunson *et al.*, 2012). Through variable-flow control, mine refrigeration systems can be optimised by varying the water flow according to actual cooling loads, which in effect depend on the ambient temperature and chilled water demand. Using the identified variable-flow strategy one can optimise the supply-side of the chilled water. When a strategy or technology can be incorporated to reduce the demand of the chilled water, it will be possible to achieve even greater EE results.

It is shown that when service water distribution systems are incorporated with water reticulation systems, which is used in various places for cooling of ventilation air, large savings is possible (Gunderson, 1990; Whillier, 1980; Vosloo *et al.*, 2012). Service water is mainly distributed to production areas and the consumption, thereof, is approximately proportional to the rate of production (Vosloo *et al.*, 2010; Whillier & Van der Walt, 1977).

As stated earlier, due to limitations in underground heat rejection capacity and simplicity of surface refrigeration plants, surface cooling systems are preferred. In addition to cool ventilation air, chilled water is supplied underground by means thereof. This may be used in air-cooling devices adjacent to the working areas or as service water used in drills, dust suppression and sweeping (Howes, 2011). The cooling of service water as well as water used for remote cooling, such as MCUs, can significantly reduce electrical power consumption on mine refrigeration systems (Vosloo *et al.*, 2012).

Water is gravity fed through a series of high pressure piping networks to the working areas, the pressure increases by approximately 1000 kPa for every 100 m head. Hence, some form of water reduction is necessary to reduce the water pressure to safer working pressures (Vosloo *et al.*, 2010). Combining this increased water pressure and increasing water quantities required underground, saw the introduction of energy recovery devices to help improve the electricity consumption (Gunderson, 1990; Van der Walt & De Kock, 1984):

- Usually water turbines coupled to pumps or generators,
- 3-CPS (Three Chamber Pipe System) and
- underground refrigeration plants.

The 3-CPS and turbine systems are very efficient and practical alterations to the inefficient dissipaters. The problem with these very effective techniques is with the initial cost and time for implementation. The amount of water consumption underground must be of such quantity that the energy recovery resulting therefrom justifies the initial implementation (Gunderson, 1990; Vosloo *et al.*, 2010).

The used underground mine service and fissure water is channelled in trenches towards settlers, where mud is separated from the water. The water then flows into hot storage dams where it is pumped to the surface (dewatering system) (Thein, 2007). The hot water is then filtered and re-cooled for reuse in the water cycle, where the excess water is dumped into the environment, thus closing the reticulation system.

In this case, the objective is to reduce the amount of chilled water supplied underground, which will reduce the load on the dewatering system. In effect, the amount of chilled water required from the surface refrigeration plant will be reduced as well. This strategy will in effect result in electrical energy savings on the refrigeration system and dewatering system. The demand reduction in chilled water required underground will in effect reduce the cooling load on the refrigeration machines. The dewatering system will extract less water and therefore, pump cost savings can be achieved (Gunderson, 1990; Gunson *et al.*, 2012; Vosloo *et al.*, 2010).

In the following sub-sections, possible chilled water DSM strategies will be described and discussed. A viable solution for optimising platinum mines underground cooling system will be considered in terms of PBP. Further techniques to reduce mine water uses are explained by Gunson *et al.* (2012).

Water pressure control

Water leakages and wastage is a common occurrence in underground deep level mines. It is found that mining levels or areas where production has ceased are still supplied with water. The problem, even with pipes that are blanked off, is the water leaks that occur between the shaft water column and the abandoned mining section (Vosloo *et al.*, 2010). One technique Vosloo *et al.* (2010) implemented is to control water pressure entering underground mining levels to reduce this water wastage.

Figure 30 shows the water pressure rate as a function of water flow downstream of a valve, which is normally situated on each level near the shaft, and can be represented by a logarithmic function. This trend is unique for each level and is dependent on the pipe size and layout, valve specification and end users downstream of the valve (Vosloo *et al.*, 2010). It is important to realise that a downstream water leak at high pressure will cause increased chilled water wastages.

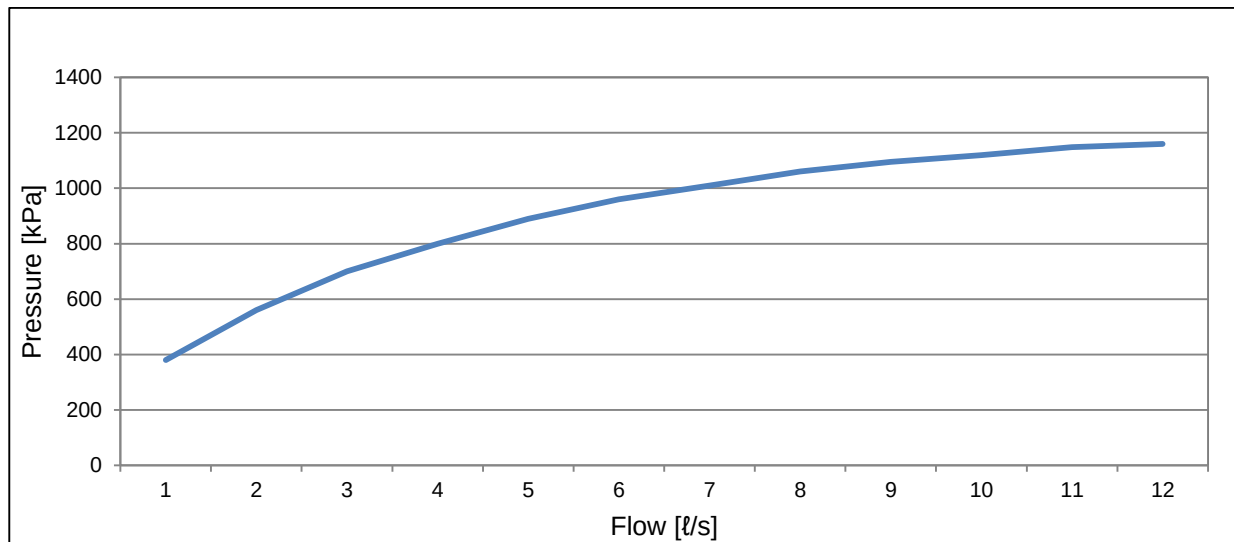


Figure 30: Relation between water pressure and flow (Vosloo *et al.*, 2010).

Briefly described, each level has a valve configuration near the shaft that can regulate water flow and pressure. Figure 31 illustrates the simplified valve configuration with two pressure control valves and one isolation valve.

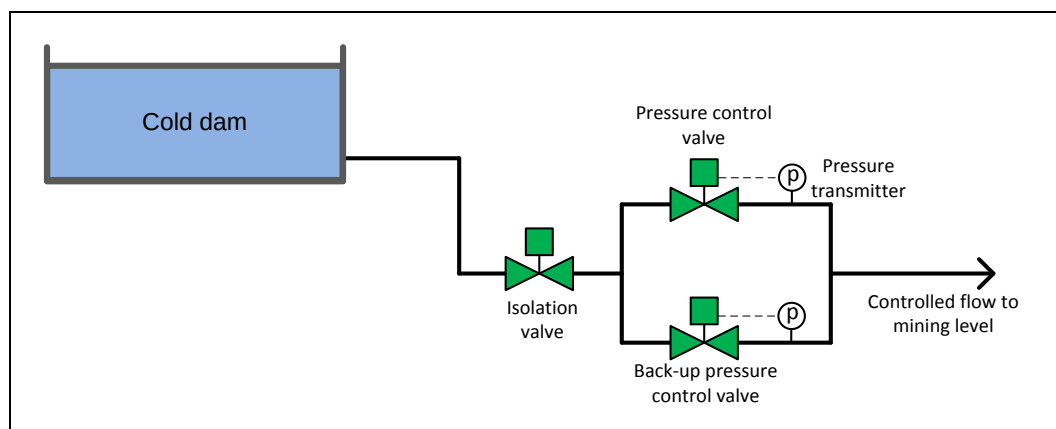


Figure 31: Water supply valve configurations (Vosloo *et al.*, 2010).

Depending on mine water flow and pressure requirements, these valves can be set to the required pressure set point. Different mining shifts and production or non-production days will determine the required pressure set point for the control and isolation valves, typically on non-production days the isolation valve will be fully closed (Vosloo *et al.*, 2010).

The problem with this reticulation strategy is that it will have large implementation costs, especially if there are no actuating valves installed initially. This strategy will be more feasible where mining production occurs at greater depths. At increased depths, mines usually consume more water and are more likely to have levels with no production. Increasing the electrical energy savings possibility, as these mines have more than one pumping station, which is usually not the case on platinum mines.

The supposition, therefore, can be made that this strategy requires higher initial pumping costs for the dewatering system and more levels of production and non-production. As a result, greater savings will be possible on the dewatering system and make the implementation thereof more viable. See Table 7 for implementation costs of such a strategy implemented on a gold mine.

Secondary cooling system optimisation

The primary ventilation distribution system delivers air to areas that need it rather than ventilating the entire mine whether or not it is required. An energy-efficient distribution system supplies the minimum quantity of ventilation air that is required, directly to each area depending on the activity. This is somewhat impractical pertaining to the complex tunnel networks and distances where ventilation is required. Mining also continuously advance further from the ventilation shaft causing the ventilation sources to be reallocated and non-working areas sealed off (Karsten & Mackay, 2012).

CC can then be used to provide secondary cooling near the stopes where primary ventilation air cannot reach. The advantage of CC is that it can be moved relatively easy to keep up with mining advances. The problem with using secondary cooling is the increase in chilled service water required underground and the increasing water quantities to be pumped to surface. Pertaining to that the volume of water that passes through CC varies according to the supply line pressure, which in effect varies throughout the day, causing further water wastage.

Another fact to consider is the chilled water temperature increases that can be experienced as soon as it leaves the chillers on surface and flows to the working areas. These temperature increases are caused by a series of factors listed below (Rawlins, 2007):

- Frictional losses,
- flow rates through pipes,
- increased geothermal gradient due to VRTs,
- fluid compression and
- specification and quality of pipe insulation.

The effects of the increased water temperatures reaching the CC must therefore be taken into consideration. This can be achieved by controlling the water flow through the CC that will ensure optimal cooling performance and minimal water wastage. Mines experience fluctuating pressures in the chilled water distribution piping underground and as a result, water flow rates increase/decrease accordingly, as shown in Figure 30. When the water flow through the CC is controlled, the cooling performance thereof will be maintained and the water wastage will be kept to a minimum. Reducing the energy consumption of the refrigeration system and dewatering system as result.

The simplest strategy to reduce unnecessary flow through CCs is by implementing either flow restricting or flow regulating valves. The objective, therefore, exists to regulate the chilled water flow entering the CC irrespective of the change in supply pressure and flow.

The problem with optimising the water flow through CC is that there usually is very little infrastructure available at the point of application. Further, CC is moved regularly to keep up with mining advances. The required infrastructure will need to allow for valve control that needs to be mobile. Alternatively, a mechanical flow regulating valve can be installed that requires no extra instrumentation. The obvious solution will be to use mechanical valves instead, to keep the installation simple and the costs to a minimum.

Mineworkers regularly tamper with essential mining equipment to delay production. It is important to provide a simple and cost effective solution that will be tamperproof and robust enough to withstand the harsh mining conditions (Marè *et al.*, 2014).

There are a few mechanical valves available to optimise the water usage of CC that will comply with these identified constraints. Two of these identified valves are explained in the following sub-sections.

A. Maric constant flow rate valve

Each CC has a designed water flow rate that allow for optimal cooling performance. When the flow rate deviates from the design it can result in unnecessary water dumping or increased outlet air temperatures. The mechanical valve shown in Figure 32 ensures a constant water flow rate is maintained, regardless of upstream pressure differentials. The valve utilises a flexible rubber control ring with an orifice, this orifice diameter open and closes correspondingly to the pressure differential, to maintain the pre-set flow rate (Maric Flow Control, 2011).

This valve installation as shown in Figure 33 will make it possible to reduce the water wastage through the CC, by maintaining a constant flow rate at all times regardless of the upstream pressure inconsistencies.



Figure 32: Maric 50mm x 3 orifice screwed brass constant water flow control valves adopted from (Maric Flow Control, 2011).

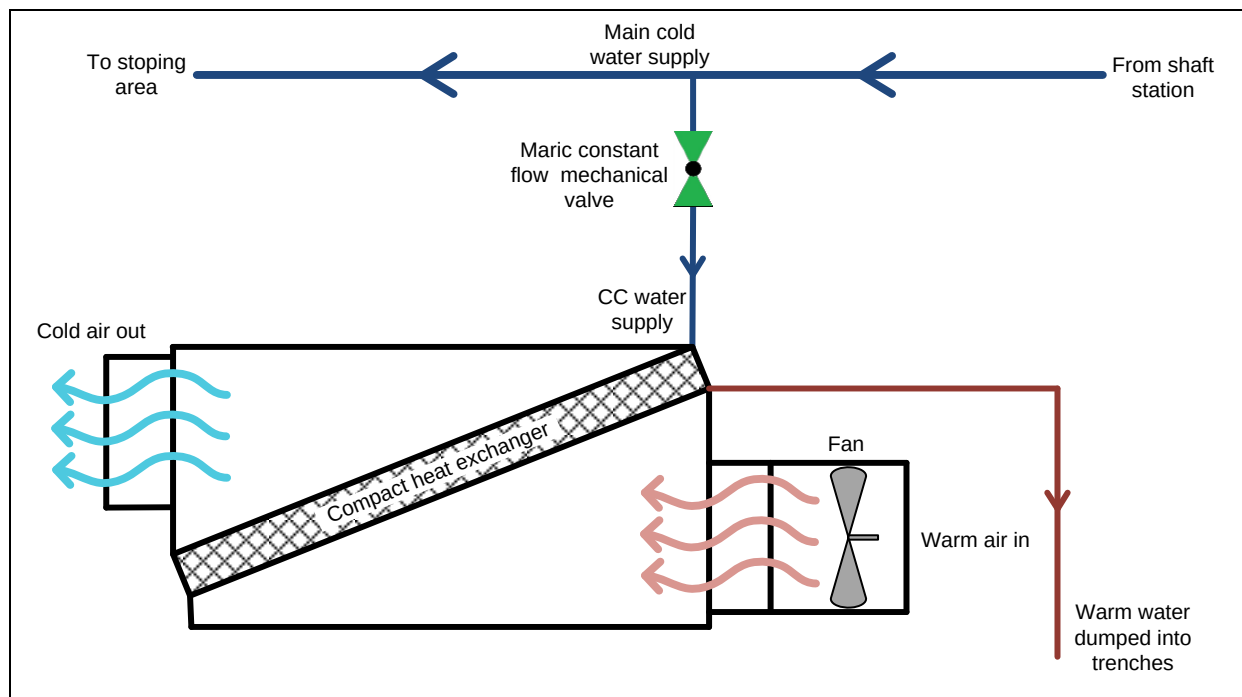


Figure 33: Schematic diagram of Maric cooling car valve assembly.

Figure 34 illustrates the typical range and accuracy of the Maric constant flow valve. It is shown that the flow is maintained at the rated flow for a wide range of pressure differentials. Theoretically, with the Maric valve fitted, regardless of upstream pressure deviations, the water flow through the CC will remain relative constant. This of course causes the volume of water dumped into the trenches to remain relatively constant throughout. Whereas before, the flow

will increase in relation to the pressure increase as shown by Figure 30. Therefore, minimising the water wastage caused by pressures increases.

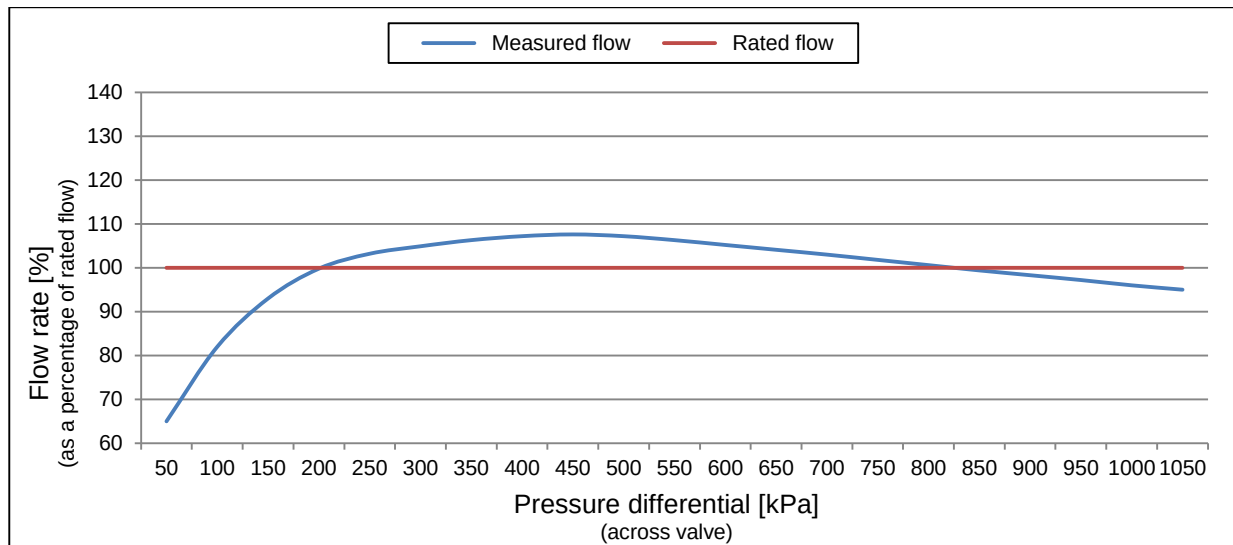


Figure 34: Typical performance of valve irrespective of body size or flow rate (Maric Flow Control, 2011).

Marè et al. (2014) performed tests on a gold mines' CC with a flow regulating and flow-restricting valve. It was established that the flow-regulating valve was the best-fit valve to use due to its ability to sustain a constant water flow. This regulating valve was a Maric constant flow rate valve as shown in Figure 32.

An electrical saving of 37.5 kW was achieved with the flow-regulating valve per application. This includes the savings due to less pumping and the chiller energy saving (Marè et al., 2014). The summary of the cost savings is summarised in Table 7.

B. HPE constant flow rate valve

The mechanical HPE CC valve system ensures a constant flow through a CC irrespective of the flow demand used for downstream operations. The valve reduces water wastage by only dumping water to mining trenches when the downstream demands from operations are less than the flow required through the CC. See Appendix B for a further detailed explanation, a summary explanation will follow here.

If the demand from downstream operations is more than the CC flow requirement, the water will be directed back into the main service water supply line, assuming that the pressure is within the design range. The valve configuration and CC valve assembly is shown in Figure 35 with a schematic thereof shown in Figure 36.



Figure 35: HPE constant water flow control valve (Hydro Power Equipment (Pty) Ltd, 2012).

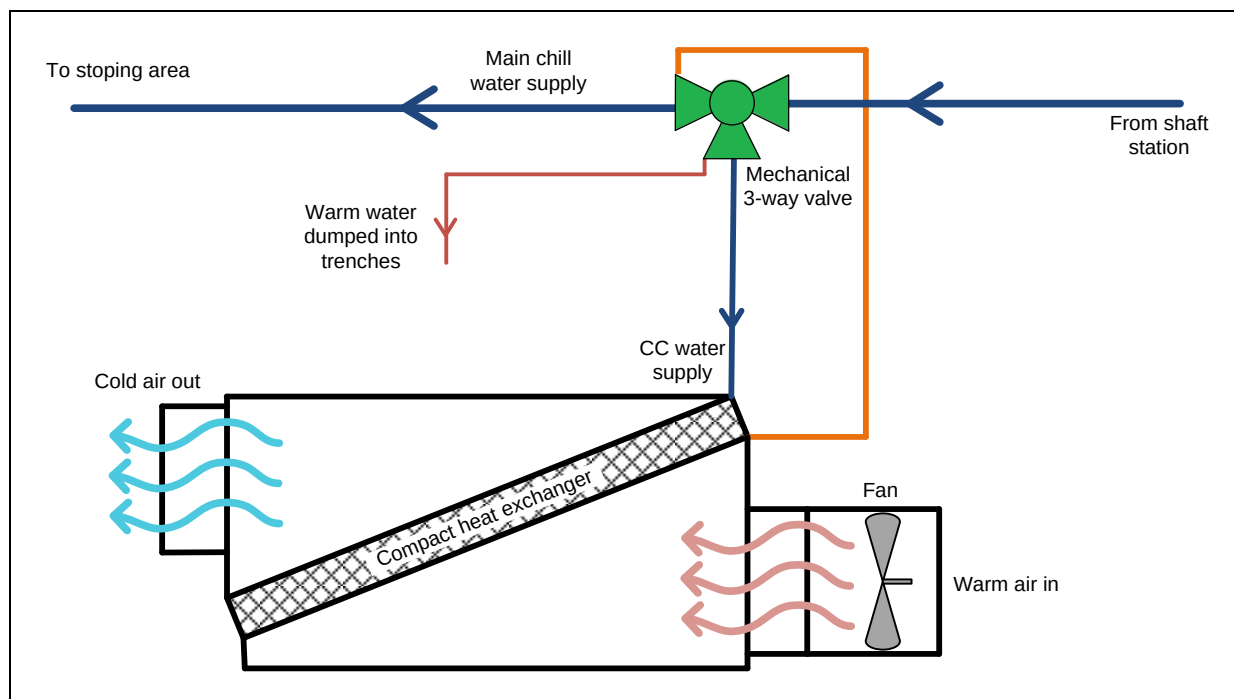


Figure 36: Schematic diagram of HPE cooling car valve assembly.

Even though both HPE and Maric valves ensure a constant flow rate through the CC, the HPE has the advantage of returning used water to the service water line. Thus, the water wastage expected from the HPE application shows the potential to be less than that of the Maric valve.

The disadvantage of the HPE valve is the fact that the working pressure of the valve must be pre-set by the manufacturer to that of where it will be implemented, as the valve operation may deviate from the design. The valve is installed into the main water supply line, which causes a substantial pressure drop over the valve. It is essential for that reason to keep the pressure

drop into consideration if there is more than one CC installed on the same main water line. It should be verified that the pressure losses are acceptable before application. The Maric valve should rather be considered when the pressure losses are significant.

Feasibility of chilled water demand management

Table 7 below summarises the savings achieved from implementing the different identified chilled water DSM strategies or equipment. The savings achieved is updated with 2014/2015 Eskom Megaflex electricity tariff structure. The pressure control and Maric valve figures illustrated in Table 7 were obtained from Vosloo et al. (2010) and Marè et al. (2014) finding's. The theoretical calculation made to determine the HPE valve savings are shown in Appendix B.

Equipment costs for pressure the control strategy implemented by Vosloo et al (2010) includes all project costs like PLC programming, supply and installation of all equipment, commissioning and labour costs. The cost for the pressure control strategy includes the control of numerous mining levels of the case study gold mine. Whereas the equipment costs for the Maric and HPE valve only include the supply for a single valve respectively.

Table 7: Chilled water demand savings with respective strategies (2014/2015 electricity tariff).

Strategy / Equipment	Water saving [kl/day]	Average power saving [kW/day]	Annual cost saving [R]	Equipment cost [R]	PBP [Months]
Pressure control	1300	449	2 061 687	2 249 863	13
Maric valve	237	37.5	172 178	4 784	0.4
HPE valve (theoretical)	423	55.6	255 289	40 040	1.9

With the focus of the study on optimising the surface refrigeration system and budget constraints, it is impossible to implement the variable flow control strategy with the underground water pressure control strategy. The focus therefore placed on the management of the CC water flow with the respective valves.

Even though the Maric valve shows the shortest PBP, it will be more sensible to implement the HPE valve if one considers the savings achievable over a longer period. For that reason, it was decided to install the HPE valve system on the case study platinum mine's four CCs.

2.5. OBSTACLES FOR IMPLEMENTING EE TECHNOLOGIES ON MINES

The significant awareness of safety around the underground environmental conditions in underground mines caused it to become one of the biggest concerns for the mining industry. When alterations are suggested to the cooling and refrigeration system of most mines, they are very careful and in some cases, these systems are seen as inflexible (Calitz, 2006).

Research has shown that not many mines want to install DSM projects because of the following reasons (Calitz, 2006):

- Their mind-set is that they know how to run their equipment best.
- Resistance to change, everything is going on very well; there can be no improvement.
- Lack of capital to install equipment that is more efficient.
- Uncertainty regarding the future, reluctant to commit resources for long-term projects, investors requires payback periods in months rather than years.
- Failure of old DSM projects – making mines reluctant to implement new projects.
- Mining personnel not showing the necessary interest and enthusiasm to maintain projects and unsure for suitable practical implementations.

To convince mines to implement DSM projects on their cooling system requires detailed research, investigation and simulations. It is very important to understand mining equipment operations thoroughly and ensure that all system constraint and variable are considered in the simulation model.

In some cases, mines request further detailed investigation on essential equipment as they are sceptic about the imposed technology, equipment and control strategy. Thorough investigations can improve the accuracy of the simulated results and resolve in accurate and practical cost saving estimations (Holman *et al.*, 2013). At the end, this will ensure for a respectable practical project for the mine.

2.6. REQUIRED ALTERATIONS

The refrigeration and cooling system configurations on mines is site specific and the existing infrastructure differs accordingly. Each optimisation strategy will require different alterations and equipment for successful implementation as a result. Again, placing the focus on how important the investigation is to make certain on the required infrastructure, which will lead to an accurate project implementation cost analysis and minimise project implementation delays. This will improve the accuracy on the project cost estimation and therefore, the payback period after implementation.

To implement Eskom EEDSM projects relevant data, like power and ambient temperature, must be made available to measure the actual project savings achieved after implementation. It will be desirable that all relevant data be logged onto servers that can be accessed remotely.

It is essential to automate equipment so that one can view and control the system remotely from a centralised point. Mines usually make use of a PLC that controls all equipment automatically and SCADA systems that allow human interface with field equipment. The mining equipment that controls equipment make use of a complex network of fibre, profibus, modbus or a combination thereof for communicating with the PLC.

When adding equipment to the refrigeration and cooling system, it is mandatory to add this equipment to the PLC and SCADA interface. Changes to the infrastructure and communication networks are required to make DSM possible.

Each refrigeration and cooling system has its own distinct control strategy to deliver mine specific constraints and requirements. When developing a new separate overhead control strategy it is essential to accommodate the complex system efficiently. This will ensure reliability and optimal system control while adhering to the constraint while ensuring that DSM takes place automatically.

It is mandatory to integrate new control strategies effectively to ensure control from the same central point as the mine SCADA system. This will enable the collective energy management of the new proposed optimisation strategy of the refrigeration and cooling system. To achieve effective and automatic control a real-time energy management system (EMS) will be required. Du Plessis et al. (2013) developed such a real-time energy management system with the financial support of HVAC International (Pty) Ltd. (2012) to effectively implement, control, monitor and report savings of the refrigeration and cooling auxiliaries.

2.7. CONCLUSION

A need has been identified to reduce the electricity consumption on the large refrigeration and cooling systems as found on platinum mines. The large electricity users within the refrigeration and cooling system are identified so that the focus can be placed on identified equipment when proposing an optimisation strategy.

Through the literature review, a better understanding is brought forward so that the relevant system control operation and design can be identified. With this knowledge, the constraints and considerations can be analysed in more detail to be able to propose a better system optimising solution at the end.

The variable-flow strategy resulted in an average daily power saving of 1 540 kW for respective gold mines. In other words, all of the refrigeration systems electrical energy consumption was reduced by 35% on average. This shows that the variable-flow strategy developed and energy management system can effectively be used for a variety of cooling systems to realise cost-effective energy savings. This was achieved without affecting the mine service deliveries.

The variable-flow strategy, therefore, is identified as the most effective optimisation strategy to improve platinum mines refrigeration and cooling systems. The VSDs used to vary the pump flows allow for automatic control from the current mine PLC and SCADA system that can improve the proposed system redundancy as well.

The identified secondary cooling system contributing to the cooling load experienced by the refrigeration system. A mechanical valve identified that shows the possibility of reducing the water wastage of CC. Two types of valves were considered to implement on mine CC cars. The HPE 3-way valve theoretically shows to have improved water wastage reducing capabilities. This can reduce chiller and dewatering system electricity loads. Therefore, the HPE valve system will be implemented on the case study.

CHAPTER 3. OPTIMISATION MODEL DEVELOPMENT



Setup and development of an optimal refrigeration and cooling system control strategy.

3.1. INTRODUCTION

The information provided in the literature provides a background understanding for the relevant system components and principles used for operation. This platform improves the quality of decision making when identifying and proposing optimisation strategies to implement on the now familiar refrigeration and cooling systems.

It was identified that a variable-flow strategy with the use of VSDs show the most promising potential to optimise mine refrigeration and cooling systems by controlling pump speeds, with reduced pump power input as a result. The implementation of VSDs provides an extra benefit of controlling the required cooling load according to the load demand, resulting in reduced chiller compressor power.

The benefits of improving the chilled water demand underground provide the potential to achieve greater electricity savings on multiple mining systems. A mechanical valve was identified that has the potential to reduce the chilled water wastage on secondary cooling equipment. This can result in reduced power consumption on both the dewatering and refrigeration systems.

Throughout this chapter, the refrigeration and cooling system of a case study platinum mine will be investigated and analysed. This will provide a reference point for the power consumption and will highlight points where the system may have potential for optimisation. Thereafter a solution will be proposed and simulated to quantify the feasibility of the strategy in terms of project payback periods.

3.2. ELECTRICITY LOAD WITH BASELINES AS REFERENCE

3.2.1. Overview

The uncertainty about the effectiveness of industrial EE projects can be improved with the accurate measurement of data and energy savings, which will improve the estimation of the expected savings more accurately. Therefore, standard protocols have been developed to quantify energy savings with accurate results obtained and verified to deliver successful strategy implementation savings (ASHRAE, 2002; US Department of Energy, 1996). In SA Measurement and Verification (M&V), guidelines for EEDSM projects and programmes are published by Eskom's Corporate Services Division Assurance and Forensic Department to verify the energy saving results (Den Heijer, 2009).

Independent M&V teams are contracted by Eskom to ensure that energy savings realised with DSM projects are measured and verified according to the mentioned standards (Xia & Zhang, 2012). This was also applied for the proposed optimisation strategy on Mine A, the case study platinum mine. The independent M&V team was fully responsible for auditing the refrigeration system and all measured data before and after implementation. Including the development and verification of all electrical and system data used in this study (Eskom Corporate Service Division, 2013).

3.2.2. Baseline development

To establish a power consumption baseline for the refrigeration system the daily consumption thereof was measured and recorded. When there is no data available for the power consumption of the refrigeration system, temporary data recording power meters can be installed to obtain the power usage. The independent M&V team use this data to develop an electrical baseline for the strategy. The daily electricity consumption of the total refrigeration system prior to project implementation is reflected in the baseline shown in Figure 37.

Three summer months (January – March 2012) were used to develop the baseline profile. The scaling of the baseline that is done according to ambient conditions will compensate for the exclusion of winter months in the baseline. The verified baseline shown in Figure 37 is categorised into weekdays, Saturdays and Sundays. The baseline is compiled in this manner to accommodate the different tariff structures of Eskom's Megaflex tariff structure (Eskom, 2013).

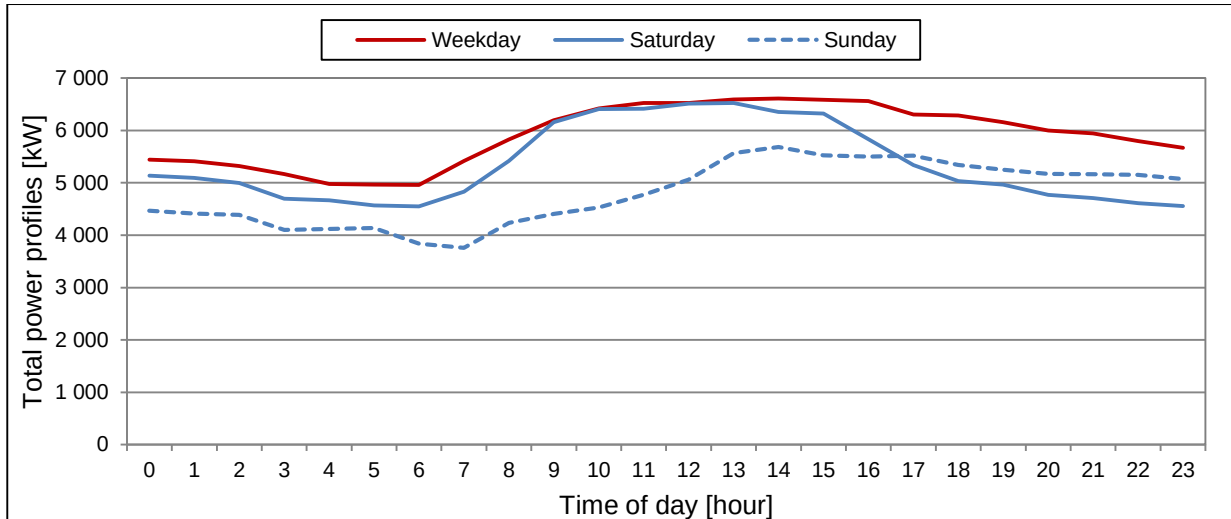


Figure 37: Mine A surface refrigeration and cooling system total average electricity baselines.

The lower chilled water demands experienced over weekends are due to mining production decreases experienced, which contributes to a lower measured Saturday and Sunday baseline.

The Sunday baseline is noticeably lower than the weekday baseline, especially in the morning hours (6:00 – 12:00 am). The refrigeration system is usually switched off during these hours to do regular maintenance. The morning hours is mostly used for maintenance as colder ambient temperatures are experienced during these hours. The refrigeration system is started around 13:00 by mine personnel to allow the system to recover, before production commences again on Monday. This mostly takes place on off-weekends, usually at the end of each month.

Data displayed in Appendix A, Figure 66, along with the calibration certificate shown in Figure 68, indicates the accuracy of the power (kW) data obtained for the refrigeration system before and after project implementation. All other data was obtained from the on-site SCADA system.

3.2.3. Baseline scaling

Measuring and comparing energy consumption of pre- and post-implementation periods is a method to quantify the energy savings achieved on the system. However, cooling system electrical energy usage is typically found to be a function of ambient weather data and/or production variables. These variables are prone to changes frequently observed between pre- and post-implementations periods (Du Plessis, 2013). It is, therefore, important that these changes be accounted for, to ensure accurate reported savings after implementation (Kissock & Eger, 2008).

Regression modelling is used in principle to measure savings included in all verification standards (US Department of Energy, 1996; ASHRAE, 2002; Den Heijer, 2009). Pre-implementation data is typically used to develop a weather and production-dependent regression model. This model presents an accurate correlation between the system electrical energy usages, weather and/or production verified data. This model can then be used to calculate the daily energy consumption of the system from the weather and production data daily (Du Plessis, 2013).

The model is then used post-implementation to calculate what the daily system energy consumption would have been, had there been no system alteration. The reflecting measured baseline data points are then scaled in relation to the calculated regression model. The average scaled baseline is equal to the average calculated by the model. If there are no major changes in the system, the daily energy savings can be calculated by subtracting the scaled baseline with the post-implementation power profile (Du Plessis *et al.*, 2013).

$$P_{savings} = P_{scaled\ baseline} - P_{post-implementation} \quad (3.1)$$

The case study mine, Mine A, has a variable temperature chiller installation, where the power consumption of the refrigeration system will mainly depend on the daily ambient temperatures. This was justified with the regression model, where an accurate model, which correlates between the daily average electrical power usage and average ambient temperature, was used. The regression model developed was verified by the contracted M&V team and subsequently approved by Eskom (Eskom Corporate Service Division, 2013)

The equation, based on the daily data obtained during the baseline period (January 2012 to March 2012), was averaged for each hour of the day. All weekend, public holidays and condonable (data loss) days were excluded from the data set. The independent M&V team was responsible for verifying all data used to measure the savings achieved and performance is correct and accurate. The equation that was delivered is as follow:

$$y = 142.49x + 2485.5 \quad (3.2)$$

y = Calculated daily average electricity consumption of the system [kWh/day]

x = Measured daily average ambient DB temperature [°C]

Equation 3.2 is used to calculate the scaled power baseline using the daily average weather data. Equation 3.1 is then used to calculate the true daily energy saving. The importance of comparing equivalent pre- and post-implementation data is emphasised from the energy measuring standards. Data, therefore, is regarded as condonable when mine production shutdowns and data loss occurs.

3.3. REFRIGERATION AND COOLING SYSTEM CONSTRAINTS AND VARIABLES

3.3.1. Refrigeration and cooling system background

Mine A, a platinum mine situated in the BIC with a surface refrigeration system and four underground CC, is to be investigated. The mine was selected as a case study due to its large contribution to PGM operations in SA. With the high mining production, increased cooling loads are experienced which results in high cooling demands (Mudd, 2012).

Figure 38 illustrates the surface refrigeration and cooling system components with a simplified connecting piping network layout.

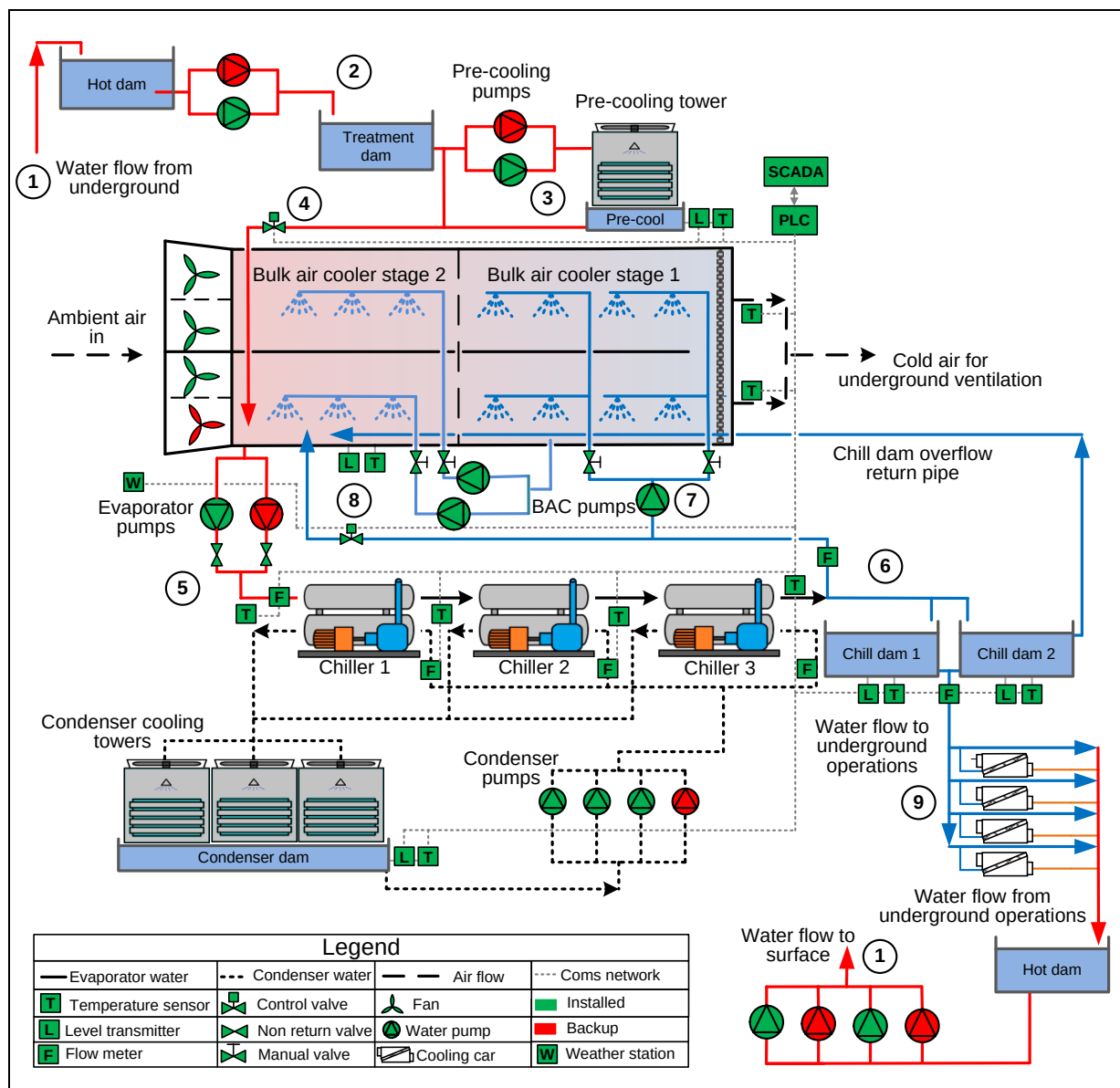


Figure 38: Mine A refrigeration system prior to project implementation.

The general operating conditions of the refrigeration and cooling system are as follows:

1. Hot water is pumped from underground and enters the surface hot dam at a temperature of 25°C.
2. From the hot dam, the water is pumped through the water treatment system and is stored in a water treatment dam.
3. From the treatment dam, water is pumped through a pre-cooling tower and is stored in the pre-cooling sump.
4. From here, the water is gravity-fed through an actuating valve that sustains a pre-set BAC sump level. The average temperature in the BAC sump is 13°C.
5. The BAC sump water is then pumped at 330 l/s through three fridge plants in series to provide chilled water at 5°C in the chilled dam.

As explained during the literature review, chillers are connected in series to accommodate varying water and ambient temperatures. This is achieved by switching chiller machines on or off to accommodate temperature variances without having an effect on the water supply.

There are bypass valves at the inlet and outlet of the chiller machines, these valves are mainly used when a chiller is taken offline – to ensure that the water flow to the mine is not influenced. The combined nominal cooling capacity of the surface refrigeration system is 19 MW with a COP of 4.5 at a condenser water inlet temperature of 25°C and evaporator water outlet temperature 6°C.

6. From the fridge plants, chilled water flows towards two 3 ML surface chill dams and a two stage horizontal BAC.
7. A mixture of chilled and BAC sump water is then sprayed through the BAC nozzles with one first stage pump and two second stage pumps.
8. The water can also flow by means of an actuating valve to the evaporator pump suction pipe, where it mixes with the pre-cooled water in the BAC sump. This is done to maintain a constant chiller evaporator water inlet temperature.
9. From the chilled water dams, water is supplied underground by demand for mining activities. These activities include the operation of four secondary CC to provide secondary ventilation air.

The surface refrigeration machines, condenser cooling tower, BAC and pre-cooling tower specifications are displayed in Table 8 to Table 11 respectively.

Table 8: Mine A surface chiller machine specifications.

Description		Unit
Number of chillers	3	-
Make	Howden	-
Compressor type	Screw	-
Compressor motor rating	1 800	kW
Refrigerant	Ammonia	-
Voltage	11 000	V
Cooling capacity per chiller	6 450	kW
COP	4.5	-
Evaporator outlet temperature	5	°C
Condenser inlet temperature	24.6	°C
Evaporator water flow	350	kg/s
Condenser water flow	440	kg/s
Evaporator pump motor rating	330	kW
Number of evaporator pumps	2	-
Condenser pump motor rating	275	kW
Number of condenser pumps	4	-

Table 9: Mine A surface condenser cooling tower specifications.

Description		Unit
Number of cooling towers	3	-
Water inlet temperature	30	°C
Water outlet temperature	26	°C
Water Flow	440	kg/s
Air inlet WB temperature	22	°C
Number of cooling tower fans	3	-
Condenser fan motor rating	90	kW

Table 10: Mine A surface BAC specifications.

Description		Unit
Number of BACs	1	-
Water inlet temperature	6	°C
Water outlet temperature	13	°C
Water flow	240	kg/s
Air Flow	260	kg/s
Air inlet WB temperature	16	°C
Air outlet WB temperature	12	°C
Number of BAC fans	4	-
BAC fan motor rating	160	kW

Table 11: Mine A pre-cooling tower specifications.

Description		Unit
Number of cooling towers	1	-
Water inlet temperature	26	°C
Water outlet temperature	20	°C
Water flow	90	kg/s
Air inlet WB temperature	18	°C
Number of pumps	2	-
Pump motor rating	110	kW

3.3.2. Constraints and variables

With each refrigeration and cooling system, relevant constraints exist to deliver mine specific requirements according to specified system control strategies. When implementing new control strategies it is essential to understand the functionality, limits and constraints that exist. This, to ensure the system is not affected negatively in any manner. Therefore, it remains essential that these fixed constraints be adhered to during and after implementation of new optimisation strategies.

To ensure that these constraints are adhered to, safety trips are programmed into the system PLC. A typical built-in safety parameter that protects the chiller evaporators from freezing is the evaporator water flow. If this flow is lower than the minimum trip value the water in the evaporative heat exchanger can potentially freeze. Therefore, as a precautionary measure, the chiller machines will trip automatically if the flow is too low to ensure that this does not occur.

Some of these important parameters listed in Table 12 to Table 14, allow the system and relevant equipment to function safely within the pre-set operating conditions. These conditions were set during the system design and installation to prevent permanent damage to equipment. It is vital that all existing limits are considered when proposing system alterations.

The entire refrigeration and cooling system is fully automated and all relevant equipment can be controlled from the SCADA system. This is also true for the chiller machines that have built-in safe start-up and shutdown sequences to ensure the correct procedures are followed throughout operation. The load control on the chiller machines are also done automatically by the PLC.

The simplest way to distinguish between parameters that can be altered and constraint that cannot be changed is by categorising them. Van Greunen (2014) categorised variables according to controllable and uncontrollable variables. Uncontrollable variables cannot be

changed as they are set by design limitations. Controllable variables are ones that can be changed within the pre-set limits.

Table 12 to Table 14 provide the system limits that needs to be taken into account when implementing variable flow control by means of VSDs. Table 12 shows the three chiller machines temperature and flow constraint ranges. Any of these constraints can cause the chiller machine to shutdown/‘trip’, resulting in possible machine damage or production losses.

It is important to take note that there are more constraints (interlocks) built in the PLC that is not relevant to the variable flow strategy and is controlled by the PLC. Nevertheless, it remains important to be aware of this as the varying flow can cause chiller ‘trips’ as result of reduced flow rates.

Table 12: Mine A Chiller controllable water system ranges.

Chiller 1 -3 limits	Unit	High high alarm	High alarm	Low alarm	Low low alarm
Condenser water dam temperature	°C	30	25	11	10
Condenser water flow	ℓ/s	450	440	300	280
Evaporator water in temperature	°C	25	20	3	1
Evaporator water out temperature	°C	15	10	0.7	0.1
Evaporator water flow	ℓ/s	380	360	215	200

Table 13 shows the BAC system constraints. The air outlet temperature for the BAC is defined by the underground ventilation requirements and is one of the refrigeration system deliverables to ensure safe and productive mining operations underground.

Table 13: Mine A BAC system variable ranges

BAC Limits	Unit	High high alarm	High alarm	Low alarm	Low low alarm
BAC air outlet temperature	°C	15	12	4	3
BAC dam level (% full)	%	98	95	55	45
BAC dam water temperature	°C	30	25	5	3

The second deliverable from the refrigeration system is the chilled water that needs to be supplied at a set temperature range as shown in Table 14. It is important to maintain dam levels within the limits to ensure sustainable chilled water supply for underground mining operations to prevent mining operational loses.

Table 14: Mine A chill dam system variable ranges

Chill Dam Limits	Unit	High high alarm	High alarm	Low alarm	Low low alarm
Chill dam temperature	°C	30	25	3	2
Chill dam level (% full)	%	100	95	60	50

Variables that cannot be controlled are the ambient air temperature, underground water requirements and hot dam temperatures. Even though the hot dam temperatures can be reduced with the pre-cooling tower, the temperature drop achieved is still dependent on the ambient air conditions.

3.4. OPTIMISED SOLUTION ON IDENTIFIED SYSTEM INEFFICIENCIES

3.4.1. Overview

It is important when proposing alterations to the refrigeration system that the service delivery of the system is not affected negatively. It should rather be expected that the proposed optimisation strategy improve the service delivery and efficiency thereof.

From the literature study, it was found that the variable flow control model was identified as the most effective optimisation strategy to implement on a gold mine cooling system. Actual results are presented to prove the accuracy and effectiveness thereof in Chapter 2. Now the feasibility of adopting this model to implement it on platinum mines' refrigeration and cooling systems will be investigated. The case study platinum mine (Mine A) is identified as the best fit application to prove the effectiveness and adaptability of the variable flow strategy developed by Du Plessis et al. (2013).

Mine A's refrigeration and cooling system control will be investigated to identify the possibility of optimising the entire system. This will be achieved by incorporating a new variable flow control strategy with the existing system. The first step was to investigate the system control and identify control inefficiencies.

3.4.2. Present system inefficiencies

Pre-cooling water flow

Analysing the current refrigeration and cooling system control will provide insight to inefficient system control and equipment that will lead to possible suggested improvements. The refrigeration and cooling system automated control is programmed into the PLC controller to allow reliable system control. Even though safety measures were taken, the general lack of instrumentation and network link maintenance resulted in some controls to become redundant.

The WB temperature used for the pre-cooling tower control is calculated from the weather station installed on-site. The PLC uses the DB temperature and Relative Humidity (RH) measured by the weather station to calculate the respective WB temperature. This process failed due to communication problems experienced between the weather station and PLC. As a result, the technician forced a constant value of 14°C into the PLC. The problem with this is that the pre-cooling tower fan and pump is controlled according to this WB temperature.

When the hot water temperature is higher than the ambient WB temperatures the pump and fan will start to maintain a pre-set pre-cooled sump level. Otherwise, when the hot water

temperature is lower than the ambient WB temperature the water will bypass directly into the pre-cool sump. The problem with the forced value is the water will be heated instead of cooled when the measured ambient WB temperature is higher than the water temperature. This will result in unnecessary chiller machine power consumption due to the elevated evaporator inlet temperatures. Therefore, the chiller compressor will have to work harder to achieve the same chilled water temperature.

Evaporator water flow

Figure 39 illustrates the evaporator pumps and make-up water pipe configuration and layout. The make-up water pipe is not shown as it is inside the BAC spray chamber. The make-up water flow to the BAC sump is controlled by means of a pneumatic automatic actuating valve to maintain a BAC sump level of 98%.

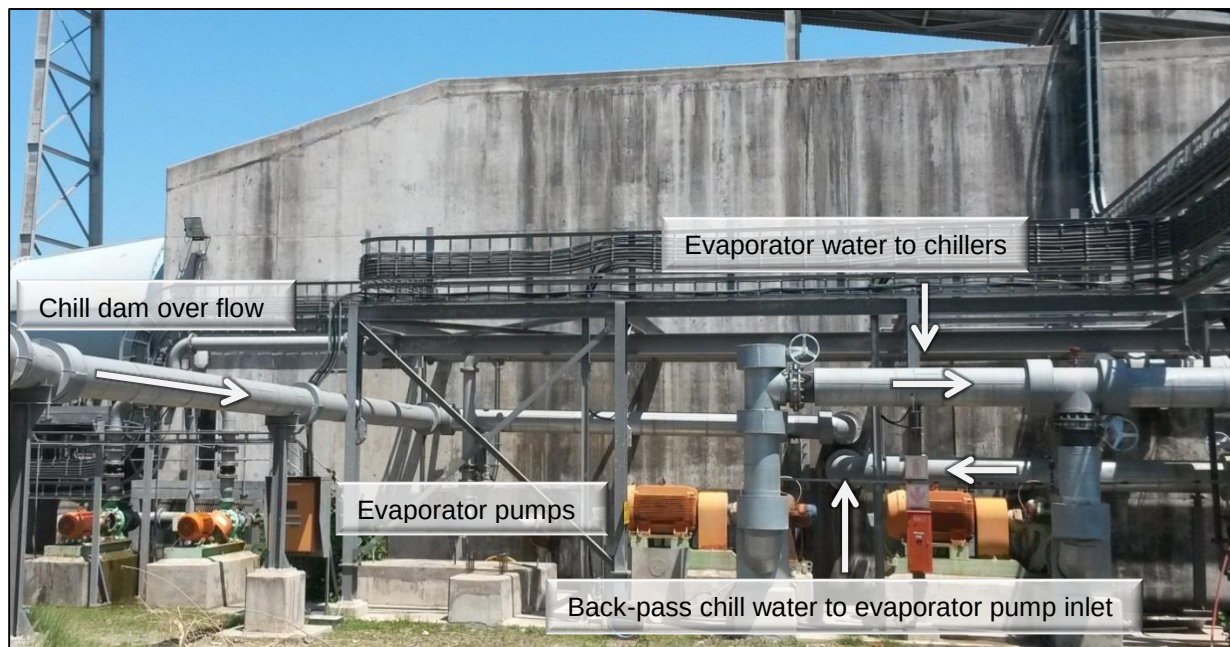


Figure 39: Mine A evaporator pump pipe configuration and design at BAC.

Consequently, hot pre-cool water is dumped regularly into the BAC sump close to the evaporator pumps suction pipe. This causes the BAC sump temperature to rise in correspondence to the valve control. As a result, the chiller machines experience evaporator water temperature fluctuations, as shown in Figure 40. In an attempt to reduce this effect, chilled water is directed towards the evaporator pump suction pipe by means of a back-pass pneumatic automatic actuating valve.

Figure 40 and Figure 41 represents a single day's data (15:00 –18:00) acquired in November 2013 with 2 minute intervals. For this day, Chiller 1 and Chiller 3 were in operation. Chiller 1

inlet and Chiller 1 and Chiller 3's outlet temperatures along with the BAC air outlet temperature is illustrated graphically in Figure 40. It is reasonable to conclude that the control of the actuating valve controlling the chilled water flow towards the evaporator pump suction, no longer works or the control thereof is inefficient and inadequate.

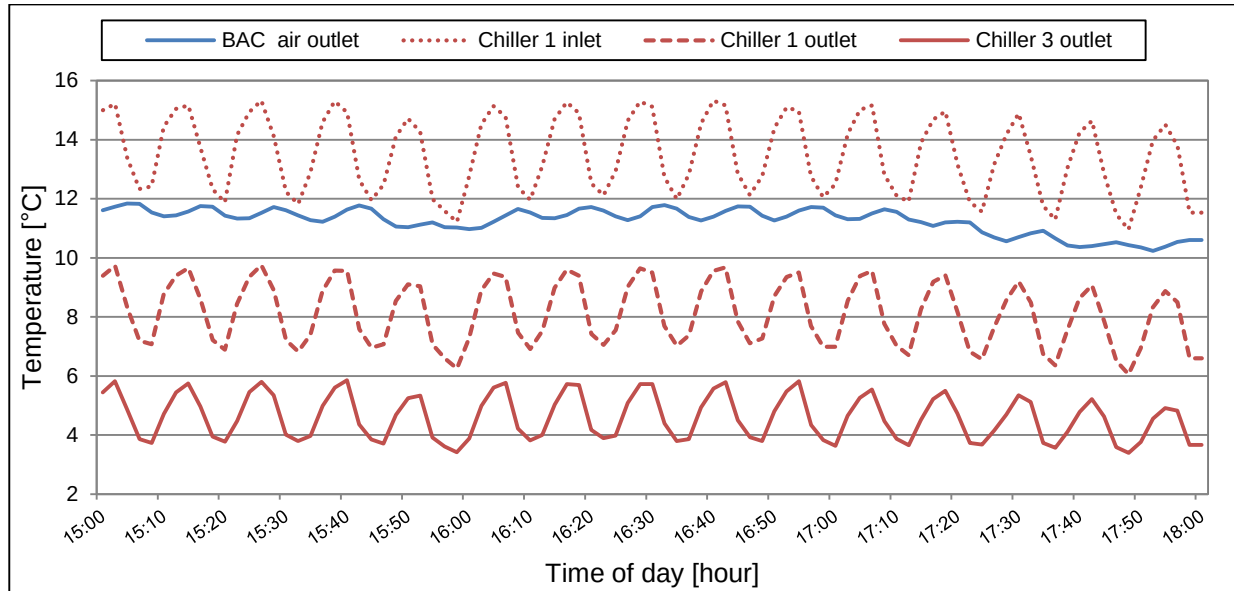


Figure 40: Inefficient evaporator water temperature control of Mine A.

The effect of the intermittent opening and closing of the automatic actuating valve controlling the warmer make-up flow into the BAC sump can be seen clearly. A varying chiller evaporator outlet temperature of about 2°C is experienced throughout. If the valve opens, the evaporator temperature increases as a result and vice-versa for when the valve closes again. The ripple effect of this can be seen through to the BAC air outlet temperature as well, exemplifying the negative effect of this inefficient control.

This is definitely not ideal for the chiller machines' load control. This causes the sliding valve on the compressor to open and close constantly to compensate for the varying cooling load and as a result, the power usage of the compressor also fluctuates accordingly. It is shown that the total power usage fluctuates up to 600 kW for the illustrated time. The varying power load of the compressors can be seen on the total refrigeration system power consumption as shown in Figure 41.

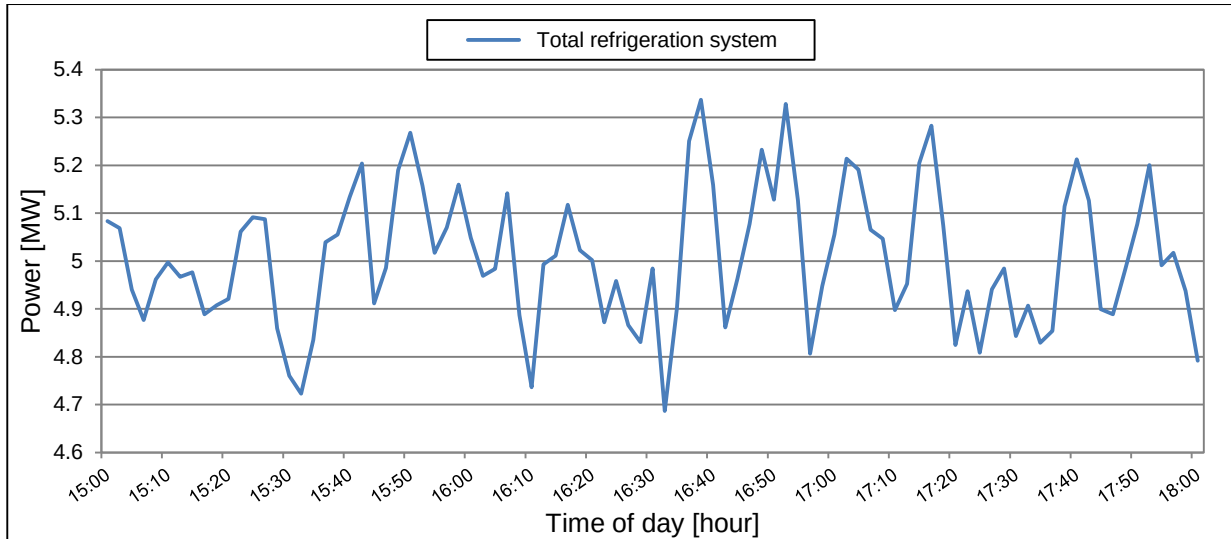


Figure 41: Refrigeration system total power consumption.

Further, the chillers are installed in series to accommodate varying cooling loads throughout and to maintain a constant water supply by doing so. Mine A, in fact experiences varying water flow requirements as well. Secondary cooling is mostly performed during summer months and not the winter months on Mine A. Secondary mine cooling is mostly achieved by four CC installed underground. As a result, the varying cooling load experienced on the chillers is a combining effect of the ambient temperature changes and chilled water requirements experienced.

The evaporator pumps force water through the chillers at a constant water flow rate throughout the year and cannot be adjusted for varying chilled water requirements. The only control that exists in this system to accommodate the decreasing cooling load is to reduce the amount of active chillers. Mostly three chillers are used in the summer months and two chillers during the winter months to sustain the system cooling requirements. Therefore, the colder winter months are used to perform yearly maintenance.

The chill dams overflow occasionally as a result of the constant evaporator pump flow rate and decreased underground chilled water consumption. The chill dam water overflows and returns to the BAC sump and is then recirculated through the chillers, resulting in unnecessary cooling loads on the chillers. Figure 42 show the chill dam overflow and supply pipe network. It, therefore, is suggested that control should be installed to monitor and control this more efficiently.

There are no observed mine practises to throttle the evaporator flow to reduce the recycling of chilled water from the chill dams back to the BAC sump. This presents the most probable

energy saving opportunity on the system. As both the evaporator pump and chillers present the opportunity to reduce their power consumption by the reduced evaporator flow.

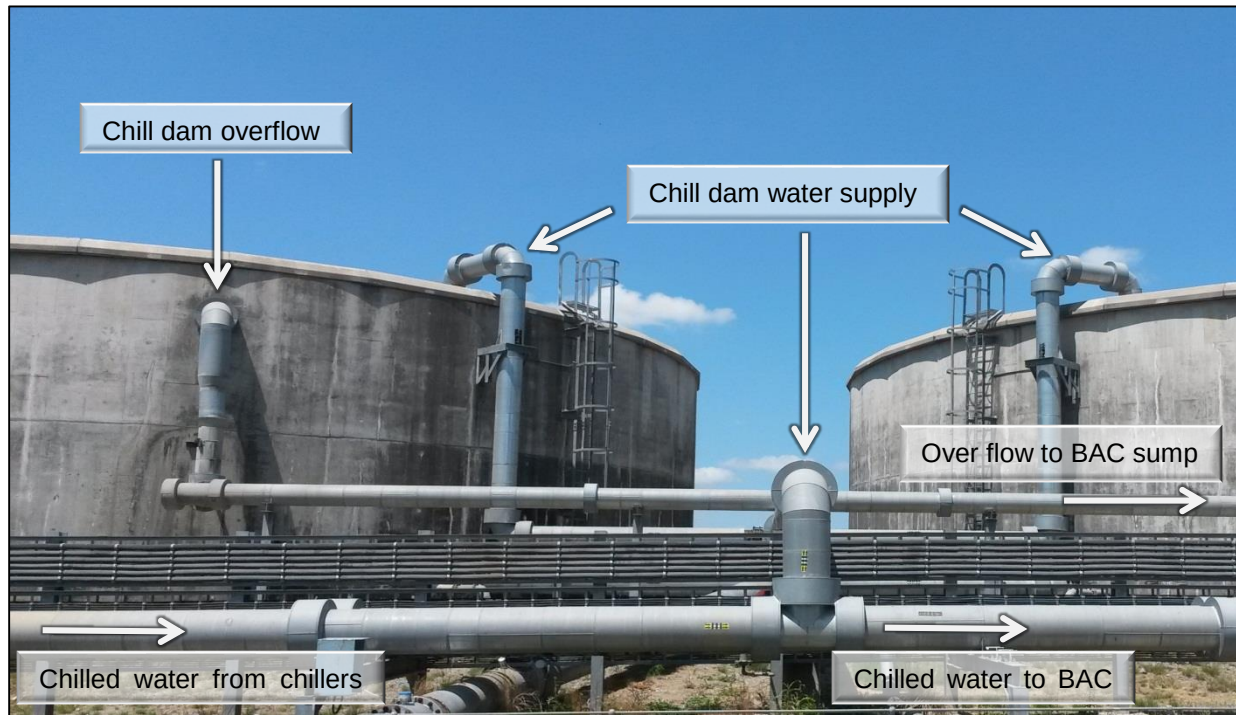


Figure 42: Mine A chill dam water supply and overflow pipe network.

Condenser water flow

The heat generated in the cooling proses of the chillers is dissipated to the atmosphere by means of the condenser water circuit. The condenser water circuit entails condenser pumps that force water at a constant flow rate through the chiller's condenser heat exchanger, where after the water is forced through the spray nozzles of the condenser cooling tower. The amount of heat the water gains (difference between the condenser in and outlet temperatures) when flowing through the condenser depends on the cooling load the chillers experience.

When high cooling loads are experienced, the water temperature difference will increase accordingly, resulting in the cooling towers to dissipate more heat. This is pertaining to that the cooling towers perform according to design performance to supply water at the required chiller condenser inlet temperature. With increased average condenser temperature, the chiller COP can decrease since higher condenser refrigerant temperatures are required (Du Plessis *et al.*, 2013).

The theoretical heat exchange through the condenser is given by Equation 3.3 (Borgnakke & Sonntag, 2009).

$$\dot{Q}_c = \dot{m}C_{pw}(T_{wo} - T_{wi}) \quad (3.3)$$

where,

$\dot{Q}_c$ = Theoretical heat exchange in the condenser [kJ]

$\dot{m}$ = Mass flow of the water through the condenser [kg/s]

C_{pw} = Specific heat coefficient of water [kJ/kg.K]

T_{wo} = Condenser water outlet temperature [K]

T_{wi} = Condenser water inlet temperature [K]

From Equation 3.3 it can be seen that if the mass flow is kept constant at the design point, but the thermal load is lower than the design, the temperature rise in the condenser water will also be lower than designed for. With low average condenser temperature, the chiller COP can improve since it lowers the condenser refrigerant pressure required (Du Plessis, 2013).

The potential to save pumping energy by reducing the flow according to the temperature rise design is apparent. This is of particular interest since it is shown in the literature review that the COP of the chiller is not affected significantly if at all, when implementing variable flow on both the condenser and evaporator circuit of the chiller simultaneously (Du Plessis, 2013).

BAC water and air flow

The data shown in Figure 43 is average hourly data for one summer month (November 2013) and one winter month (July 2013). Mine A requires the BAC air outlet temperature not to exceed 10°C throughout the year. As illustrated by Figure 43 this is not always achieved during the summer months (September – April) as the temperature could only be maintained at 12°C.

This proves that the chillers are not cooling the water enough to achieve the desired BAC outlet temperature of 10°C during the summer. This can be a result of poor chiller performance due to the lack of maintenance. These factors can cause the equipment's performance to deteriorate with time (Holman *et al.*, 2013). Therefore, it is required that regular maintenance is performed to clear all sediment build-up within the equipment.

Alternatively, this can be a result of outdated control strategies that are used with underperforming equipment, which are no longer performing according to design specifications. It is apparent to update the system control accordingly to achieve the required design outputs like chill dam and BAC outlet temperatures.

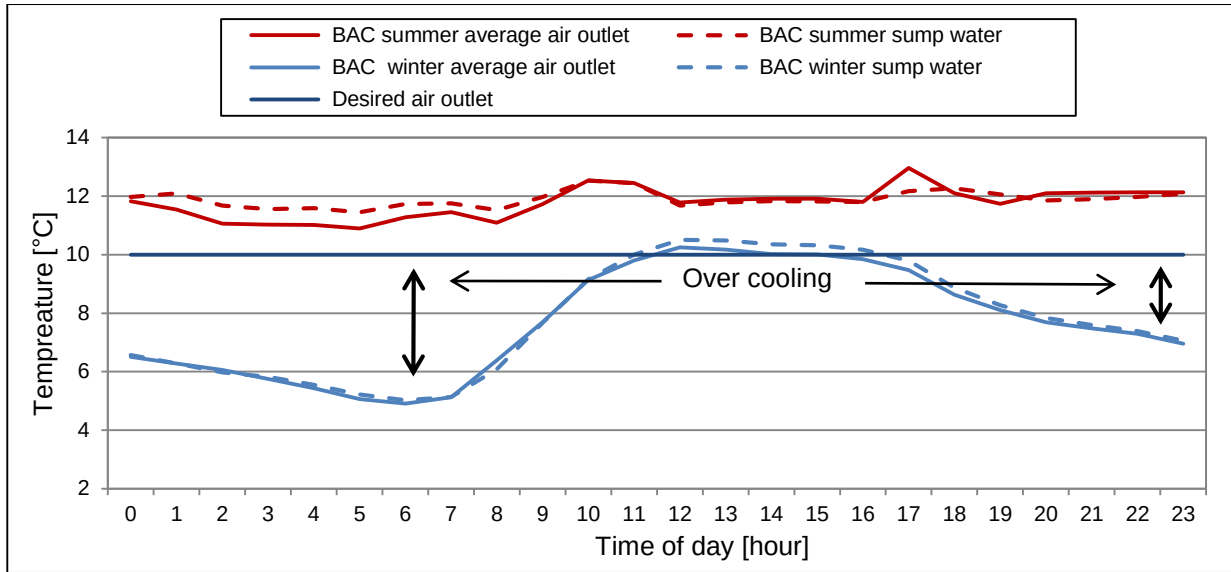


Figure 43: Mine A average BAC sump and air temperatures for winter (July 2013) and summer (November 2013).

In the winter season (May – August) the pre-determined BAC air outlet temperature is achieved. Further, it is shown that the air is over-cooled due to the reduced ambient temperatures experienced during winter months. This over cooling suggests that the spray water flow through the BAC can be reduced to lower the cooling achieved by the BAC. This will resolve in pump savings if the flow is reduced by means of VSDs. The colder BAC air outlet temperatures experienced late nights and early mornings suggest there is daily potential for BAC water flow control.

It is important to notice that the BAC sump water temperature and air outlet temperature have a correlation between them throughout operation. This is due to the first and second stage BAC spray pumps that extract water from the sump. It is not illustrated in Figure 38, but the first stage BAC pump extracts a mixture of chilled water and BAC sump water as shown in Figure 44. Therefore, when the sump temperature is reduced, more heat extraction can take place between the spray water and air, due to the increased delta temperature. As a result, the air temperature can be reduced more effectively or the pump flow can be reduced accordingly.

It is evident when more pre-cooled water is dumped into the BAC sump, the BAC sump water temperature will increase. Ultimately, the BAC air outlet will increase in correspondence thereto. High evaporator flow rates will cause the pre-cool water flow to increase to maintain the BAC sump level, this if the chill dams are not overflowing. This will in affect speed-up the rate at which the BAC air temperature will increase. This is definably not favourable during the warmer hours of the day.

The potential exists for the evaporator pumps rather to pump more water during the night (22:00 – 06:00) than during the day as lower ambient conditions are experienced. The increased make-up water flow will not affect the BAC air temperature as expected for during the day. This will only be achieved if the chill dam capacity is enough to supply the underground chilled water demand through the day with reduced evaporator flow.



Figure 44: Mine A BAC first stage spray pump water supply and delivery network.

Importantly, if the evaporator water flow is reduced, the following variables can be affected as a result thereof:

- Chiller water cooling.
- Water flow to the chill dams.
- Water flow to BAC sprayer pumps.
- Chilled water supply temperature.
- BAC sump temperatures.
- BAC air outlet temperature.

The above-mentioned points, thus, are highlighted as the most important variables to consider when simulating and implementing a variable-flow control strategy on the evaporator pumps.

CC water flow

As explained, there are four CC installed underground at Mine A. From the literature review, CC requires a chilled water flow rate of 7 l/s to ensure optimal cooling. The same quantity of

water that flows through the CC is dumped into the mining trenches. This result in constant water wastage of about 7 ℓ/s daily for each CC installed. From the literature review, there are mechanical valves that show the potential to reduce the amount of water wasted by a CC.

3.4.3. Proposed optimisation strategy

On Mine A's refrigeration and cooling system potential for optimisation were identified. It was concluded that a need exists to optimise the present control inefficiencies identified earlier on the system, to improve the power consumption thereof. Considering the cooling load fluctuations experienced by the refrigeration system and the fact that the controls to accommodate these fluctuations are non-existing or neglected, there exists considerable potential for optimising the present control strategies to realise electrical energy savings.

The daily varying evaporator inlet water and ambient weather temperatures cause the chiller machines operation to deviate from the desired load conditions, resulting in reduced COP values. Present chiller control only consists of switching a chiller machine in/out of operation when cooling load deviances are experienced. Therefore, the time before a chiller is taken out of operation, the chance of chillers not operating at desired loading conditions are eminent, which result in reduced chiller COP values. This reduced cooling load conditions can be controlled more effectively with the proposed variable flow strategy (Du Plessis *et al.*, 2012).

It is shown that due to outdated control strategies and deteriorating equipment performances the system was unable to achieve design chilled water and BAC air outlet temperatures. Further, the unnecessary recirculation of chilled water due to the lack of water flow control imposes the need to implement an optimised control strategy, to address this inefficient control. VSDs are widely used in the industry to control the water flow of cooling equipment (Van Greunen, 2014). VSDs regulate the speed of electrical motors driving pumps or fans by controlling the frequency of the voltage delivered to the motors. In addition to the equipment control capability, a measureable electrical saving is achieved with the reduced motor speeds.

CC used underground dump chilled water constantly into mine water trenches, causing ineffective utilisation of chilled water. As a result, additional chilled water is required from the surface refrigeration system. This additional water then has to be pumped back to surface. Therefore, the relevant dewatering equipment consumes unnecessary additional electrical power.

As discussed in the literature, mechanical valves exist that show the potential to reduce the water wastage on mine secondary cooling systems. Thereby, this additional electrical power

usage can be condensed. These valves use differential pressures to adjust the water flow accordingly, that ensures a constant water flow through the CC.

Figure 45 illustrates where the proposed equipment will be installed on Mine A's refrigeration and cooling system.

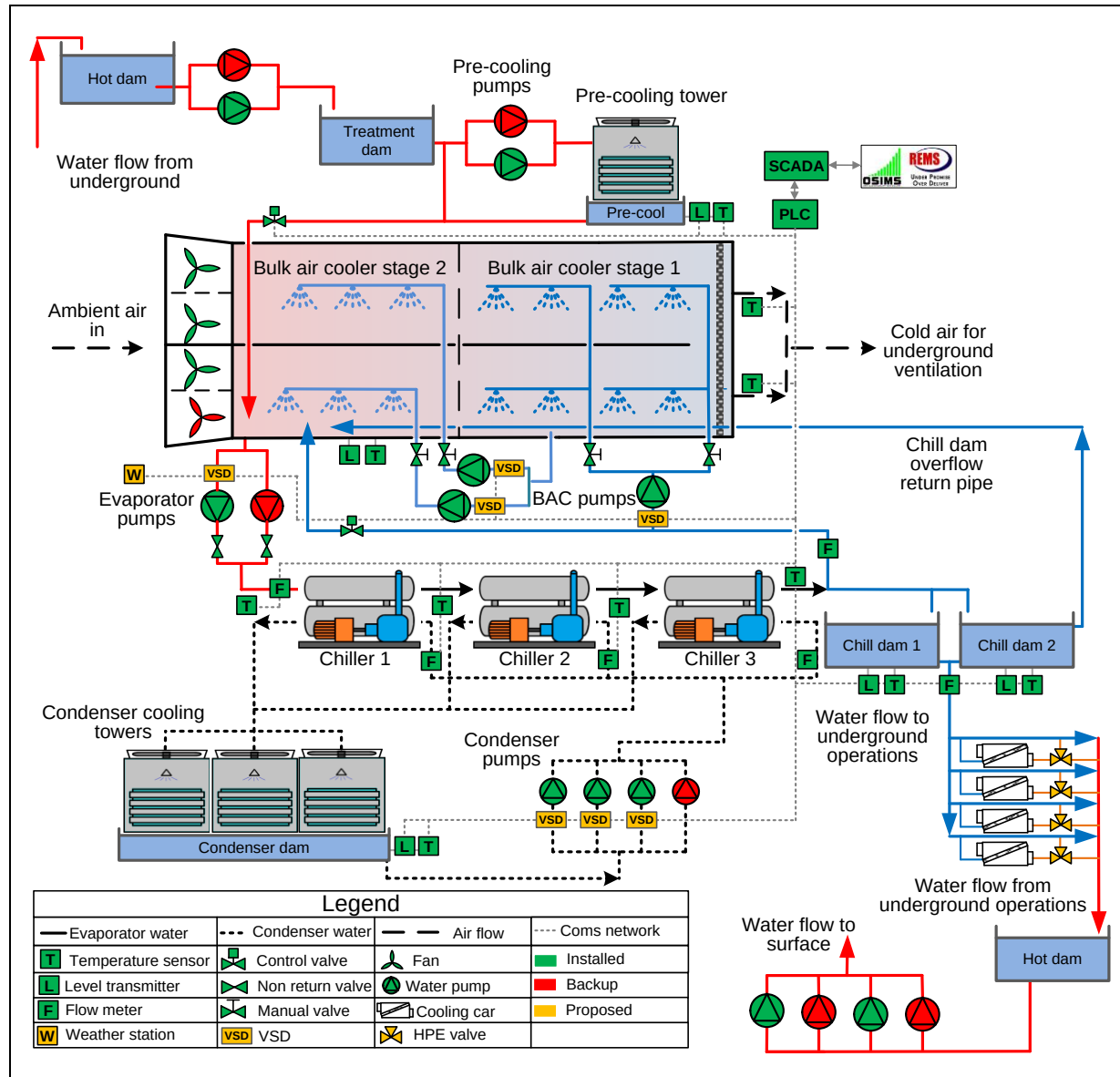


Figure 45: System layout with proposed infrastructure for Mine A.

As the present control is out of date, inefficiency is evident with the following electric energy wastages noted:

- General lack of efficient chiller control to accommodate cooling load variances,
- unnecessary chilled water recirculation through chillers,
- not extracting the optimal delta temperature for chiller condenser, and

- constant chilled water dumping by mine CC.

This creates the need for a modernised improved control strategy to implement on all relevant auxiliaries. This control can be implemented by installing mechanical control valves on the CC and VSDs for all relevant pumping equipment. This will allow for a reduction in chilled water demand underground and enable the water flow control and automation needed for successful control. It is vital that this control respond in real-time according to operational inefficiencies.

The EMS previously mentioned will be used to automatically control and optimise all necessary auxiliary equipment. This system will allow for the implementation of suggested optimisation strategy in order to achieve electrical energy savings. Figure 46 shows the control communication diagram implemented with the EMS.

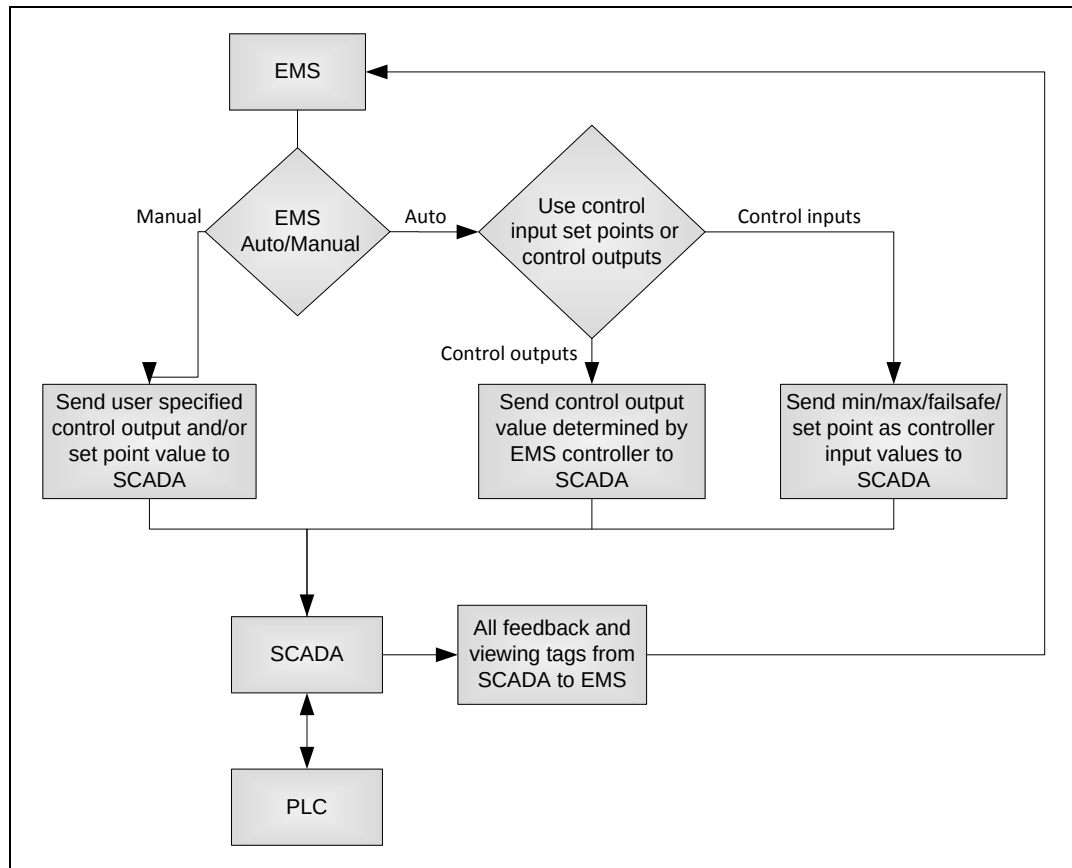


Figure 46: EMS control logic diagram adapted from Van Greunen (2014).

It will be essential to implement a redundant system to achieve constant optimal system performance. Therefore, an extra failsafe is built into the refrigeration system PLC where users can define safe control limits and parameters that will be used should the EMS fail. The failsafe control logic diagram is shown in Figure 47.

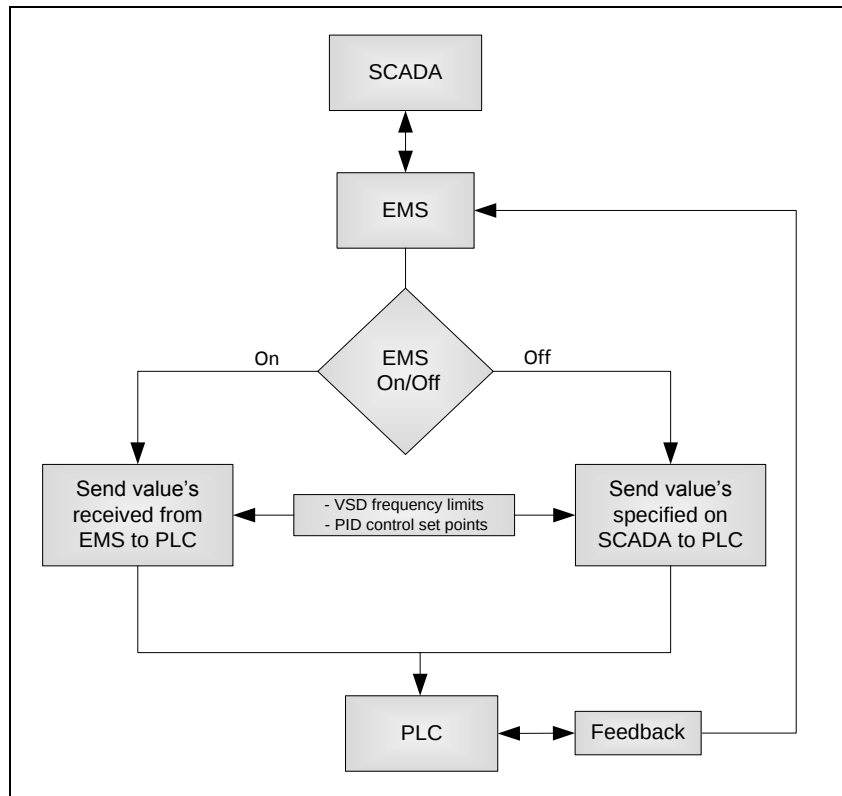


Figure 47: EMS to SCADA control communication diagram.

The general control logic implemented for the VSDs are simplified to improve the redundancy of the EMS control. The VSDs will control the flow rates of each pumping system according to set values laid out in the EMS. This includes the frequency limits that will be connected to the relevant flow constraints of each individual system. System constraints and control limits will typically be determined with the commissioning phase of the implementation.

The following sections will explain the proposed control for the evaporator, condenser, BAC, pre-cooling and CC water flow.

Pre-cooling flow control

The proposed solution for the pre-cooling tower control is to restore the weather station WB temperature reading on the SCADA. This will ensure that the existing pre-cooling tower Proportional Integral Derivative (PID) controller functions according to the original design specifications. Secondly, it is proposed to optimise the PID controller adjusting the make-up water flow to the BAC to allow a more constant water supply to the BAC sump. This will reduce the water temperature spikes experienced through the evaporators. The control logic diagram is illustrated by Figure 48.

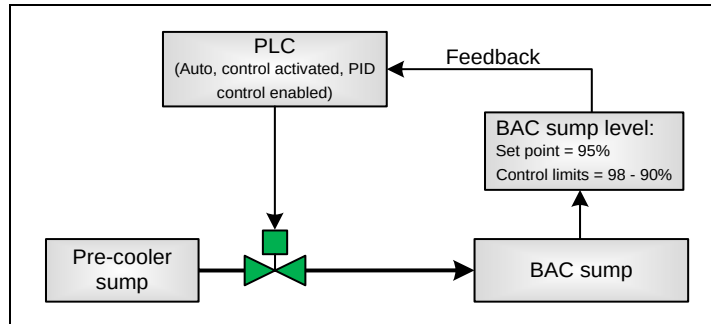


Figure 48: BAC sump pre-cooling water flow control logic diagram for Mine A.

Evaporator flow control

Dams serve as a storage medium to absorb the peak chilled water demands during mine drilling shifts. Therefore, it is essential that the relevant chill dam levels are always maintained between the specified levels.

It is proposed to install VSDs on the evaporator water pumps. The water flow will then continuously be controlled by means of PID control logic. The PID controller will ensure that the chill dam levels are maintained. Figure 49 shows the evaporator flow control diagram when implementing VSDs. The VSDs will reduce the water flow if the BAC outlet temperature is lower than the set point and if the chill dam levels are within the set dam level limits.

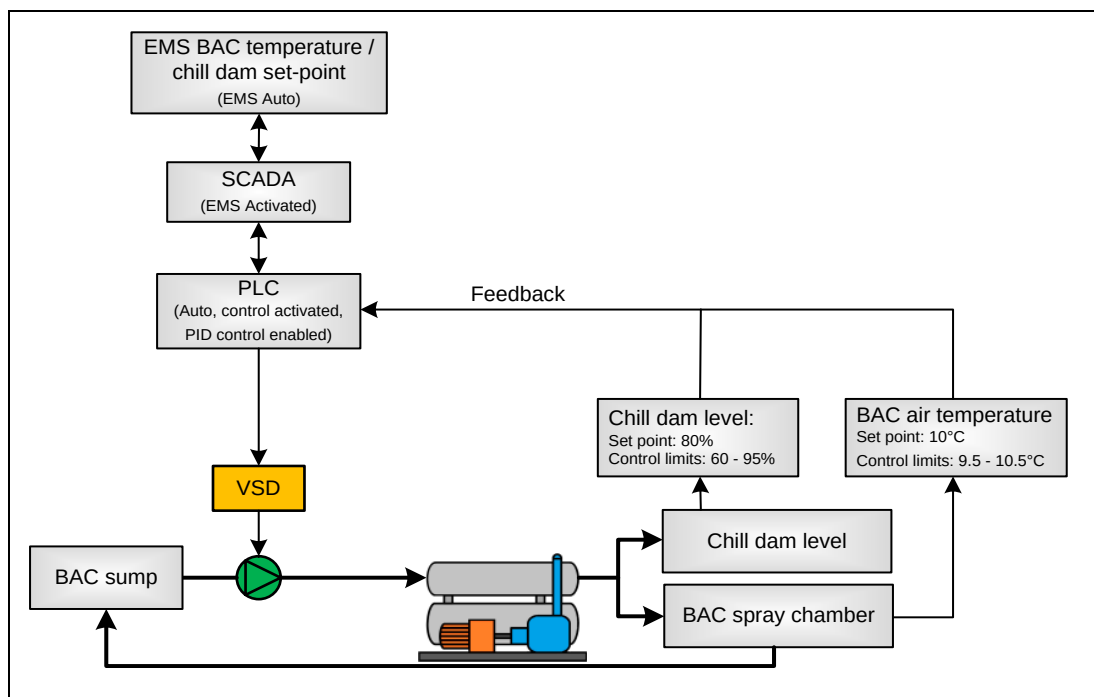


Figure 49: Mine A evaporator water flow control logic diagram.

Further, it is proposed that the back-pass PID valve controller is switched back to auto and optimised to reduce the evaporator inlet water temperature spikes experienced. The same PID

control logic is used for the actuating valve controlling the back-pass water flow to the evaporator pump water suction pipe. This PID control logic controller is already built into the refrigeration system PLC and can be altered on the SCADA system.

The evaporator water temperature is used as control feedback for the PID controller on the chilled water back-pass actuating valve. In summary, the control will open the back-pass valve according to the make-up water valve position. The control diagram is illustrated in Figure 50.

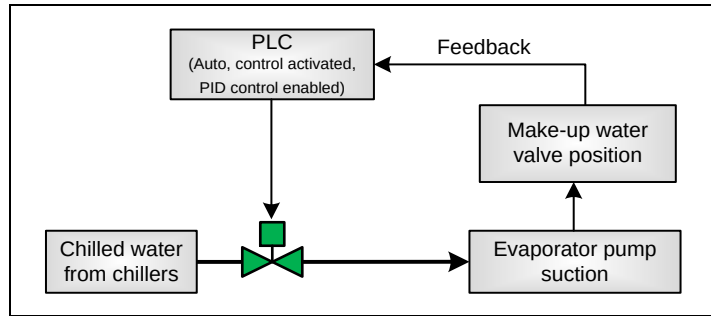


Figure 50: BAC sump make-up water flow control logic diagram.

Condenser flow control

It is proposed to install VSDs on all the condenser pumps. The condenser VSD speed will be controlled by means of a PID control loop to maintain the design water temperature difference across the condenser. Figure 51 shows the communication control diagram for the proposed water flow control when implementing VSDs on the all condenser pumps.

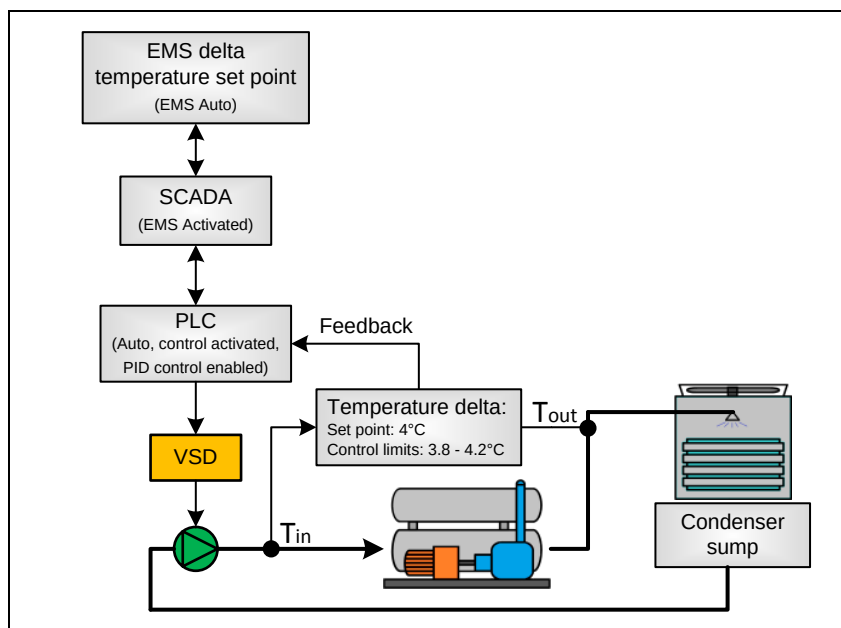


Figure 51: Mine A condenser water flow control logic.

BAC flow control

The cooled ventilation air supplied by the BAC maintains underground temperature condition and form part of the required service deliveries specified by Mine A's staff. The specified DB air temperature for the BAC to ensure and maintain the maximum allowable WB temperature at or below 27.5°C is 10°C (Vosloo *et al.*, 2012). It, therefore, is proposed to install VSDs on the BAC spray pumps to control the water flow through the spray nozzles accordingly. PID control logic will be used to adjust the VSD speeds to maintain the BAC air outlet temperature at 10°C.

From knowledge gained in the literature review, it is noted that when water flow rates sprayed through the nozzles are reduced, the air outlet temperature will increase as a result. Figure 52 shows the BAC spray water flow control communication diagram when implementing VSDs on the pumps. With this proposal, a more constant BAC outlet air temperature supply is expected along with reduced pump energy consumption.

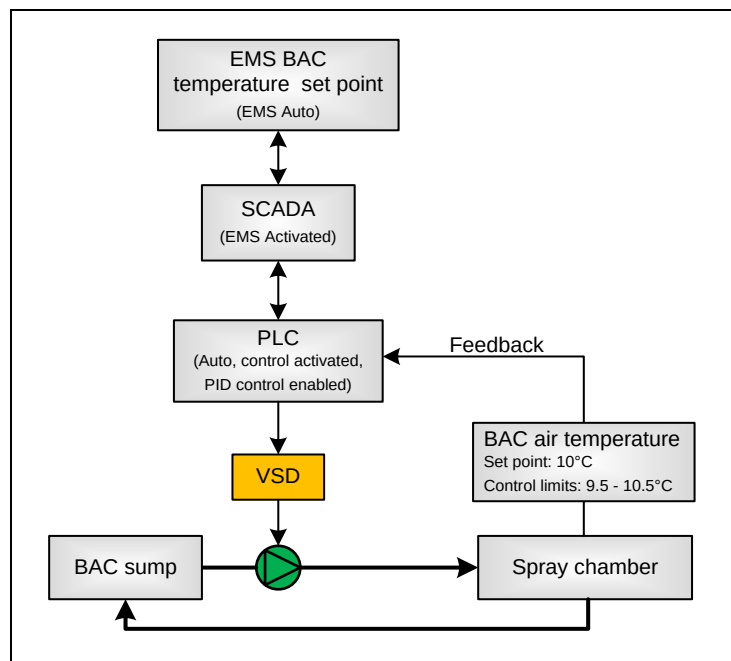


Figure 52: BAC water flow control logic diagram.

CC flow control

The HPE mechanical valve presents the best potential to implement on platinum mine CC to reduce the chilled water wastage thereof. This valve will only dump water if the downstream chilled water flow demand is lower than the required flow through the CC. It is expected that the flow through the CC will be maintain at the design and average water dumped daily will be reduced. Therefore, it is proposed to install HPE 3-way mechanical valve on all four mine CCs.

3.5. VERIFICATION AND SIMULATION MODEL

The refrigeration and cooling system of the case study was modelled using Process Toolbox (PTB) ³. Two models were developed. Figure 72 and Figure 73 in Appendix C shows screen shots of the two simulation models developed for Mine A. The first model was used to verify the accuracy of the developed simulation model. This was achieved by simulating one random winter (2013/07/18) and summer day (2013/11/21) respectively. These simulated results are then compared to actual data acquired from the portable power logger and mine SCADA system. This provides a measure to verify the accuracy of PTB and the developed simulation model.

The utilised variables for the verification model for these simulated days, as measured on the SCADA system and portable power meter are shown in Table 30 in Appendix C. These variables include power data, chiller running statuses, ambient DB temperature, RH and pre-cooling tower inlet water temperatures. The simulation model was validated by placing these variables into the simulation model with the specified refrigeration system constraints as explained in Section 3.3.2.

In Figure 53 the actual power profile as measured by the portable power meter is compared to the power output profile achieved from the simulation model.

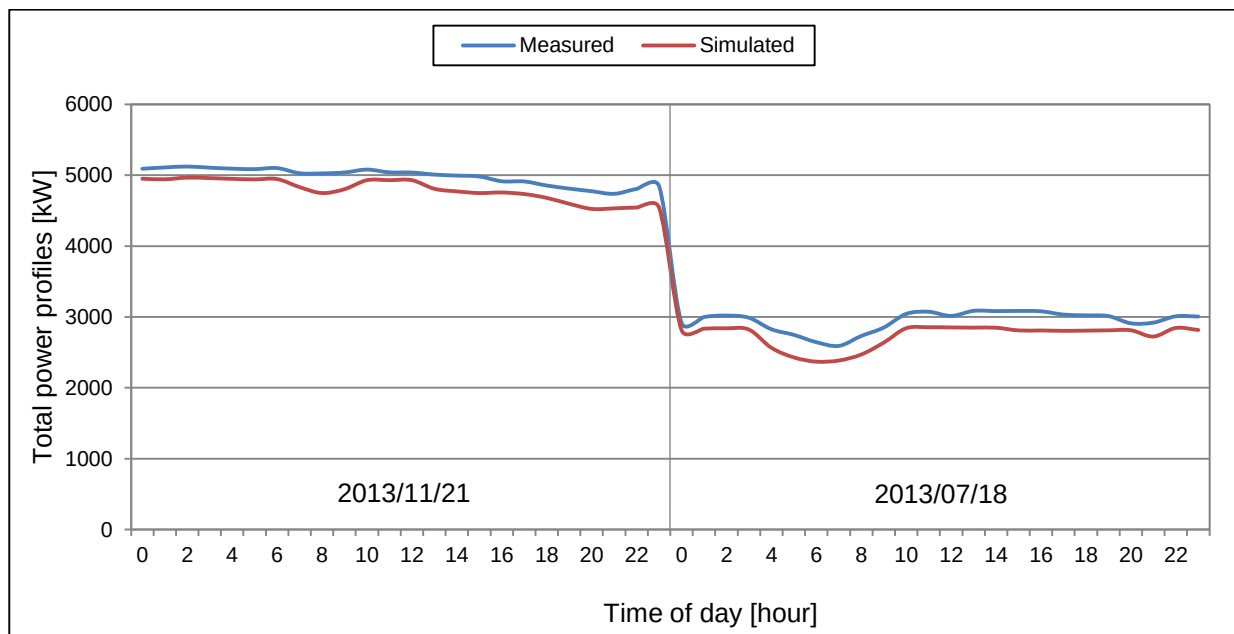


Figure 53: Validation of simulation model power profile with data measured on 2013/11/21 and 2013/07/18.

³ Process Toolbox Flow Solver is transient thermal hydraulic component bases simulation and optimisation tool.

The simulated power output had a correlation of 99% and an average percentage error of 5.5%, when comparing the two power profiles. The measured data incorporated all power consumed by the refrigeration system. The simulation did not include the filtration plant and the relevant transfer pumps. Thus, an average power difference between the simulated and measured power was expected, pertaining to all refrigeration equipment that were excluded from the simulation model.

The BAC air temperature output profile of the simulation is compared to the actual measured temperature profile as shown in Figure 54. It is important that these temperatures correlate accurately, as the evaporator and BAC pump VSDs are controlled according to this temperature.

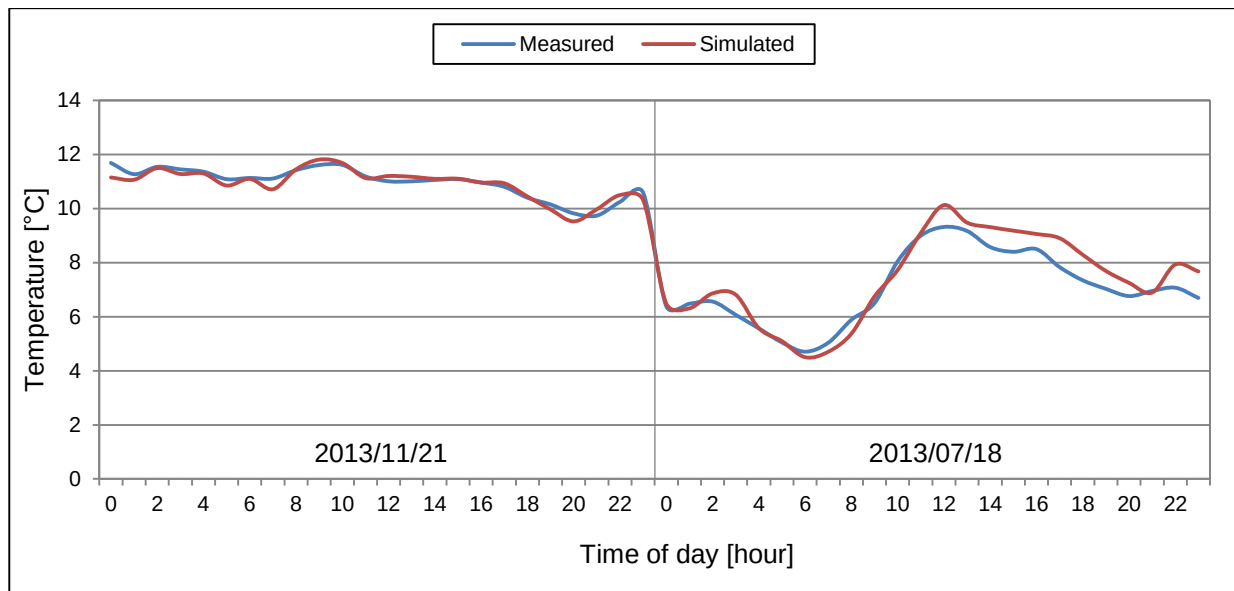


Figure 54: Validation of simulation model BAC outlet temperature.

The simulated BAC outlet temperature had a correlation of 97% and an average percentage error of 0.02%, as compared to the actual temperature profile measure on the SCADA. This proves that when simulating the VSD control in the second model the outcome is expected to be accurate. This will result in a more accurate simulated potential savings as well for the proposed optimisation strategy.

It is, therefore, reasonable to conclude that PTB is an accurate simulation packet to use. It is shown that the model developed accurately represents the refrigeration system. The developed model will be used to simulate the proposed variable flow control adapted for Mine A.

3.6. SIMULATED SAVINGS

3.6.1. Overview

The case study requires a large capital investment to install the proposed equipment to realise the electricity savings. The potential return on investment must be set to determine the feasibility of the case study.

3.6.2. Process Toolbox

The accuracy of the model was verified. The simulation model will be used with assurance to simulate the potential savings with the proposed optimisation strategy. The second model used to determine the potential savings is shown in Figure 73. This model was used to determine a power baseline for the four seasons (summer to spring) before any variable flow control was implemented.

Firstly, a baseline profile was simulated with relevant weather data measured for the four consecutive seasons. Thereafter the same seasonal weather data were used along with the proposed strategies identified, implemented into the model, were simulated to determine the potential yearly savings. These simulated power profiles are shown in Figure 55.

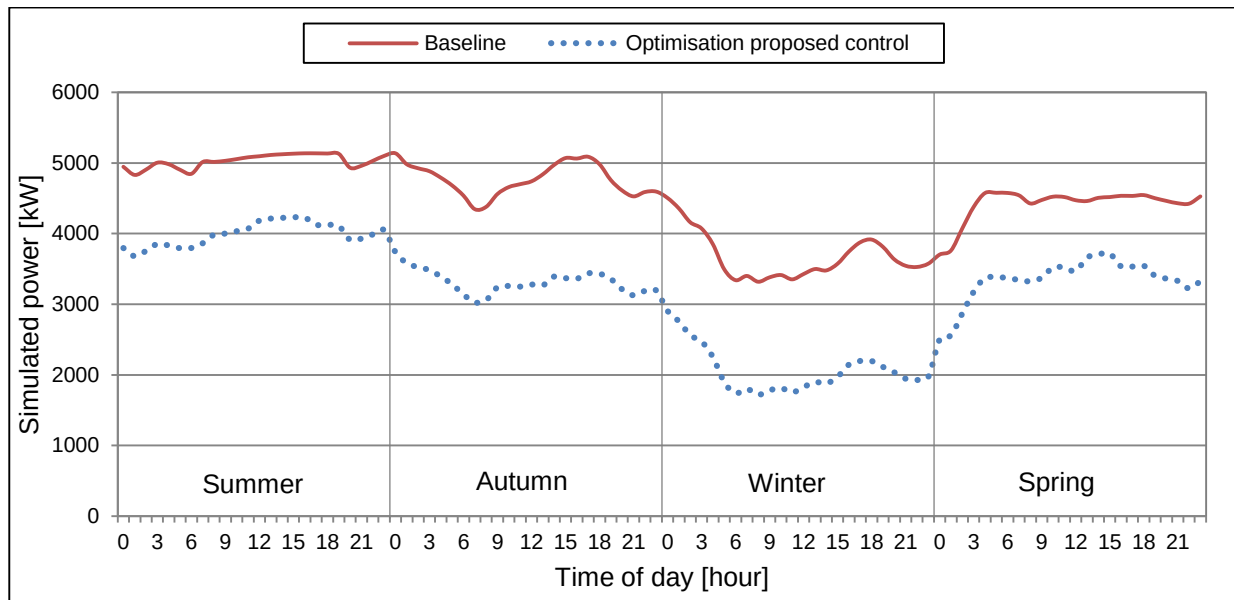


Figure 55: Seasonal simulated total surface refrigeration and cooling system power profiles.

The average simulated weekday electricity consumption and potential savings are summarised in Table 15. As shown an average daily saving of 1 294 kW can be expected annually. This translates to a 29% reduction of the simulated power baseline, which converts

to an average daily cost saving of R14 700 that can be expected on average throughout the year.

Table 15: Average weekday simulated VSD power and cost savings.

Season	Simulated power [kW]			2014/2015 tariff structure costs [R]		
	Baseline	VSD	Saving	Baseline	VSD	Saving
Summer	5 027	3 991	1 035	55 186	43 493	11 693
Autumn	4 767	3 317	1 451	51 951	35 423	16 528
Winter	3 678	2 065	1 613	75 671	57 245	18 426
Spring	4 419	3 340	1 079	48 692	36 546	12 147
Average	4 473	3 178	1 294	57 875	43 176	14 698

The expected yearly savings are summarised in Table 16. The year was broken into two seasons, low demand and high demand, according to the Eskom tariff structures (Eskom schedule of standard prices, 2014). The weeks were broken down according to the Eskom Megaflex tariff structure where different tariffs structures are applied to weekdays, Saturdays and Sundays (Eskom schedule of standard prices, 2014).

Table 16: Mine A expected annual average savings based on simulation model.

Saving	2014/2015 tariff structure costs [R]	
	Low demand season (Sept – May)	High demand season (Jun – Aug)
Weekday	2 475 862	2 182 268
Saturday	442 608	259 206
Sunday	406 349	179 959
Annual weekday	4 658 130	
Total annual	5 946 252.56	

3.6.3. Verification of pump savings

An accurate and simplified measure to determine the potential electricity savings that can be realised with reduced flows from the respective pumping equipment was with the use of the Affinity Laws (Van Greunen, 2014). Equation 3.3 and Equation 3.4 were used to calculate the power usage of the respective system pump motors when maintained at the minimum allowable flow as stated in Table 12. The best-case savings that can be expected with the implementation of VSDs can be calculated as follows:

$$P_1 = P_{rated} \times \eta \times L \quad (3.3)$$

Where,

P_1 = Actual motor power consumption [kW]

η = Electric motor efficiency [%]

L = Electric motor load factor [-]

$$\frac{P_1}{P_2} = \left(\frac{Q_1}{Q_2}\right)^3 \quad (3.4)$$

Where,

P_2 = Calculated motor power consumption at reduced flow [kW]

Q_1 = Measured water flow rate at full motor speed [ℓ/s]

Q_2 = Reduced water flow rate [ℓ/s]

The combined pump motor electricity saving that can be realised for the BAC, evaporator and condenser circuit pumps respectively with a motor efficiency of 95% and load factor of 90% are shown in Table 17.

Table 17: Mine A estimated pump motor savings calculated from Affinity Laws.

Description	Unit	BAC	Evaporator	Condenser
Number of pumps	-	3	1	3
Motor rated power	kW	132	330	275
Motor power (P_1) ($\eta=0.95$) ($L=0.9$)	kW	113	282	235
Measured flow 1 (Q_1)	ℓ/s	175	330	350
Reduced flow 2 (Q_2)	ℓ/s	87	230	280
Power at reduced flow (P_2)	kW	16	112	141
Flow reduction	%	50	30	20
Individual pump savings	kW	97	170	94
Total Pump savings	kW	290	170	283
Combined savings	kW	743		

It is calculated that a maximum pump power saving of 743 kW is possible with the reduced flow rates specified in Section 3.3.2 for the respective pumping systems. The achievable pump savings is, however, dependent on the chiller schedules and ambient weather conditions. This provides a good benchmark though by means to verify the results attained from the simulation model.

3.6.4. CC calculated savings

The calculation and assumptions used to calculate the proposed savings with the implementation of the HPE mechanical valve on all four CC are shown in Appendix B. A brief summary thereof will follow here.

Presently each CC dumps 18.4 Mℓ water per month, if assumed that each CC consumes a constant flow of 7 ℓ/s. It is calculated that the HPE valve will only dump 6 Mℓ water per month. This results to a reduction of 67% in water wastage that can be expected for each CC. This

translates to an average power reduction of 230 kW on the pumping system. Consequently, a summer weekday saving of R2 630 and a winter weekday saving of R4 840 according to the Eskom 2014/2015 Megaflex tariff structure can be expected. The calculated respective weekday savings are summarised in Table 18.

Table 18: Expected annual savings based on CC calculations and assumptions

Saving	2014/2015 tariff structure costs [R]	
	Low demand season (Sept – May)	High demand season (Jun – Aug)
Weekday	483 884	309 889
Saturday	86 167	37 015
Sunday	78 913	25 758
Annual weekday	793 773	
Total annual	1 021 625.47	

Through the implementation of the HPE mechanical valves on all four CC it was calculated that an average annual saving of R1 021 625 can be realised on Mine A. This will result in a PBP of less than 2 months with the equipment cost provided in Table 7.

3.7. CONCLUSION

It was shown that the data acquired from the portable and permanent power meters are accurate within acceptable limits. A verification simulation model of the surface refrigeration and cooling system was then developed that accurately represented the measured power and system temperatures. This verified model was used to simulate potential savings with the proposed optimisation strategies. Data used pre- and post-implementation, along with the method used to calculate the energy savings, were verified by an independent auditor as accurate.

An overview of the inefficient equipment and control strategies on the case study platinum mine's refrigeration and cooling systems were identified. Optimisation strategies were proposed to address these identified system inefficiencies. It was shown that the optimisation strategies have control parameters to adhere to incorporate mine standards and system constraints. By controlling according to the system constraints will ensure sustainability and avoid production losses.

The proposed underground chilled water demand management equipment savings were calculated to verify the feasibility of implementing this equipment on Mine A's CC. It was calculated that with the implementation of the HPE mechanical valves on all four CC an average annual electricity cost saving of R1 021 625 could be realised. This will result in a PBP of less than 2 months.

Electricity savings were verified for the variable-flow control strategies adapted for Mine A refrigeration and cooling system through the use of simulations and calculations. The simulations were modelled and the accuracy thereof verified, to present the expected savings accurately.

The electricity savings expected from the simulated variable-flow control strategies will result in an annual cost saving of R5 946 252. The PBP for the case study, therefore, is expected to be 6.2 months based on Mine A's installation costs shown in Table 6.

The expected PBP for the both proposed optimisation strategies are 6.2 and 2 months. It is reasonable to conclude that it will be financially viable to implement both these strategies on the case study platinum mine.

CHAPTER 4. CASE STUDY: IMPLEMENTATION OF PROPOSED SOLUTION



Verification using a platinum mine refrigeration and cooling system as case study.

4.1. INTRODUCTION

With the implementation of the optimisation strategy to improve the EE of the refrigeration and cooling system, a detailed analysis is required to determine the results thereof. In this chapter, the implementation of the proposed strategy will be discussed, along with the change in chiller COP and the service delivery of the refrigeration and cooling system. The electricity saving achieved are determined. These results will be used to indicate the feasibility of the case study in terms of project payback periods.

The intervention findings will be discussed and presented in detail pertaining to all relevant data acquired pre- and post-implementation. The discussion will include an analysis of new data obtained and provide a comparison between inefficiencies identified in Chapter 3. Through considering the inefficiencies identified the power consumption prior to the intervention will be considered to provide the extent of project success achieved.

4.2. CONTRACTOR MANAGEMENT

4.2.1. Contractor selection

Project management plays a key role in the successful implementation of such a large case study. As the initiative is an Eskom funded DSM project, the allocation of funding is fixed and implementation times usually limited. It is of utmost importance that the most important components, namely time and the budget management be dealt with accordingly. The managing components are considered as the constraints to determine the choice of equipment and contractor selection.

Three contractors were invited to quote for the complete supply and installation of all required infrastructure to allow complete automatic control and monitoring of the case study. The quotes had to cover all required alterations needed to sustain effective savings and monitoring of the system. All equipment needed was described by the contractor and had to comply with mine standards and preferred equipment.

The delivery time of VSDs is considered as an important factor, considering that it can take up to 12 weeks to be shipped to site. This time frame is largely dependent on whether or not it has to be shipped from overseas. The quotes received are summarised in Table 19. The costs shown include all project costs relating to the implementation. The implementation period includes all respective components, shipping, installation and commissioning time thereof.

Table 19: Subcontractor quote comparison

Quoting Company	Cost of supply and installation (Excl VAT)	Implementation period (days)	Previous experience with ESCO
Subcontractor A	R7 931 163	158	Yes
Subcontractor B	R3 763 555	-	Yes
Subcontractor C	R3 093 801	98	Yes

Subcontractor C was chosen due to the engineering solution, equipment warranty and free training they provided for mine personnel on the VSD. The unique engineering solution resulted in their quote being the lowest along with the shortest installation time. In addition, all relevant work required was within their capabilities, this simplified the management of the project. With the lower costs more VSDs could be installed, which will result in more savings.

The implementation period specified by contractor C took longer than specified, due to problems encountered during the commissioning of the VSDs. These problems will be discussed in Section 4.2.2. The delays did not compromise the project since the platinum mine

experienced strikes for most of the first half of 2014. This allowed the contractor to finish the work, as the performance period could not commence during the labour strikes.

4.2.2. Problems encountered

When the commissioning commenced at the case study, the subcontractor encountered problems with earth leakage tripping when any of the VSDs were started. The solution was to install separate earth cables between each VSD and pump.

The reason for each motor requiring a separate earth cable between the VSD and electrical motor are due to harmonic distortion caused by the VSDs. The harmonics are a result of the non-linear load, which consumes power in pulses (Saidur *et al.*, 2012). This causes harmonic ripples to be fed back into the power grid. These ripples affect the equipment without harmonic filters. In this case, it was all the equipment without VSDs installed on them.

This caused project to be delayed to allow for the installation of the additional cables. It is very important to ensure that thorough on-site investigations are done to minimise project delays as in this case.

4.3. OPTIMISATION STRATEGY IMPLEMENTED ON CASE STUDY

4.3.1. Overview

As stated earlier an EMS program will be used to implement the resulting system control parameters. Four viewing modes were created in the EMS setup presenting detailed control and data logging pages. The overview page is shown in Figure 56 and the detailed condenser, evaporator and BAC control overview pages, data logging and trending page are presented in Appendix E by Figure 77 to Figure 79.

To ensure that the relevant system constraints for the chillers and auxiliaries are avoided at all times, the EMS allows for safety parameters, which will ensure that control occurs within the pre-set safe parameters. This will ensure that the automatic system control is maintained with minimal need for manual alterations. This allows mine personnel only to change the required VSD controller set points if alterations are required with the assurance that the system will not be affected negatively.

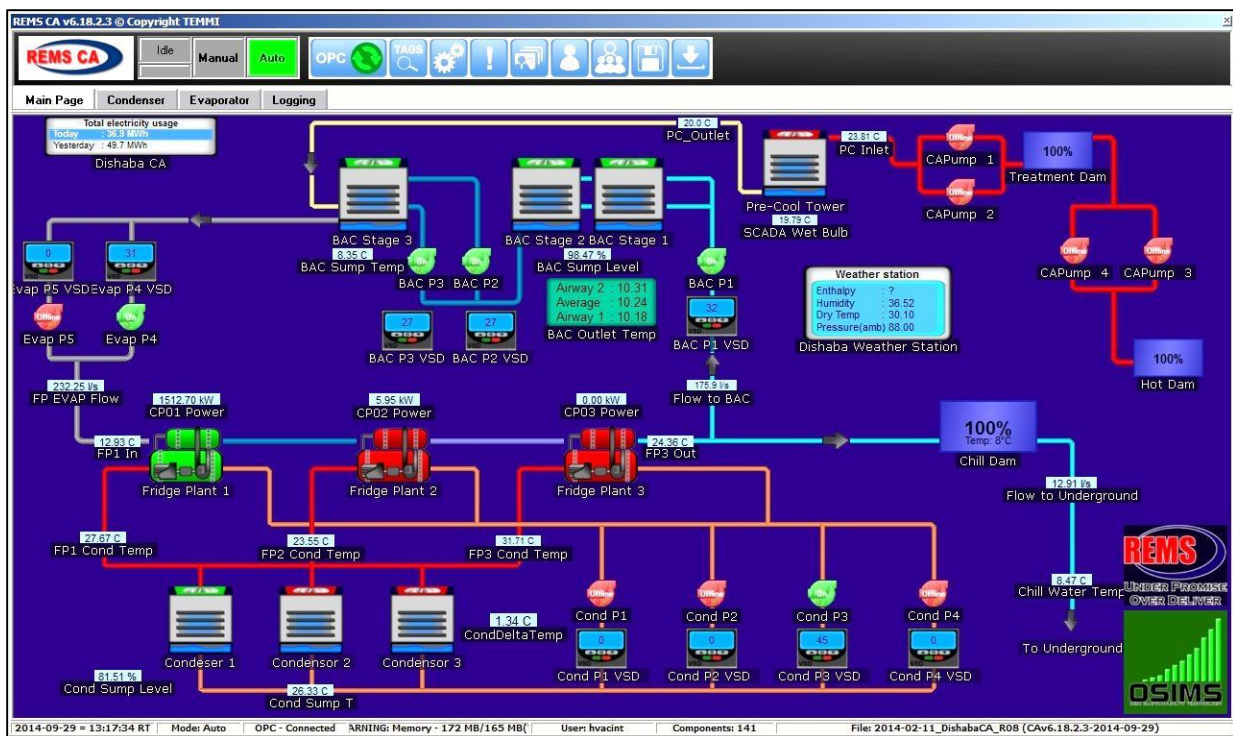


Figure 56: EMS print screen- main overview of chiller plant and auxiliaries.

All system control parameters are controlled and trended by the system PLC and SCADA as mentioned in Section 3.3. All critical and relevant parameters are shown on the EMS pages. The EMS will monitor all controllable system operational parameters that can be affected with the strategy implementation.

Some of these include evaporator, condenser water flow and BAC air outlet temperatures. It is important that these controllable operational limits are not exceeded. The following section will provide all the flow versus frequency limits for the given water circuit control limits as measured during the commissioning of the project.

4.3.2. Resulting chiller evaporator control

Table 20 and Table 21 show the set points for the chiller machine evaporator and condenser water circuit VSD controllers respectively. The minimum and maximum frequency values were determined with on-site testing pertaining to the respective flow rate constraints.

Table 20: Mine A Chiller evaporator pump VSDs control parameters.

Parameter	Evaporator Pumps
Control	Closed loop PID
Feedback input signal	BAC outlet air temperature
Set-point	10°C
Minimum VSD frequency	31 Hz
Maximum VSD frequency	50 Hz
Minimum flow	230 l/s
Maximum flow	360 l/s
Low flow alarm	215 l/s
Low flow trip	200 l/s

The control description is to increase the pump speed when the BAC outlet air temperature exceeds the temperature set point. When the temperature drops below the temperature set point, decrease the pump speed utilising closed loop PID control logic.

4.3.3. Resulting chiller condenser control

Increase the condenser pump speed when the condenser water delta temperature difference (condensers water temperature out minus condenser water temperature in) exceeds the temperature set point. When the temperature drops below the temperature set point, decrease the pump speed utilising closed loop PID control logic.

The average feedback signal is calculated as follows:

$$\nabla T_{avg} = \frac{RFB_1(T_{1o}-T_{1i})+RFB_2(T_{2o}-T_{2i})+RFB_3(T_{3o}-T_{3i})}{RFB_1+RFB_2+RFB_3} \quad (4.1)$$

where,

∇T_{avg} = Condenser average delta water temperature [°C]

RFB = Respective chiller running feedback status [-]

T_o = Respective chiller condenser outlet water temperature [°C]

T_i = Respective chiller condenser inlet water temperature [°C]

Table 21: Mine A Chiller condenser pump motor VSD control parameters

Parameter	Condenser Pumps
Control	Closed loop PID
Feedback input signal	Average condenser delta water temperature
Set-point	3°C
Minimum VSD frequency	45 Hz
Maximum VSD frequency	50 Hz
Minimum flow	310 l/s
Maximum flow	450 l/s
Low flow alarm	300 l/s
Low flow trip	280 l/s

4.3.4. Resulting BAC control

Table 22 show the set points for the BAC first and second stage water pumps respectively. More cooling is achieved by the first stage spray chamber as most of the spray water is received directly from the chillers. Colder water is, thus used for cooling the air in the first stage. Consequently, more cooling can be achieved with less pumping power as may be expected from the second stage spray chambers.

Therefore, the resulting control description is to increase pump speed when the BAC outlet air temperature exceeds the temperature set point. If the temperature drops below the temperature set point, decrease the pump speed utilising closed loop PID control logic. The VSDs will stop to reduce the pump speed at the minimum frequency and will speed-up again when the control output is 5% above the minimum.

Table 22: Mine A BAC pump motor VSD control parameters

Parameter	BAC stage 1 Pump	BAC stage 2 Pumps
Control	Closed loop PID	Closed loop PID
Feedback input signal	BAC outlet air temperature	BAC outlet air temperature
Set-point	10°C	10°C
Minimum VSD frequency	25 Hz	25 Hz
Maximum VSD frequency	50 Hz	50 Hz

4.4. SYSTEM EFFICIENCIES

The project was successfully implemented by March 2014. As a result of the labour strikes the platinum mining sector experienced through until the end of June 2014, it was best practise to exclude the data between these periods, as the refrigeration system did not operate as per usual operating conditions.

Considerable data sets that illustrate the before and after implementation effects were considered, in accordance with the M&V standards and procedures as discussed previously. 01 July 2014 to 30 September 2014 was used to analyse the effect of the resulting variable-flow control strategy. Data for the same time frame in 2013 was used to compare the post-implementation system operations. All data hereafter referring to before and after implementation periods, therefore, refers to these months.

4.4.1. Pre-cooled water flow control

The evaporator water temperature fluctuates daily due to the make-up water flow actuating valve control as explained previously. It was expected to be possible to improve the control of the existing pneumatic actuating control valve to reduce the evaporator water temperature spikes. It was proven not to be possible with the present control limitations and system design

4.4.2. Chiller COP

Before the discussion for the respective chiller COPs commence, it is important to note that after implementation one chiller was sufficient to sustain the required processes sufficiently throughout the assed period. This was prescribed to the 1 MW reduced cooling load that was required from the chillers. This was caused by the decreased BAC sump temperature that resulted in reduced evaporator temperatures and reduced evaporator water flows as shown in Table 23.

Table 23: Mine A average critical variables before and after implementation.

Implementation	Chillers inlet water [°C]	Chillers outlet water [°C]	Chiller cooling [kW]	BAC water [°C]	Evaporator flow [ℓ/s]
Before	10.32	5.65	6 697	8.43	343.18
After	8.89	3.28	5 660	7.15	241.34

Through the implementations of the resulting variable flow control strategy it was expected that the respective COP would increase. An increase in COP is an indication of improved efficiency for the respective systems. Table 24 shows the resulting average weekday power, cooling and COPs attained before and after project implementation.

Table 24: Mine A Chiller performances realised after project implementation.

Description	Chiller 1		Chiller 2		Chiller 3	
	Before	After	Before	After	Before	After
Power [kW]	1 074.5	1 325.3	1 015.8	1 097.6	-	-
Cooling [kW]	4 542.3	6 466.2	5 240.1	4 904.6	-	-
COP [-]	4.2	4.9	5.2	4.5	-	-
Average [%]	14.7		-17.1			

The change in COP of Chiller 3 could not be evaluated, as it was offline for maintenance during the assessment period.

A partial increase in Chiller 1's COP is the result of higher cooling that was achieved for a small increase in compressor power. This increase can be prescribed as Chiller 1 that was operated more effectively at the design cooling load. Chiller 1 was mostly used during September 2014 and Chiller 2 during July and August 2014. Therefore, a decrease on the cooling demand for Chiller 2 was to be expected, as colder ambient weather conditions were present.

From the literature review, it was concluded that slide valves are used to control the variance in cooling demands delivered by chillers. If the sliding valve closes, the cooling delivered by the chiller is reduced along with the compressor power. When chillers do not operate at design cooling loads, reduced COPs can be caused by the compressor load control. This explains why Chiller 2's COP decreased during the assessed period. The reduced cooling load caused the chillers load control to reduce the cooling load delivered, but the subsequent compressor power consumption did not decrease sufficiently to maintain a constant COP value.

It, however, resulted that the overall efficiency of the system was not affected by this decrease in COP of Chiller 2 as the pump saving achieved outweighed the efficiency loss on Chiller 2.

4.5. ELECTRICITY SAVINGS OBTAINED THROUGH OPTIMISATION

4.5.1. Overview

To evaluate the success of the optimisation strategy, it is evident that the energy saving realised must be evaluated first.

In Section 3.6, the verified simulation model developed with actual system data for the four seasons predicted a potential electrical saving of 1 294 kW. This translates to an average reduction of 29% for the simulated power baseline on the case study platinum mine refrigeration system.

In Section 3.6.3, the pump savings expected for the proposed reduced flow rates was calculated with Equation 3.3 and 3.4. To verify the savings proposed by the simulation model. Through these equations, it was calculated that a combined best-case pump saving of 743 kW could be expected with a motor efficiency of 95% and motor load factor of 90% through the implementation of VSDs.

In Table 25, it is shown that the actual best-case saving achievable with VSDs implemented on the respective pumps to be 650 kW. The discrepancy between the calculated best-case pump savings before and after implementation was due to the difference in load factor assumed and measured. The actual motor load factors are illustrated in Table 25 below. It was established that the actual motor load factor was 5% lower on average than first assumed. Therefore, the actual motor power savings are lower than first calculated.

Table 25: Mine A actual measured pump best-case motor savings realised with VSDs.

Description	Unit	BAC	Evaporator	Condenser
Number of pumps	-	3	1	3
Motor rated power	kW	132	330	275
Actual motor power	kW	108	273	215
Actual load factor (L) ($\eta=0.95$)	%	86	87	82
Full motor speed / flow rate	Hz / ℓ/s	50 / 175	50 / 330	50 / 350
Motor speed / flow rate reduced	Hz / ℓ/s	25 / -	31 / 230	45 / 280
Power at reduced flow	kW	14	70	160
Speed reduction	%	50	38	10
Individual pump savings	kW	94	203	55
Total pump savings	kW	282	203	165
Combined savings	kW	650		

It remains eminent though that the Affinity Law is an effective tool to estimate the pump savings that can be expected from reduced flow rates.

Figure 57 graphically summarises the overall system pump savings achieved during the assessment period. It is shown that an average pump saving of 742 kW was achieved over the assessment period, which is larger than the 650 kW shown in Table 25. As stated earlier, only one chiller was used throughout the assessment period, resulting in one condenser pump being switched off, therefore, achieving higher condenser pump motor power savings as calculated for in Table 25. The average pump savings achieved during the assessment period is shown Figure 57 graphically.

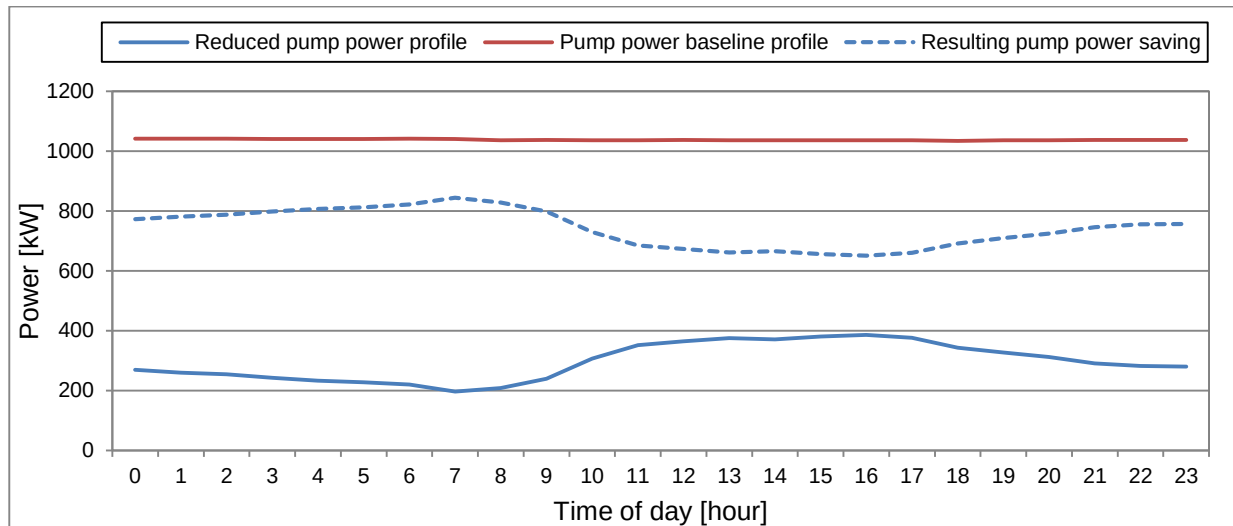


Figure 57: Mine A average overall system pump power savings achieved during the assessment period (July – September 2014).

In the following sections the evaporator, condenser and BAC pumping systems savings are evaluated individually, before considering the total energy savings achieved for the combined refrigeration and cooling system.

4.5.2. Evaporator pump savings

The effect of the optimisation strategy through variable-flow control on the evaporator pump power usage was investigated. The evaporator pump electrical power saving realised during the assessment period are shown in Figure 58. The average power consumption of the evaporator pumps before and after implementation is shown as a function of the average evaporator water flow rate.

Figure 58 shows a significant reduction in the water flow rate and the associated pump power input. An average evaporator flow reduction of 30% resulted in the power input decreasing by 63% on average for the assessment period. This translates into an average power saving of 172 kW for the 3-month period. This is 6.2% of the overall savings achieved on the refrigeration system optimisation strategy.

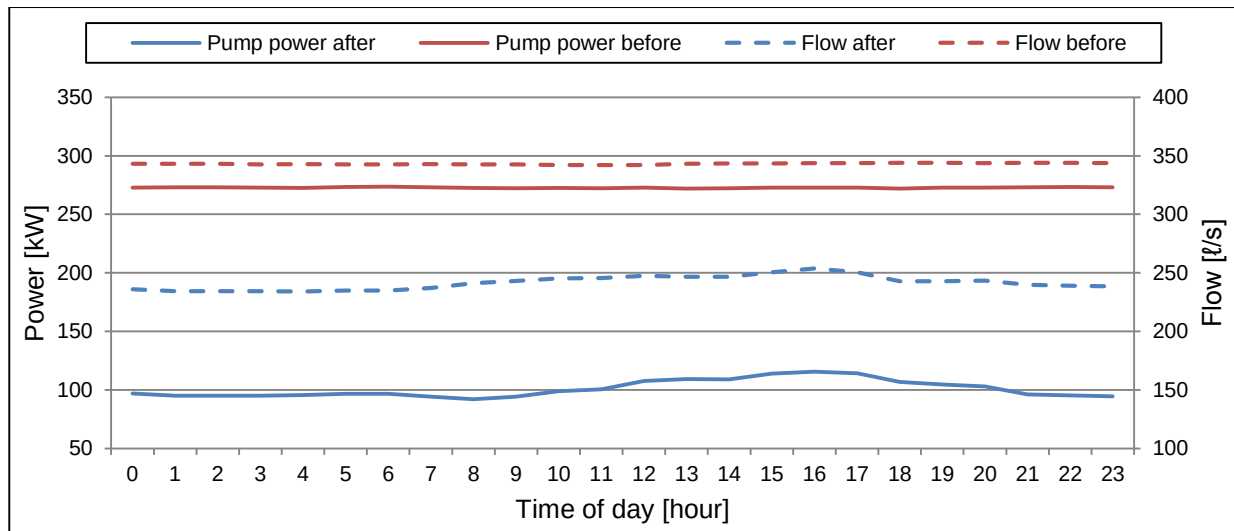


Figure 58: Mine A daily average evaporator pump power and water flow rate before and after implementation.

It is concluded from the post-implementation results shown in Figure 58 that the evaporator flow rates were more accurately modulated to match the chilled water demand, while staying within the prescribed system constraints. This is shown in Figure 62 through to Figure 65, where it is illustrated that the service delivery of the system was maintained within the limits.

4.5.3. Condenser pump savings

The electrical energy savings realised by implementing the proposed variable-flow control on the condenser water circuit are quantified in Figure 59. It was not possible to indicate the respective pump power as a function of the flow, as the flow meters installed on the refrigeration condenser water circuit were non-functional.

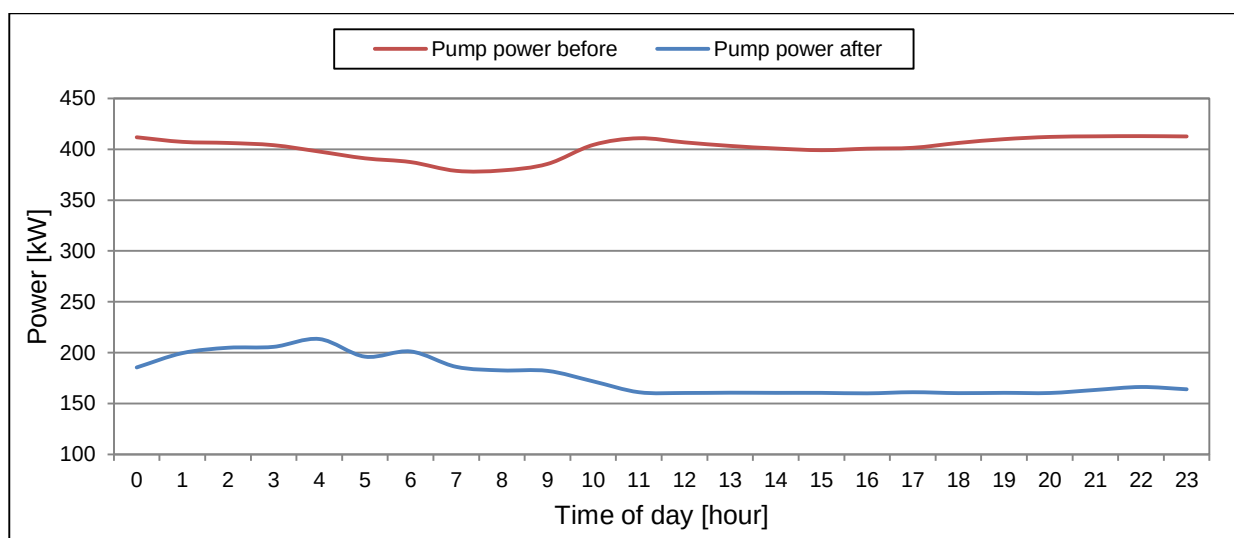


Figure 59: Mine A daily average condenser pump power profile before and after implementation.

Figure 59 shows a significant reduction in the associated pump power input. An average decrease of 56% was realised for the condenser pump power during the assessment period. This translates to an average power saving of 226 kW, where 89% of the saving achieved was a result of one condenser pump that was switched off during the 3-month period. This contributed 8.1% to the overall savings achieved for the refrigeration system.

4.5.4. BAC pump savings

The BAC spray pump savings realised by the implementation of the BAC air temperature variable-flow control are shown in Figure 60. Only the respective spray pump electrical data were considered here, the average BAC outlet air temperatures are shown in Figure 65.

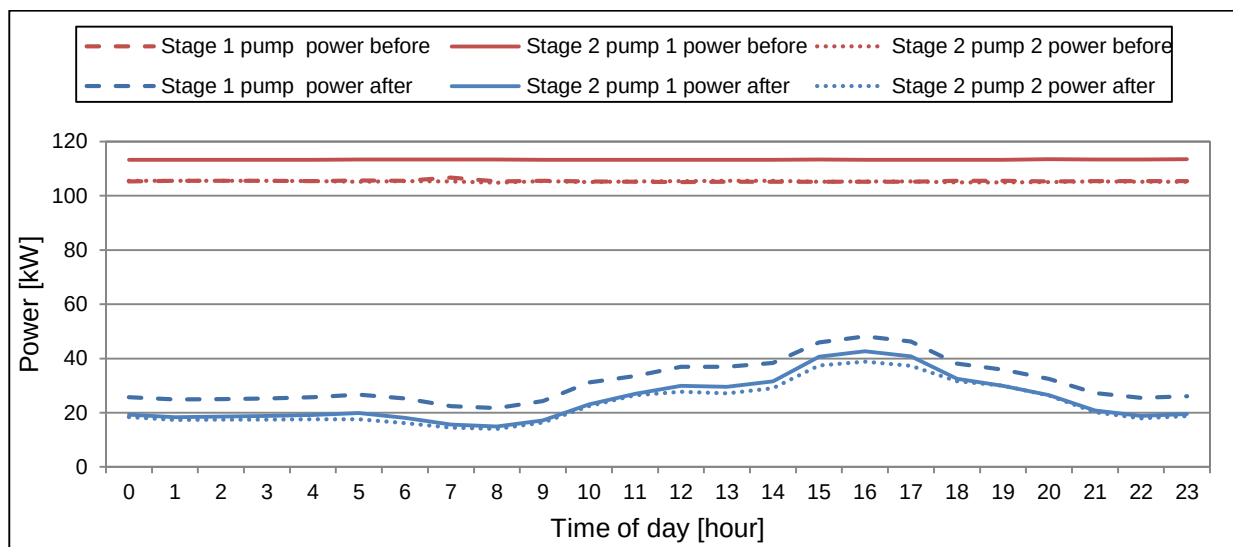


Figure 60: Mine A daily average BAC spray pump power profile before and after implementation.

It is apparent from Figure 60 that there was a significant decrease in the average daily power usage, which resulted in a decrease in chilled water consumption. The flow is not presented, as no flow meters are installed on the respective pumps. The average power input of all three spray pump chambers was reduced by 76%. This translates to an electrical power saving of 245 kW, which contributes 8.8% to the total savings achieved.

It is concluded from the post-implementation results shown in Figure 60, that the chilled water flow through the spray chambers were more accurately controlled to match the ventilation air cooling demand. This was achieved while remaining within the prescribed system constraints. This is shown in Figure 65, where it is illustrated that the service ventilation air delivery of the system was maintained within the limits.

4.5.5. CC savings

The platinum mining sector experienced the longest strike in the history of SA during the implementation of the project (Chamber of Mines of South Africa, 2013). It was agreed upon that Mine A was responsible to install the valves on all 4 CC. As a result of the strikes, Mine A experienced significant amount of losses (Baxter, 2014). Therefore, when mining production commenced after the 5-month strike period, mine personnel were not able to install the valves in time. Consequently, no results have been measured to include the results thereof in the proceedings.

4.5.6. Combined system

Figure 61 shows the integrated refrigeration system energy savings that were achieved during the 3 months assessment period. The power usage measured and verified by the independent M&V team for the entire system was monitored at the main electricity feeders (Eskom Corporate Service Division, 2013) as shown by Figure 67 in Appendix A. The entire system energy savings discussed here, therefore, include the savings achieved from the evaporator, condenser and BAC water flow control as described separately. The entire system saving will also illustrate the total effects of the average daily flow reduction on the corresponding chiller machine power consumption.

Figure 61 shows the typical power profile before implementation of the combined refrigeration system, as measure and calculated using Equation 3.2. The after implementation power profile represents the actual average power consumed during the assessment period. Therefore, the hourly average electrical power savings realised can be calculated with Equation 3.1.

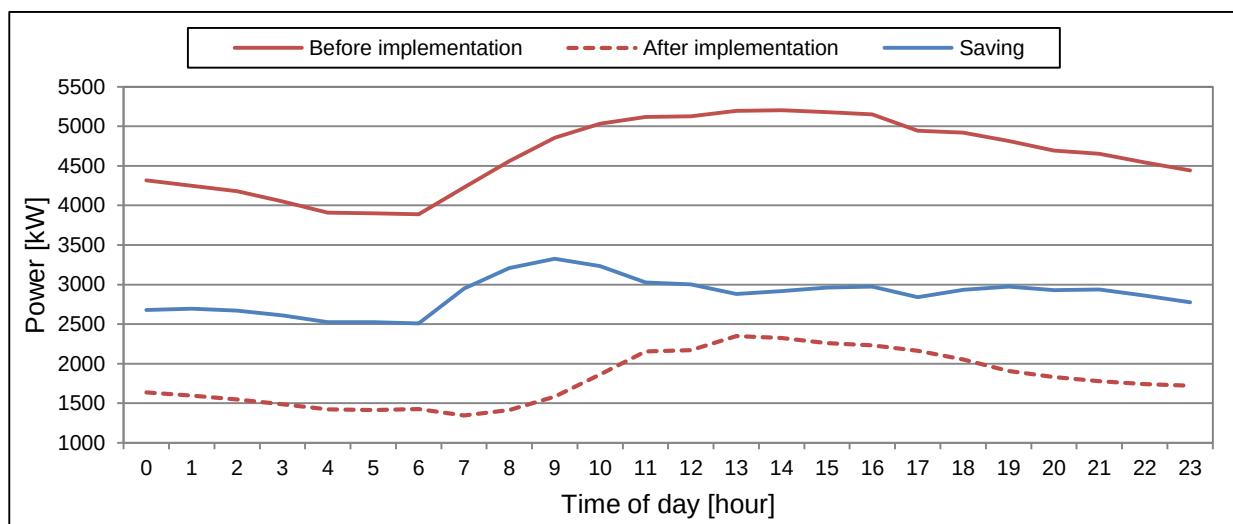


Figure 61: Actual average weekday refrigeration, scaled baseline and saving achieved during the assessment period.

Table 26 shows that the average weekday electrical power consumption of the total refrigeration system decreased by 2873 kW or 62% during the assessment period. It is shown that the post-implementation period power consumption has the same power profile than the pre-implementation scaled baseline profile. Average increases of power consumption during the afternoons illustrate the increase in cooling demand experienced during the afternoon hours. The substantial decrease in power consumption, therefore, illustrates that the refrigeration system definitely is controlled more effectively according to the cooling demand.

4.5.7. Summary

A summary of the total average weekday power saving measured and discussed for the assessed period, as well as the predicted saving by the simulation model, is given in Table 26.

Table 26: Mine A combined cooling system average electrical power saving summary.

2014	Baseline power [kW]	Actual power [kW]	Power saving [kW]	Measured saving [% of baseline]	Simulated saving [% of baseline]
July	3 743	1 373	2 523	67	43
August	4 719	1 925	2 794	59	23
September	5 432	2 130	3 302	61	20
Weekday	4 632	1 810	2 873	62	29
Average	4 161	1 467	2 712	65	32

Comparing the actual measured electricity savings with that simulated in Section 3.6, it is apparent that the predicted savings are less than that measured after implementation. This can be prescribed to the decrease in chilled service water demand for underground operations. Unfortunately, the mine was installing new control equipment on the refrigeration system piping network resulting in no underground flow data for comparison.

The factor that caused the higher electricity saving than first simulated for was contributed to the reduced evaporator flow rates. It was shown that the whole system's water temperature was reduced more effectively than simulated for. It was that these reduced system temperatures could be maintained effectively throughout the day. Therefore, reducing the cooling loads experienced by the refrigeration machines more effectively. This resulted in one chiller to be sufficient to sustain the cooling demand of the system throughout the assessment period.

It can be concluded that the average electrical energy usage of the case study platinum mine was reduced by 62% by implementing the proposed optimisation strategy, described and simulated in this study. The saving achieved includes the following contributing system optimisation achieved:

- Reduced pump power at part-load conditions.
- Reduced chiller cooling loads.
- Decreased water volumes handled by the chillers.
- Increased effective control for part-load conditions.
- No recycling of chilled water through the BAC sump.
- Reduced ventilation air overcooling by the BAC.

The average weekday, Saturday and Sunday savings achieved are summarised in Table 27. An average low demand season saving of R6.02-million and average high demand season saving of 3.85-million is expected. The average weekday electrical power saving of 2 873 kW, result to an average annual weekday saving of R9.88-million.

Table 27: Mine A overall average annual cost saving.

Saving	Average electrical power saving [kW]	2014/2015 tariff structure costs [R]	
		Low demand season (Sept – May)	High demand season (Jun – Aug)
Weekday	2 873	6 023 596	3 857 637
Saturday	2 804	1 046 831	449 692
Sunday	2 459	840 657	274 399
Annual weekday	2 873	9 881 232	
Total annual	2 712	12 492 812	

Table 28 summarises the total project cost, savings achieved and expected PBP after project implementation. It is shown that the average electrical power saving of 2 712 kW will result in a PBP of less than 3 months and a return on investment time of 10 months.

Table 28: Mine A summary of project costs and relating expected payback period.

Summary of case study results	
Electrical energy savings	2 712 kW
Annual electricity cost savings	R12 492 812
Installation cost	R3 093 801
Duration of installations	7 months
Payback period (PBP)	3 months
Return on investment	10 months

To prove the savings achieved were attained without affecting the refrigeration system negatively. It is important to demonstrate that service deliveries of the case study platinum mine refrigeration system were unchanged or improved as a result of the implementation.

4.6. SERVICE DELIVERY

The energy saving achieved by implementing the developed strategies cannot be considered without representing the effects on the service delivery for the refrigeration and cooling system. It remains important to measure and verify the effects after implementation even though the strategies were developed specifically with mine service delivery as system design control inputs.

The data used to verify the changes experienced after project implementation are the same 3 months (July – September) used for the assessment period the year before. Therefore, data referring to before project implementation was measured during the same 3-month period in 2013 and after project implementation was measured during the assessment period in 2014.

4.6.1. Chilled water

The effects of the optimisation strategy on the respective mine chilled water service delivery are shown in Figure 62 to Figure 64.

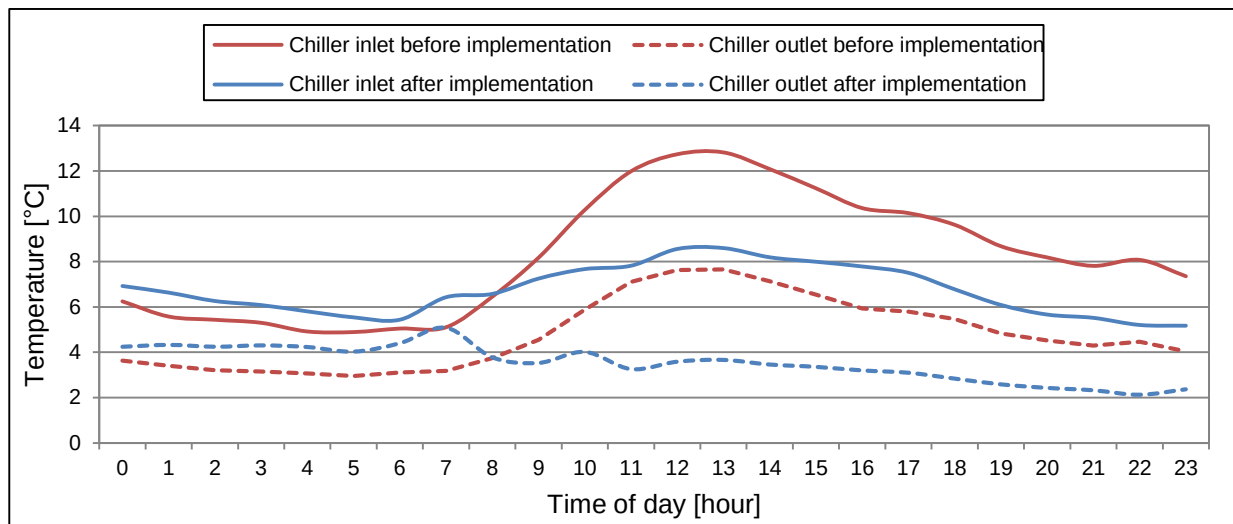


Figure 62: Mine A daily profile of evaporator inlet and outlet temperatures measured during the assessment months.

It is shown by Figure 62 that the average chiller inlet and outlet evaporator water temperatures were reduced after the implementation. It is important to note the magnitude of the reduced average outlet and inlet temperature during the afternoon hours. This is important as higher cooling loads are normally experienced during these hours, a result caused by elevated ambient temperatures. These elevated ambient temperatures, therefore, caused the evaporator temperatures to increase significantly before the implementation, as shown by the red lines.

Thus, highlighting the positive result achieved with the proposed evaporator water flow control strategy, not only was the outlet temperature reduced, but the average evaporator inlet temperature as well. Resulting in reduced cooling loads experienced by the chillers, consequently improving and reducing the chiller machine electrical power consumption.

Although it was shown that the average daily chilled water temperature requirements were not affected negatively after implementation, it remains important to evaluate typical daily operation profiles of the chill dam levels. This is eminent, to ensure that the system profiles fluctuate within acceptable limits.

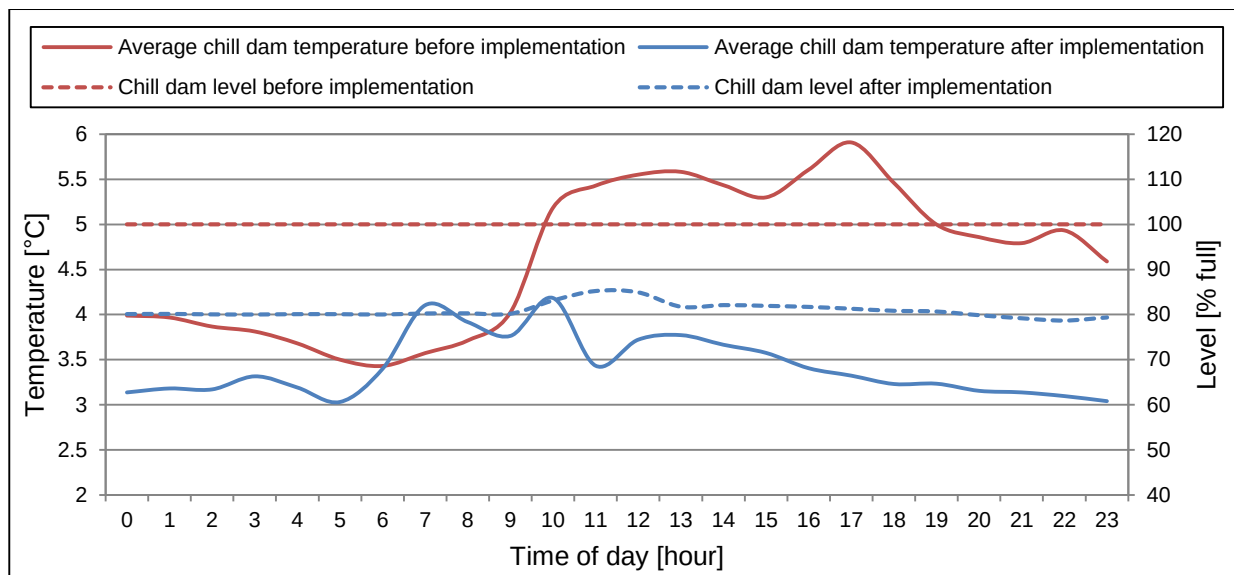


Figure 63: Mine A typical average daily profile of chill dam temperature and level measured during the assessment months.

Figure 63 shows that average chill dam temperature after implementation was maintained at a lower constant temperature then before. This was achieved while maintaining an average chill dam level of about 80%, which was well within acceptable limits. However, this caused a decrease in the amount of water overflowing back into the BAC sump, reducing the recirculation of chilled water, previously recognised as inefficient water control. Consequently, contributing to the overall refrigeration system power consumption decrease realised.

The evaporator water temperature decreases identified on the chiller inlet and outlet water earlier are directly related to the decreases shown in Figure 64, which represents the average BAC sump temperature. The decrease in BAC temperature caused the evaporator to decrease correspondently, pertaining to the evaporator water pump, which draws water directly out of the BAC sump. This is shown in Figure 39.

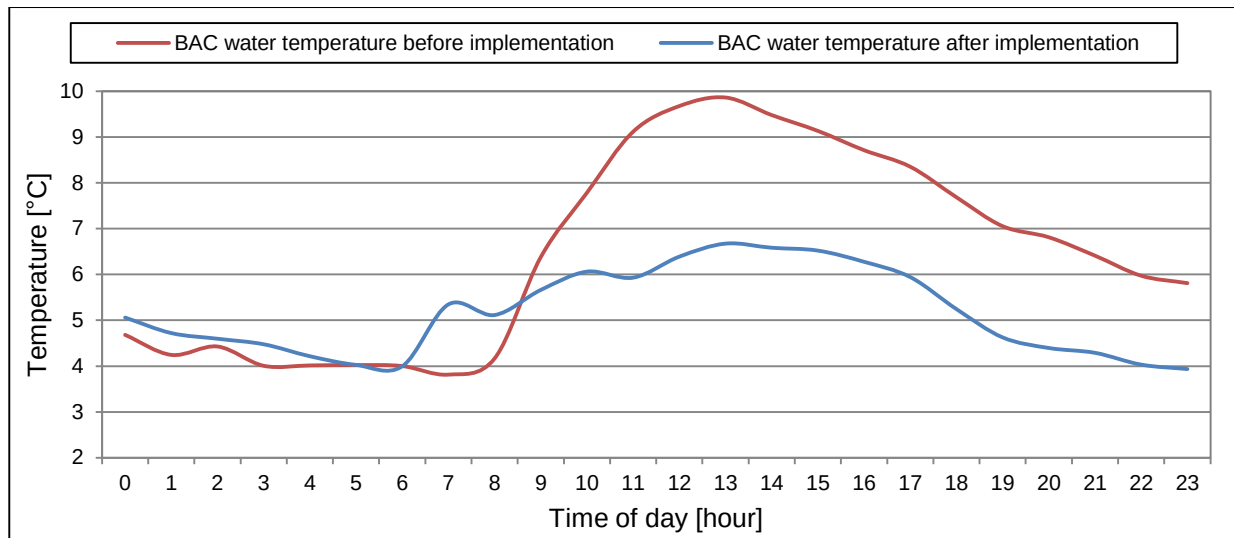


Figure 64: Mine A typical daily profile of BAC water temperature measured during the assessment months.

4.6.2. Ventilation air

The investigation of the effect of the BAC water flow control strategy on the cooling of the ventilation air sent underground is demonstrated in Figure 65. An average increase in the BAC air outlet temperature can be noted, a result of the BAC spray pumps controlling on a set point of 10°C. Even though the BAC pumps reduced the chilled water flow sprayed through the nozzles, which was established from the reduction in pump power usage as shown in Figure 60, the outlet air temperature was maintained.

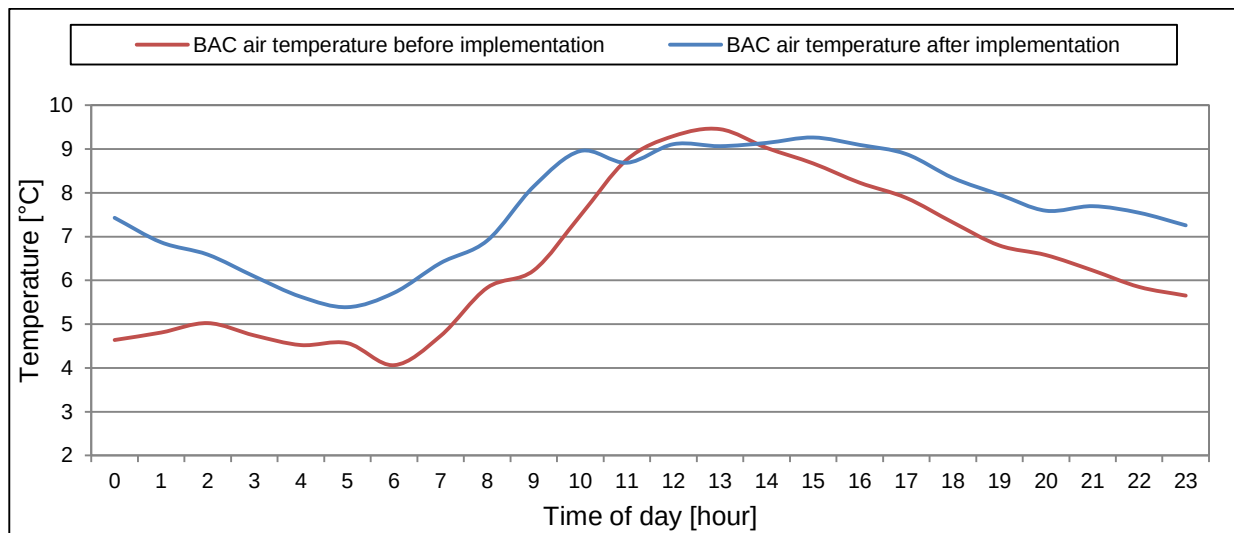


Figure 65: Typical daily profile of BAC air temperature measured during the assessment months.

From the only practical possible comparative evaluation, the ventilation air condition after the implementation remained within acceptable limits. Never reaching higher temperatures than measured before implementation.

4.6.3. Summary

Table 29 provides a summary of the results explained, in regards to the effects experienced on the service delivery with the implementation of the optimisation strategies on the refrigeration and cooling system.

Table 29: Summary of the effects on Mine A's refrigeration and cooling system service deliveries.

Service variables	Unit	Before implementation	After implementation	Change [%]
Evaporator water inlet	°C	8.3	6.7	18.8
Evaporator water inlet	°C	4.8	3.5	26.7
Chill dam temperature	°C	4.6	3.5	25.2
Chill dam level	%	100.0	80.9	-19.1
BAC water temperature	°C	6.5	5.2	20.3
BAC outlet air temperature	°C	6.5	7.6	-14.8

Table 29 shows that the mine service delivery requirements are achieved effectively throughout and improved overall as a result. It is explained why negative percentages for the chill dam level and BAC air temperature attained, actually contributed to deliver a more efficient overall refrigeration system. The only negative result is the average increase in ventilation air temperature, but this was shown too remained within the controllable limits.

It is preeminent that the implementation did not only maintain the service delivery requirements, but improved the overall efficiency and output of the relevant systems and equipment.

4.7. CONCLUSION

The proposed optimisation strategy implemented on the case study platinum mine refrigeration and cooling system showed to have improved the overall energy consumption significantly. For the 3-month assessment period, an average daily electrical energy saving of 2.7 MW or 65% of the baseline power was realised. This extrapolated an annual energy cost saving of R12.5-million, resulting in a PBP of 3 months. Unfortunately, the combined savings of the dewatering system could not be verified, as the valves were not installed in time on the underground CC.

The total savings achieved are a direct result of the evaporator, condenser and BAC pump savings along with the savings achieved on the chillers since the overall system was controlled more efficiently. The savings on the chillers resulted from the evaporator water flow control that reduced the back-pass of chilled water from the overflow of the chill dams, effectively the overall systems water temperature was reduced as a result of the combined water flow control strategies.

It is showed that the overall performance of the refrigeration and cooling system was not adversely affected by the implemented optimisation control strategies. The COP of the chillers and performances of the subsystems did not vary significantly after the strategies were implemented. It is concluded that the implementation did not only maintain the service delivery requirements, but improved the overall output of the relevant systems and equipment.

CHAPTER 5.CONCLUSION



The overall summary and success of the dissertation pertaining to the optimisation strategy developed and implemented on the case study mine follows. Suggested solutions and recommendations are highlighted for future research.

5.1. SUMMARY OF STUDY

The platinum industry has been hit by the combined impacts of falling PGM prices, escalating production costs and labour strikes. It is shown that while mines experience strikes there is still critical equipment that need to operate on a continuous basis. This contributing to the fact that platinum mines do not only lose production during strikes, but the consumption of the ever-increasing electricity remains high as well. The potential, therefore, existed to match the supply to the demand of identified energy intensive mining operations.

Refrigeration and cooling systems were identified as one of these energy intensive operations that presented potential for optimisation. The availability of Eskom EEDSM funded projects made the implementation of optimisation strategies on refrigeration and cooling systems more attractive. The DSM strategy will not only help Eskom to reduce the demand of electricity, but also assist mines on managing their production cost increases. The biggest contributor for the production cost increases experienced by mines is shown to be electricity costs.

Through the literature review, thorough knowledge of typical large mine refrigeration and cooling systems operation and performances were congregated. This provided the foundation to be able to identify possible energy saving opportunities on these systems, with provided insight on unique operational requirements and limitations. Existing optimisation strategies developed were identified. It was shown that through combining the distribution system of service water with the water reticulation system large savings could be achieved. It, therefore, was decided not only to optimise the supply of the service delivery, but the demand thereof as well.

Inefficiencies were identified on the surface and secondary underground cooling equipment of the case study platinum mine. The proposed optimisation strategies and equipment were both evaluated by a simulation model and verification calculations. It was indicated that through these evaluation strategies a daily average electricity demand of 1.3 MW could be realised on the surface refrigeration system. The potential savings calculated for the optimised CC flow control valve could result into an electrical saving of 230 kW on the dewatering pumping system. These strategies showed an average daily saving potential of R14 590 and R2 607, resulting in a PBP of 6.2 and 1.9 months distinctively.

Subsequent system constraints identified during the optimisation model development were incorporated into the EMS with project commissioning, assigning relevant VSD frequency

limits according to the known restrictions. Safe control parameters were inserted into the SCADA system to maintain the resulting savings more effectively.

The average annual power savings realised after project implementation during the 3-month assessment period resulted to an EE of 2.7 MW (65%). This translated to an annual cost saving of R12.5-million, while the implementation costs amounted to R3.1 million. The predicted PBP, therefore, was shown to be 3 months, with a return on investment period of 10 months.

The effects of the proposed strategies on the refrigeration and cooling system service deliveries were compared. Data measured for the same three months before and after implementation were used to verify the effect of the implemented strategies.

These results provide sufficient evidence to prove the feasibility of adapting the variable-flow strategies developed by Du Plessis et al. (2013) on a case study platinum mine. Through implementing VSDs on the case study platinum mine variable-water flow control was achieved on the platinum mine refrigeration and cooling systems.

Unfortunately, the mechanical valves could not be installed in time on the secondary CC, due to the platinum strikes experienced during project implementation. Consequently, no results have been measured to include in the conclusion.

The case study, therefore, proved that the generic variable flow strategy identified is versatile enough to optimise platinum mines refrigeration and cooling systems.

5.2. RECOMMENDATIONS

It is shown that the proposed optimisation strategy implemented on the case study platinum mine reduced the electricity costs thereof significantly. The potential to optimise the case study refrigeration and cooling system to achieve even greater cost savings, the following additional opportunities can be investigated:

- Firstly, it is proposed to rectify the pre-cooling water flow control valve. To maintain a more constant supply of pre-cooled water into the BAC sump, this to reduce the evaporator water temperature spikes shown in Figure 40. This will possibly not reduce the electricity costs, but allegedly reduce the maintenance costs of the chillers, especially the load control equipment.
- Secondly, the extent of installing VSDs on the relevant equipment fans, especially the BAC fans.
- Thirdly, it will be eminent to investigate the potential to implement optimised load-shifting refrigeration system control. With optimal chiller and auxiliaries schedules, the electricity consumption can be reduced in the morning and evening peak periods. Thus further investigation should include the capacity to which extent this can be achieved during the peak periods.

It is presented that with the integration of various cooling systems and the combined water reticulation, increased electrical savings potential can be realised. Therefore, the focus of this study was to optimise the supply and demand of the refrigeration and cooling systems. It was shown in this study that reduced chilled service water wastage underground theoretically presents potential EE on both the dewatering and refrigeration system.

This could, however, not be confirmed with actual measured findings. Therefore, the combined effect on the dewatering and surface refrigeration systems must be investigated when optimising the chilled water demand and supply. This will justify the theoretical savings presented in the proceeding discussed.

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APPENDIX A – POWER DATA VALIDATION

Figure 66 along with Figure 68 indicate the accuracy of the power data obtained during the study. The data of the portable logger versus the permanent loggers later installed is validated in Figure 66. Figure 68 shows the calibration certificate of the portable logger used to measure the baseline for the project. Figure 67 illustrates where the portable logger and power meters were installed to measure the total power consumption of the refrigeration system.

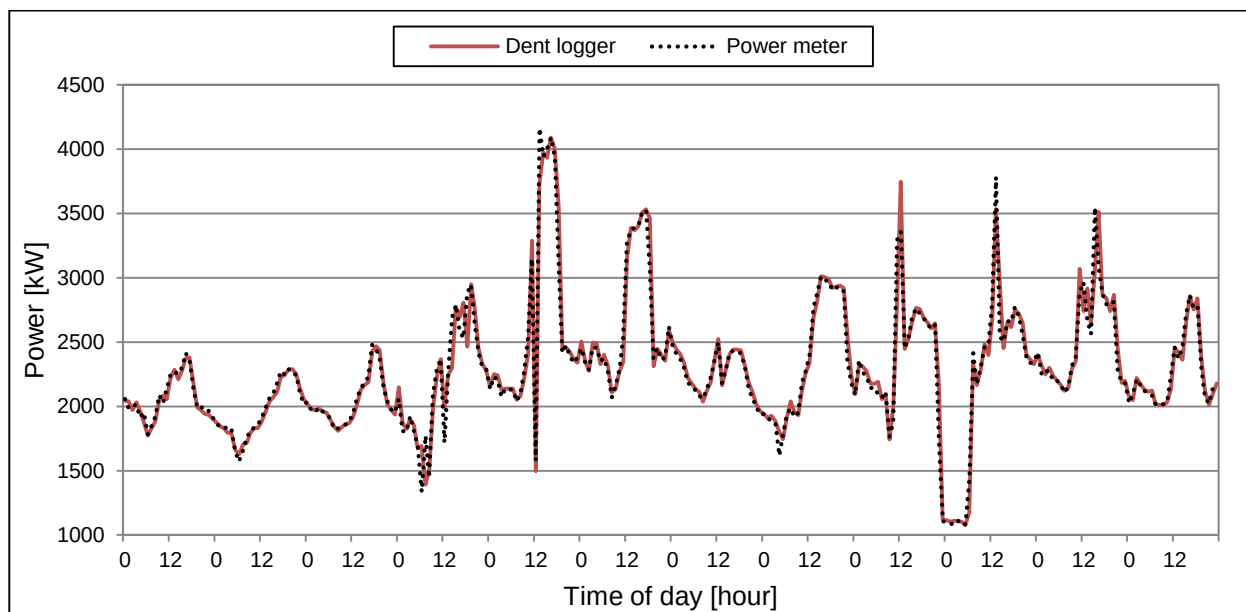


Figure 66: Portable and permanent power meter data comparison.

The data presented in Figure 66 presents 12 days' worth of data measured by the portable and permanent meters respectively. The data measured had an average error of 0.3%, indicating that the permanent logger had been calibrated correctly. This exercise was performed to verify the calibration of the permanent loggers to ensure that the correct power data is measured before and after the project implementation.

The permanent loggers used to determine the total refrigeration system power consumption is illustrated visually in Figure 67. The portable and permanent power meters were installed on the main incomer where all the power consumed by the refrigeration system can be measured from one centralised point.

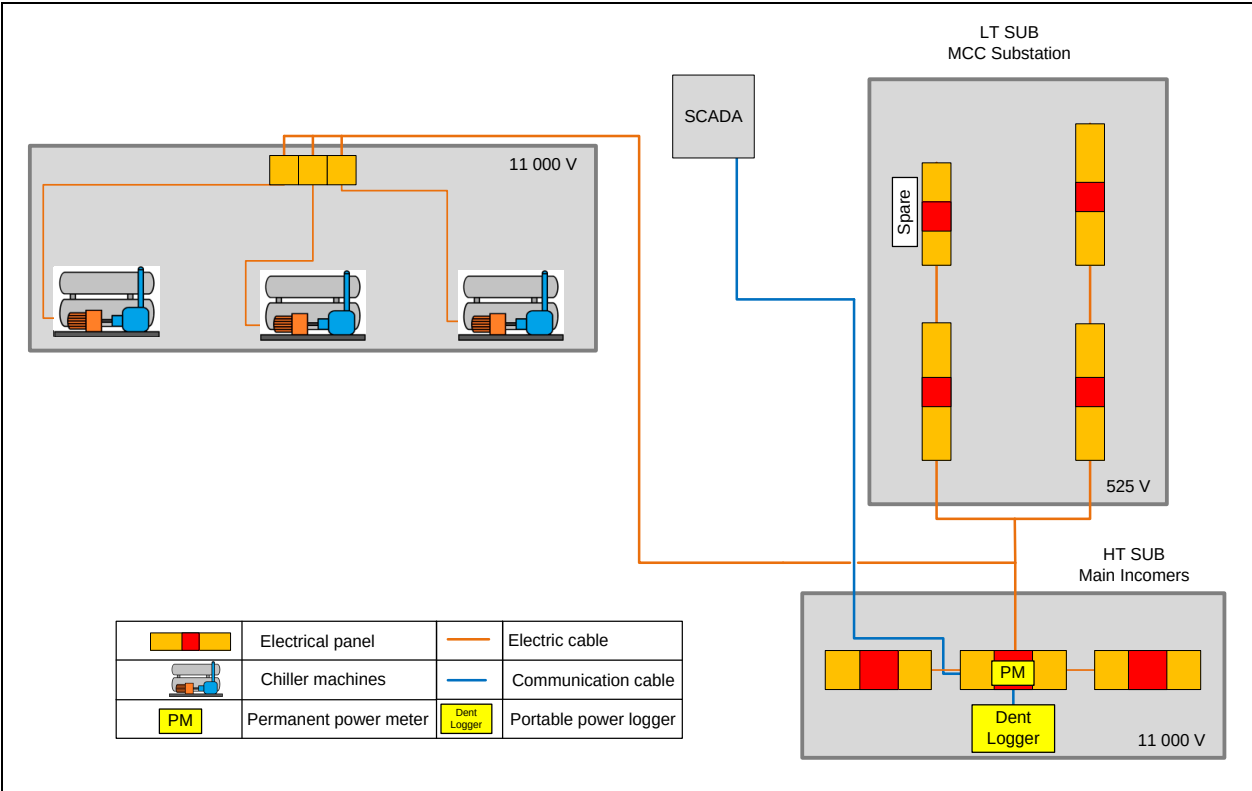


Figure 67: Illustration of Dent logger and power meter installation.



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 Bend, OR 97702 USA
www.DentInstruments.com

Logger Calibration Data Sheet

Logger Information

Date: 12/2/2010	Time: 15:09:43	Serial #: EAAC3
ID: IL400.064 Logger	Type: ELITEpro	Description: DENT ELITEpro
Modem: NONE	Memory: 512K	Amp Scalar: 0.00091769
Technician: KCH		Volt Scalar: 0.42467448

Logger Measurements

Channel Measurements	Description	Reference Measurement	Logger Values	Per Cent Error
Channel 1	Amp	150.45	150.44	0.01%
Channel 2	Amp	150.45	150.44	0%
Channel 3	Amp	150.45	150.46	0%
Channel 4	Amp	150.45	150.46	0%
Channel 1	Volt	500.24	500.19	0.01%
Channel 2	Volt	500.24	500.37	-0.03%
Channel 3	Volt	500.24	500	0.05%

Calibration Reference Instruments used:

Hewlett Packard 34411A Multimeter, Serial #s MY48004529

The calibration of this logger is traceable to the National Institute of Standards and Technology (NIST) using the above reference instruments.

Version 64 Firmware Note: If external power to the ELITEpro is lost (no wall transformer or line power) the logger will automatically switch to internal battery UNLESS the logging interval is 3, 15 or 30 seconds. For these intervals logging will stop until power is again applied.

Figure 68: Main incomer Dent logger calibration sheet.

APPENDIX B – HPE 3-WAY VALVE PROCESS AND POSSIBLE SAVING

HPE CC valve system operation

As mentioned in Chapter 2 the mechanical HPE CC valve system ensures a constant flow through a CC irrespective of the flow demand used for downstream operations. If the demand from downstream operations is more than the CC flow requirement, the water will be directed back into the main service water supply line, assuming that the supply line pressure is within the design range of the valve. This is illustrated graphically in Figure 69.

CCs have a chilled water design flow rate of about 7 l/s that is required through the compact heat exchanger for optimal cooling. As a result of the relative high water flow and inefficiencies experienced in the heat transfer rate between the water and air in the compact heat exchanger, the water can be used again for further downstream cooling operations.

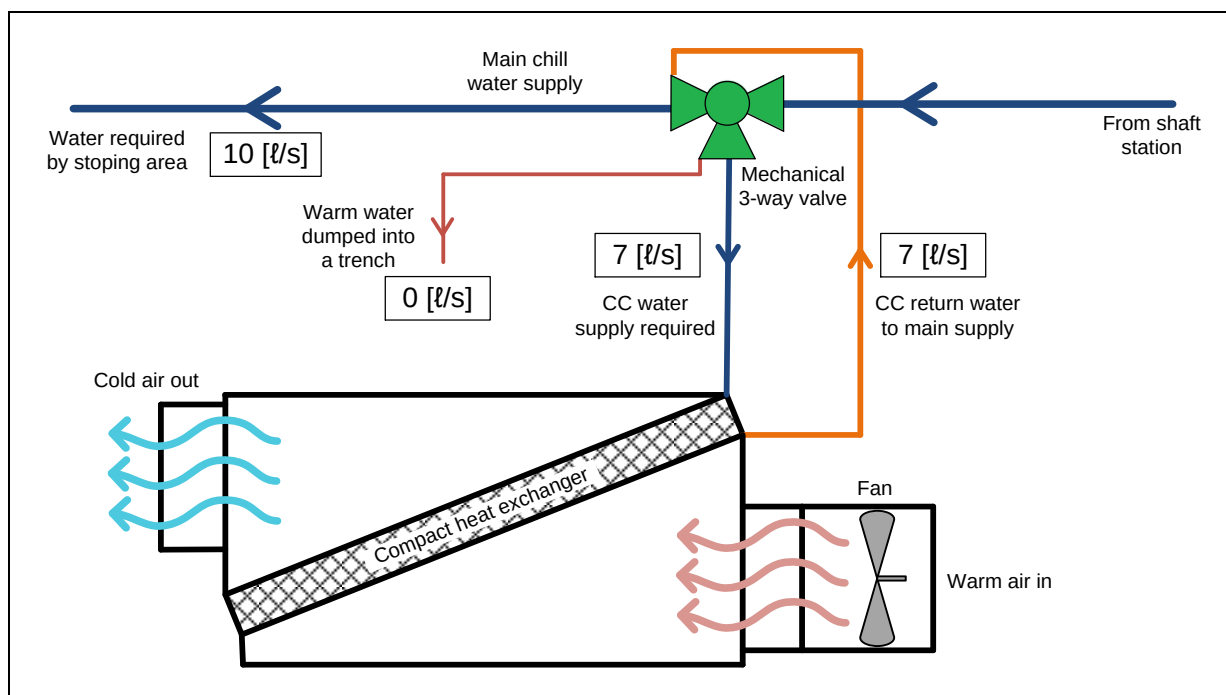


Figure 69: HPE CC valve high flow illustration

This is typically the case with mine drilling shifts where the downstream water usage is higher than the water required by the CC. This is when water is used in the stope to cool drilling equipment. Figure 70 illustrates the different mining schedules during a 24-hour period and the different TOU billing schedules of Eskom.

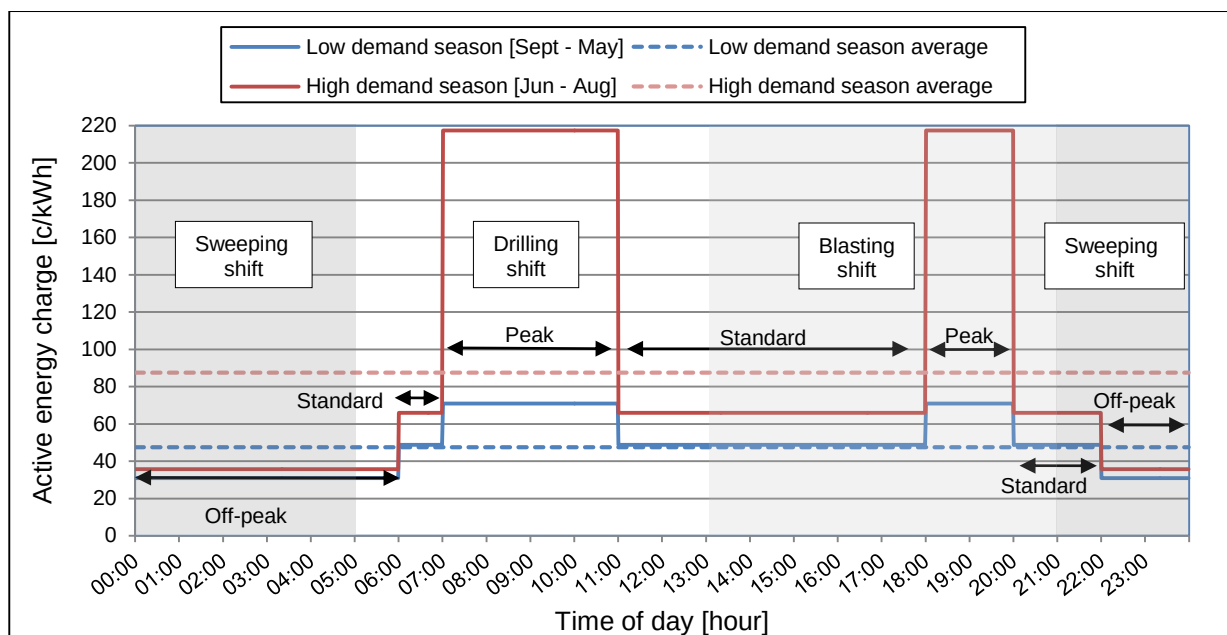


Figure 70: Megaflex tariff structure vs. mining schedule (Transmission zone <300 km and voltage >500V & < 66kV (Eskom schedule of standard prices, 2014)

The valve will reduce water wastage by only dumping water when the downstream demand from operations is less than the flow required through the CC. As a result, water will only be dumped in the sweeping and blasting shifts. This is illustrated in Figure 71, where the downstream pressure is assumed to be 3 l/s. This will result in the valve only dumping the difference between the downstream flow and CC flow requirement.

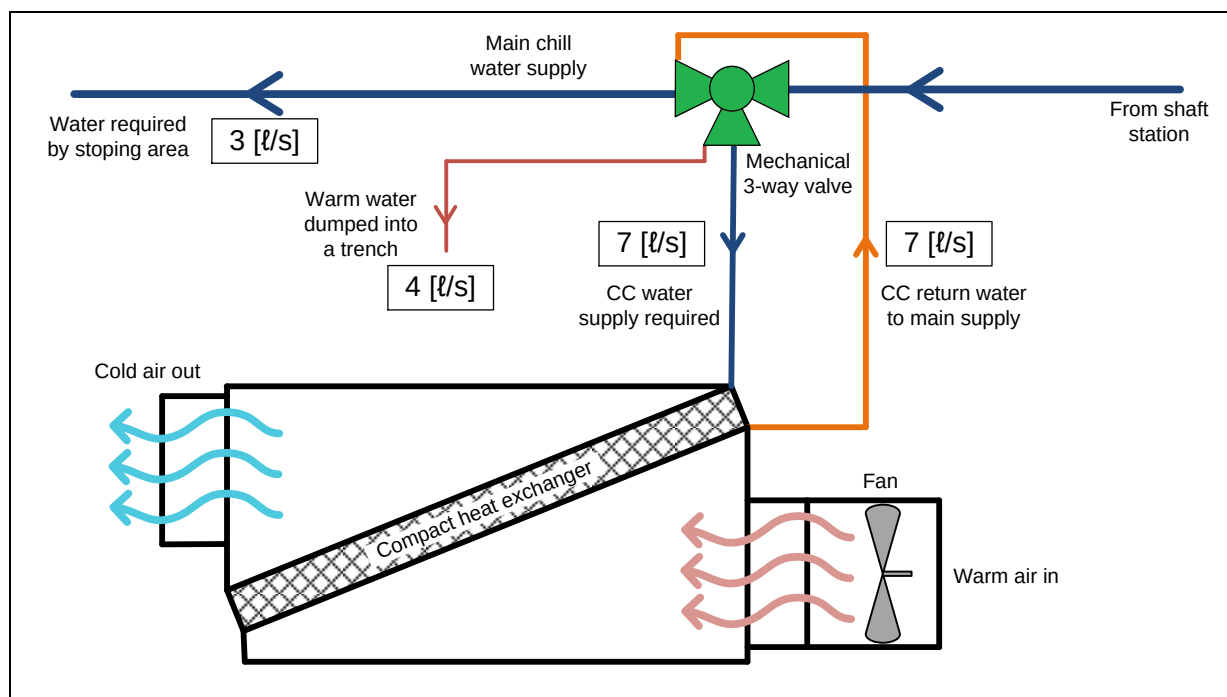


Figure 71: HPE CC valve low flow illustration

HPE CC valve system saving calculations

The theoretical savings achievable from a HPE valve will be calculated below with the following assumptions:

- Assume a mine uses 4 CC throughout the year.
- CC each consumes a constant flow of 7 ℓ/s.
- 365 days per year.
- 168 hours per week.
- 24 hours in a week.
- CC downstream flow rises during production periods is more than 7 ℓ/s. During this time, the CC will use production water without dumping to the mining trenches.
- The flow raise is experienced for 5 days a week and 8 hours per day (drilling shift).
- Downstream flow during non-production period is 3 ℓ/s. This flow can be a result of pipe leaks and the sweeping shift consuming water.

The water consumed per CC can be calculated as follows:

$$\begin{aligned} \text{Water consumed per CC} &= 7 [\ell/s] \times \frac{365}{12} [\text{days/month}] \times 24 [\text{hours/day}] \times 3600 [s/h] \\ &= 18.4 [\text{M}\ell/\text{month}] \end{aligned}$$

The hour per week a CC will use and not dump water is calculated as follows:

$$\begin{aligned} \text{Hours CC is not dumping water} &= 5 \times 8 \\ &= 40 [\text{h/week}] \end{aligned}$$

Therefore, the hours per week the CC will dump 3 ℓ/s water is:

$$\begin{aligned} \text{Hours CC is dumping water} &= 168 - 40 \\ &= 128 [\text{h/week}] \end{aligned}$$

Now the mean flow each CC will dump per month is:

$$\begin{aligned} \text{Mean flow per CC} &= (0 \times 40 + (7 - 3) \times 128) / 168 \\ &= 3.05 [\ell/s] \\ &= 6 [\text{M}\ell/\text{month}] \end{aligned}$$

If there was no intervention with the valve, each CC would have dumped 18.4 Mℓ /month. With the valve, only 6 Mℓ /month is dumped, therefore resulting in a saving of:

$$\begin{aligned}
 \text{HPE valve saving per CC} &= 18.4 - 6 \\
 &= 12.4 \text{ [M}\ell\text{/month]} \\
 &= 4.7 \text{ [}\ell\text{/s]} \\
 &= 4.7 \times 10^{-3} \text{ [m}^3\text{/s]} \\
 &= 17 \text{ [m}^3\text{/h]}
 \end{aligned}$$

And,

$$\begin{aligned}
 \text{Reduction in water wastage} &= 12.4/18.4 \\
 &= 67 \%
 \end{aligned}$$

Cost savings

The theoretical power consumption that is expected from a pumping system, related to the static head and the delivered flow, can be calculated from the equation below (Van der Zee, 2013).

$$P_{Theoretical} = \frac{Q \times \rho \times g \times h}{3.6 \times 10^3} \quad (B.1)$$

where,

$P_{Theoretical}$ = Theoretical pumping system energy [kW]

Q = Flow rate [ℓ /s]

$\dot{m}$ = Mass flow [m^3 /h]

ρ = Density of the fluid [kg/m^3]

g = Gravity acceleration constant [m/s^2]

From this equation, the theoretical cost saving relating to the pumps can be calculated with the realised reduced flow rate.

$$\begin{aligned}
 \text{HPE valve pump cost saving per CC} &= \frac{17.64 \times 999.97 \times 9.81 \times 1200}{3600} \\
 &= 57.7 \text{ [kWh]}
 \end{aligned}$$

This will result in an EE of 230 kWh on the pumping system when installed on all four mine CCs. A daily average summer weekday saving of R2 630 and a winter weekday saving of R4 840, therefore, can be expected. This will lead to an annual average weekday saving of R793 773. All cost savings are calculated according to the Eskom 2014/2015 Megaflex tariff structure (Eskom schedule of standard prices, 2014).

APPENDIX C – SIMULATION

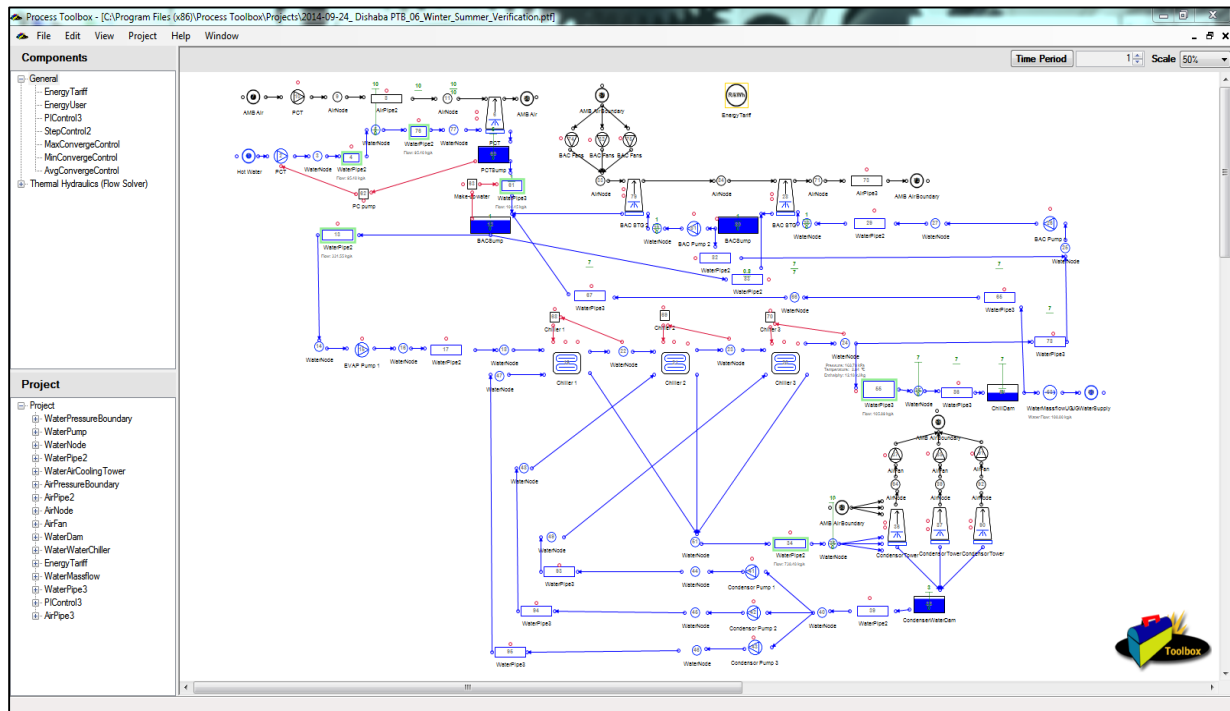


Figure 72: Verification and baseline simulation model.

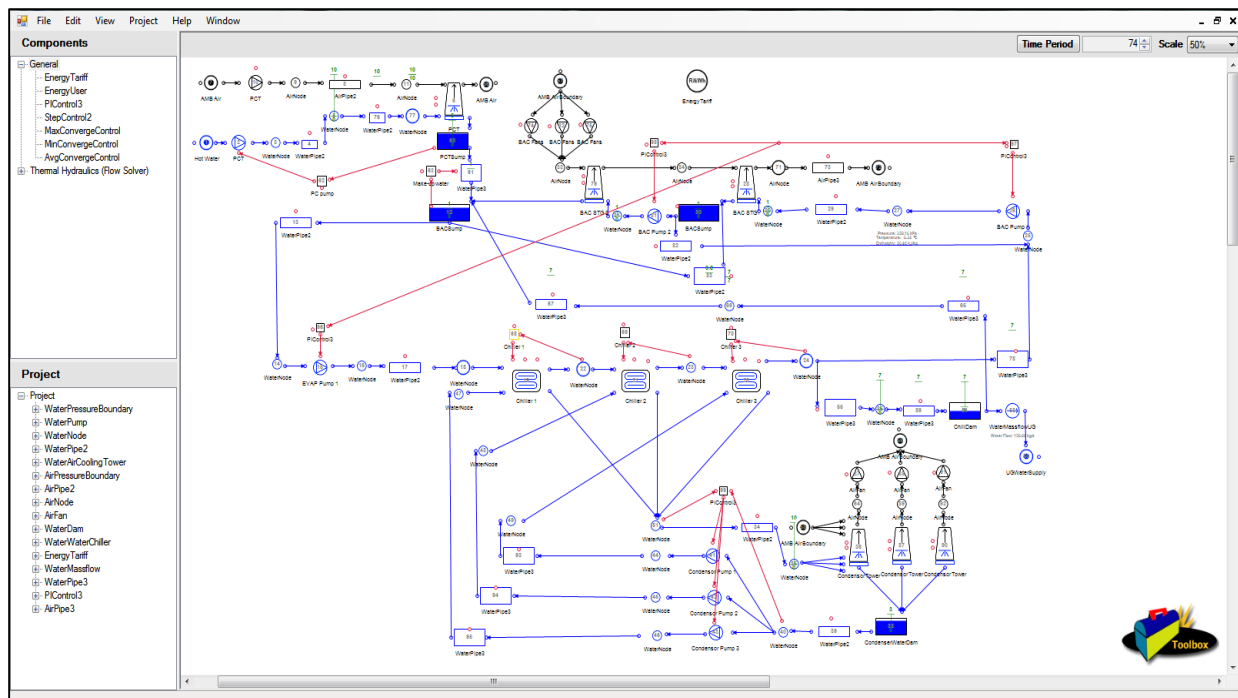


Figure 73: Proposed savings simulation model with VSD control.

Table 30: Verification simulation model input variables.

Hour	Chiller 1 Status	Chiller 2 Status	Chiller 3 Status	DB Temp [°C]	RH [%]	Pre-cooled inlet Temp [°C]	Power [kW]
1	1	0	1	19.7	89.1	20.3	5 090.8
2	1	0	1	19.5	91.6	20.1	5 109.3
3	1	0	1	19.5	93.9	19.8	5 122.3
4	1	0	1	19.6	93.4	19.7	5 105.9
5	1	0	1	19.3	93.1	19.7	5 092.3
6	1	0	1	19.1	95.8	19.6	5 085.4
7	1	0	1	19.7	93.8	19.5	5 100.5
8	1	0	1	20.5	89.7	19.2	5 027.7
9	1	0	1	21.7	81.9	18.9	5 025.4
10	1	0	1	23.3	75.7	18.7	5 038.6
11	1	0	1	24.8	68.3	18.6	5 079.2
12	1	0	1	25.2	64.0	18.5	5 040.1
13	1	0	1	26.0	61.5	18.6	5 038.1
14	1	0	1	26.1	59.7	18.7	5 008.8
15	1	0	1	26.0	59.7	18.7	4 994.8
16	1	0	1	26.3	58.4	18.6	4 982.1
17	1	0	1	26.5	57.3	18.7	4 914.2
18	1	0	1	25.9	58.3	19.3	4 911.9
19	1	0	1	24.8	63.2	19.7	4 854.5
20	1	0	1	23.3	67.8	19.8	4 811.1
21	1	0	1	22.5	70.0	19.7	4 774.0
22	1	0	1	21.7	72.3	19.5	4 737.3
23	1	0	1	21.1	75.6	19.3	4 806.1
24	1	0	1	20.7	77.9	19.2	4 845.5
25	1	0	1	13.5	55.2	20.0	2 917.0
26	1	0	1	13.6	61.8	19.8	2 999.2
27	1	0	1	12.6	65.0	19.2	3 019.6
28	1	0	1	9.0	73.5	18.5	2 988.6
29	1	0	1	8.5	77.4	17.9	2 826.2
30	1	0	1	7.7	77.5	17.7	2 747.2
31	1	0	1	7.5	73.1	17.6	2 644.4
32	1	0	1	6.2	71.7	17.3	2 592.0
33	1	0	1	9.6	72.0	17.6	2 731.9
34	1	0	1	12.1	67.3	19.1	2 850.6
35	1	0	1	14.5	63.6	20.9	3 043.0
36	1	0	1	16.7	54.6	22.5	3 073.5
37	1	0	1	18.9	44.4	23.5	3 014.8
38	1	0	1	19.9	36.5	24.1	3 086.3
39	1	0	1	20.8	32.8	24.5	3 082.8
40	1	0	1	20.9	33.4	24.5	3 085.1
41	1	0	1	20.5	36.2	23.5	3 080.2
42	1	0	1	19.3	37.7	22.8	3 033.8
43	1	0	1	17.2	42.9	21.9	3 022.8

Appendixes

44	1	0	1	15.9	47.6	20.7	3 012.4
45	1	0	1	15.3	50.3	20.0	2 910.3
46	1	0	1	15.2	50.3	20.6	2 920.2
47	1	0	1	14.8	52.2	21.1	3 009.7
48	1	0	1	13.9	56.4	20.5	3 005.9

APPENDIX D – ADDITIONAL RESULTS



Figure 74: Average performance achieved as function of average ambient temperature for July 2014.

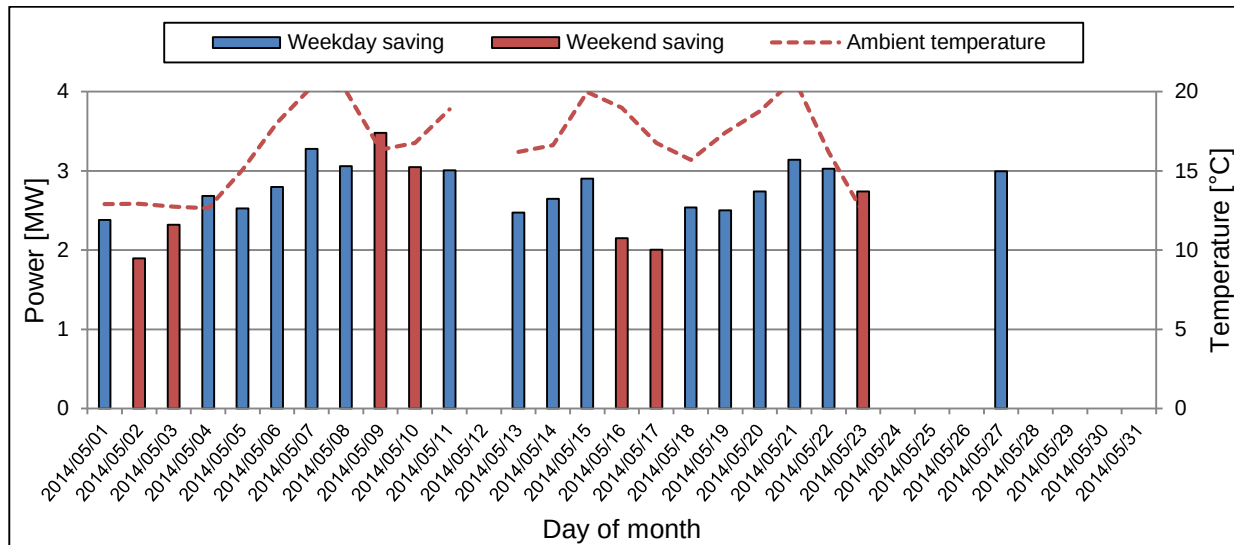


Figure 75: Average performance achieved as function of average ambient temperature for August 2014.

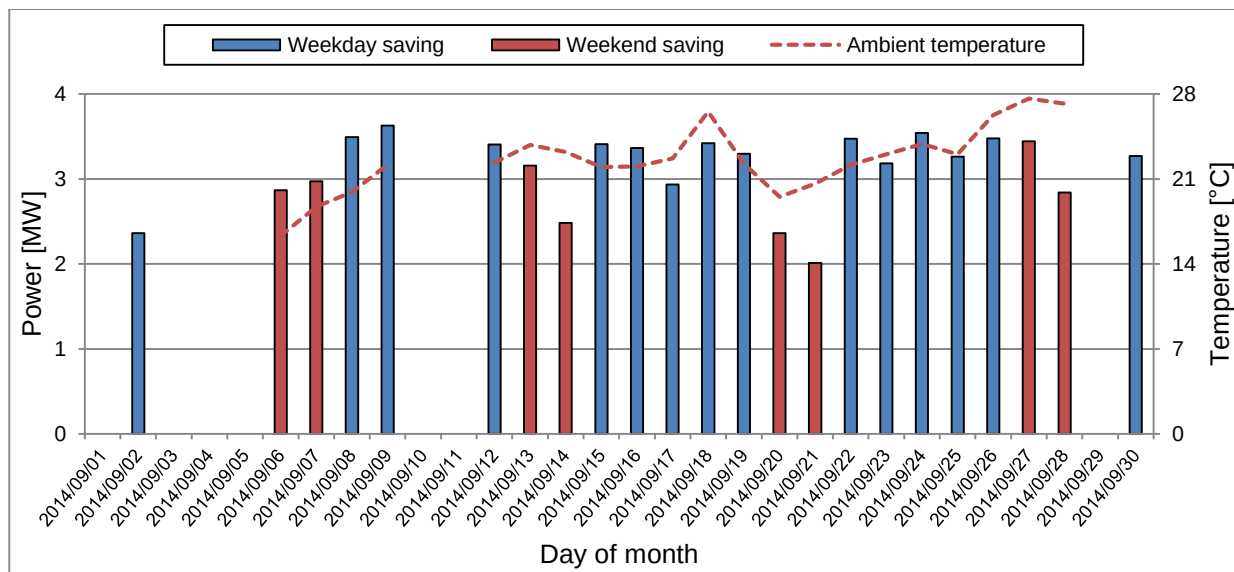


Figure 76: Average performance achieved as function of average ambient temperature for September 2014.

APPENDIX E – ADDITIONAL IMAGES

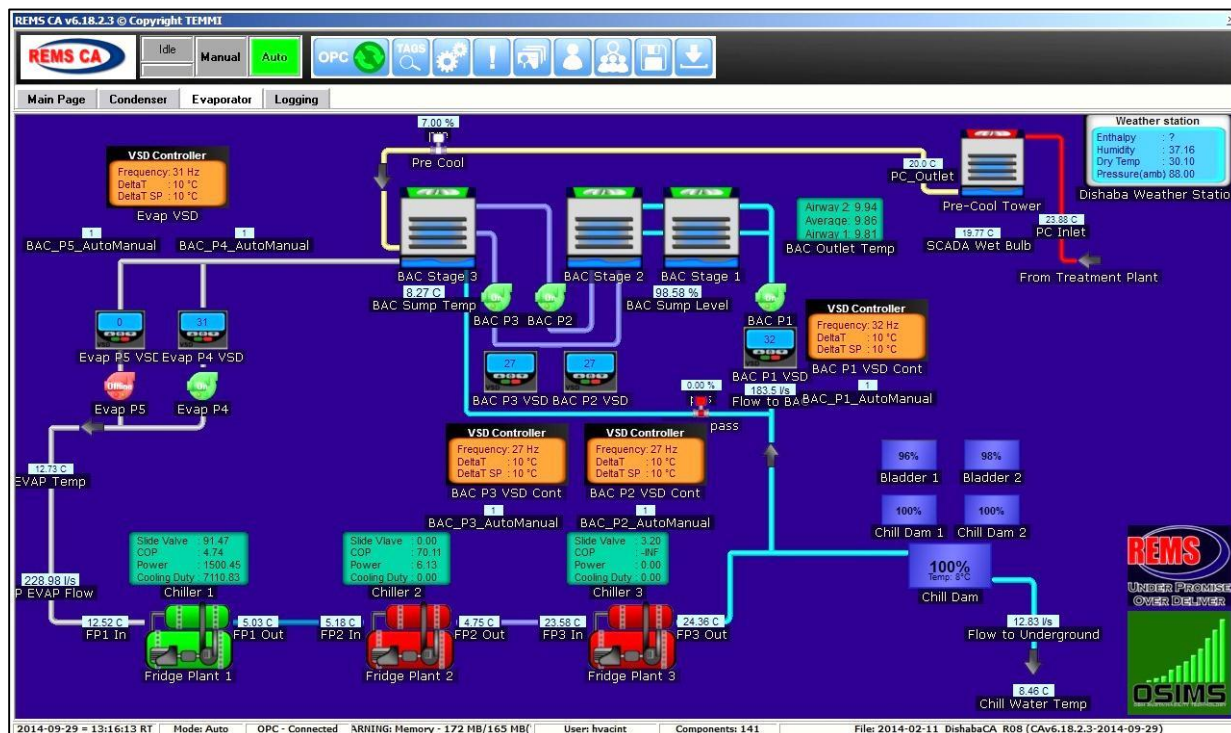


Figure 77: EMS print screen – evaporator and BAC water network and respective VSD controllers

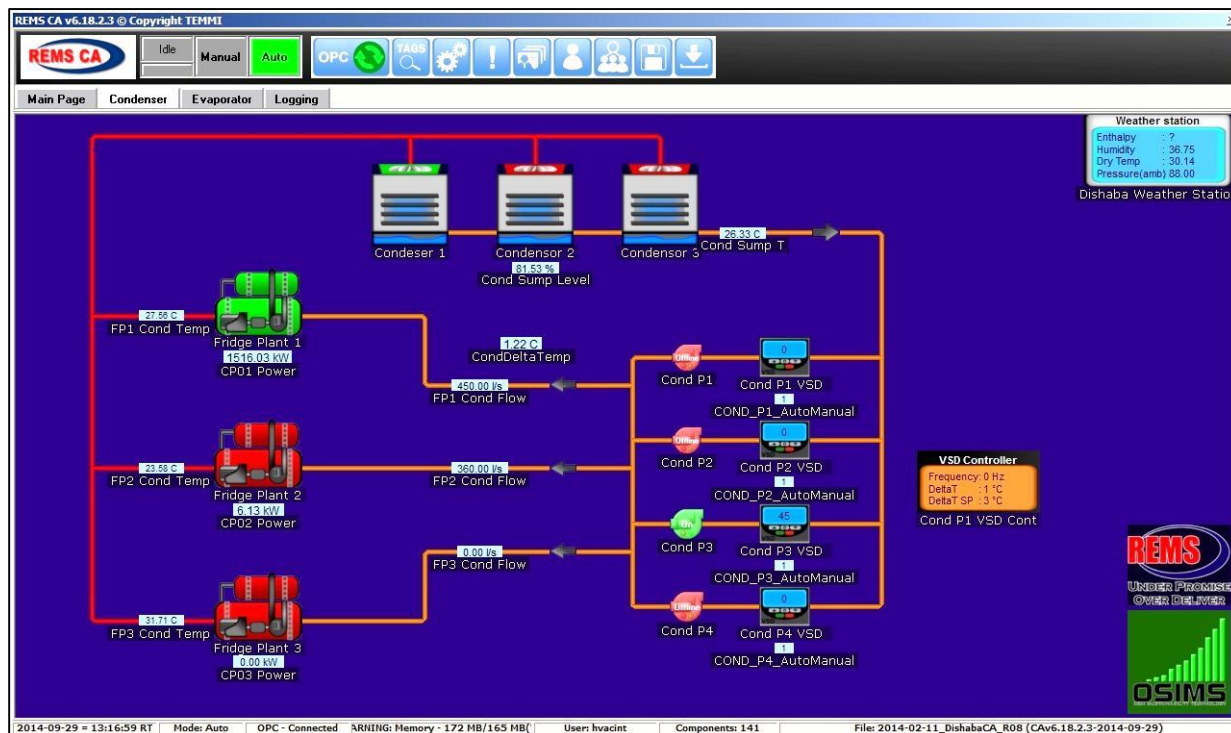


Figure 78: EMS print screen – condenser water network and VSD controller

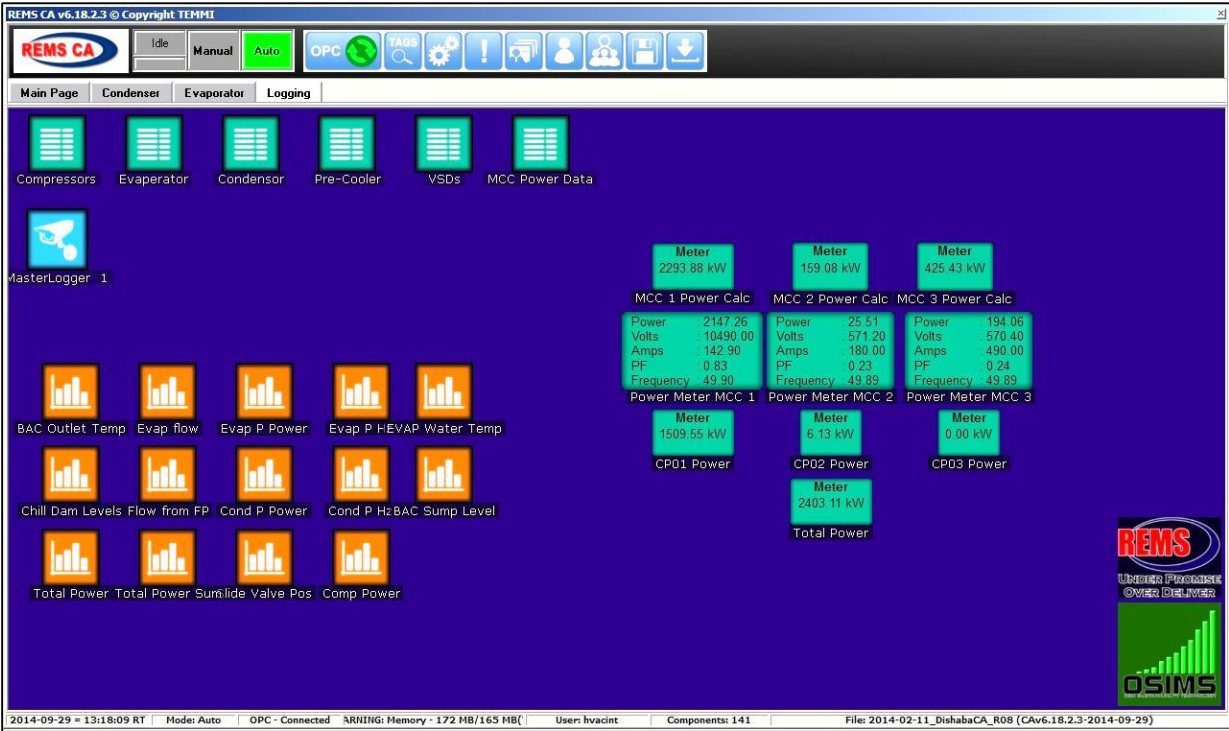


Figure 79: EMS print screen – data logging, trending and power meter



Figure 80: VSD installed on the evaporator pumps.



Figure 81: VSDs installed on the BAC spray pumps.