

Improving existing DSM initiatives on mine refrigeration systems for sustainable performance

AJH Nel
22739637

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Supervisor: Dr JF van Rensburg

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Abstract

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- Author:** Andries Johannes Hendrik Nel
- Supervisor:** Dr JF van Rensburg
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South Africa, as a young developing country, is dependent on a sufficient electricity supply for ongoing economic development. With an increasing gross domestic product and an alarming growth rate attributed to the abundant resource endowments, and historical low coal and electricity prices, emphasis is placed on the main economic drivers for sustainable growth.

South Africa has the largest reserves of gold, platinum and coal in the world. It therefore comes as no surprise that mining is considered as one of the main, if not the cornerstone of economic development, contributing up to 14% of South Africa's electricity usage. The global electricity paradigm is highlighted by the staggering demand increase projected for South Africa. The national power utility, Eskom, is currently busy with large capital expansion projects for increasing the supply as a last condonable effort to satisfy the current and growing demand.

The electricity price has increased dramatically over the last few years to aid the utility's supply expansion projects. The gold mining sector, however, is under immense pressure to reduce operational costs, especially with increasing labour unrests and stringent governmental policies. The daunting reality imposed on mines is subsequently to mine more efficiently without affecting production adversely.

Since mining is done at great depths in South Africa, refrigeration systems was identified as one of the largest electricity consumers on mines. The general operation, control and equipment stance of the refrigeration systems are, however, inefficient and oversized. As a result, several demand-side management (DSM) initiatives have previously been

implemented on mine refrigeration systems, which notably reduced not only the electricity usage but also the operational costs. Furthermore, the DSM initiatives contributed positively towards the feasibility of mines to stay competitive in a global market.

Although significant electricity cost savings were realised as part of the DSM initiatives, project deterioration occurs over time, eroding the viability of sustained electrical cost savings. It is therefore critical to identify the factors affecting the performance of DSM initiatives to develop a strategy that includes measures to improve the existing DSM initiatives on mine refrigeration systems for sustainable and optimised performance.

Implementing such a performance strategy will ensure effective and efficient use of the existing DSM initiatives on mine refrigeration systems. The strategy will ensure that the electrical cost savings and optimised performance of the refrigeration system are maintained by including detailed monitoring, control and reporting measures of key performance indicators.

The feasibility of such a strategy was proved using case studies by analysing the post-implementation effects on two underperforming deteriorating refrigeration systems, situated at two separate gold mines, with existing DSM initiatives. The study validation has shown that a sustainable average daily power saving of 1.8 MW was achieved during the course of 15 months for Mine A; with a sustainable average daily power saving of 1.62 MW over the course of 17 months for Mine B. As a result, the average electrical cost savings amounted to R11.9 million for Mine A and R12.1 million for Mine B.

In order to fully appreciate the results, the average electricity reduction was quantified as a percentage for both mines, achieving a combined reduction of 24%. The developed performance strategy therefore improves existing DSM initiatives on mine refrigeration systems for sustainable performance.

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Abbreviations

AC	Alternating current
BAC	Bulk air cooler
COP	Coefficient of performance
CPI	Consumer price index
DSM	Demand-side management
EMS	Energy management system
ESCO	Energy services company
HMI	Human-machine interface
IPMVP	International Performance and Verification Protocol
KPI	Key performance indicator
M&V	Measurement and verification
NERSA	National Energy Regulator South Africa
NMD	Notified maximum demand
OEM	Original equipment manufacturer
OLE	Object linking and embedding
OPC	OLE for process control
PI	Proportional-integral
PID	Proportional-integral-derivative
PLC	Programmable logic controller
PTB	Process Toolbox
SCADA	Supervisory control and data acquisition
TOU	Time-of-use
VCR	Vapour-compression refrigeration
VRT	Virgin rock temperature
VSD	Variable speed drive

Nomenclature

List of symbols

Symbol	Description	Unit
C_{AC}	Annual incurred costs	(R)
C_E	Capital expenditure	(R)
C_{IC}	Initial capital investment	(R)
C_p	Specific heat constant	(kJ/kg.K)
C_S	Capital electricity cost savings	(R)
\dot{m}	Mass flow rate	(kg/s)
η_W	Water-side efficiency	(%)
\dot{Q}_{evap}	Refrigerating rate	(kW)
$T_{a\ inlet}$	Air inlet temperature	(°C)
$T_{w\ inlet}$	Water inlet temperature	(°C)
$T_{w\ outlet}$	Water outlet temperature	(°C)
\dot{W}_{comp}	Compressor motor power	(kW)

List of units

Symbol	Description	Unit
°C	Temperature	(degrees °C)
G	1×10^9	(giga)
g	Mass	(gram)
Hz	Frequency	(hertz)
J	Energy	(Joule)
K	1×10^3	(kilo)
ℓ	Volume	(litre)
m	Distance	(metre)
M	1×10^6	(mega)
R	Currency	(ZA rand)
s	Time	(second)
t	Mass	(ton)
T	1×10^{12}	(tera)
US\$	Currency	(US dollar)
V	Voltage	(volt)
W	Power	(watt)
Wh	Energy	(watt-hour)

Chapter 1

Introduction



“Learn from yesterday, live for today, hope for tomorrow.

The important thing is not to stop questioning.”

– Albert Einstein

1.1 South African energy climate

1.1.1 Introduction

South Africa, as part of the emerging national economies association between Brazil, Russia, India, China and South Africa (BRICS), is critically reliant on unwavering sufficient electricity supply for ongoing economic development [1]. Rapid expansion and industrialisation have led to South Africa having one of the highest energy intensities in the world [2]. South Africa, with a gross national income per capita of US\$7 190 in 2013, has tripled its gross domestic product since 1996 [3].

The growth rate experienced in the last couple of decades can be attributed to South Africa's resource endowments and to the historically low coal and electricity cost to consumers [4]. This economic growth pattern is of an increasing global concern, especially regarding the management and sustainability of energy resources [5]. The global electricity demand is projected to increase by 33% between 2010 and 2030, with South Africa's electricity demand projected to increase by 59% between 1990 and 2020 [5], [6].

South Africa's primary electricity utility company, Eskom, is thus under constant strain to satisfy the growing demand in South Africa [7]. In 2007, their lack of generation capacity led to demand exceeding supply. Eskom instigated load shedding as a temporary mitigation measure to assist in meeting the demand [8]. As a result, R50 billion was lost from the economy in the first quarter of 2008 according to the National Energy Regulator South Africa (NERSA) [7].

Eskom, with a generation capacity of 41 994 GW, currently produces 95% of the electricity consumed in South Africa [9]. Eskom also supplies 45% of electricity used in Africa, making it the seventh-largest utility in the world with the majority of electricity produced using baseload coal-fired power stations [10].

The utility is busy with a capital expansion programme that aims to increase the overall capacity with 17 170 MW by 2018 [11]. However, Eskom only managed to increase its capacity with 6 137 MW by the end of 2014 [12]. The virtually stagnant progress can be attributed to unscheduled maintenance, a higher consumer price index (CPI), meagre management and labour unrests – all the while crippling the utility's resources [8]. The

approximate construction time of eight to ten years for a single power plant also contributes to the significant challenges faced by Eskom [13].

According to Sebitosi, energy conservation is the most sensible means of deferring capacity expansion infrastructure – especially where traditional market monopoly utilities such as Eskom are involved. Figure 1-1 illustrates the electricity demand distribution of various consumers according to client type. The most prudent approach to initiate energy conservation will thus be to target the largest energy consumers [1].

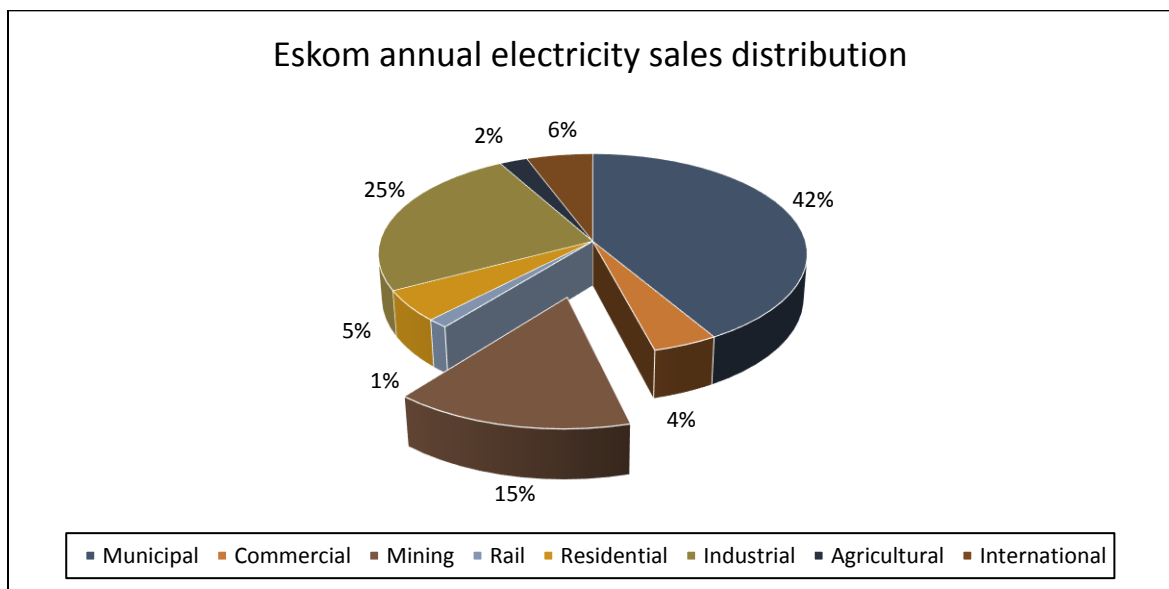


Figure 1-1: Eskom annual electricity sales distribution 2014 [9]

1.1.2 Energy conservation strategies

A proven conservation strategy, called demand-side management (DSM), was introduced by Eskom in 2005 [1]. The purpose of DSM is altering the traditional electricity paradigm from where the demand is exclusively matched with the electricity transmitted, towards a load management controlled approach [14].

Therefore, DSM is an approach that focuses on managing the electricity demand during peak periods through load management and energy efficiency strategies [15]. The World Energy Council defines energy efficiency as the reduction of energy used for a specific service/activity [2]. According to the International Energy Agency, DSM is far more cost-effective than conventional supply-side policies and further reduces the environmental effects and costs associated with supply management [11]. This fully aligns with South Africa's

commitment to the Secretariat of the United Nations Framework Convention on Climate Change, which involves reducing greenhouse emissions with 34% by the end of 2020 [16].

Eskom outsources to several independent corporations, but mainly subcontracts accredited energy services companies (ESCOs) to implement DSM projects [9]. The ESCO establishes a partnership, and manages the project relations between Eskom and the consumer to ensure that all project deliverables are fulfilled [17].

Eskom has contributed more than R1.36 billion to DSM projects during the financial year of 2013/2014 [9]. This commendable financial contribution is apparent when one considers the savings achieved by the DSM programme since inception (as illustrated by Figure 1-2).

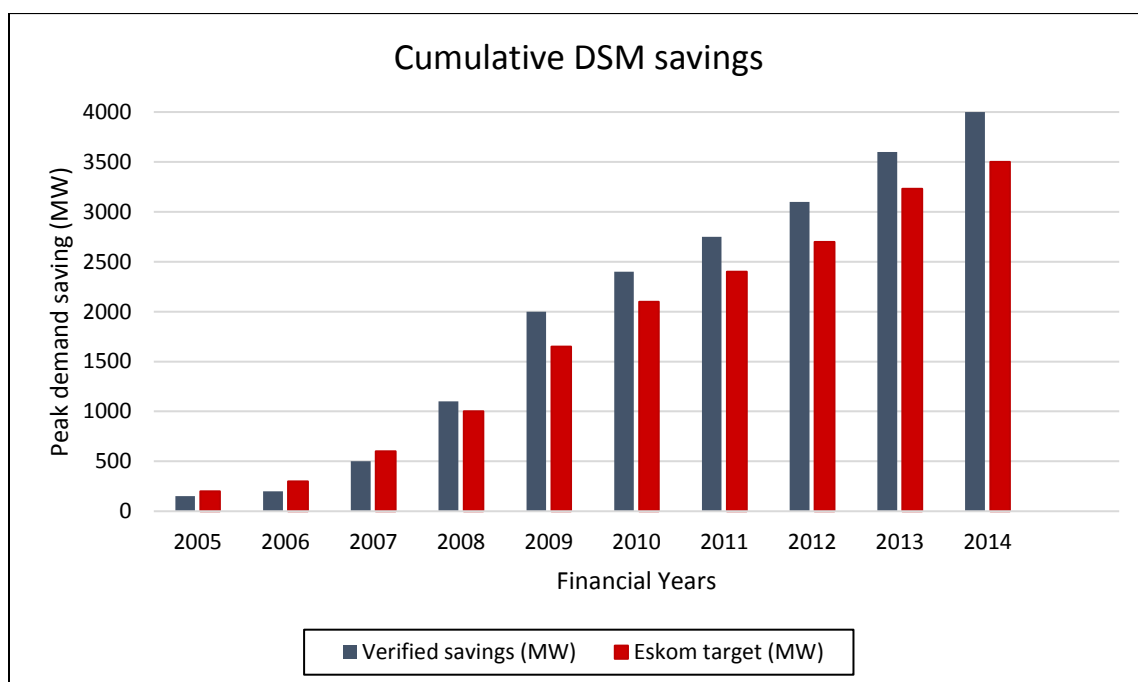


Figure 1-2: DSM savings history [9]

Although the savings have increased substantially each year, Eskom still requires a vast reduction in electricity usage to be able to contribute successfully towards sustainable economic growth [4]. Nevertheless, DSM is still the leading, most cost-effective, proven method to relieve short-term strain on a national power network [18]. Studies have shown that DSM could be the main catalyst required to enable the behavioural changes for industry to reconsider their stance on energy efficiency [19].

According to Schutte, the historical low coal and subsequent low electricity price left little to no incentive for consumers to save electricity, especially for exorbitant energy users [8].

Mining and industrial sectors can contribute positively towards energy savings in South Africa, but often lack the expertise or resources required for energy management programmes [9]. Current infrastructure used throughout the mining and industrial sectors is oversized, incorporating excessive design safety factors and outdated control systems which results in energy wastage [20].

According to Kaplan, as cited by Newbery and Eberhard the lateral investment in new technological advances and competencies is fundamental, not only for industry, but also for developing countries with energy intensive economies [21]. Using modern technology can, therefore, reduce the energy intensity of a sector while increasing the life cycle [22].

1.1.3 The mining sector in South Africa

South Africa has the largest reserves of coal, gold and platinum in the world [23]. Thus, it is apparent that mining is one of the most important, if not the main economic driver in South Africa [24].

Government forces mining companies to continually improve their labour relations and realise their socio-economic responsibilities through structured development programmes [25]. Amidst the abundance of natural resources, the economic feasibility of sustaining these development programmes is drastically declining, especially if one considers Figure 1-3, which illustrates the higher than inflation Eskom electricity tariff increases.

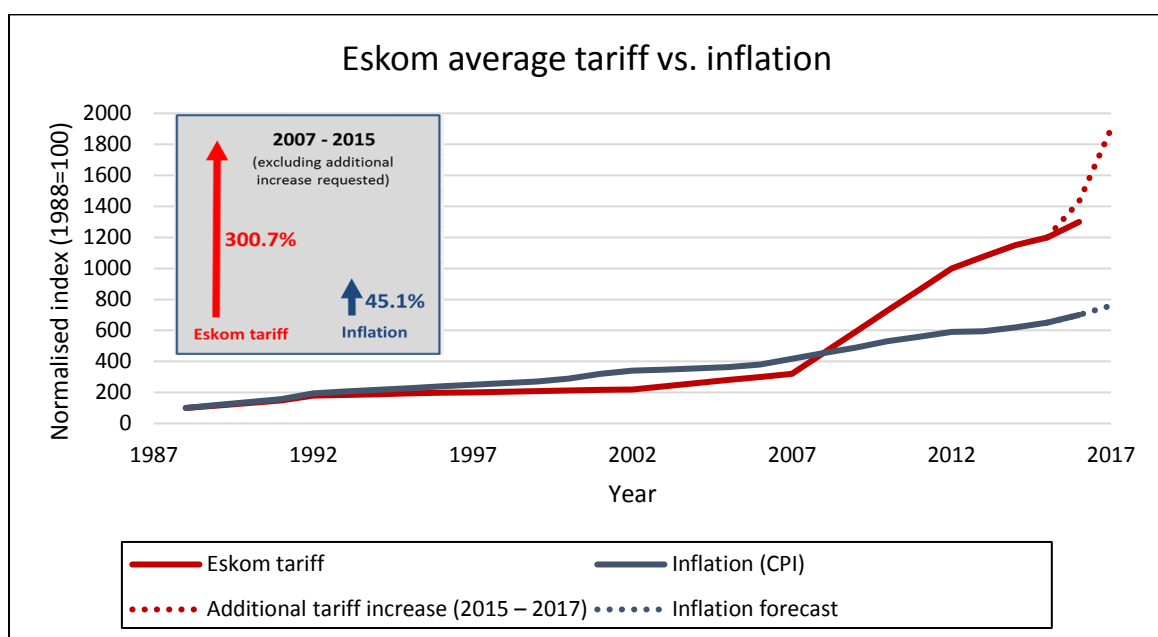


Figure 1-3: Electricity and inflation increase comparison [9], [26], [27]

The increasing electricity tariff, CPI, labour unrests and more stringent governmental laws all contribute towards the various challenges already faced in industry by increasing the operational costs [28].

Figure 1-4 illustrates the decreasing trend of the gold and platinum prices over the last couple of years. Mines are left to resort to drastic cost-cutting measures in an attempt to reduce operational costs, which could yield negative effects [3].

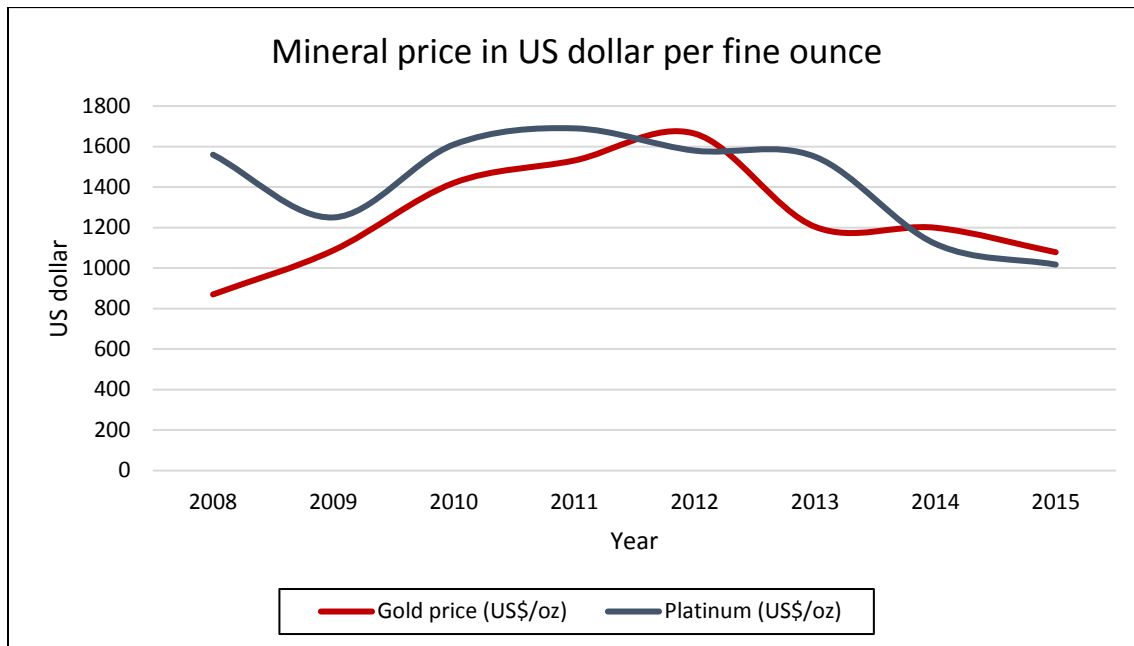


Figure 1-4: Average annual mineral price since 2008

Gold mines consume roughly 47% of the total mining industry's electricity consumption, with a typical gold mine using between 110 GWh and 610 GWh of electrical energy annually [9], [29]. The dwindling gold price coupled with the immense electricity tariff increases, therefore, diminish the viability of gold mining in South Africa.

It is imperative for the mining industry to improve upon the status quo of energy efficiency. Furthermore, mines need to drive any and all energy savings initiatives with the necessary rigor, adapting through the latest technologies and behavioural changes to ensure sustainable operation and competitiveness [28].

1.2 Energy management potential on refrigeration systems

Studies have shown that there are ample opportunities to implement DSM initiatives on different deep-level gold mining systems [19], [30]. Figure 1-5 illustrates the electricity distribution across the different systems of a typical gold mine in South Africa.

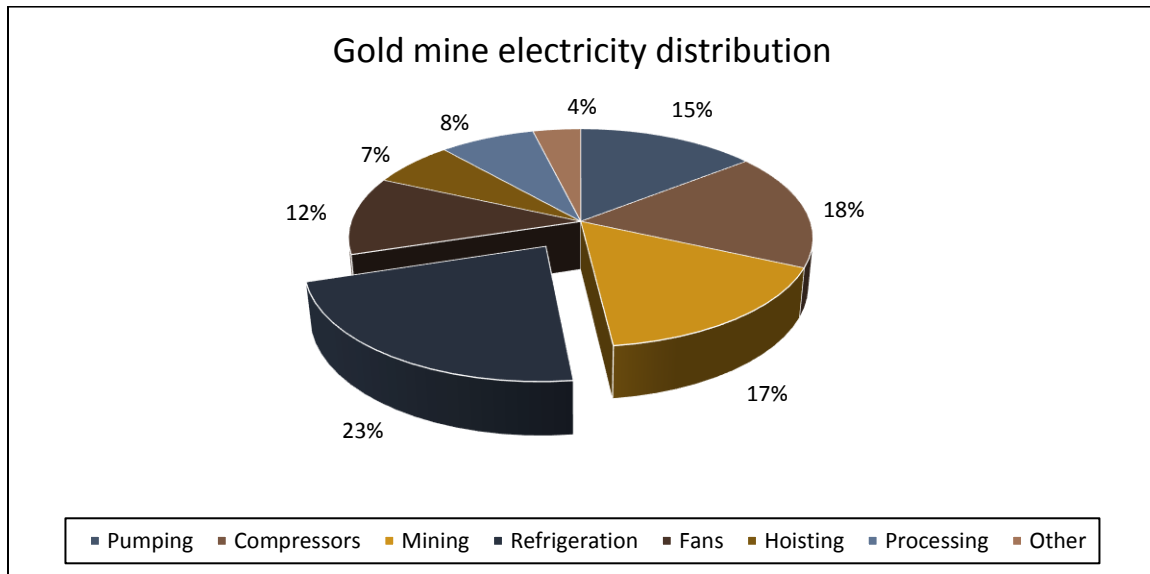


Figure 1-5: Typical gold mine electricity distribution

Since mining is done at great depths in South Africa, the 23% electricity usage for refrigeration systems comes as no surprise [11]. Els stated that cooling underground relies solely on refrigeration systems [31]. Hence, the thermal load required for cooling is further dependent on the virgin rock temperature (VRT) and average ore-breaking depths [32].

Although refrigeration systems are critical for safe and legal mining operations, the general consensus among industry and experts remains – equipment is oversized and inefficient [11]. Furthermore, these pieces of equipment have outdated control strategies, which, if updated, could yield significant electrical cost savings while also allowing more funds available for capital expansion expenditure [18].

This study will therefore focus on improving DSM initiatives on mine refrigeration systems for sustainable performance in South Africa. Gold mining typically occurs between 3 km and 4.8 km deep in South Africa [11], [33]. As a result, South Africa has eight of the ten deepest gold mines in the world, with only two of the mines situated outside South Africa's borders in Ontario, Canada [34].

The single most important challenge faced in deep-level mining is ensuring a safe operating environment with very low thermal stress exposure for all employees. Refrigeration systems must ensure a working area temperature less than the legal limits, which are 27°C wet bulb and/or 32°C dry bulb [35], [36]. This is a monumental task when considering that VRTs are commonly well in excess of 61°C at the current mining depths in South Africa [37]. Figure 1-6 illustrates the typical VRTs found throughout different regions in South Africa.

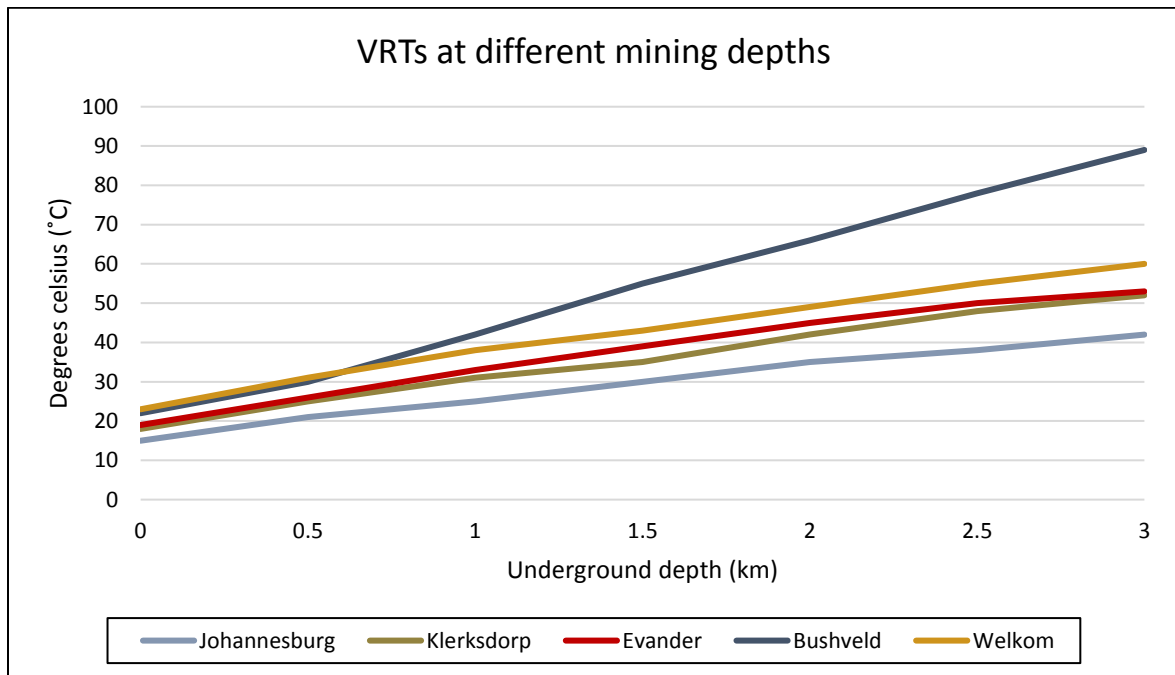


Figure 1-6: VRT of different regions in South Africa at depths[11]

Refrigeration systems have large capacities for the systems to cope with extreme geothermal increases of between 18°C/km and 25°C/km as experienced in South Africa [38], [39]. It is expected that the refrigeration system of a deep-level mine will have a cooling load capacity of approximately 32 MW. A refrigeration system typically supplies 375 kW of cooling per kiloton per metre (kt/m), which is required at mining depths of more than 3.0 km [8], [15].

The first deep-level refrigeration technologies were developed by the Chamber of Mines Research Organisation during the early 1970s [40]. Since the inception of these technologies, very little has been done to improve upon the initial design, control and efficiencies [41]. The electricity consumption of these systems can be reduced significantly by introducing new technologies, control strategies and by applying energy efficiency practices. As such, ESCOs have already implemented DSM initiatives successfully on mine refrigeration systems [27].

A case study completed on 20 mine refrigeration systems revealed an annual electrical energy consumption of 1.3 TWh. The study further focused on implementing new energy efficient technologies, resulting in an estimated annual energy saving of 168 GWh. Furthermore, a carbon dioxide emission reduction of 153 kt/year and cost reduction of US\$8 million would be realised if implemented. The accompanying pilot study revealed an actual electrical energy reduction of 30% [42].

Although the impact of the savings achieved is more than significant, there is, however, still ample room left for improving implemented DSM initiatives. According to Groenewald, project deterioration often occurs once the ESCO has fulfilled its contractual obligations [27]. The real challenge is sustaining the electricity cost savings for the entire operational life cycle [19].

To conclude, refrigeration systems are critical for safe and legal mining operations, especially in deep-level South African gold mines. Refrigeration systems pose great energy management potential and several DSM initiatives have already been implemented successfully. Improving these DSM initiatives is key to enabling sustainable electricity cost savings.

1.3 Project sustainability

The emphasis for companies to stay competitive is portrayed by their commitment towards the future where sustainability takes precedence in their financial outlook [28]. Therefore, the mining and industrial sectors must comply with the global trend towards energy management and energy efficient practices [19].

Gomes *et al.* define sustainability as the capacity to maintain a service and/or activity outcome. In terms of the mining industry, sustainability aims to minimise the inherent environmental effects associated with mining [28].

Although the Chamber of Mines of South Africa has committed itself and its active members to sustainable practices, both voluntary and mandatory, several obstacles hamper the implementation of such practices [43].

More so, Sütterlin *et al.* argue that energy saving actions based on curtailment is far harder to implement than it is to adopt efficient technologies [44]. This fact is evident when one

considers the DSM impact of a typical refrigeration project in Figure 1-7. The target was met during the first three months where the ESCO had to prove target feasibility; thereafter the mine was responsible for sustaining the savings, which show clear deterioration.

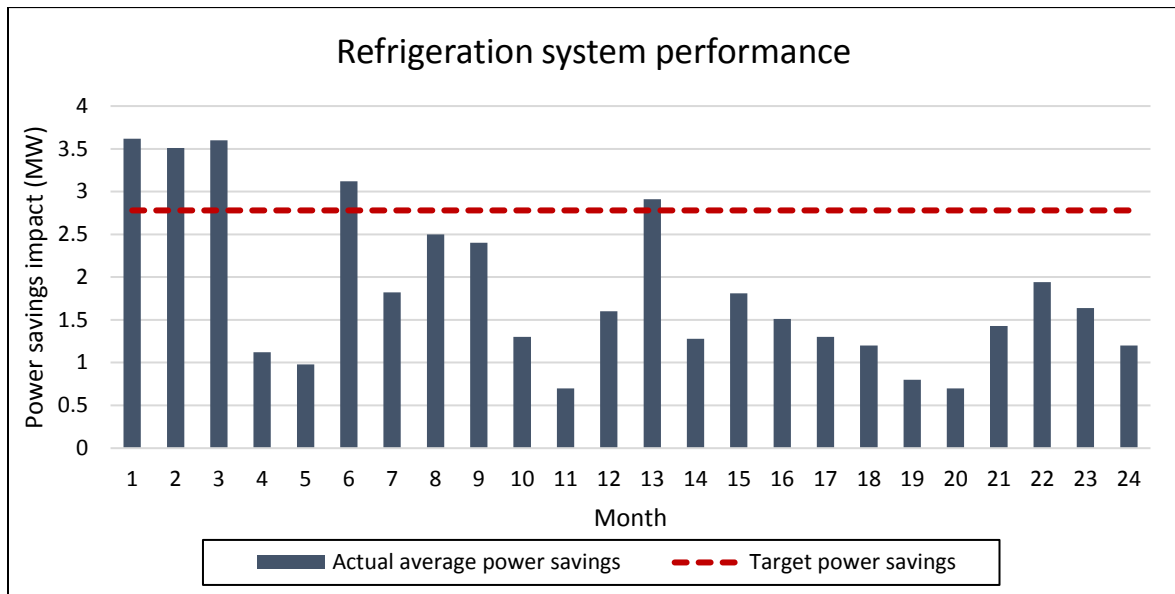


Figure 1-7: Refrigeration system performance over time

Project deterioration can be ascribed to several factors such as poor maintenance, system parameter changes or defective and inefficient equipment [27]. However, the lack of energy saving behaviour is one of the main stumbling blocks experienced during DSM projects [19].

All factors considered, existing underperforming DSM initiatives can be improved considerably with the majority of projects demanding very little capital investment. Furthermore, these projects can be considered as “low-hanging fruit” to increase electrical cost savings.

1.4 Problem definition and research hypothesis

It is reasonable to conclude from the prior sections that there is a dire need to lower the electricity demand in South Africa. Subsequently, the mining sector, and in particular gold mines, was identified as the main electricity consumer where environmental control could account for up to 40% of total electricity costs [11]. The mining sector further suffers from using outdated and inefficient equipment.

The higher than inflation electricity tariff increases exacerbated the immense need for mines to lower their operational costs through DSM cost-reduction measures.

Mine refrigeration systems were identified as one of the main electricity consumers, contributing up to 23% of the electrical energy used by a typical deep-level gold mine. Henceforth, several DSM initiatives have previously been implemented on mine refrigeration systems yielding notable electrical cost savings.

Although significant savings had been achieved through these initiatives; project deterioration occurs over time, eroding the viability of sustained electrical cost savings. It is consequently imperative to identify the challenges that halter project performance and especially, sustainability.

The study will therefore focus on developing a generic performance strategy to improve not only existing DSM initiatives on mine refrigeration systems to promote sustainability, but also performance. As a result, the study hypothesis can be defined accordingly:

By identifying the factors and challenges that contribute to project deterioration, a performance strategy can be developed that would improve the sustainability and performance of existing DSM initiatives on mine refrigeration systems through greater realised electrical cost savings without affecting any service delivery requirements adversely.

A mine, with existing DSM initiatives experiencing project deterioration, will be identified and investigated for improvements. The new improved strategy will be implemented on the mine's refrigeration system. This should increase the refrigeration system's performance without affecting production negatively. Furthermore, the strategy should lower the mine's operational costs without adding large capital investments.

To conclude, a significant decrease in the mine's electricity cost must be realised. Also, the generic strategy must prove feasible for all existing DSM initiatives. Although the study is set on deep-level gold mines, there is potential for the strategy to be implemented in several other sectors and industries where refrigeration systems are present.

1.5 Study overview

A summary of the study sections that follow is shown. The study is systematically organised to satisfy the research objectives and abide by the scientific method.

Chapter 1: Introduction – A synopsis for the study is given, starting with a general background regarding the current economic climate and electricity usage in South Africa. The potential of DSM initiatives on mine refrigeration systems is discussed. The deterioration in project sustainability is shown and the need to improve existing DSM initiatives are identified. The study problem statement, research objectives and scope are formulated.

Chapter 2: Mine refrigeration system investigations – Existing DSM initiatives on mine refrigeration systems are investigated. The investigation pertains to defining refrigeration systems and individual electricity consuming components. The investigation further stretches to identifying typical service delivery requirements, performance considerations and factors affecting existing DSM initiatives. An encapsulated view of the effects on project performance/sustainability is discussed and existing DSM initiatives are reviewed for further improvement.

Chapter 3: Improved sustainability performance strategies – Deterioration of existing DSM initiatives is identified and discussed. The potential improvement of existing DSM initiatives on mine refrigeration systems through performance strategies is developed and discussed in detail. The proposed performance strategy is verified and the economic feasibility is investigated.

Chapter 4: Energy saving implementation – The performance strategy developed in Chapter 3 is implemented on a mine with existing deteriorating DSM initiatives. The actual and simulated results are compared and the critical factors discussed. Verification and validation of the proposed strategy are also presented and discussed in detail.

Chapter 5: Conclusions and recommendations – A final all-encompassing conclusion is drawn from the study results. Further recommendations and relevant considerations for future developments are revealed.

Chapter 2

Mine refrigeration system investigations



“The noblest pleasure is the joy of understanding.”

– Leonardo da Vinci

2.1 Introduction

South Africa's vast endowment of minerals has played a crucial role in developing the country's economy [23]. For this reason, South Africa's mineral industry, which is based primarily on gold, has contributed significantly towards continued economic growth. The current economic downturn, low gold price, and increasing production and labour costs emphasise the immense need for South African gold mines to lower their operational costs [24].

It is essential to review key considerations and factors of refrigeration systems regarding improving existing DSM initiatives for sustainable performance before commencing with developing the strategy. These factors will contribute towards the contextualisation and summation of the strategy development as applicable in further chapters.

Accordingly, the review provides detailed information and background of concepts and techniques relevant to the study. Refrigeration systems and auxiliary equipment, known as "cooling auxiliaries", involved with the system operations are discussed in this chapter to further elaborate and build upon the research hypothesis.

Current optimisation techniques and existing DSM initiatives on mine refrigeration systems are reviewed and discussed to investigate potential improvements in terms of sustainability practices.

An overview of the constraints and service delivery requirements is identified and discussed, which has to be adhered to throughout the strategy development phases. Finally, key performance indicators (KPIs) of existing systems are identified and discussed to quantify comprehensive deliverables of the proposed strategy.

2.2 Refrigeration systems on deep-level mines

2.2.1 System overview

South Africa has some of the deepest mines in the world, with mining operations far exceeding depths of 3 km [33]. High VRTs, fissure water, machinery, high geothermal gradient increases, and autocompression of ventilation air introduced large heat loads underground [45]. For this reason, researchers from the National Institute for Occupational Safety and Health conducted a heat-stress exposure case study that exhibited an optimum

work environment temperature lower than 27.5°C (wet bulb) [46]. As a result, refrigeration systems are primarily required for artificial environmental control to ensure conditions conducive to safe and productive mining [22], [45].

According to Brake, South Africa is the largest user of mine refrigeration with an estimated 300 refrigeration machines installed [47]. Refrigeration systems comprise of surface and underground systems working in conjunction to deliver the required artificial cooling [8]. Surface refrigeration systems are used not only to supply dehumidified cold air, but also chilled water to underground working areas [48]. Although using underground refrigeration systems is generally found to be common practice, surface refrigeration systems, however, are preferred due to an increased heat-rejection capacity [37], [49].

Although refrigeration systems is the fundamental medium used in artificial cooling, the complex interaction with cold water and ventilation systems should not be overlooked [49]. Consequently, mine refrigeration systems have diverse layouts and configurations that are dependent on individual mine's service delivery requirements and specific mining depths [50]. Even though there is a vast array of differences, the fundamental principles, methods, concepts and components for refrigeration systems essentially remained the same since their inception [41].

A schematic layout of a typical surface refrigeration system integrated with the water reticulation system is illustrated in Figure 2-1. Accordingly, the figure also conveys the fact that the water is used in a semi-closed loop, as defined by Schutte [8].

Hot service water (1), typically ranging between 31°C and 34°C (dry bulb) is pumped from underground and collected and stored in the hot surface storage dam (2). The hot water is then pumped (3) or gravity-fed to the precooling towers (4). A portion of the water leaving the hot surface storage dam is usually cleaned and treated using sand filters [51]. The precooling towers (4) cool the hot water to a temperature within 2°C of ambient conditions, based on the ambient temperature having a lower temperature than the hot service water.

Thereafter, the cooled water is collected and stored in the precooling sump (5). Precooling has a very high coefficient of performance (COP) since no refrigeration is required, which contributes immensely towards a higher overall system efficiency [52]. From the precooling sump, the water is pumped by the evaporator pumps (6) through the refrigeration machines or chillers (7).

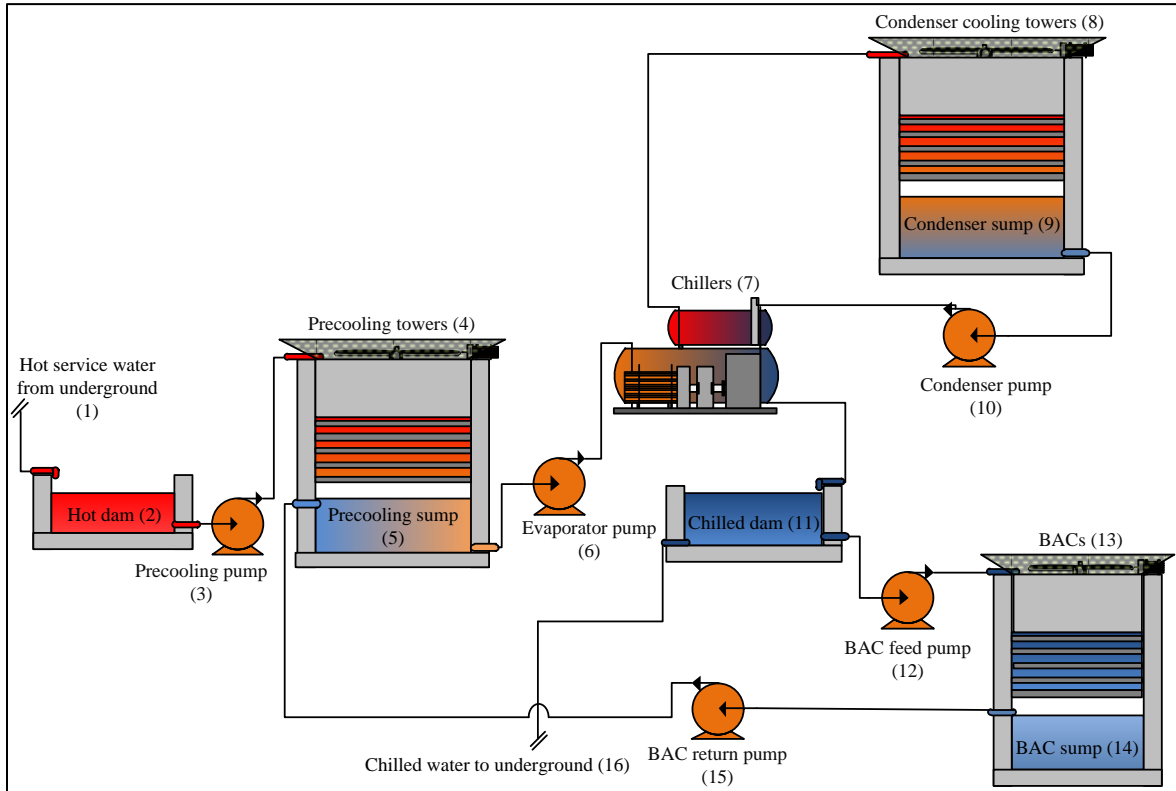


Figure 2-1: Schematic layout of a typical surface refrigeration system

The water flows through the evaporator heat exchanger of the refrigeration machine and is further cooled to below 4°C [47]. If the precooling sump temperature is too high, a portion of the chilled water leaving the evaporator heat exchanger is recirculated into the inlet pipe through a back-pass valve [36], thus effectively lowering the inlet temperature and ensuring a higher refrigeration machine efficiency [32].

The water exiting the refrigeration machine is stored in a chilled water dam (11), from where it is gravity-fed underground (16) and pumped (12) to the bulk air coolers (BACs). The BACs incorporate the chilled water to dehumidify and cool the ambient air, usually at a wet-bulb temperature of 6.5°C, before it is forced underground using fans [53]. The warmer water is collected in the BAC sump (13) and pumped further (15) into the precooling sump (5).

The condenser pumps (10) are used to circulate the water through the refrigeration machines (7) and condenser cooling towers (8) in a closed loop to dissipate the heat generated through the cycle into the atmosphere. After the heat is rejected to atmosphere, the colder water is collected in the condenser sump (9) to be reprocessed through the closed circuit.

It is clear from this process that several electric inputs are required. The most significant electricity consuming components are refrigeration machines and other auxiliary equipment such as induction motors, various cooling towers, BAC fans and several water-transfer pumps [36].

The thermal transfer of the water is displayed in Figure 2-1, which concurrently shows that the highest thermal exchange is experienced in the refrigeration machines. As a result, the electrical use of the refrigeration machines far outweighs that of any other component. Table 2-1 shows the typical installed motor rated capacity of the different components.

Table 2-1: Typical installed motor capacity

Components	Installed rating [kW]
Fans	100–150
Pumps	90–250
Refrigeration machines	1 100–1 500

The following section will elaborate on the functioning and detail of the different components to determine the overall DSM effect on the system.

2.2.2 Refrigeration machines

Refrigeration machines are used to supply chilled service water to various surface and underground end-users [47]. These machines usually operate by ammonia absorption or vapour-compression refrigeration (VCR). Industry prefers VCR due to its low maintenance cost and rudimentary design [8].

As soon as a fluid reaches its saturation temperature, phase change occurs at a constant temperature provided that the applied pressure (saturation pressure) remains constant [54]. During this stage, the fluid draws out latent heat from its surrounding medium to change into a vapour [36]. This vapour is transported and compressed to a higher pressure and subsequent saturation temperature that enables the vapour to be condensed, rejecting heat to its environment [54]. The transfer of latent heat is the fundamental principle on which all refrigeration cycles such as the VCR cycle is based [53].

The working fluid or refrigerant is primarily chosen for its physical properties such as its pressure-temperature relationship to comply with the necessary cooling requirements of the

mine [52]. Service water is commonly chilled from 28°C to 4°C for mining operations to occur [53].

Calm led a study showing that the refrigerants freon (R134a) and ammonia (R717) are both ideally suited for the temperature and pressure ranges experienced on mines [50]. Although freon is a hydrofluorocarbon, it falls outside the scope of the Montreal Protocol (1987) with only its emissions being controlled by the Kyoto Protocol (1997) [55]. Thus, freon is preferred for both surface and underground applications and is commonly used in industry as a substitute fluid for older R-12 and R500 refrigerants [50].

Ammonia is a very efficient and economical refrigerant, particularly in the production of chilled service water or ice slurries [53]. Although ammonia has many benefits over the more common freon refrigerant, it is limited to only surface applications due to its flammability and corrosiveness [50].

Figure 2-2 illustrates the VCR cycle used in mine refrigeration machines. The cycle along with its most crucial components will be explained briefly in the following section.

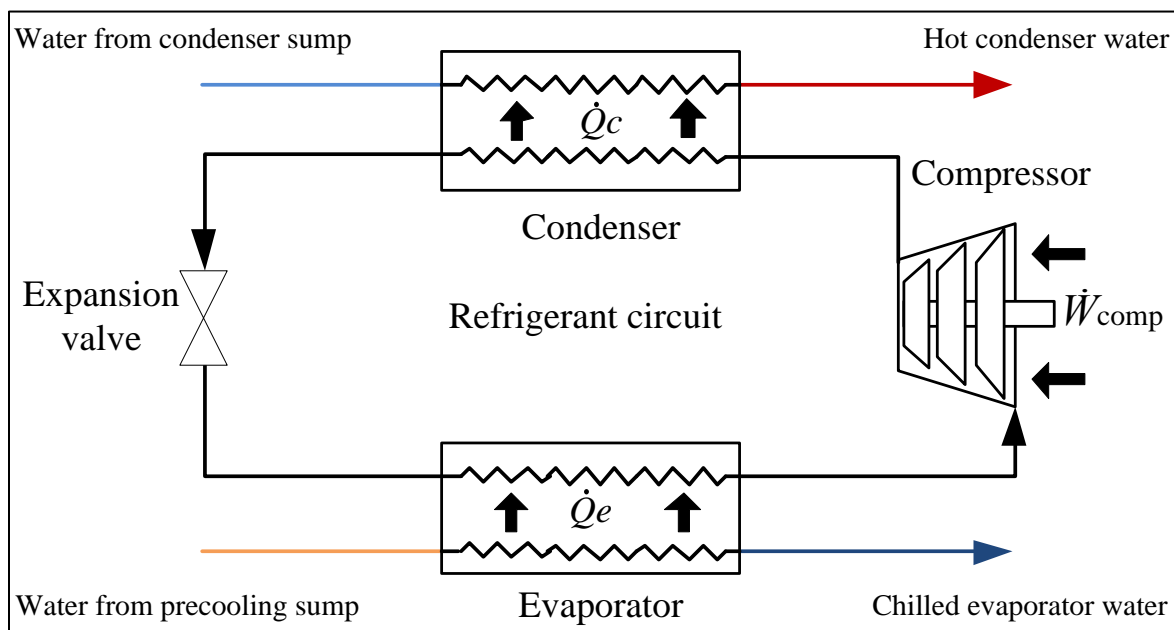


Figure 2-2: VCR cycle layout

The basic VCR cycle consists of four essential components; namely, the compressor, expansion valve, and finally the evaporator and condenser (heat exchangers) [54]. Shell-in-tube heat exchangers are preferred for mining operations; however, plate heat exchangers

are occasionally used where there are physical space constraints [52]. The water typically flows inside the tubes of the heat exchanger with the refrigerant (freon) inside the shell [53]. Service water is chilled in the evaporator through evaporative latent heat transfer to the refrigerant resulting in a low-pressure refrigerant vapour [36]. The refrigerant is compressed to a higher pressure and subsequently a higher temperature by the compressor, which enables the latent heat transfer from the refrigerant to the condenser water [54]. After the refrigerant is condensed, the high-pressure fluid is flashed through an expansion valve and the accompanying drop in pressure results in a low-temperature low-pressure fluid, effectively completing the sequence [53].

The VCR cycle requires work from a compressor (as an input) to compress the refrigerant vapour [56]. Although reciprocating compressors exist, their lack of capacity results in only two compressor types being considered for mining applications [52]: screw and centrifugal compressors, which control the load by slide valves and inlet guide vanes respectively [57].

The slide valves and inlet guide vanes continuously regulate the refrigerant flow rate and the latent heat transfer to ensure a constant evaporator water outlet temperature is achieved (with varying inlet conditions) [57]. Centrifugal compressors are favoured for large capacity applications with a relatively constant pressure ratio. However, screw compressors are favoured for variable load conditions (as seen in Figure 2-3) [58].

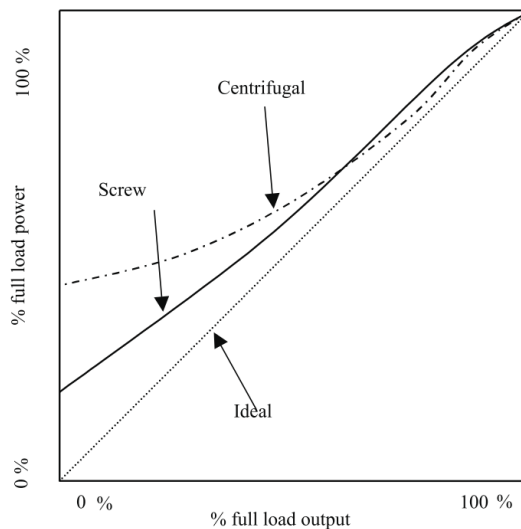


Figure 2-3: Compressor efficiency comparison [52]

The type and capacity of the compressor is dependent on the specific cooling load required for achieving the selected evaporator water outlet temperature [55]. Furthermore, the cooling load directly affects the power consumption of the compressor's electric motor, which is the main contributor towards the refrigeration machine's electrical energy usage [53].

Stoecker and Jones define the COP as a dimensionless value that represents the amount of useful refrigeration divided by the nett work input [59]. Additionally, this value is a measure of not only the refrigeration machine's performance, but also of the cooling efficiency (as shown in Equation 2-1) [54].

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \quad (2-1)$$

Where,

$$\begin{aligned} \dot{Q}_{evap} &= \text{rate of thermal energy absorbed by the evaporator (kW)} \\ \dot{W}_{comp} &= \text{compressor electric motor power (kW)} \end{aligned}$$

The refrigeration rate is further defined in Equation 2-2 [54]:

$$\dot{Q}_{evap} = \dot{m}C_p(T_{w\ inlet} - T_{w\ outlet}) \quad (2-2)$$

Where,

$$\begin{aligned} \dot{Q}_{evap} &= \text{rate of thermal energy absorbed by the evaporator (kW)} \\ \dot{m} &= \text{water mass flow (kg/s)} \\ C_p &= \text{specific heat constant (kJ/kg.K)} \\ (T_{w\ inlet} - T_{w\ outlet}) &= \text{temperature difference of water (K)} \end{aligned}$$

Observe from Equation 2-1 that a high COP value indicates that a refrigeration machine operates efficiently [36]. Small capacity refrigeration machines usually operate with a COP of 3, whereas large machines can achieve a COP value up to 6 [52].

If one considers both Equation 2-1 and Equation 2-2, a conclusion can be drawn that the evaporator cooling load is mainly influenced by the inlet water temperature and evaporator water mass flow rate. Subsequently, if these parameters are reduced it will result in a higher COP [36]. The inverse was also proven on the condenser side with a condensing temperature and condenser water mass flow increase resulting in a higher COP [52], [53].

Therefore, it is clear that a large difference between the condensing and evaporating temperatures results in a low COP. Hence, several different refrigeration machine configurations are available to counteract these negative effects, thus increasing the COP as illustrated by Figure 2-4 [53].

According to McPherson, the most frequently used refrigeration machine process configurations are: parallel, series, and parallel-series configurations (as illustrated in Figure 2-4) [53].

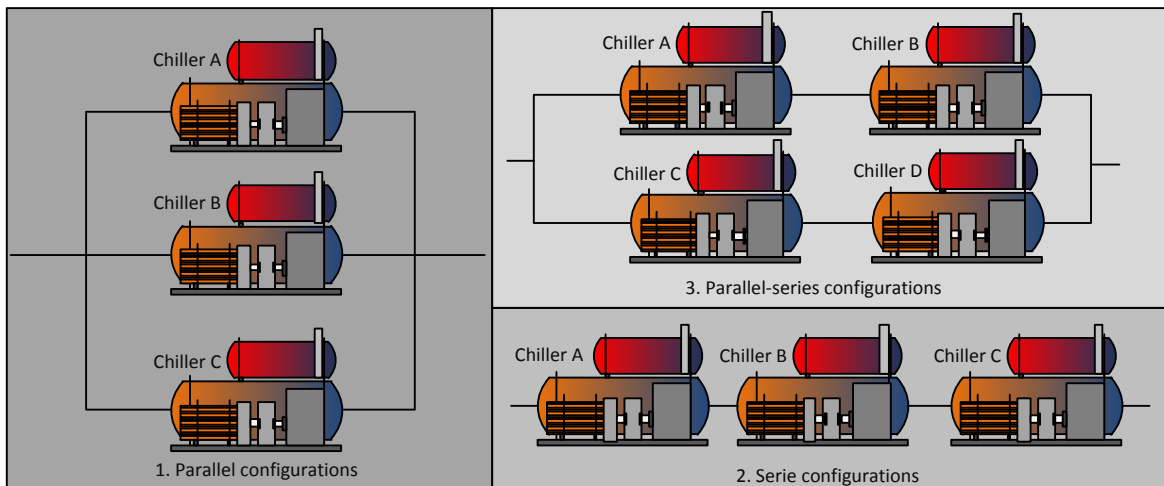


Figure 2-4: Common refrigeration machine process layout [57]

Parallel configuration is used in applications for variable flow control where the cooling load is determined by the seasonal water volume [57]. Series configuration is used in applications with variable temperature control where the flow remains relatively constant throughout the year but the inlet water temperature varies. The cooling load is thus primarily determined by the fluctuating refrigeration inlet water temperatures [59]. Finally, parallel-series configuration is used in applications where variable flow and temperature control are required. This type of configuration is typically employed where surface refrigeration machines supply both BACs and underground cooling dams with chilled water [42].

2.2.3 Cooling towers

Mechanical forced-draft counterflow wet-cooling towers are used in mining to cool not only the hot mine service water before entering the evaporator circuit, but also the refrigeration machine condenser circuit (as illustrated in Figure 2-1) [53]. These cooling towers are classified as direct heat exchangers and work on the principle of evaporative cooling,

whereby the lower ambient air temperature is used to cool the hot mine service water [60]. The essential features and basic layout of such a cooling tower can be seen in Figure 2-5.

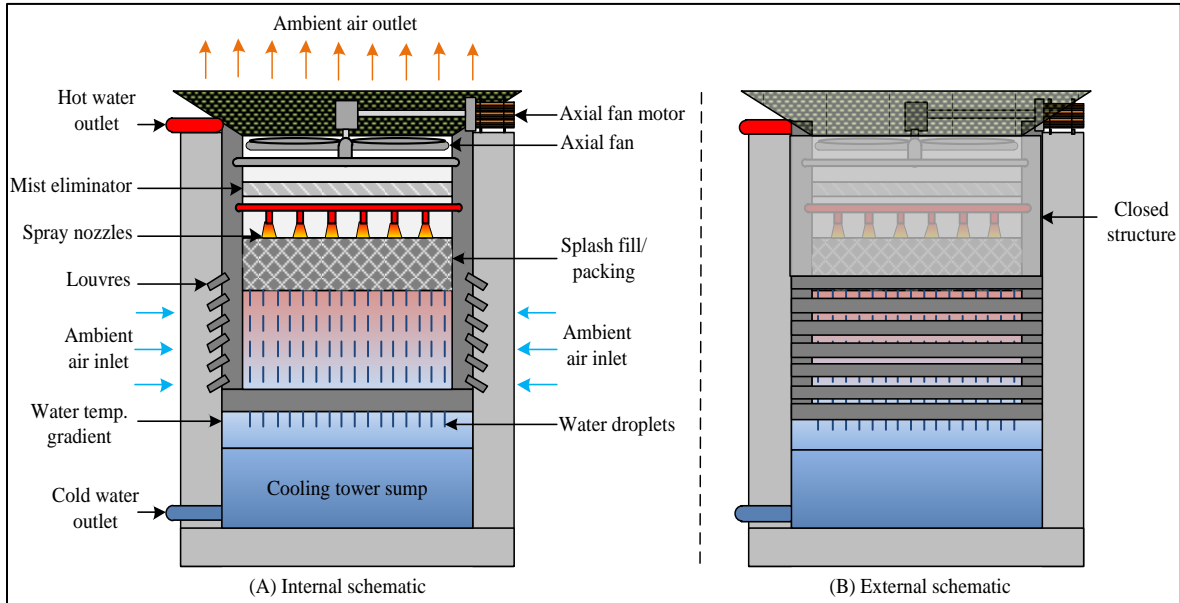


Figure 2-5: Schematic of a typical vertical induced draft cooling tower [36]

The term “direct heat exchanger” refers to the physical contact area between the two fluids contributing towards the heat exchange – in this case the water and air [54]. As Figure 2-5 indicates, hot mine service water enters the cooling tower from the hot dam and is sprayed as droplets inside the tower using spray nozzles. At the same time, ambient air is forced up through the tower by an axial fan, which ensures a counterflow direction between the air and water droplets. The water droplets and air pass through the packing, which increases the contact time for heat transfer between the fluids and distributes the flow evenly throughout the tower [57].

Research has shown that a vertical packing orientation will promote heat and mass transfer between the air and water, which will subsequently result in a higher thermal performance [61]. The typical airflow through a 10–20 m tower containing packing ranges from 2 m/s to 3.5 m/s [53]. After heat transfer occurs, the cooled water is collected in a storage dam or sump and distributed to the different users. The warm air is extracted into the surrounding atmosphere by axial fans situated at the top of the structure.

Note that water is continuously lost in the system by both evaporation and drift [57]. Figure 2-5 illustrates a mist eliminator collecting water droplets, thus minimising the effect of drift. Although the water loss typically accounts for less than 0.2% of the total circulated

water, there are several negative effects associated with operating systems under such conditions including corrosion, impurity build-up and scaling [53], [62].

McPherson states that the performance of a cooling tower is fully contingent on the operational conditions [53]. Therefore, operational parameters such as water temperatures, flow rates and heat loads will affect the cooling tower's efficiency [36]. Inadequate flow and pressure will affect the distribution patterns inside the tower, leading to scaling and ultimately a decreased performance [57]. Furthermore, dust and contaminants can enter the system, creating blockages in the packing and louvres. These blockages will have a negative snowball effect on the system performance and efficiency but can significantly be reduced with regular maintenance [52].

All the operational parameters should thus be considered when developing an energy savings strategy that uses system alterations for optimisation, sustainability and control [63].

2.2.4 BACs

Chilled water spray chambers, better known as BACs, are primarily used in mining for shaft ventilation cooling applications [53]. BACs can be situated on surface, or underground where they supply a specific mining level or centralised shaft column with cold dehumidified air [62].

The BAC is thus an evaporative spray-type direct heat exchanger, much like the cooling towers defined in Section 2.2.3. However, the heat transfer now occurs in the opposite direction than in cooling towers due to the inlet water having a lower temperature than the air wet-bulb temperature [36].

In essence, if one considers the cooling tower configuration as illustrated by Figure 2-5, it is apparent that a vertical BAC not only has the same configuration but also possesses further ducting at the air outlet. The ducting is added to direct the cold air to the shaft and critical working areas [48]. BACs have a typical heat transfer capacity of up to 20 MW, with surface BACs accounting for the largest capacity due to fewer physical constraints [53]. Maintenance often occurs during the colder winter months because the ambient conditions leave enough scope for individual BACs to be shut down [27].

Underground BACs are typically employed in applications where rock face and haulage temperatures require cooling. Additionally, the dust concentration will be reduced by using BACs as described by Schutte [32].

Studies have shown that mobile cooling cars and small direct-contact spray chambers are frequently used in applications where underground ventilation is insufficient at the working area [36]. These heat exchangers work on the same principle as BACs, but serve as secondary mobile cooling units to cool the most critical working areas [31].

The KPIs applicable to cooling towers also apply to BACs but are measured inversely due to the heat transfer directional differences [53]. Heat transfer efficiency is traditionally expressed in terms of range and approach, especially when just a few parameters such as water temperature and air inlet temperature are available for measurement, as seen in practice [64]. Note that the COP of refrigeration machines is inherently dependent on the efficient and effective operations of cooling towers and BACs [55].

Hence, if the cooling towers or BACs are inefficient and ineffective, a temperature rise would result, which would lower the COP of not only the refrigeration machines, but also the entire cooling system [57]. The method to calculate the water-side efficiency of a BAC is shown in Equation 2-3.

$$\eta_W = \frac{(T_{w \text{ outlet}} - T_{w \text{ inlet}})}{(T_{a \text{ inlet}} - T_{w \text{ outlet}})} \quad (2-3)$$

Where,

η_W	=	water-side efficiency (%)
$T_{w \text{ inlet}}$	=	water inlet temperature (°C)
$T_{w \text{ outlet}}$	=	water outlet temperature (°C)
$T_{a \text{ inlet}}$	=	air inlet wet-bulb temperature (°C)

The range is defined as the difference between the inlet and outlet water temperatures. Subsequently, the approach is defined as the difference between the air wet-bulb inlet temperature and the water outlet temperature [36].

2.2.5 Auxiliary pumps

Historically, mines used single-stage axial and centrifugal pumps in water flow distribution and reticulation networks [65]. However, multistage centrifugal pumps are favoured in modern mining due to the availability, serviceability, ruggedness and total pumping head [66]. The recent technological development in computational fluid dynamics further contributed towards an overall improved centrifugal pump design, lowering the occurrence of negative factors including cavitation and/or surging [67]. Therefore, multistage centrifugal pumps are utilised throughout mine refrigeration systems to reticulate the evaporator, condenser and BAC water. Since the pumps operate independently from refrigeration machines, they are termed as auxiliary equipment [68].

The internal operation of a centrifugal pump is based on the principle that a fluid containing a large amount of kinetic energy is converted to pressure energy once the fluid is accelerated radially outwards by the rotating impeller [53], [65]. The efficiency of the conversion is dependent on the impeller, diffuser and volute (casing) design [65].

The designed performance of a centrifugal pump is expressed in terms of its characteristic curve, as illustrated by Figure 2-6. It is required that all factors displayed in Figure 2-6 are considered before pump selection occurs [69].

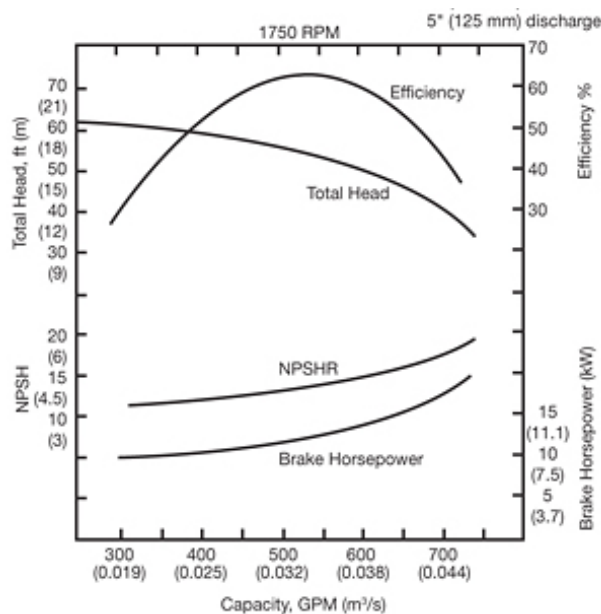


Figure 2-6: Typical characteristic pump curve (adapted from [70])

Pump selection can be simplified by matching the pump characteristic curve with the system resistance curve [69]. The system resistance curve indicates the static head required against

the system flow rate, which can be used to determine the pump's operating point [70]. Furthermore, the operating point must be selected closest to the high efficiency range yielding a best efficiency point that would ensure that the pump is operating at its highest efficiency attainable [65], [69].

The operation of a centrifugal pump is governed by the laws of similarity [65]. These laws describe the different relationships among operating parameters. If one considers these laws, it is apparent that a change in impeller speeds will alter the characteristic curve of the associated pump [71]. Also, valve operations will affect the system flows and pressures further [70]. Although the impeller rotational speeds influence the pump's characteristic curve, studies have shown that centrifugal pumps are well-suited for variable speed drive (VSD) control and have since been widely implemented by industry [42].

Using VSDs in centrifugal pump applications enables pumps to maintain the same efficiency with a large reduction in electric motor power [70]. This phenomenon is seen as a result of the reduced flow and variable control, which enables the pump operating point to follow an isoefficiency trend line [42].

The use of VSDs is particularly suited in refrigeration systems since friction is the main contributor towards system pressure losses [65]. However, using VSDs is detrimental to system efficiencies in applications that require a large static head, subsequently increasing wear rates and maintenance [69]. The electrical energy savings must thus be evaluated against several factors, such as maintenance and operational changes, to be classified as being feasible.

The most typical pump configurations used within mine refrigeration systems are the inline and parallel pump configurations (as demonstrated by Figure 2-7) [57]. The inline pump configuration is specific to parallel refrigeration machines and enable effortless pump speed control of individual chillers [53]. In contrast, the parallel pump configuration uses a common manifold to supply series or parallel-series refrigeration machines [53].

Pressure loss experienced over the common manifold results in unfavourable control conditions, which can only be neutralised by adding refrigeration machine inlet valves [57]. The valves enable the control of flow and pressure entering each individual refrigeration machine.

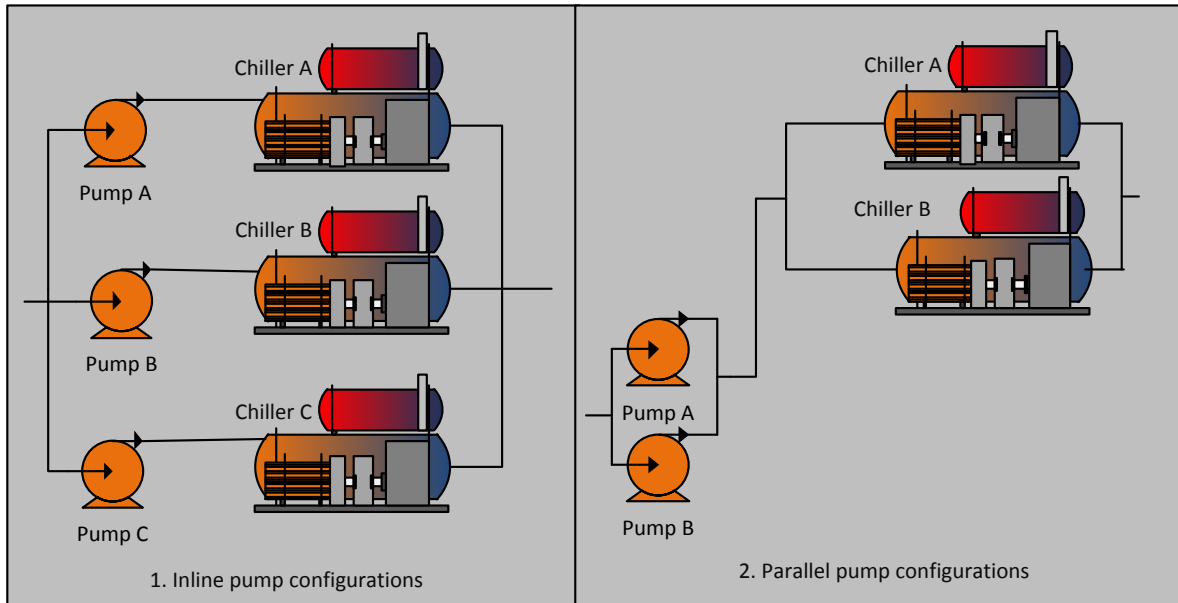


Figure 2-7: Auxiliary pump configurations [57]

2.2.6 Thermal storage dams

Refrigeration systems require storage dams to serve as added buffers for absorbing the variable service delivery requirements as experienced in deep-level gold mining [53]. Also, these dams not only increase the chilled water supply capabilities of the refrigeration and cooling systems, but also the hot service water storage capacity of the reticulation system [53].

Refrigeration systems are therefore designed to provide a constant chilled water supply for underground use [47]. The variation seen in the chilled water demand can be ascribed to the numerous different end-users and seasonal changes [57]. Additionally, seasonal changes can reduce the overall operating temperatures, enabling the use of fewer refrigeration machines to achieve the designed water supply temperatures [36].

The variation in chilled water demand affects the location and storage capacity of the thermal storage dams [62]. Although the mine refrigeration system is classified as an open system, chilled water storage dams are completely encapsulated to prevent temperature losses to atmosphere [57]. Likewise, the chilled water storage dams are typically in close proximity of shafts to circumvent further frictional losses and related temperature increases [52].

Mines recirculate chilled water to the precooling sump and underground cooling dams once the surface chilled water storage dam reaches full capacity [32]. This practice relies on manual valve operations that are extremely inefficient, especially when multilevel valve

throttling is required [57]. Introducing variable flow control is thus extremely beneficial to a system lacking storage capacity [11].

The dam level control and capacity can severely be restricted due to contaminants accumulating in the water supply and subsequently storage dams [68]. Also, if production water usage exceeds the settlers' operation (conical storage dams used to purify the water from heavy contaminants such as grit or mud), it would contribute to a higher contaminant content, thus restricting water flow inside the mine even further [51].

The thermal storage dams therefore require regular maintenance to ensure peak operating conditions and maximum storage capacities [66]. If these dams are maintained, fully integrated and controlled in the refrigeration system, significant electrical cost savings can be realised as shown by Schutte [8] and Van der Bijl [72].

2.2.7 Refrigeration system control

Refrigeration systems are typically controlled through the use of an integrated energy management programme called a supervisory control and data acquisition (SCADA) system [73]. The SCADA system is integrated with various programmable logic controllers (PLCs) that send and receive various input and output signals from the field instrumentation and components [74].

The integration of the whole system is based on an object linking and embedding process-control connection that allows the data to be converted from a certain type of signal to the next, which is required for a different process [75]. Figure 2-8 illustrates a typical PLC integrated with a human-machine interface (HMI) near a refrigeration machine, which displays process variables and system information [73].

The SCADA system relies on the accuracy and sensitivity of values obtained from the field instrumentation. Since the historical values are used for optimisation and forecasting practices, it is absolutely critical for the instrumentation to be calibrated and maintained on a regular basis [75]. The most common types of instrumentation used by industry are thermocouples, pressure gauges, flow meters, power meters and relative humidity meters [56].

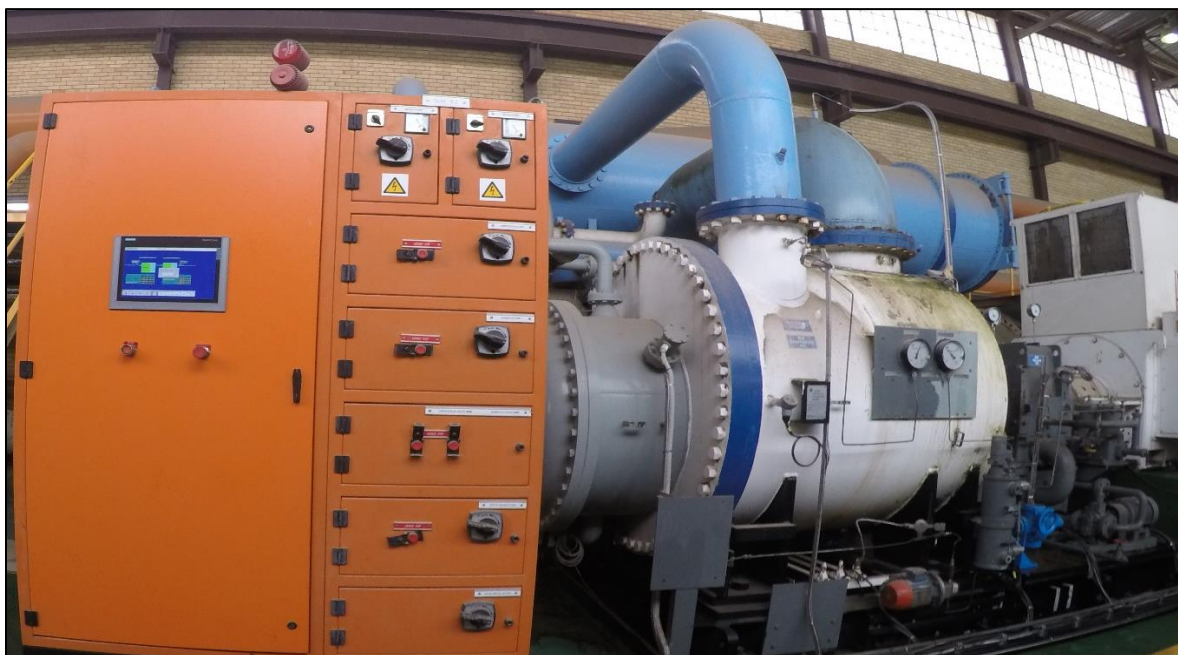


Figure 2-8: PLC with HMI integration for refrigeration machine control

2.3 Refrigeration system optimisation

2.3.1 Optimisation foreword

Mine refrigeration systems typically operate under strenuous conditions for long periods using outdated and inefficient equipment resulting in very little to no control [68]. Although this is the case with most gold mines in South Africa, several energy efficiency strategies are currently employed to lower the power consumption and increase the refrigeration system's performance.

In this section, current energy efficiency practices are investigated and the effects thereof analysed. Abdelaziz, Saidur and Mekhilef define three pillars of improving energy conservation among industry and mining. These pillars include energy policies typically approved by government, using energy efficient equipment and general energy management [5]. Since the South African government has already approved energy efficiency incentives in the form of the 12L and 12I tax rebates, and energy efficient equipment requires large capital expenditure, this study will incorporate energy management [76].

2.3.2 Variable flow energy efficiency optimisation strategies in refrigeration systems

The introduction of VSDs in industry led to the development of several energy efficiency strategies, which are fully integrated with an energy management system [77]. Furthermore, research has shown that significant electrical cost savings have been achieved in a variety of applications using VSDs [78]. It is therefore apparent that using VSDs is extremely applicable in mining and is thus accepted as the norm [78].

A VSD is defined as a component that controls the speed, torque and power of electromechanical drive systems by varying the frequency of the alternating current (AC) voltage supplied to the electric motor [77], [79]. In South Africa, the typical frequency range is limited to a maximum of 50 Hz, as opposed to 60 Hz as seen in West Japan and the United States of America [48].

Although VSDs have widespread applications, VSDs are more efficient when integrated with compatible motors [79]. Nevertheless, systems that do not have VSD-compatible motors can be retrofitted for VSD control, which would still yield a significant improvement in system efficiency [78].

Currently VSDs are the most effective instruments for achieving electrical cost savings in industry, and subsequently also mine refrigeration systems [78]. In mining, VSDs are typically integrated on pumps, compressors, fans, conveyers and winders [79]. As a result, several variable flow optimisation strategies have been implemented on mine refrigeration systems as discussed in the following section [42].

Evaporator control

Lee and Yik pioneered a variable flow optimisation strategy for the evaporator loop in mine refrigeration systems [80]. The strategy is primarily based on the evaporator water flow rate control by using VSDs on the evaporator pumps [42]. The chill dam level can therefore be maintained by controlling the evaporator pumps' speed, thus in effect controlling the water flow rate. Figure 2-9 highlights the basic components involved in the evaporator flow control loop.

The evaporator flow control loop must thus ensure that an adequate chill dam temperature and flow are supplied to satisfy the underground demand [36]. Since the flow rate is controlled continuously, the use of throttling valves is rendered obsolete [79]. Also,

integrating an open back-pass valve from the refrigeration machine to the precooling sump is no longer required for optimal control [79]. The integration of VSDs on the evaporator control loop therefore enables the evaporator pumps to follow the best efficiency point during operation, resulting in large electrical cost savings [77].

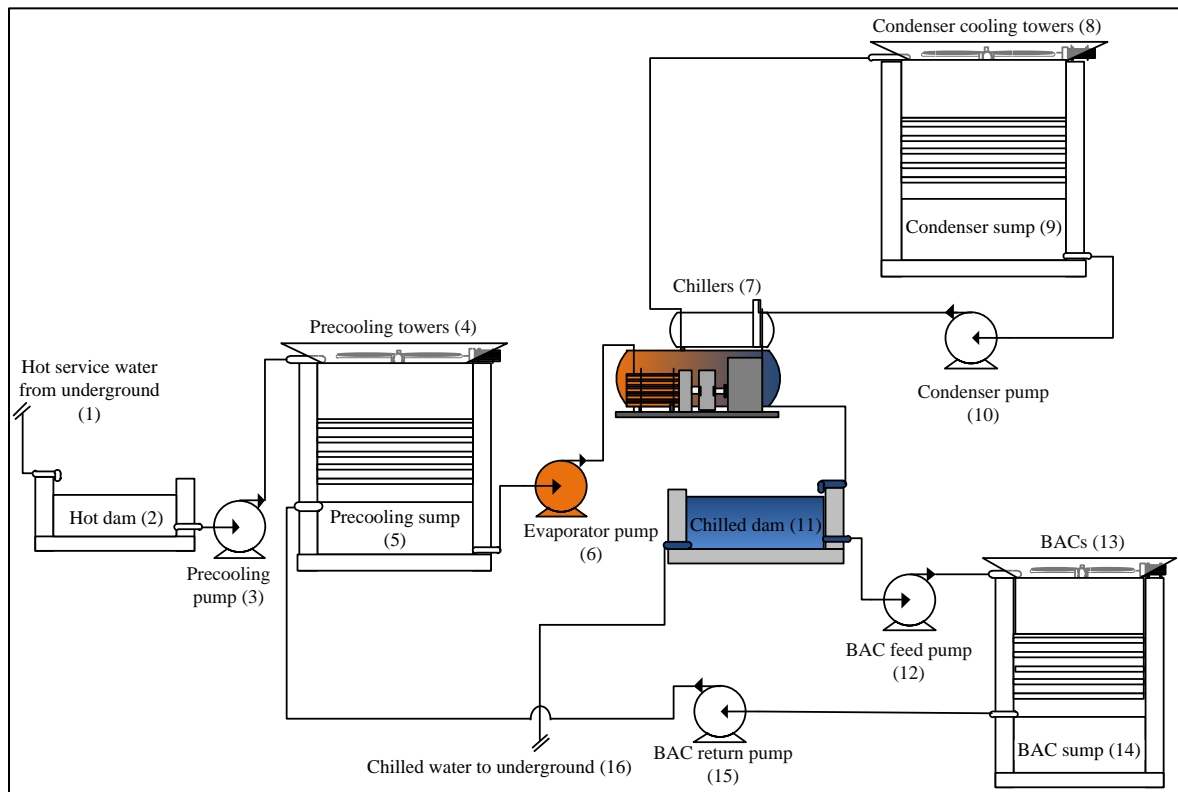


Figure 2-9: Evaporator flow control loop

Refrigeration machines are dependent on the evaporator flow rate to maintain a constant chilled water outlet temperature [58]. The evaporator pumps must adhere to the requirement and provide enough flow for the refrigeration machines to achieve the outlet temperature set points without tripping. In this manner, each refrigeration machine will reduce the refrigerant flow rate and subsequently the pressure ratio through guide vane control, which would further increase the electrical cost savings [79].

Condenser control

A variable flow optimisation strategy was also developed for the condenser loop in mine refrigeration systems [81]. Similar to the evaporator control, the condenser control also uses VSDs to control the water flow rate, but the control is applied to the condenser flow control loop as demonstrated by Figure 2-10.

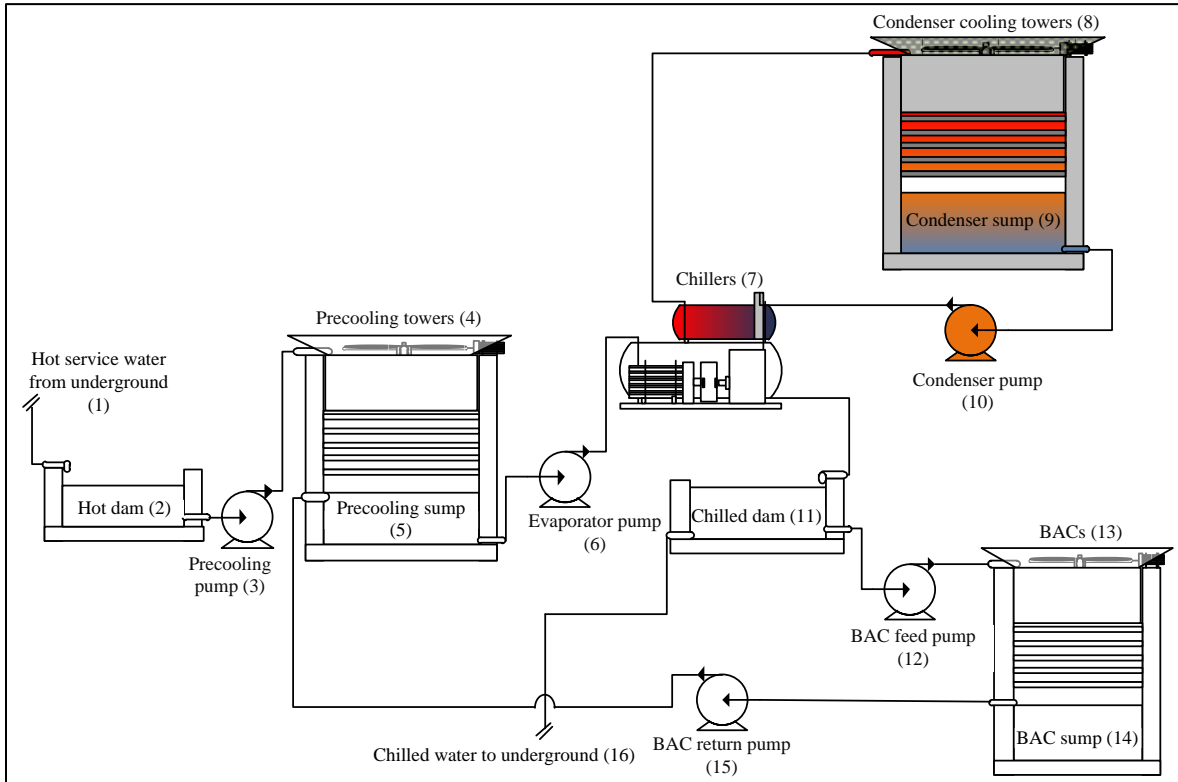


Figure 2-10: Condenser flow control loop

Using VSDs on condenser pumps enables the flow rate to be controlled to maintain a constant temperature difference across the condenser vessel [42]. Furthermore, the condenser flow control loop operates close to design conditions, rendering the use of throttling valves unnecessary. The throttling valves should, as is the case with the evaporator flow control loop, be left fully open [81].

The optimisation strategy is required to account for ambient conditions, since the cooling towers and subsequently the condenser water temperatures are affected significantly [78]. The refrigeration machines are dependent on the condenser flow rate to enable the guide vane control and increase the electrical cost savings further by reducing the refrigerant flow and pressure ratio required for sufficient heat transfer [79].

One should, however, consider the adverse effects associated with condenser control because it is so dependent on ambient conditions. Adverse effects can include fouling in the condenser vessel, reduced heat transfer capabilities or increased power usage [11]. Although these negative factors should clearly be considered, studies have shown that the electrical cost savings potential verifies the strategy to be feasible [79].

BAC control

After the condenser and evaporator control proved to be viable, a variable flow optimisation strategy was developed for the BAC loop in mine refrigeration systems [11]. Although there are several mine refrigeration configurations, the optimisation strategy as a whole is constrained by the temperature of the BAC outlet air [36]. The temperature of the BAC outlet air may not exceed 6.5°C wet bulb or there will be insufficient cooling, which can lead to heatstroke or mine fatalities [46].

The strategy is established for using VSDs on BAC feed pumps to control the flow rate and subsequently the heat transfer in the BAC according to ambient conditions [42]. This strategy will enable sufficient ventilation air supply during all load conditions as opposed to normal conventions that result in overcooling when part-load conditions are present. Figure 2-11 illustrates a typical BAC flow control loop used in open cycle mine refrigeration systems.

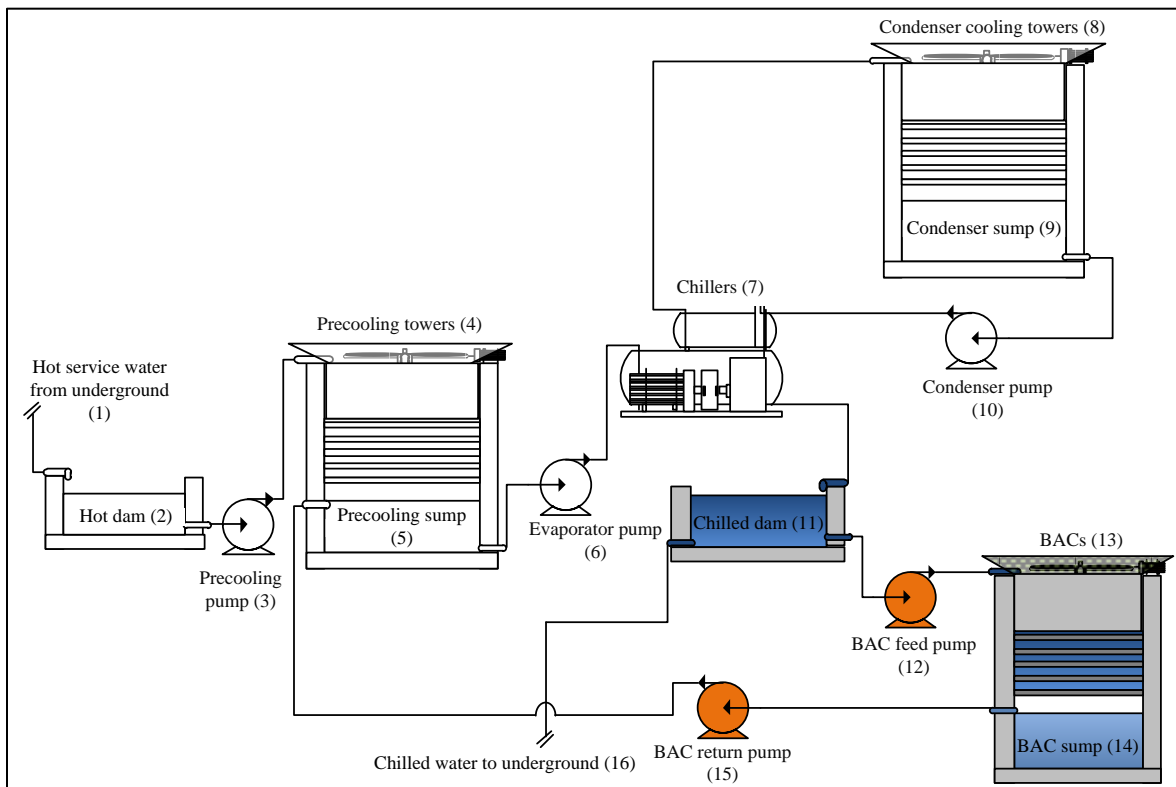


Figure 2-11: BAC flow control loop

Depending on the configuration of the refrigeration system, further measures are implemented as part of the strategy to increase the electrical cost savings. The use of VSDs

on BAC return pumps, for instance, can be applied in which the BAC sump level is maintained through a closed proportional-integral-derivative (PID) control loop [57]. Furthermore, BAC throttling valves can be opened fully to ensure that efficient near design flow conditions are achieved. Additionally, regular maintenance can be applied to the BAC flow control loop to ensure an increase in electrical cost savings and sustainability [82].

Precooling control

The introduction of the evaporator control resulted in the development of the variable flow optimisation strategy for the precooling loop in mine refrigeration systems [42]. Furthermore, the evaporator control is dependent on the precooling strategy to ensure a balanced system [51]. However, note that there are applications where precooling control is applied without the incumbent evaporator control [36].

The precooling strategy is based on using VSDs on the precooling feed pumps to ensure that a constant precooling sump level is maintained. This strategy will enable near design flow rate operating conditions resulting in electrical cost savings for such a system (as illustrated by Figure 2-12).

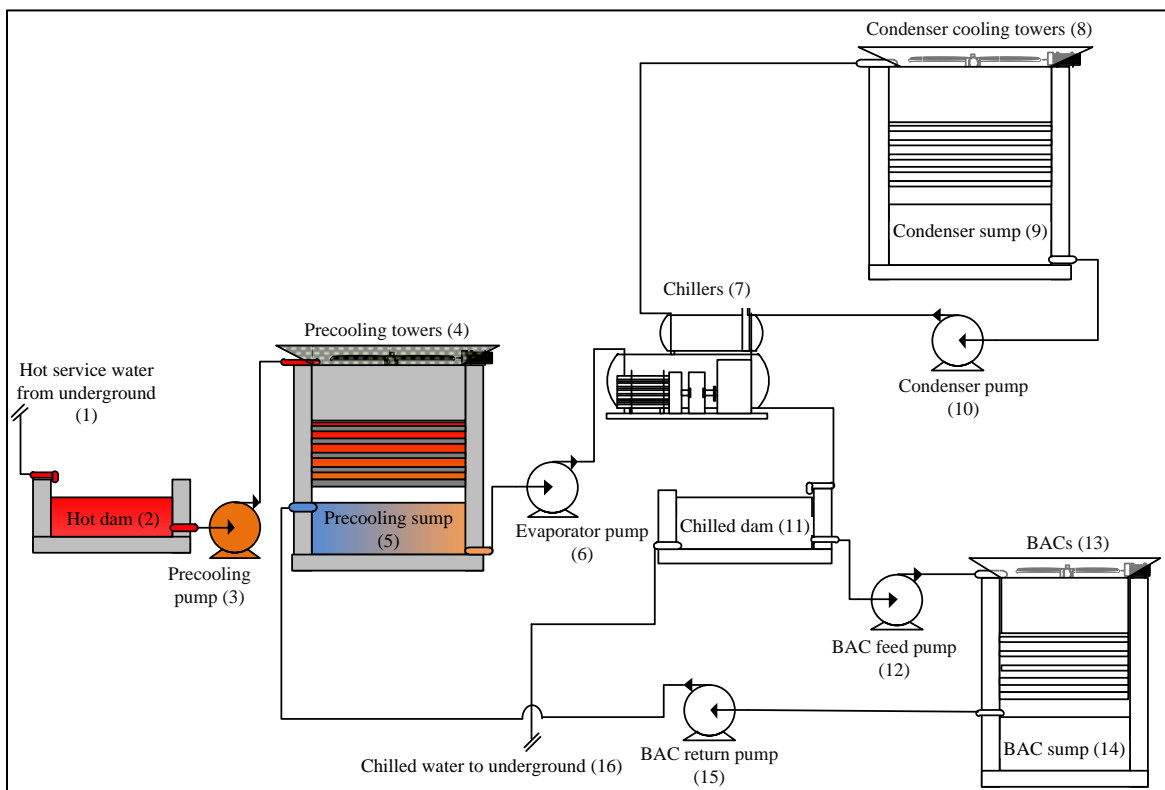


Figure 2-12: Precooling flow control loop

As experienced with the BAC flow control loop, using VSDs requires that all the throttling valves are left fully open to ensure complete VSD control. Subsequently, improved precooling sump temperatures will be achieved [31].

It is clear that all the variable flow optimisation strategies can be applied simultaneously to optimise one refrigeration system and ensure large electrical cost savings without affecting the cooling demand and mine production adversely.

2.4 Existing DSM initiatives on refrigeration systems

2.4.1 Existing DSM initiatives foreword

DSM initiatives are widely used in several countries as energy conservation measures [19]. Furthermore, these initiatives aim to lower the overall electricity consumption or reduce the daily electricity consumption profile to achieve electrical cost savings for clients, promote energy efficiency practices and relieve some strain on utility companies [18].

Since DSM strategies are still the leading, most cost-effective, proven method to relieve short-term strain on a national power network, Eskom followed the global trend and introduced incentives for DSM initiatives in South Africa by late 2005 [1], [18].

Du Plessis, however, identified the immense need for further DSM initiative development to ensure that projects are implemented successfully on time, within budget while adhering to a predefined set of methodologies [11]. This study's focal point will therefore specifically be on improving DSM initiatives on mine refrigeration systems and the methodology developed will only be applicable as such.

2.4.2 DSM general analysis

DSM initiatives require the use of an energy management system (EMS) for effective and efficient operational control [83]. The EMS must provide real-time response capabilities for monitoring and controlling purposes [64]. Lee and Cheng undertook a research study including 305 cases that showed that the sustainability of DSM initiatives are directly dependent on the functioning of the EMS [83].

The highest verified electrical cost savings achieved in heating, ventilation and air-conditioning systems amounted to a staggering reduction of 46.9% in overall system electricity consumption [83]. The importance of an integrated EMS should not be

overlooked, especially where complex refrigeration systems are concerned, which demonstrated that DSM initiatives could not have been implemented without using an EMS [77].

The EMS should integrate the entire refrigeration system, and consider several variables through the entire control spectrum of each component and subsystems [81]. Additionally, the refrigeration system must operate according to an optimised control philosophy that has provisional control for any system changes, such as broken or inefficient equipment, that may occur [11].

DSM initiatives also require a thorough background study where the most important operational parameters are defined and recorded to determine the effect of the initiatives on the system [27]. The background study can include KPIs such as chill dam temperatures, water flow rates, dam levels and equipment efficiencies. These KPIs will represent boundary conditions that can be incorporated in an initial system analysis study to measure and determine the overall system performance [32].

2.4.3 DSM implementation analysis

Throughout the initial DSM system analysis, the system is defined according to the KPIs – including general restrictions and operational constraints. However, research has shown that supplementary constraints first appear during the implementation phase [78].

The newly identified constraints can be mitigated through similar solution measures or further analysed through a detailed operational analysis [27]. The analysis would result in the information necessary to modify the strategy to specifically suit the operational requirements of a refrigeration system. Schutte and Groenewald reason that changing any operational parameters should be for the overall improvement of the system and its sustainability [8], [27].

Another measure to ensure that the improved strategy remains sustainable is to constantly monitor and document all system parameters during the implementation phase [72]. As a result, the data can be analysed and compared with forecast values to determine whether project deliverables will be satisfied or if further alterations are required.

Operational parameters can be monitored, controlled and recorded using an EMS [83]. Integration between the SCADA system and EMS is therefore required to ensure automatic

control and monitoring [11]. Although the SCADA system and EMS have full operational control over the refrigeration system, secondary redundancy measures must be put in place to prevent data loss if the automatic control systems are down [42].

2.5 Typical mine refrigeration system requirements

2.5.1 Refrigeration system requirements overview

In order to determine the full extent of implementing DSM initiatives, the essential operational parameters and KPIs must be identified. Furthermore, these factors must be considered and analysed before further strategy development may transpire.

According to Holman, Heyns and Pelzer, the performance and sustainability of DSM initiatives are extremely dependent on the strategy whereby the initiatives were implemented [68]. This section will focus on the specific refrigeration system requirements that need to be adhered to with the purpose of improving the strategy and associative system operations.

2.5.2 Refrigeration system requirements

In order to effectively implement a DSM initiative, the mine refrigeration system requirements need to be identified and adhered to during strategy development [11]. The requirements will serve as control constraints and assist in analysing boundary conditions. The specific boundary conditions, typically identified as crucial system parameters, can be used for measurement and verification (M&V) processes or be incorporated further in auditing resolutions [51].

Schutte contemplates gold ore production and safe mine operating conditions as the most essential components to be considered in strategy development [8]. This statement becomes apparent when one considers the function of a refrigeration system – controlling the environmental conditions inside a mine [62]. The refrigeration system is supplying sufficient chilled water to the BACs and underground end-users for environmental control [57].

Chilled water must be available on demand and within the specified design temperatures at all times [82]. Chilled water temperature, dam level and BAC air outlet temperature can consequently be classified as characteristic boundary conditions [84]. Chilled water is typically used by mine personnel for local cooling as well as in BACs for air cooling [36].

If the boundary conditions are consequently kept within the specified limits, the production and working environment will not be affected adversely but can be improved [85]. The crucial system parameters can be incorporated and analysed to determine the effect of the implemented DSM initiative [52]. Research has shown that chilled water temperatures (crucial parameter) of between 2.5°C and 6.5°C are acceptable for safe mining conditions [36], [40]. Lower temperatures can lead to compressor surges and sediment build-up in the heat exchangers, resulting in refrigeration machine trip conditions [11].

Chilled water temperatures will therefore enable BACs to supply sufficient cold dehumidified air to achieve a working area temperature lower than 27.5°C (wet bulb) [46]. Analysing crucial system parameters enables the mine to comply with governmental laws and policies regarding operational health and safety [35], [45]. The implementation of an improved strategy should therefore account for several factors to ensure conditions conducive to safe and productive mining [22].

2.6 DSM initiatives performance review

2.6.1 Performance review foreword

In order to accurately quantify the effect of an implemented DSM initiative, the cooling load must be characterised before implementation [86]. In mining and refrigeration systems, the load is measured directly to acquire a load profile, which in turn provides insight into production schedules and the specific load requirements [87].

This following section will focus on the process and considerations that need to be adhered to in order to quantify and verify the performance of an implemented DSM initiative accurately. The most typical sustainability challenges associated with existing DSM initiatives will also be identified and discussed.

2.6.2 M&V

The performance of DSM initiatives is determined by analysing boundary conditions and the associated electric power consumption of the refrigeration systems before and after implementation (as previously stated in Section 2.5).

Eskom typically contracts independent M&V teams from tertiary institutions to audit and assist ESCOs with quantifying DSM initiatives [88]. The M&V teams report to NERSA and

abide by the International Performance and Verification Protocol (IPMVP) that stipulates the methodologies and procedures used to ensure that the effects of DSM initiatives are accurately quantified [86].

The IPMVP assists M&V teams in the planning and execution stages of the electric power consumption baseline development [87]. A baseline is defined as the normal electricity consumption of a refrigeration system without the effect of the implemented DSM initiative [86]. Van der Merwe and Grobler constitutes the baseline as the heart of the M&V process [89].

It is therefore extremely important for all parties (ESCO, M&V team and Eskom) to agree and confirm all assumptions and protocols during the baseline development stage [88]. This agreed upon baseline is incorporated after the implementation phase to determine the electrical energy savings [90].

The electrical energy savings consider both the real and reactive energy, as stipulated in Appendix A, the Eskom Megaflex tariff [9]. The electrical energy savings calculation also includes an adjustment, which is determined by including a regression model [86]. The regression model is incorporated into the electrical energy savings calculation to compensate for system changes [86]. Since refrigeration machines rely on ambient conditions and production schedules, using a regression model is creditable [89].

The detail of the baseline development will be discussed further in Section 4. All calculations, regression models and assumptions for the DSM initiatives will comply with the above-mentioned protocols.

2.6.3 Challenges in existing DSM initiatives

In South Africa, gold mining mostly occurs underground [33]. The underground conditions should thus be carefully controlled to ensure that they are conducive to safe and productive mining. It is imperative that the refrigeration system is sustainable and reliable – even under strenuous operating conditions [32].

The vast effect that the refrigeration system has on underground mining conditions results in it being one of the biggest safety concerns for mines, especially for deep-level gold mines in South Africa [33]. Mines are consequently extremely conservative when it comes to any and all changes or alterations proposed to the refrigeration system [62].

It is apparent from research that the sustainability of DSM initiatives deteriorates over time due to several technical and human-related factors [19]. The main factors attributed to the deterioration are [27], [84], [88]:

- *The human factor:* The lack of educational awareness coupled with a resistance to change result in a wrongful approach from the mine personnel. They are generally inflexible in their belief that no further improvements can be made upon the existing system, even when presented with empirical evidence. Existing underperforming DSM initiatives incite mining personnel's reluctance for further implementation possibilities.
- *Large capital expenditure projects:* Mine personnel typically focus on the initial cost of equipment rather than the life cycle cost approach, which justifies DSM initiative infrastructure upgrades or equipment.
- *Uncertainty and availability:* In the current unstable economic climate, mine personnel are reluctant to allocate resources to long-term projects. Furthermore, energy efficiency technologies are mostly only available abroad, which requires equipment to be imported. This further extends the project implementation period.
- *Human interference:* Mine operators typically interfere with the automated EMS, switching from automatic to manual control for no valid reason. Unfortunately, this has a detrimental effect on the project performance and overall electrical cost savings.
- *Lack of capacity:* Refrigeration systems require enough thermal storage capacity to enable a DSM initiative. The performance of the refrigeration cycle is therefore directly dependent on the storage capacity of the whole system.
- *Cooling loads:* Cooling auxiliary projects are dependent on refrigeration machines to satisfy the cooling load during hot, humid summer days. This provides enough scope for implementing DSM initiatives.
- *Infrastructure:* DSM initiatives rely on the necessary infrastructure to enable the optimised control of the refrigeration system. If, for example, one refrigeration machine broke down, the whole control philosophy would need to be adjusted to operate sustainably.

- *Control*: Gold mines typically implement production endeavours, which change and optimise system parameters. This can often lead to DSM project deterioration when control systems are not updated or shutdowns occur for long periods.

Literature shows that in order to implement or improve existing DSM initiatives, a thorough understanding of the current mine's operations is required. Research has to be done on all risks and queries that the mining personnel might have, especially when the safety of their colleagues are involved. Special attention must be given to investigations and simulations of production-influencing factors. Improving DSM initiatives must not impact production negatively but, if possible, must rather serve as a performance enhancer.

2.6.4 Refrigeration system sustainability requirements

Research has shown that using an EMS is crucial to enable the long-term sustainability of DSM initiatives [83]. The control philosophy should furthermore aspire to improve and optimise the refrigeration system for sustainable performance [51].

The sustainability can be improved by implementing constant monitor and reporting services. These services will inform project engineers of project degradation and assist them in developing a solution or doing a root cause analysis [74]. Similarly, the constant feedback and improved communication will enable preventative maintenance on a component level, thus decreasing shutdown times and increasing operations [91].

Existing DSM initiatives' sustainability should further be improved by implementing updated robust control systems [75]. The control system should possess proven security and redundancy functionalities. The maintenance schedules of these systems need to be monitored and adhered to, and components need to be monitored [27].

If all system parameters are updated and KPIs are considered in strategy development, the sustainability of an existing DSM initiative can vastly be improved. The next section will serve as a conclusion to the chapter, encapsulating the most important lessons shown through the research.

2.7 Conclusion

The most significant considerations applicable for improving existing DSM initiatives on mine refrigeration systems were reviewed. It was found that existing DSM initiatives on mine refrigeration systems are unsustainable and performance deteriorates over time, thus emphasising the need of this specific study.

The normal operations and KPIs associated with the refrigeration system and its components were analysed. The analysis established a clear working knowledge of the fundamental theories associated with evaluating refrigeration systems and their components. As a result, these factors will have to be incorporated throughout the strategy development to attain an all-inclusive outcome.

Various optimisation strategies currently employed in industry were scrutinised. The study revealed that although there are many optimisation strategies and technologies, they are rarely applied in deep-level South African gold mines. Furthermore, the detailed literature indicated hidden operational constraints and requirements that are only applicable during strategy implementation. The improved strategy should therefore account for any and all operational constraints to ensure sustainable electrical cost savings on mine refrigeration systems.

Environmental health and safety requirements of gold mines were examined. The most important parameters to consider are chilled water temperature and BAC air outlet temperature since they influence mine personnel and subsequently production directly. The review further showed that if crucial system parameters are kept within an acceptable tolerance range, production will experience no adverse effects.

An in-depth performance review of DSM initiatives indicated the relevant procedures and protocols inherent to efficient refrigeration system operations. Challenges in existing DSM initiatives were critically analysed and discussed. It was found that several human and technical factors affect the performance and subsequently sustainability of DSM initiatives on mine refrigeration systems.

The sustainability requirements associated with refrigeration systems were analysed in a holistic approach. The analysis revealed several crucial factors to be included in strategy development.

It is apparent from the research that existing DSM initiatives on mine refrigeration systems are unsustainable and underperforming. However, there is ample room to develop an improved performance strategy that will yield an increase in performance and subsequently sustainability.

In conclusion, all the relevant considerations were identified to be incorporated in strategy development. In Chapter 3, the focus will be on the feasibility of existing DSM initiatives to develop a comprehensive improved performance strategy. The improved performance strategy will then be verified and evaluated accordingly.

Chapter 3

Improved sustainability performance strategies



“If one way be better than another, that you may be sure is nature's way.”

– Albert Einstein

3.1 Introduction

Several DSM initiatives have been implemented all over the world in various industries [19]. Moreover, DSM initiatives have been implemented and developed on local soil for gold mines since the early 1990s [33]. The aim of these initiatives was lowering operational costs by reducing electricity usage without affecting mining production adversely.

Groenewald quantified that most existing DSM initiatives on gold mines are underperforming and are consequently unsustainable [27]. Mines often struggle to prevent and mitigate project deterioration, especially when the initial target savings can no longer be achieved. Heyns conducted an audit exposing an instance where project deterioration progressed to such an extent that the DSM initiative was totally abandoned [92].

Research has shown that most mines divert back to inefficient energy practices once projects deteriorate [68]. Furthermore, mines seldom give the necessary attention to deteriorating DSM initiatives until the projects become unviable or the adverse effects are felt. It is evident that the likelihood of improving DSM initiatives is considerably increased when one considers and analyse other underperforming projects [74].

This chapter will therefore focus on developing a performance strategy to improve existing DSM initiatives on refrigeration systems for sustainable performance. The development will occur by considering and analysing a mine that has underperforming DSM initiatives on its refrigeration system.

Mine A will serve as a specimen mine to review and implement the proposed performance strategy. Furthermore, analysing underperforming DSM initiatives on the refrigeration system of Mine A will enable a streamlined performance strategy implementation approach. In line with M&V procedures and governmental policies, the performance strategy will be verified and the economic feasibility investigated.

3.2 Feasibility of existing DSM initiatives

3.2.1 Case study overview

As mentioned previously, the analysis of current underperforming DSM initiatives on refrigeration systems will aid in developing a generic performance strategy, specifically to increase project sustainability of existing initiatives [68].

A critical analysis was done on Mine A after project deterioration and underperformance were observed on the mine's refrigeration system. The original DSM initiative was investigated and implemented at the deep-level gold mine during the last quarter of 2010. The DSM initiative primarily focused on satisfying the cooling demand through optimising control of the refrigeration system.

Mine A has increased production since the implementation period, which resulted in higher cooling loads. This case study was therefore selected to illustrate and quantify the viability of an improved performance strategy. The original control philosophy and crucial system parameters were investigated in detail to define and encapsulate the existing DSM initiatives.

It was found that variable flow control was used throughout the entire surface refrigeration system (as seen in Figure 3-1). The refrigeration machines are configured in a parallel arrangement to enable seasonal flow control with each refrigeration machine featuring its very own evaporator and condenser pump. The refrigeration system supplies chilled water to BACs and underground end-users. The refrigeration system has recycling capabilities with a chilled water recycling line.

The original DSM initiative's control and equipment specifications are presented in Appendix B. The DSM initiative was developed and implemented with full operational equipment control. The efficiency and effectiveness of the DSM initiative rely on the functioning of the equipment used to achieve the electrical cost savings.

3.2.2 System operational overview

In order to quantify the effect of the existing DSM initiatives, one should clearly define the existing system and its operational parameters [27]. The following section provides background on the existing system operations. Figure 3-1 illustrates the refrigeration system of Mine A, which can be used as reference for the following discussions.

Water is pumped at 27°C from the underground dewatering system to the surface hot dam. Typically, 21 MI of water is pumped per day during daily mining operations. The hot water is cooled by passing it through precooling towers, from where it is pumped and stored in the second surface hot dam at a temperature of 10°C.

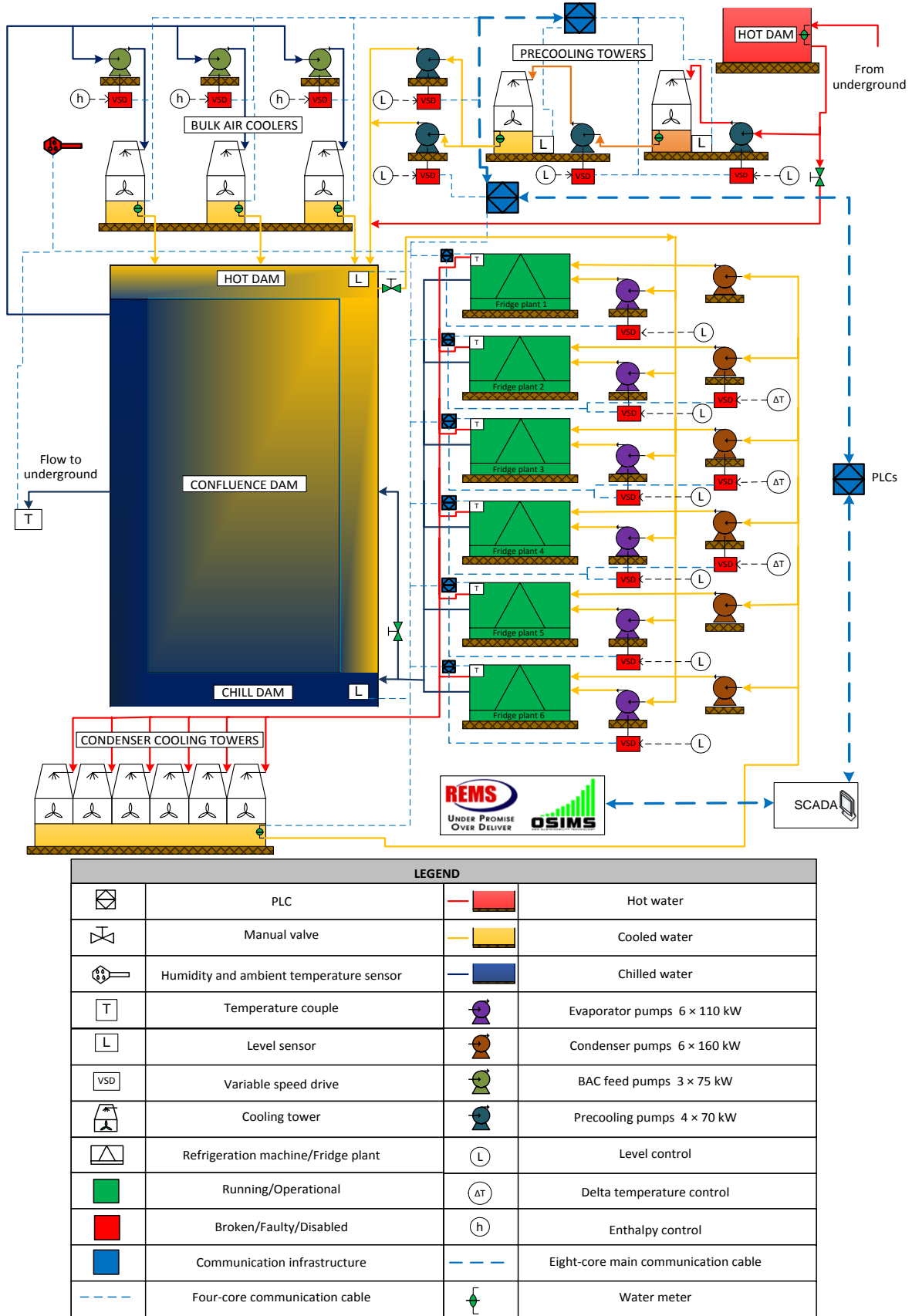


Figure 3-1: Mine A refrigeration system process and instrumentation diagram

Water is subsequently passed from the surface hot dam through six 6.5 MW refrigeration machines to cool the water to 2.8°C. From there, the chilled water is pumped to the chill dam. Even though the chilled water is primarily stored in the chill dam for distribution, the chilled water can simultaneously be used for temperature control in the hot dam through valve throttling.

From the surface chill dam, approximately 730 ℓ/s of chilled water is passed through the BACs to achieve BAC air outlet temperatures lower than 8°C. The outlet air typically ranges between 5°C and 7°C. After the air is cooled, the BAC outlet water at 10°C is pumped and stored in the surface hot dam (precooled).

Similarly, the surface chill dam feeds chilled water to the underground chill dam situated on Level 38 (38 L). The resulting gravity-fed pressure coupled with auto-compression of the chilled water mean that the water can firstly be passed through a Pelton turbine to generate electricity before entering the 38 L chill dam. The chilled water is consequently distributed from the 38 L chill dam to the different mining end-users.

The water at 27°C is then collected and stored in a dewatering dam situated on 75 L, from where it is pumped to surface. Operating the refrigeration system is a continuous process and the sequence is reinitiated once the water reaches the surface hot dam.

Control summary

The variable flow DSM initiatives at Mine A have been active for two years before being completely decommissioned in 2012. The initial control philosophies of the associated DSM initiatives are explained in the subsections that follow. It is absolutely crucial in the analysis and synthesis of a performance strategy to state and understand the initial control conditions.

Precooling flow control loop

The hot surface dam and both precooling sumps were controlled through the VSDs to maintain a dam level of approximately 90%. The back-pass and throttling valves were decommissioned to enable full VSD control.

Evaporator flow control loop

The chill dam level was controlled to maintain a constant dam level of 90%. Furthermore, both the hot dam and recycling valves were decommissioned to enable full control.

Condenser flow control loop

The condenser pumps were controlled to enable a constant temperature rise of 5°C across the condenser side of the refrigeration machines. All throttling valves were decommissioned as the case with the other control loops.

BAC flow control loop

The BAC feed pumps were controlled using a Testo weather station that determined the ambient enthalpy to maintain a constant BAC outlet air temperature. The control occurred on a linear basis to modulate the pumps' flow rate to achieve the outlet air temperature set point of 7°C.

It is apparent that the initial control was extremely basic and unrefined. Initially, there were only a few system constraints and the operational limits were set accordingly. In the following section, the root causes of the decommissioning are critically analysed for each control loop as well as the EMS to develop a performance strategy to improve existing DSM initiatives on mine refrigeration systems for sustainable performance.

3.2.3 Root cause analysis of existing DSM initiatives

3.2.3.1 Evaporator flow control loop

Existing control

Analysing the existing operation of the evaporator flow control loop revealed that the six VSDs installed on the evaporator pumps were disabled by mine personnel. The entire variable flow strategy was therefore disabled. The root cause was determined to be the result of low evaporator flow rates during refrigeration machine start-ups. The evaporator flow rates were lower than the minimum required flow during machine start-up conditions and the refrigeration machines tripped as a safety measure.

As a result, the mine personnel resorted back to old energy inefficient practices. The evaporator pumps were set to operate at a maximum, even when part-load conditions were present. The evaporator flow was controlled by recommissioning the throttling valves to ensure a constant evaporator outlet temperature of 3°C. The control employed through the throttling valves was, however, very unrefined and frequently resulted in overcooling.

The overcooling froze up the refrigeration machines repeatedly, resulting in lost production and promoting evaporator tube scaling and fouling. Furthermore, the BAC air outlet temperatures were consequently lower than the designed set points, which resulted in lost electrical cost savings.

The mine, however, felt that the inefficient practices were justified as long as production occurred. Since the refrigeration system is cardinal to mining, they would rather mine for short periods at a time than not mine at all.

Proposed control

The evaporator flow control loop is primarily centred on the control of a constant chill dam level. The input frequencies of the VSDs can therefore be adjusted on the proportional-integral (PI) control logic through the PLC to incorporate higher start-up values during lower chill dam levels. This alteration would enable higher flow rates, which are closer to design conditions during all loads.

Research has shown that the greatest starting point would be to control the VSDs between 60% of the designed flow as a minimum and the designed flow as a maximum [57]. Another factor to consider is the duration of cooling and subsequent machine loads during start-up. The VSDs could be controlled by PLC programming to provide a maximum flow rate for a fixed period from start-up to enable the system to satisfy the immense initial load. The normal control can commence after the maximum load period.

This solution would therefore enable full variable flow control, adhere to original equipment manufacturer (OEM) specifications, lower the likelihood of scaling or fouling, and achieve electrical cost savings.

3.2.3.2 Condenser flow control loop

Existing control

The analysis showed that the three VSD-enabled pumps were operating under manual full-load conditions. The VSD control was completely disabled and the pumps were left to operate at maximum speeds. The root cause can be attributed to the low condenser flow rates experienced during start-up and normal operating conditions.

Initial budget constraints meant that only three of the six pumps were equipped with VSDs. The condenser control loop is based on achieving a constant temperature difference across

the condenser of the refrigeration machine. Since the three pumps unequipped with VSDs were operating under maximum load conditions, the three VSD-equipped pumps had to compensate for the increased flow by reducing the pump speeds.

The pump and motor speeds were reduced to such an extent that the temperature increase across the motor windings resulted in motor damage. The VSD control was disabled by mine personnel, who resorted back to throttling the condenser valves to achieve a constant flow rate close to design conditions.

As a consequence, favourable conditions for condenser tube scaling and fouling were prompted. This furthermore increased the maintenance costs associated with cleaning the condenser tubes and cooling tower nozzles and fill.

Proposed control

In order to achieve the necessary flow rate, the input frequencies of the VSD equipped pumps can be adjusted with the PI control logic through the PLC to incorporate a sufficient minimum flow rate. The minimum flow rate would therefore satisfy the start-up and operational requirements while still enabling electricity cost savings.

The minimum flow rate would adhere to OEM requirements as well as design conditions. Incorporating the operational limits will enable the VSD equipped pumps to operate closer to design conditions without the adverse effects. The VSDs could be controlled, as seen in the evaporator flow control loop, to ensure a maximum operating speed during full-load start-up conditions.

The optimised control will therefore minimise the occurrence of scaling and fouling. The overall control loop's efficiency will therefore increase dramatically.

3.2.3.3 BAC flow control loop

Existing control

The analysis into the BAC flow control loop revealed that the three VSDs installed on the BAC feed pumps were disabled. The whole control loop was therefore disabled by the mine personnel. The root cause was determined to be the incorrect readings attained from the malfunctioning weather station.

The weather station measures the ambient dry-bulb temperature and relative humidity, which are used to determine the ambient enthalpy. The VSDs are furthermore proportionally controlled according to the ambient enthalpy to achieve a set BAC air outlet temperature. As a result of the incorrect low weather station feedback values, the pump speeds were controlled to produce a proportional low flow rate.

As explained in Section 2, the flow rate has a great effect on the water distribution inside the BAC tower that further affects the subsequent heat transfer capabilities. The low BAC water flow rate decreased the heat transfer capabilities of the tower and an insufficient BAC air outlet temperature was produced. Accordingly, the mine personnel resorted back to throttling valves coupled with maximum pump operating speeds.

The inefficient practice, however, led to an overall increase in maintenance and operational costs. This was mainly due to the costs and frequency attributed to the cleaning of the BAC nozzles, fill and tubes.

Proposed control

The BAC control loop is primarily based on the ambient enthalpy measurements from the weather station to be able to control the feed pumps accordingly. The weather station can be refurbished and recalibrated to ensure that accurate measurements are taken. The existing design can be improved by incorporating a radiation shield, which stops the radiation of any heat source that might affect the measurements.

Once the weather station is operational, the system can be improved further by varying the VSD frequency limits. The limits will have to be determined through performance tests – similar to the evaporator and condenser control loops. This will ensure that the flow distributions and pressures inside the BACs are sufficient for best efficiency design operating conditions. The throttling valves will furthermore be decommissioned to enable full variable flow control, which would realise electricity cost savings.

The ideal proposal would be to install a thermocouple, situated at the BAC air outlet duct. The thermocouple will then be incorporated in the control loop instead of the weather station to ensure constant BAC air outlet temperatures. The proposal is more reliable since the thermocouple will be fixed and calibrated inside the duct as opposed to the outside weather station, which can be damaged by heavy rain or hail.

3.2.3.3 Precooling flow control loop

Existing control

Analysing the precooling flow control loop showed that all VSDs were disabled. The root cause was attributed to defective dam level sensors on both the precooling sumps and the hot dam.

The precooling control loop is based on maintaining a constant dam level for the precooling sumps and hot dam. Incorrect feedback values attained from the sensors enabled the VSDs to reduce the pump speeds and relevant flow rates. The flow rate was subsequently lowered to such an extent that the minimum pressure for operation was inadequate and the system efficiency decreased dramatically. The flow distribution in the towers was unsatisfactory, which impeded the heat transfer capabilities.

Mine personnel disabled the VSDs and resorted back to inefficient practices. Mine personnel further recommissioned the throttling valves and enabled the pumps to operate under maximum load conditions during all hours. As a result, favourable conditions for scaling and fouling were created in the tower fill. The maintenance and operational cost increase can mainly be attributed to the cleaning of spray nozzles, tower fills and tubes.

Proposed control

In order to achieve sufficient variable flow control, the dam level sensors can be repaired and recalibrated. Once the dam level sensors are operational and accurate, the throttling valves can be decommissioned and full VSD control can be enabled.

With full VSD control, the system can be optimised by determining the frequency limits. These limits can be attained by manually varying the pump speeds and witnessing the effects on the system such as distribution patterns, flow rates and heat transfer capabilities. The relevant system parameters need to be documented and recorded for future use.

The frequency limits can subsequently be programmed into the PLC and controlled through the PI controller. The optimised proposal will minimise the occurrence of scaling or fouling, excessive motor and pump heat generation as well as insufficient pressure heads. The overall efficiency of the pumps and motors will therefore be increased by operating near optimum design conditions.

EMS

An EMS is the cornerstone of any existing DSM initiatives. The integrated system allows the automatic control of the different DSM initiatives to realise electricity cost savings (as discussed in Section 2.2.7).

The analysis revealed that the existing servers hosting the EMS have outdated software. The EMS further operated without an object linking and embedding (OLE) connection and the control was limited to only a few components as opposed to the whole refrigeration system. The root cause could be attributed to migrating the EMS without an in-depth data backup.

Further connectivity issues arose as a result of the mine upgrading to a new SCADA system. Not all existing DSM initiative control tags were compatible or incorporated in the new SCADA system. The EMS could therefore not operate with full control and the performance of the existing DSM initiative started to deteriorate.

The EMS was used in conjunction with a live monitoring system to ensure that the operational parameters stayed within the specified designed limits. The monitoring system was disabled due to the loss of the OLE connection. For this reason, the EMS was able to control without live feedback, which in turn meant that operational limits could be surpassed without any notification.

The EMS incorporated a data logging system where the data for historical operational system parameters was stored and sent to a central server. The communications of the EMS server and the address of the central server were outdated and no operational data was available. The SCADA system was thus the only viable system for retrieving operational data, which was limited to a three-month period.

The original PI control code, programmed into the PLCs as secondary control measures, was lost during the SCADA system migration. The SCADA system migration occurred without any backups, documentation or system audits. The EMS and DSM initiatives were not considered in any system changes, even though the EMS was the backbone of energy saving measures.

EMS proposal

The functioning of an integrated EMS is imperative for the sustainability of existing DSM initiatives [83]. In order to mitigate the adverse effects associated with the migration, the following strategy can be followed.

All relevant software packages installed on the servers could be upgraded to the latest available versions. Furthermore, the OLE for process control (OPC) connection can be established and secured by using watchdog control tags that notify SCADA technicians in real time of any communication issues. All relevant internet protocol addresses can be updated and tested.

The original ESCO can be contacted to provide the data packs and relevant control programming. The original programming will be incorporated with the updated tags and upgraded control software to ensure reliable control between the EMS and relevant PLCs.

The live monitoring system can be upgraded and optimised with the latest monitoring software. This will enable real-time feedback to relevant personnel regarding system operational parameters. Once all the software has been updated and the connections established, the data log system can be commissioned.

The data log system will enable mine personnel to create different trends of the operational system parameters to measure KPIs. The initial state of each parameter can therefore be compared with the same or different parameters at different stages of operation. This will serve as a tool for the mine to not only make current operational decisions, but also future system decisions.

The EMS will contribute towards the automatic, effective control of existing DSM initiatives. Using a monitoring and data log system will ensure an integrated rigid system designed for optimised performance and sustainability. The following section incorporates the root cause analysis to effectively contribute towards the development and verification of an improved performance strategy.

3.3 Improved performance strategies

3.3.1 Introduction

The feasibility of improving existing DSM initiatives on mine refrigeration systems for sustainable performance was discussed in the previous section using an example mine. The most significant system operations and KPIs of the existing refrigeration system were compared with the original configuration.

The system exhibited several alterations that are not only detrimental to project performance but also to the sustainability thereof. In this section, an improved performance strategy will be developed to increase both the performance and, specifically, the sustainability of existing DSM initiatives on mine refrigeration systems.

The techniques incorporated in the performance strategy will be verified by implementing them on Mine A. The performance of the strategy will finally be investigated and critically analysed, before implementation can commence on other mines.

3.3.2 Performance strategy summary

The section provides a summarised description of the methodological approach that can be followed to improve existing DSM initiatives on mine refrigeration systems for sustainable performance. Note that the performance strategy is designed to be applicable to all underperforming DSM initiatives on mine refrigeration systems.

The performance strategy is displayed in general terms; more detail is displayed at a later stage when the different control loops are considered individually. As a result of incorporating the feasibility analysis into the development, the performance strategy is an all-encompassing comprehensive solution. Figure 3-2 illustrates the different sections included in the performance strategy.

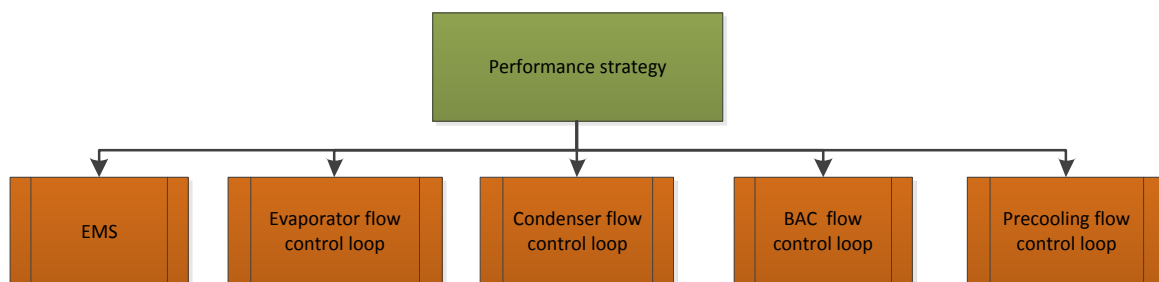


Figure 3-2: Performance strategy subdivisions

Figure 3-3 illustrates a detailed layout of the performance strategy for each subdivision.

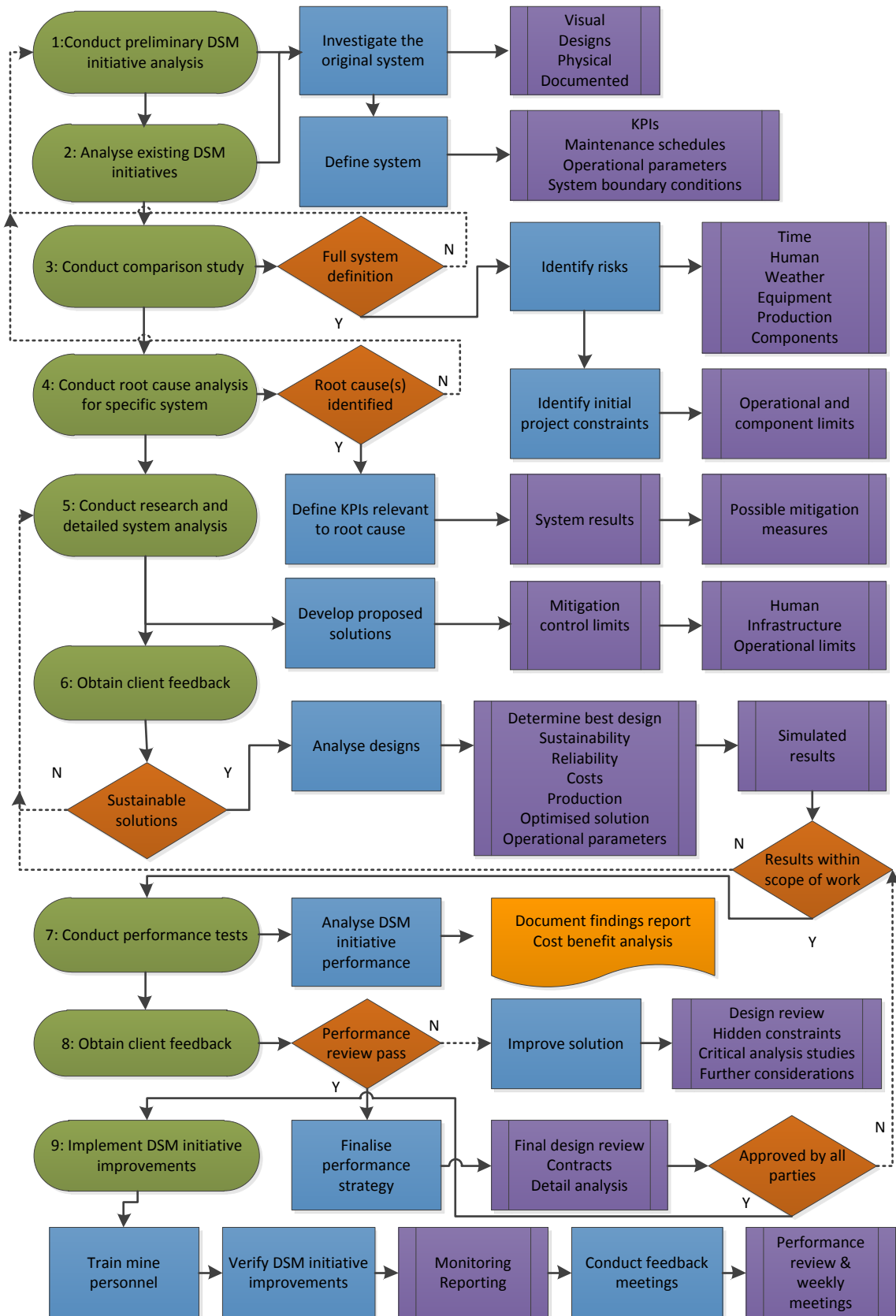


Figure 3-3: Performance strategy overview

The performance strategy, as seen in Figure 3-3, shares several attributes with the system engineering approach. Frey *et al.* contend that system engineering is the foremost approach for all future developments in the automation and DSM industry [93]. Furthermore, the approach is the only current solution possessing the necessary flexibility and underlying architecture for the complex distributed control requirements.

The performance strategy can be simplified to nine basic groups, which are listed in Figure 3-4 [93]:

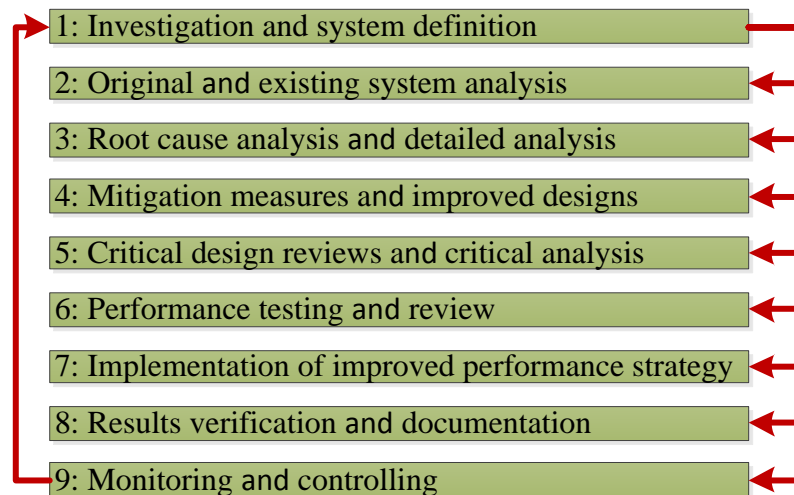


Figure 3-4: Simplified performance strategy

Although the performance strategy has several subdivisions, all nine basic groups are applicable to each subdivision. The generic model will ensure that each and every design decision to improve the existing DSM initiatives on the refrigeration systems can be referenced and reviewed to ensure sustainable performance. The following sections further elaborate on the performance strategy regarding the foremost considerations applicable in the different subdivisions.

EMS

Lee and Cheng described the use, integration and optimisation of an EMS as the cornerstone of implementing DSM initiatives [83]. The EMS is thus a crucial component in improving existing DSM initiatives, especially with sustainability in mind.

Figure 3-5 illustrates the detailed considerations specific to the EMS that are incorporated in the performance strategy. The most significant factor to consider in an EMS is the complex

integration. The constant alterations imposed from software upgrades and operational changes result in a compound system to manage and maintain.

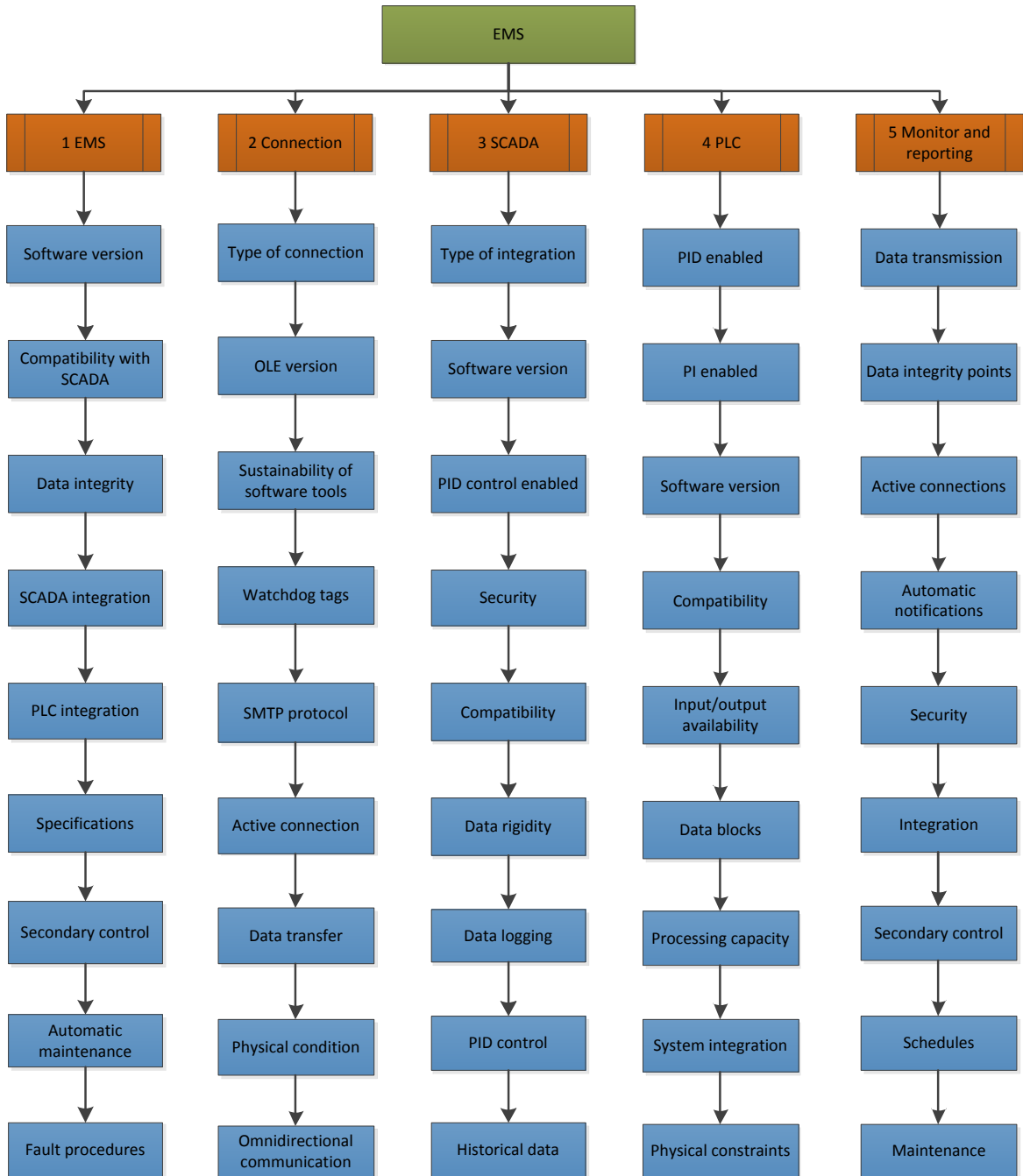


Figure 3-5: EMS performance strategy overview

Although this EMS performance strategy is designed to improve performance, it is primarily designed to improve the sustainability of the existing DSM initiatives. Note that several procedures and tools are available in industry to promote sustainability. The key is selecting and integrating the necessary resources to mitigate or improve a specific existing system.

The performance strategy must cater for every possible scenario that can occur in the gold mining industry, specifically on mine refrigeration systems.

Evaporator flow control loop

The performance strategy considerations applicable to the evaporator flow control loop are illustrated in Figure 3-6. The considerations are divided into different sections to simplify the methodology when improving DSM initiatives for sustainable performance.

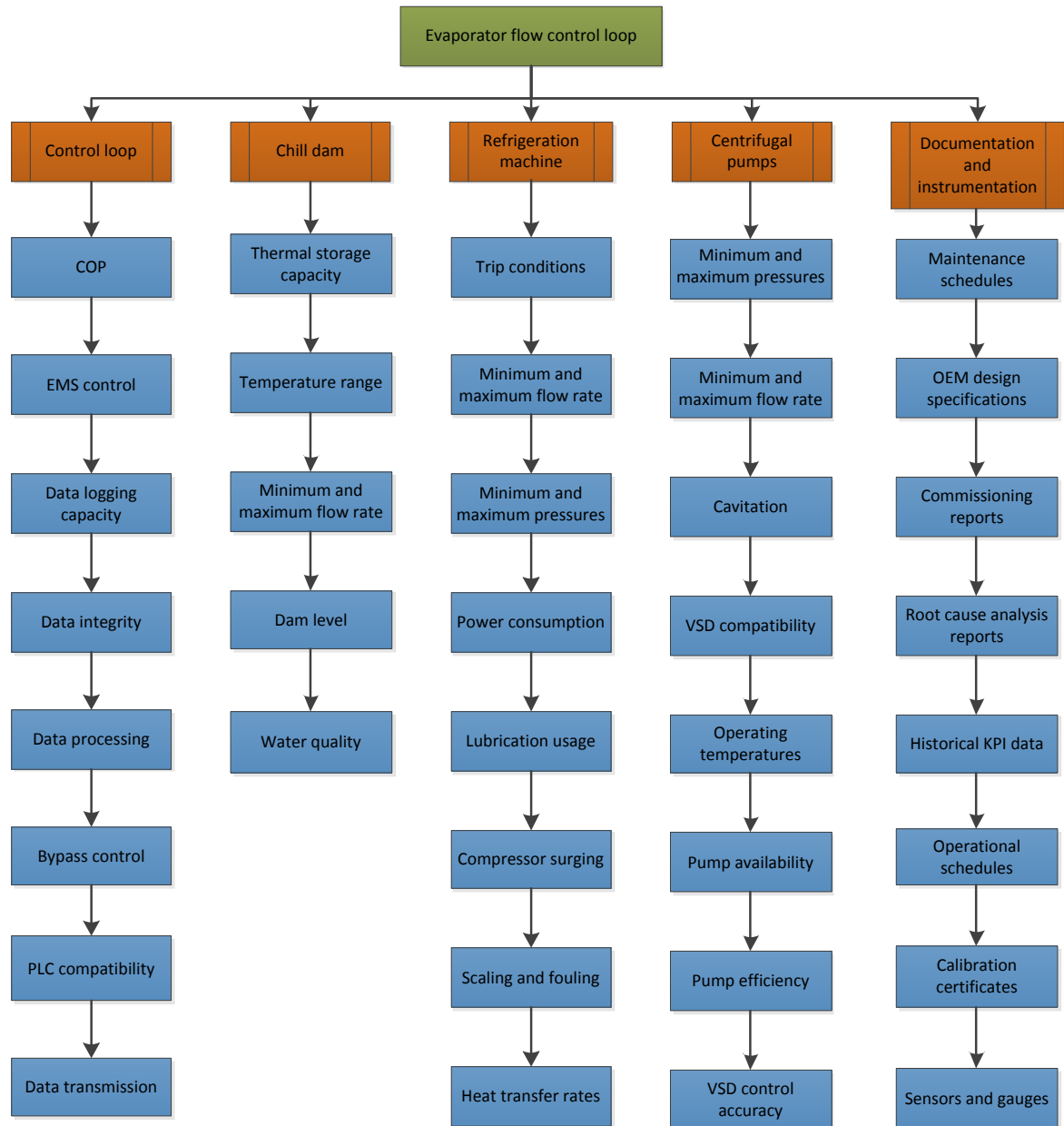


Figure 3-6: Evaporator flow control loop performance strategy overview

The detailed overview in Figure 3-6 provides insight into the different considerations and the suitability of each parameter in the process. This enables the user to define the hierarchy for each individual system of different gold mines.

Condenser flow control loop

The performance strategy considerations applicable to the condenser flow control loop are illustrated by Figure 3-7. Note the difference when compared with the evaporator flow control loop; the different control methodologies have different primary considerations.



Figure 3-7: Condenser flow control loop performance strategy overview

In some cases, the condenser flow control loop is used to achieve a constant refrigeration machine chilled outlet water temperature. In such cases, the main factor will be the outlet temperature and not the constant temperature rise over the condensers. The temperature rise can therefore be substituted with the refrigeration machine chilled outlet water temperature.

BAC flow control loop

Figure 3-8 shows the performance considerations applicable to the BAC flow control loop. The BAC control is based on the modulation of VSDs in proportion to ambient enthalpy.



Figure 3-8: BAC flow control loop performance strategy overview

Precooling flow control loop

The most significant considerations when improving existing DSM initiatives on mine refrigeration systems, specifically the precooling flow control loop, are illustrated by Figure 3-9. Note that the control is similar to the condenser loop but differs in that the control is based on maintaining constant sump levels as opposed to a temperature rise over the condenser.

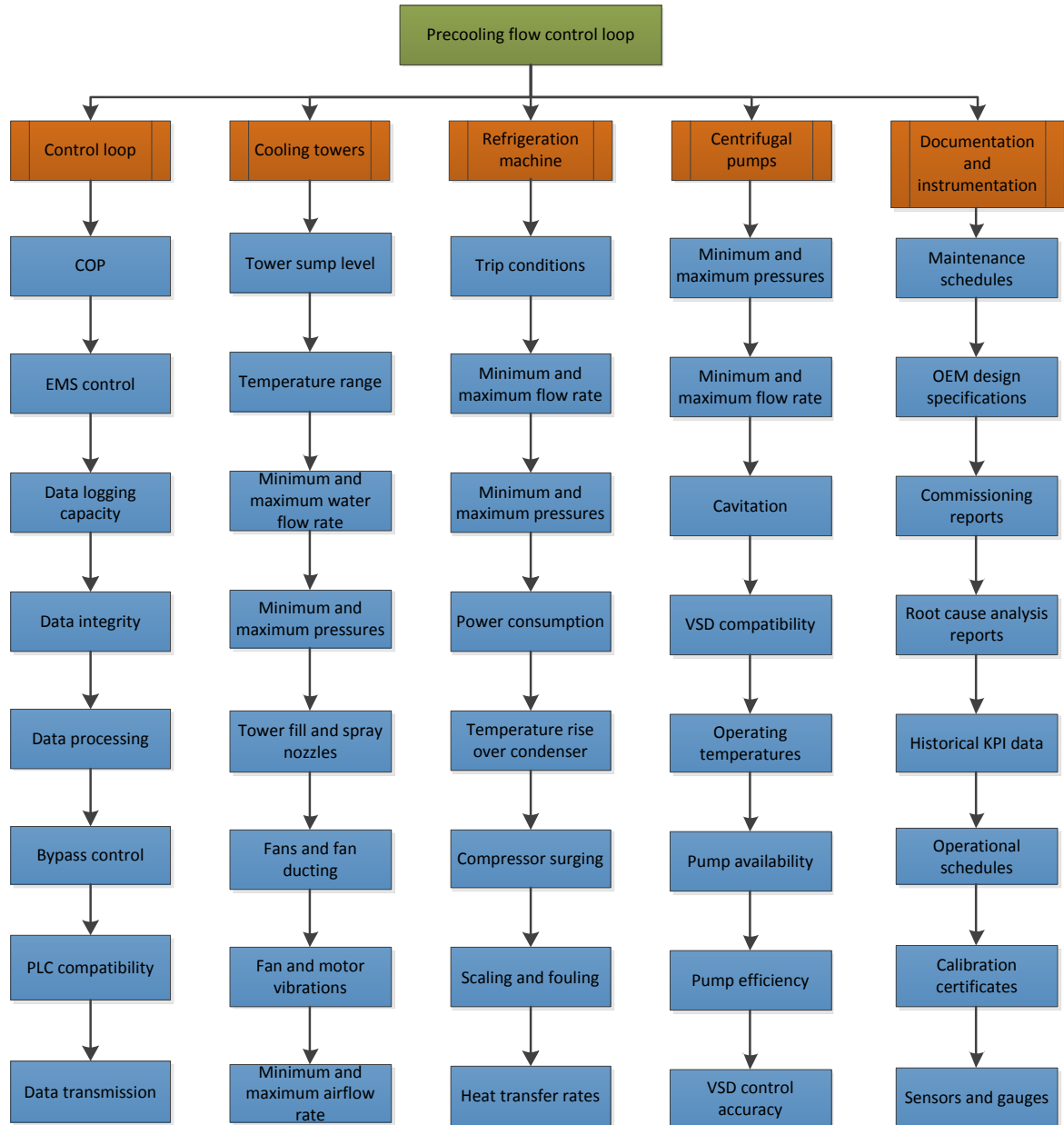


Figure 3-9: Precooling flow control loop performance strategy overview

The proposed performance strategy will be verified in Section 3.4 through detailed simulations and actual verification tests. The performance strategy will be applied to Mine A, incorporating the individual performance strategy considerations for each control loop to determine the effects thereof.

3.4 Performance verification

3.4.1 Introduction

In order to predict the full effects of implementing the proposed performance strategy, a detailed simulation model is required. This model, once verified, will enable the user to simulate the existing DSM initiatives on mine refrigeration systems. This tool will enable the user to determine the effects and make the necessary changes required to optimise the system for improved performance, but primarily for improved sustainability.

3.4.2 Simulation model

The performance of DSM initiatives on mine refrigeration systems have previously been investigated [32]. Van der Bijl [72] and Yao *et al.* [81] illustrated simulation models on the effects of load shifting in mine cooling systems and the optimal operation of refrigeration machines. Du Plessis further developed a simulation model specifically designed to show the effects of variable flow strategies on mine refrigeration systems [11].

The existing model from Du Plessis was slightly adapted and incorporated into a simulation software called Process Toolbox (PTB). The focal point of this section is to verify the accuracy of the simulation model to ultimately predict the electrical cost savings that can be achieved by using the proposed performance strategy.

The integrated simulation model takes several variables into account to balance the mass and energy equations of individual and greater systems over a predetermined time range. The time range and crucial system parameters can be varied to such an extent that all factors are represented in the model. The model also adheres to system operational constraints and system boundary conditions.

The simulation model of Mine A is based on the fundamental process flow diagram illustrated by Figure 3-10. The model shows the relation of the different input and output variables for each component in the refrigeration cycle.

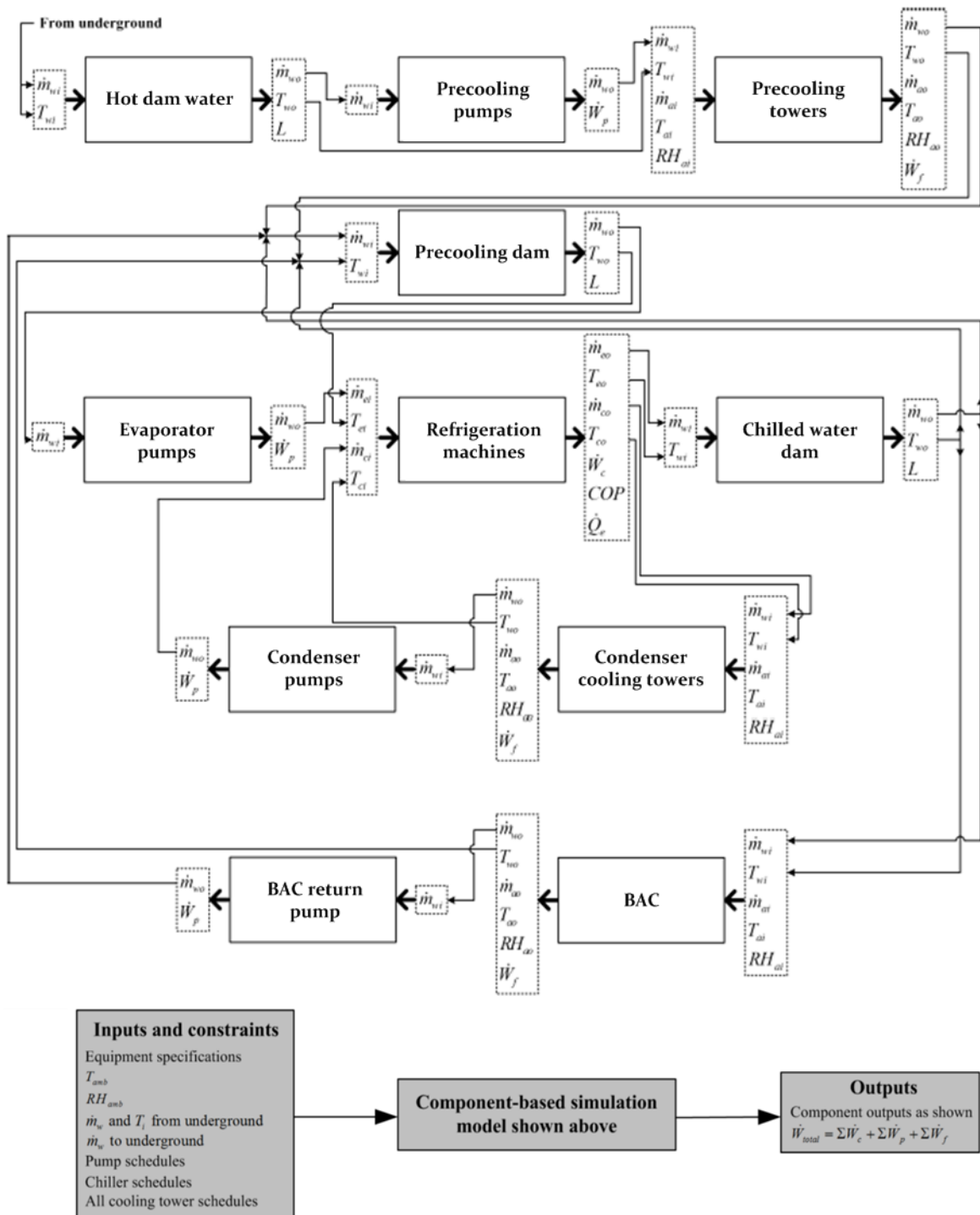


Figure 3-10: Mine A simulation model process flow diagram

Note that not all considerations and parameters are displayed in Figure 3-10. The flow diagram is a simplified illustration of the fundamental process that the simulation software follows to determine the final solution. As a result, the simulation model yields a very detailed solution that can be analysed up to individual component level.

Simulation verification

According to Schutte, the verification of the simulation model refers to the processes of examining and scrutinising the accuracy of the model so that the simulation is sufficient enough to portray and predict the actual system [8].

The performance of the existing DSM initiatives on Mine A's refrigeration system was simulated in PTB using historical empirical data attained from the portable power loggers and the mine SCADA system. Furthermore, the simulation results were analysed and compared with the actual performance results during the same period. The simulation model could therefore be verified for its accuracy and correctness.

The developed simulation model for Mine A can be seen in Appendix C. The following section will elaborate on the accuracy of the model. A typical summer weekday was used in the simulation due to the reduction of thermal cooling load requirements over weekends and also during colder winter months.

The actual and simulated power profile of Mine A are illustrated by Figure 3-11. For the purpose of this study, only the crucial system parameters are shown since they have the greatest effect on the mining operations.

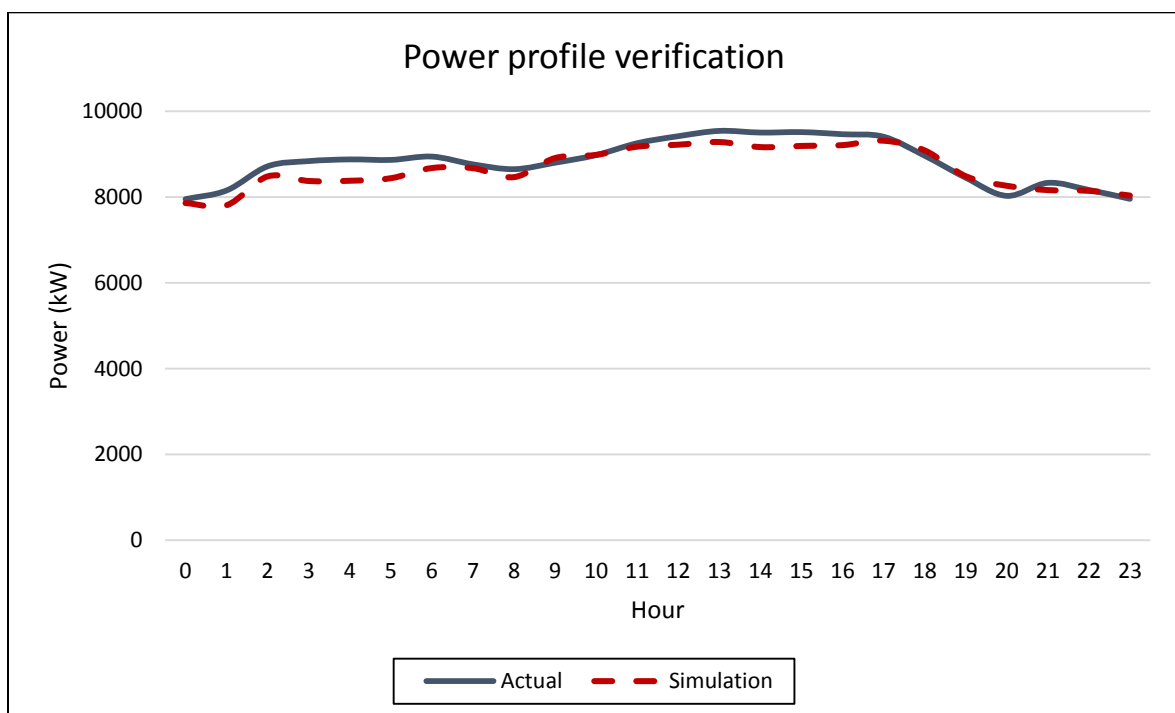


Figure 3-11: Mine A power profile verification

The power profile in Figure 3-11 will be used to determine the electrical cost saving that stems as a result from implementing the proposed performance strategy. It is thus imperative to verify the model within tolerable limits. Van der Bijl [72] and Calitz [84] state that the model is sufficient for mine applications if the simulation results are within a 10% tolerance of the actual values.

The tolerance limits are included to anticipate system changes. These changes can be attributed to several factors such as reduced efficiencies of mechanical rotational equipment or reduced heat transfer rates in the cooling towers, BACs and refrigeration machines. The severity of change is therefore dependent on the everyday maintenance and operational procedures. Scaling, corrosion and fouling may have detrimental effects on the system and simulation (as described in Chapter 2.2.2).

The comparison of the actual and simulated chill dam water temperature is demonstrated by Figure 3-12. The chill dam water temperature not only greatly affects production but also as a primary concern, the safety of mining and mine personnel.

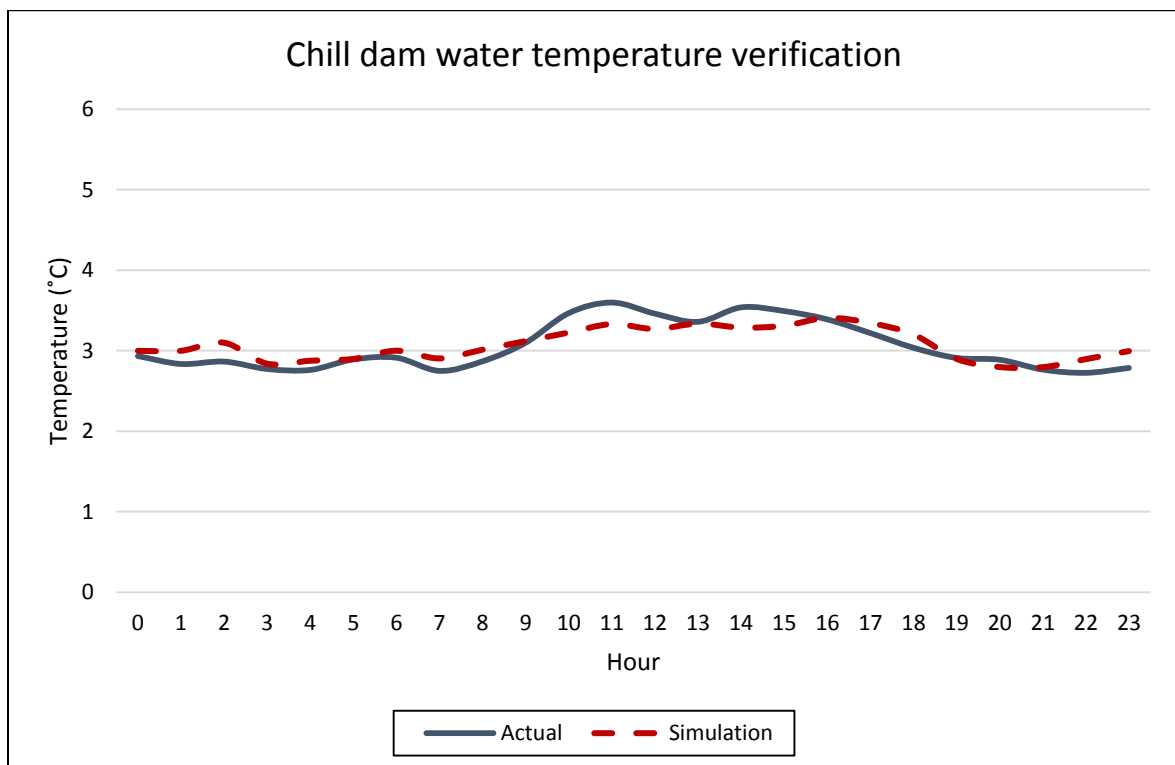


Figure 3-12: Chill dam temperature verification

The BAC air outlet comparison is illustrated by Figure 3-13. The BACs provide sufficient cold dehumidified air at 7°C for underground use. Note that the BACs incorporate the chilled water from the surface chill dam to achieve the required cooling. The BACs are therefore dependent on the heat transfer between the air and chilled water supplied from the chill dam.

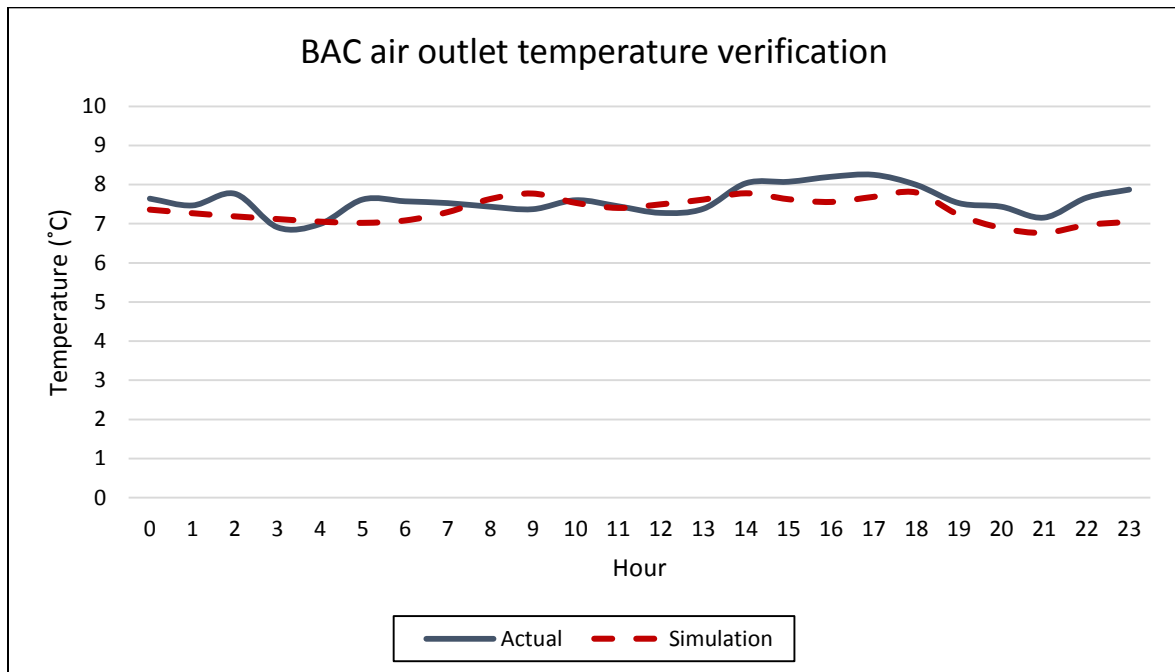


Figure 3-13: BAC air outlet temperature verification

The actual and simulated values for the crucial system parameters are summarised in Table 3-1. The average percentage difference is also shown to illustrate that the model is within the tolerable limits. PTB is thus verified as a suitable simulation model that can be applied to other existing DSM initiatives on mine refrigeration systems.

Table 3-1: Simulation model verification summary

System parameter	Units	Actual average	Simulation average	Difference
Electric power	kW	8 813.97	8 641.89	1.95%
Chill dam water temp.	°C	3.05	3.08	0.97%
BAC air outlet temp.	°C	7.59	7.34	3.29%

It is apparent that PTB complies and satisfies all model verification requirements. PTB can thus be used as a predictive resource to determine the effects of the proposed performance strategy. Since the quantification of the performance strategy is directly dependent on the electrical cost savings, the percentage difference of 2.33% is acknowledged as satisfactory.

3.4.3 Improved simulation results

In order to quantify the tangible effects of the proposed performance strategy, actual verification tests were required. However, according to Du Plessis[11], it is imperative to simulate the system with the proposed alterations before implementation commences. Thus, the proposed performance strategy was simulated by using the verified simulation model PTB. As a result, using the performance strategy should ultimately lead to an increase in electrical cost savings, performance and sustainability.

The actual verification tests occurred over the course of one summer month. All historical data was incorporated to establish system operational baselines. The power baseline is illustrated in Figure 3-11. Since all existing DSM initiatives on Mine A have been disabled, the actual data for the typical summer day shows an excellent correlation with the weekday baseline values for the corresponding month.

As part of the performance strategy, the root causes identified in Section 3.2.3 were addressed to enable full PID control. Table 3-2 illustrates the most significant alterations implemented during the testing month. Note that the PID control was implemented by using the mine SCADA; the EMS has not been updated for testing purposes.

Table 3-2: Performance strategy verification summary

Type of control	Baseline	Performance strategy	Units
Evaporator flow control loop			
VSD lower limit	50	37	Hz
VSD upper limit	50	45	Hz
Condenser flow control loop			
VSD lower limit	50	36	Hz
VSD upper limit	50	45	Hz
BAC flow control loop			
VSD lower limit	50	31	Hz
VSD upper limit	50	44	Hz
Precooling flow control loop			
Feed pump VSD lower limit	50	37	Hz
Transfer pump VSD lower limit	50	20	Hz

Strategy performance verification

In this section, the performance verification test results are compared with the original system operation. The most significant crucial system parameters are highlighted and discussed as a result of implementing the proposed performance strategy over a period of one month. All crucial faults were addressed to enable PID control. The BAC weather station was repaired and recalibrated for accurate measurements.

The average electric power profile for the testing period is illustrated by Figure 3-14. It is apparent from the figure that a large power reduction was experienced when compared with the original baseline. The reduction can be attributed to the implemented performance strategy that took previous research and studies into account. Du Plessis *et al.* [42] and Van der Bijl [72] pioneered the variable flow and load shift technologies that were specifically incorporated into the performance strategy.

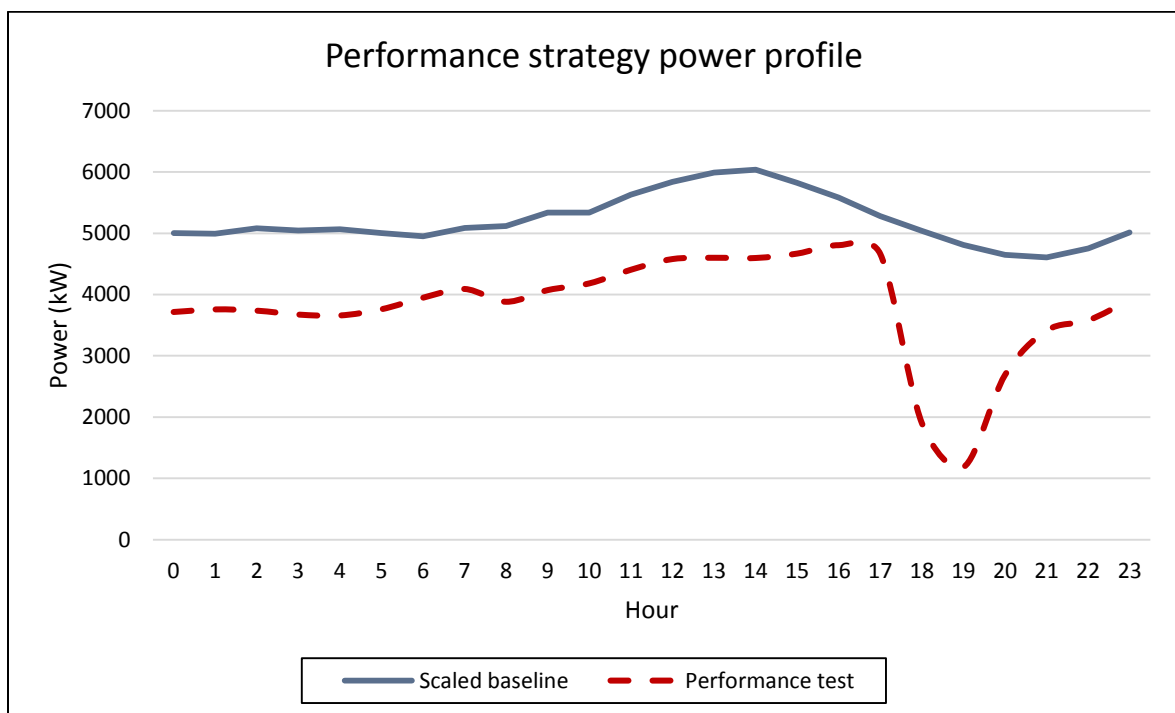


Figure 3-14: Performance strategy power verification

As a result of the performance strategy implementation, an average electric power saving of 1.4 MW was realised over the course of a typical mining weekday. Furthermore, an average electric power saving of 3.4 MW was achieved during Eskom's peak electricity tariff times (as discussed in Appendix A). The strategy thus achieved a 26.88% reduction in electric power use over a one-month period.

Figure 3-15 illustrates the number of refrigeration machines in operation before and after implementing the performance strategy. During the baseline period, all six refrigeration machines were running at full-load conditions during typical mining weekdays. The cooling load was not only satisfied but also resulted in overcooling.

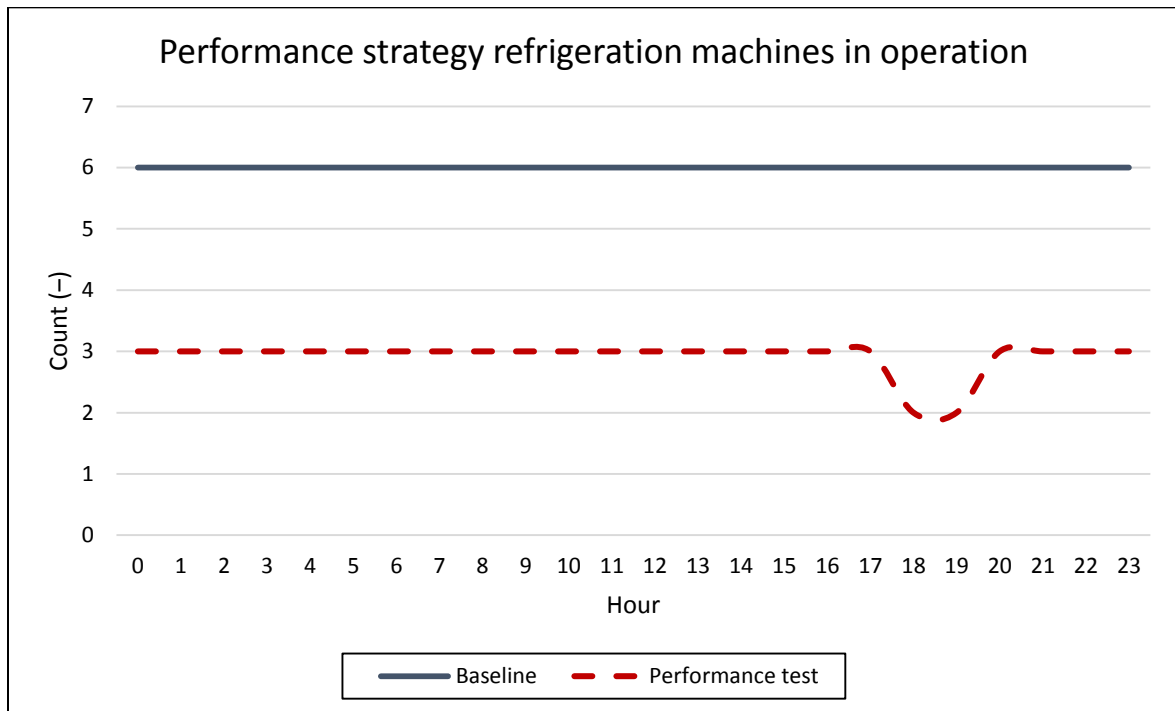


Figure 3-15: Performance strategy refrigeration count verification

If one considers Figure 3-15, it is clear that fewer refrigeration machines were needed to satisfy the cooling load, especially in peak electricity times. Not only does this contribute to increasing equipment life cycles but also to increasing sustainability, especially when part-load conditions are applicable. Half of the refrigeration machines can therefore serve as backup machines that provide versatility to the refrigeration system where maintenance and daily operations are concerned.

Chill dam water temperature is another crucial system parameter to consider when alterations are made to refrigeration systems. Figure 3-16 illustrates the average chill dam water temperature realised during the verification tests. This temperature demonstrates a 94.4% correlation with the baseline values. The actual profile illustrates a more stable temperature, with a slight increase experienced during the peak electricity times, which corresponds with the reduced number of refrigeration machines in operation.

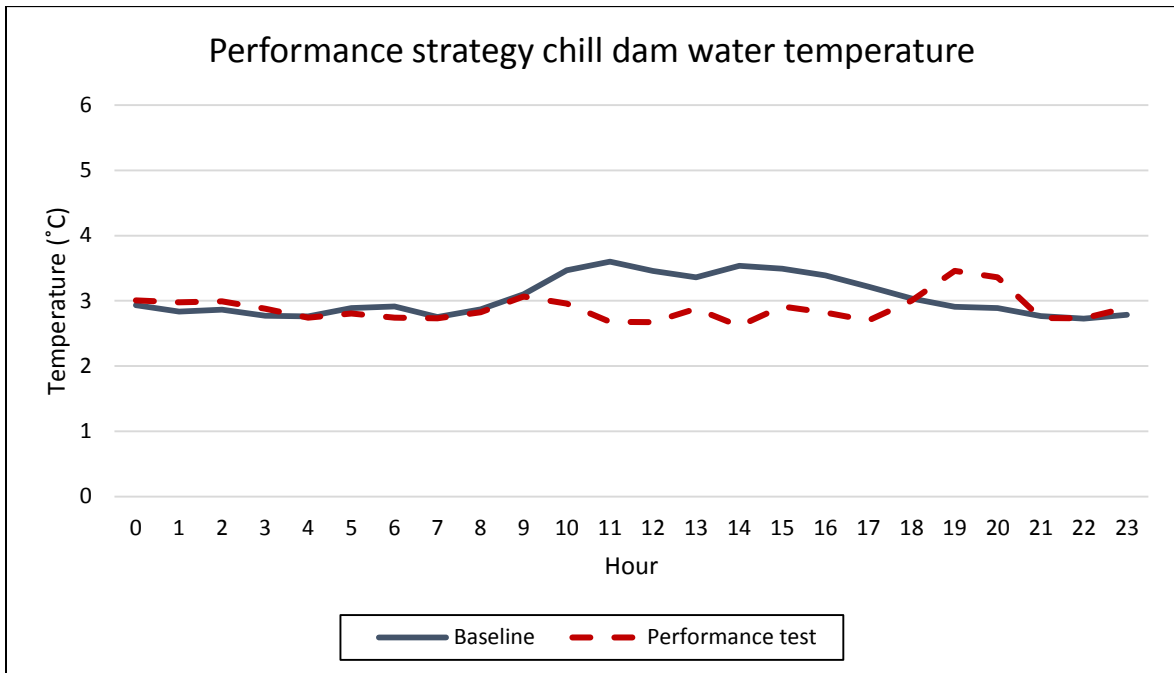


Figure 3-16: Performance strategy chill dam temperature verification

The chilled water flow rate sent underground is illustrated by Figure 3-17. Although the average water flow rate differs with only 6 ℓ/s , the focus is placed on satisfying the demand during peak mining times. The actual profile illustrates a more efficient flow rate.

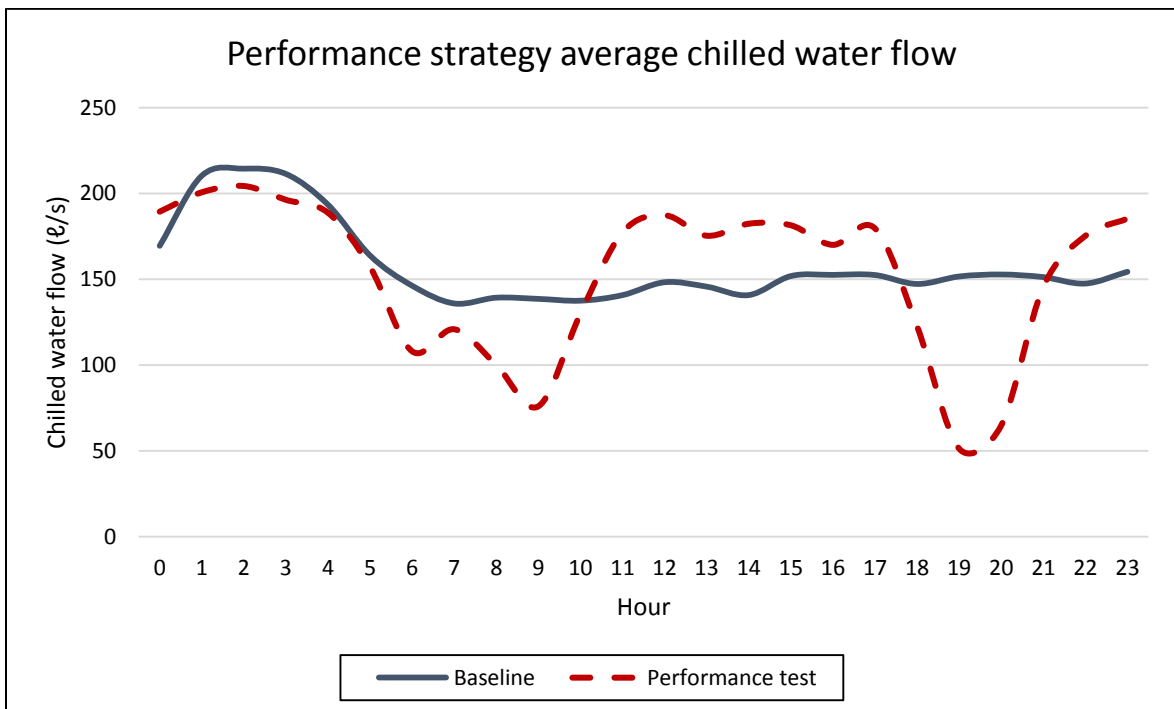


Figure 3-17: Performance strategy average chilled water demand verification

The BAC air outlet temperature experienced during the verification testing period is illustrated by Figure 3-18. The actual temperature is within the specified limits as discussed in Chapter 2.2.4.

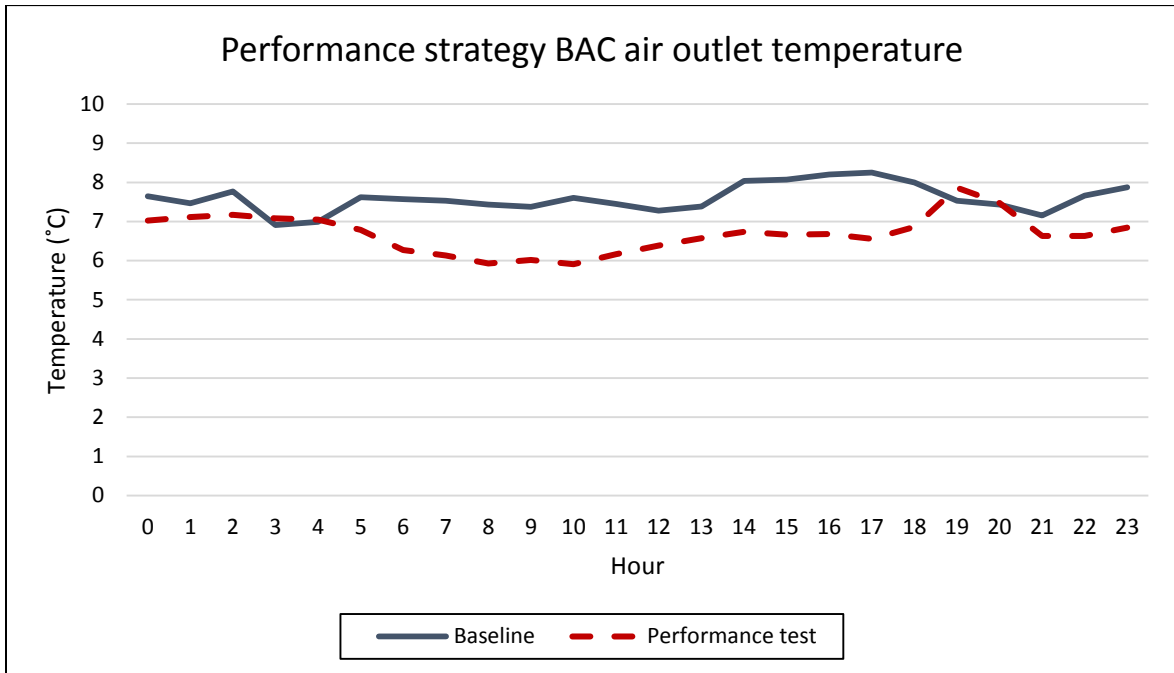


Figure 3-18: Performance strategy BAC outlet temperature verification

Note the temperature increase during the peak electricity times shown in Figure 3-18. This rise can be attributed, as is the case with the chill dam temperature increase, to fewer operating refrigeration machines being used.

It is evident from the above-mentioned figures that implementing the performance strategy had a great effect on the existing DSM initiatives on the mine refrigeration system. The focus of the performance strategy is to optimise the system but mainly to increase the sustainability of DSM initiatives. Table 3-3 illustrates a summary of the results obtained from the verification test after implementing the performance strategy.

Table 3-3: Actual verification test results summary

System parameter	Units	Baseline average	Actual average	Difference
Electric power	kW	5 211.65	3 810.74	26.9%
Chill dam water temp.	°C	3.05	2.88	5.5%
BAC air outlet temp.	°C	7.59	6.69	11.8%

3.5 Proposed economic feasibility

As discussed in Chapter 1.4, there is a need to improve existing DSM initiatives on mine refrigeration systems for sustainable performance. The preceding sections focused on developing and verifying the proposed performance strategy.

The economic feasibility of the proposed performance strategy is analysed in this section. The actual electricity cost savings realised through the verification test are determined. As a result, the economic feasibility of the performance strategy as a whole can be determined.

Electrical cost savings

The latest Eskom electricity cost tariff for 2015/2016 is illustrated by Table 3-4 [94].

Table 3-4: Eskom electricity Megaflex tariff 2015/2016 in c/kWh [94]

Hour	Summer Tariff (Sept–May)			Winter Tariff (Jun–Aug)		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
1	35.86	35.86	35.86	41.35	41.35	41.35
2	35.86	35.86	35.86	41.35	41.35	41.35
3	35.86	35.86	35.86	41.35	41.35	41.35
4	35.86	35.86	35.86	41.35	41.35	41.35
5	35.86	35.86	35.86	41.35	41.35	41.35
6	35.86	35.86	35.86	41.35	41.35	41.35
7	56.25	35.86	35.86	75.74	41.35	41.35
8	81.52	56.25	35.86	248.94	75.74	41.35
9	81.52	56.25	35.86	248.94	75.74	41.35
10	81.52	56.25	35.86	248.94	75.74	41.35
11	56.25	56.25	35.86	75.74	75.74	41.35
12	56.25	56.25	35.86	75.74	75.74	41.35
13	56.25	35.86	35.86	75.74	41.35	41.35
14	56.25	35.86	35.86	75.74	41.35	41.35
15	56.25	35.86	35.86	75.74	41.35	41.35
16	56.25	35.86	35.86	75.74	41.35	41.35
17	56.25	35.86	35.86	75.74	41.35	41.35
18	56.25	35.86	35.86	75.74	41.35	41.35
19	81.52	56.25	35.86	248.94	75.74	41.35
20	81.52	56.25	35.86	248.94	75.74	41.35
21	56.25	35.86	35.86	75.74	41.35	41.35
22	56.25	35.86	35.86	75.74	41.35	41.35
23	35.86	35.86	35.86	41.35	41.35	41.35
24	35.86	35.86	35.86	41.35	41.35	41.35

According to Figure 3-14, an average electric power saving of 1.4 MW was achieved during the course of a typical mining weekday for the verification test period. Subsequently an electric power saving of 3.4 MW was realised for the peak electricity periods. If one considers Table 3-4 and apply the actual verification test results, the actual electrical cost saving can be determined for the testing period.

The actual electricity cost saving achieved during the verification testing period amounted to R388 650. The amount is solely based on the electrical cost saving and does not include further cost reductions as a result of the implemented performance strategy. Additionally, it is extremely hard to quantify the reduced maintenance costs associated with the refrigeration system since several external factors can affect the system.

The daily and annual predicted electricity cost savings for both the summer and winter months are displayed in Table 3-5. Note that the performance strategy electricity cost saving results were verified through actual verification testing. The amounts displayed in Table 3-5 are thus based on the model, which has proven to yield an excellent correlation when compared with the actual results.

Table 3-5: Mine A predicted electricity cost savings

Description	Summer Tariff (Sept–May)			Winter Tariff (Jun–Aug)		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
-						
Daily saving	R19 432.53	R14 635.30	R12 056.75	R39 747.80	R18 251.59	R13 902.59
Annual saving	R4 975 838.50			R3 071 096.93		
Annual total	R8 046 935.43					

In industry, one of the foremost methods to determine the feasibility of a project is defining the payback period. The payback period is regarded as a measure of the amount of time needed for a project to reap economic benefit and surpass the initial capital investment and annual operational costs incurred.

If one considers Mine A, it is clear the original capital investment had already been satisfied in full. The only applicable costs incurred per annum are the maintenance and operational costs. Thus, the performance strategy can contribute towards immense electricity cost savings without large capital expenditure, emphasising the “low-hanging fruit” ideal.

The method used to determine the payback period is illustrated by Equation 2-4 [78]:

$$PBP = \frac{C_E}{C_S} = \frac{C_{IC} + C_{AC}}{C_S} \quad (2-4)$$

Where,

- PBP = payback period (years)
- C_E = capital expenditure (R)
- C_S = capital electricity cost savings (R)
- C_{IC} = initial capital investment (R)
- C_{AC} = annual incurred costs (R)

Due to client confidentiality, the exact amount for the maintenance and operational costs incurred per annum may not be disclosed. However, in accordance with the study, an annual incurred cost of R200 000 is presumed with a zero initial capital investment. The payback period with the assumptions made amounts to 0.3 months. It is widely accepted in industry to pursue projects with a payback period shorter than two years [78].

Economic feasibility conclusion

The verified simulation model was used to predict electrical cost savings over a typical one-year mining period. The latest Eskom Megaflex electricity tariff was incorporated to determine the economic feasibility of improving existing DSM initiatives on mine refrigeration systems for sustainable performance.

The performance strategy was verified through a one summer-month verification testing period. The actual realised electricity cost savings amounted to R388 650. The predicted annual electricity cost saving for Mine A was calculated to be R8 046 935. As a result, the payback period was determined to be less than a month. This contributes to the feasibility of using the proposed performance strategy for deteriorating underperforming DSM initiatives on mine refrigeration systems.

3.6 Conclusion

A case study was presented for improving existing mine refrigeration systems for sustainable performance. A mine with deteriorated underperforming DSM initiatives on the refrigeration system was identified and analysed in detail.

The existing DSM initiatives on the mine's refrigeration system and the current system operations were discussed to promote in-depth background knowledge. The feasibility of improving the existing DSM initiatives was investigated and possible solutions identified. Crucial system parameters and KPIs were used in a detailed root cause analysis of each control loop.

The analysis led to the development of a performance strategy that would improve existing DSM initiatives on mine refrigeration systems for sustainable performance. The critical performance considerations were summarised for each control loop. The considerations are of the utmost importance to compare system boundary conditions and constraints to ensure improved performance and sustainability.

A simulation model was created with the aid of the simulation software PTB, based on the pioneering work of Du Plessis *et al.* [42] and Van der Bijl [72]. Actual data from Mine A's refrigeration system was used to verify the accuracy of the proposed performance strategy. The average percentage difference between the actual and simulated values was determined to be 3.74%, which was deemed as sufficient.

The KPIs and critical systems parameters of the performance strategy simulation were compared with the actual values. The verification test period occurred over one month during which the performance strategy was implemented and the viability of the performance strategy was investigated further. As a result of the performance strategy, an average power reduction of 1.4 MW was experienced during the course of a typical mining weekday with a 3.4 MW reduction during the peak demand times.

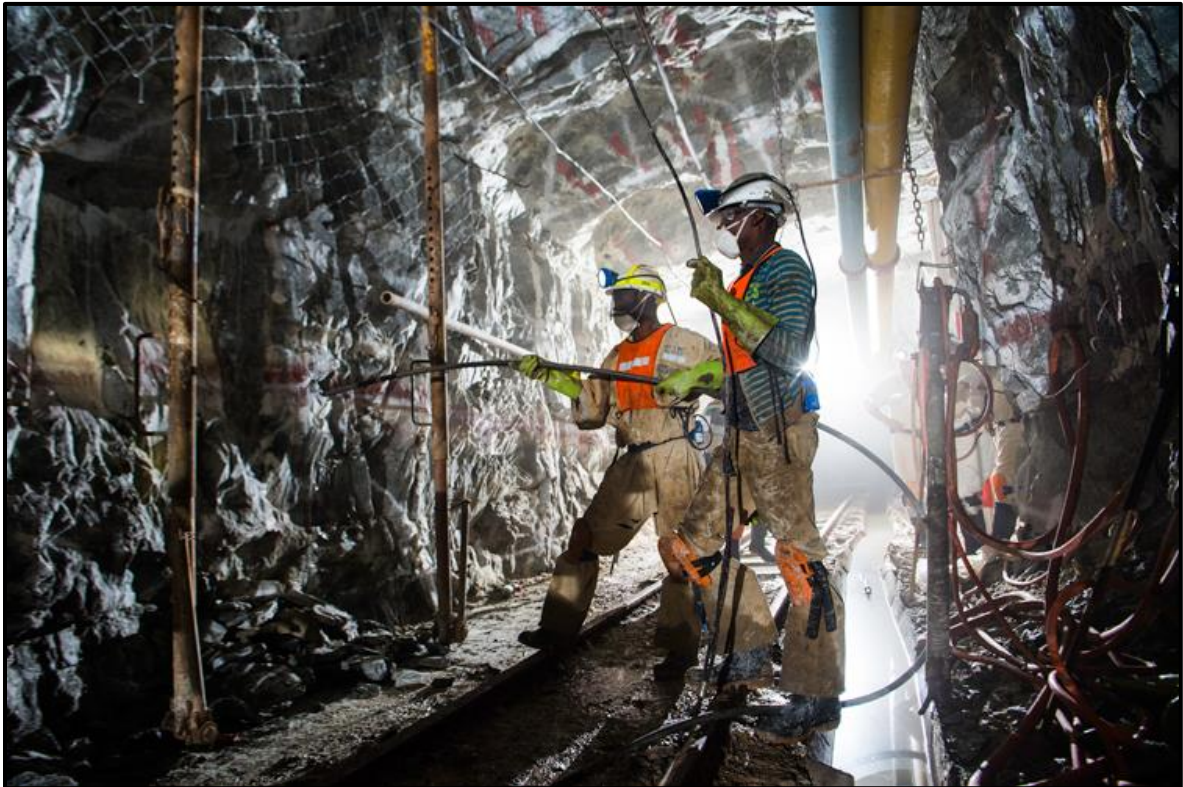
The improved performance equated to a 26.9% reduction in total refrigeration system electricity costs, which amounted to a value of R388 650 for the verification testing month. The performance strategy was therefore verified and further electricity cost savings predicted with the aid of the performance strategy and simulation model.

The economic feasibility was investigated by changing the system constraints as described by the performance strategy. It was shown that the average daily savings expected are R15 374 for summer tariff months and R23 963 for winter months. The total electricity cost saving per annum would therefore amount to R8 046 935. It is evident from the payback period that the proposed performance strategy should yield a significant power reduction and financial saving with very little to no capital expenditure required.

It can be concluded that the proposed performance strategy is feasible to be implemented across different deteriorating underperforming DSM initiatives on mine refrigeration systems. The performance strategy's generic design contributes towards a vast increase in system versatility, in turn resulting in unparalleled duplication capabilities. The performance strategy will therefore be implemented permanently on a second case study – Mine B. The following section will focus on the validation and actual electrical cost savings as a result of implementing the performance strategy.

Chapter 4

Energy saving implementation



“Simplicity is the ultimate sophistication.”

– Leonardo da Vinci

4.1 Introduction

In the preceding chapter, a performance strategy was developed to improve existing DSM initiatives on mine refrigeration systems for sustainable performance. The feasibility of the proposed strategy was critically analysed and investigated.

After the preliminary feasibility study revealed that the performance strategy was viable, it was implemented for a one-month verification testing period on Mine A to validate and quantify the actual electrical cost savings. The actual electrical cost savings realised proved the validity of the performance strategy, emphasising the immense need for further implementation and testing.

In this chapter, the performance strategy is implemented on another mine, Mine B, which has deteriorating underperforming DSM initiatives on the refrigeration system. The most significant feasibility and implementation considerations are discussed and analysed as part of a case study. Firstly, an overview of the existing refrigeration system's operations and equipment is given. Thereafter, the feasibility of implementing the proposed performance strategy is discussed in detail with the most significant system alterations defined.

Once the feasibility analysis is complete, the performance strategy implementation will commence. The results will finally be analysed in-depth to not only determine the electrical cost savings, but also the full effect on the refrigeration system operations, mine's production and subsequent mining personnel.

The performance strategy results will be validated and the expected and actual long-term results presented. As a result, this chapter will consider the complete process of implementing the proposed performance strategy. The implementation of the performance strategy should yield an increase in system performance, efficiency and especially sustainability, ensuring a significant, sustainable electrical cost saving in the long term.

4.2 Improved performance strategy implementation

4.2.1 Mine B refrigeration system overview

A critical analysis was done on Mine B after project deterioration and underperformance were observed on the mine's refrigeration system. The original DSM initiatives were investigated and implemented at the deep-level gold mine during the last quarter of 2010. The DSM initiatives primarily focused on satisfying the cooling demand by optimising the control of the refrigeration system.

It was found that variable flow control was used throughout the entire surface refrigeration system (as seen in Figure 4-1). The refrigeration machines were configured in a parallel-series arrangement to enable seasonal flow and temperature control. The condenser and evaporator pumps were individually connected to common manifolds. The refrigeration system supplied chilled water to both BACs and underground end-users.

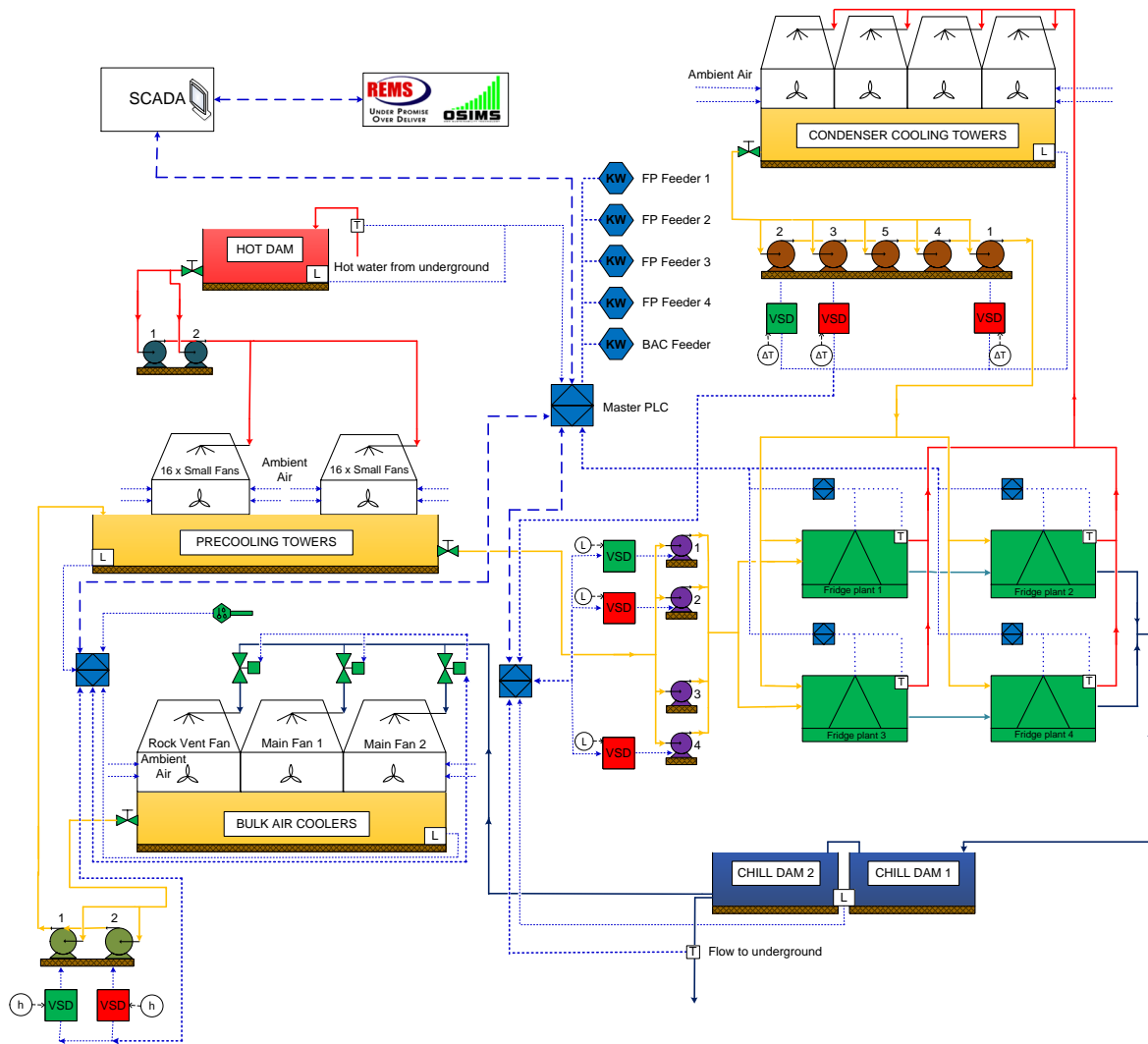
The original DSM initiative's control and equipment specifications are presented in Appendix D. The DSM initiatives were developed and implemented with full operational equipment control. The efficiency and effectiveness of the DSM initiative therefore relied on the functioning of the equipment used to achieve the electrical cost savings.

4.2.2 System operational overview

In order to quantify the effect of the existing DSM initiatives, one should clearly define the existing system and its operational parameters [27]. The following section provides background on the existing system operations. Figure 4-1 illustrates the refrigeration system of Mine B, which can be used as a reference for the discussion below.

Water is pumped at 27°C from the underground dewatering system to the surface hot dam. Typically, 27 Ml water is pumped per day during daily summer mining operations. Hot water is cooled by passing it through the precooling towers into the sumps where the water is stored at an average temperature of 24°C.

The precooled water is then pumped through two parallel-series refrigeration machines sets, each with a lead-lag configuration to produce chilled water at 5°C. The total refrigeration system has an installed cooling capacity of approximately 42 MW. The surface refrigeration system, however, is the largest contributor towards the capacity.



LEGEND			
	PLC		Hot water
	Automatic actuated valve		Cooled water
	Manual valve		Chilled water
	Humidity and ambient temperature sensor		Evaporator pumps 4 x 90 kW
	Temperature sensor		Condenser pumps 5 x 185 kW
	Level sensor		BAC return pumps 2 x 75 kW
	Variable speed drive		Precooling pumps 2 x 75 kW
	Cooling tower		Level control
	Refrigeration machine/Fridge plant		Delta temperature control
	Power meter		Enthalpy control
	Running/Operational		Eight-core communication cable
	Broken/Faulty/Not running		Four-core communication cable
	Communication infrastructure		Infrastructure connection
			Refrigeration plant infrastructure

Figure 4-1: Mine B refrigeration system process and instrumentation diagram

The chilled water typically enters the BACs at 3°C, which results in a designed BAC air outlet temperature of 7°C wet bulb. After the air is cooled, the BAC outlet water, which is at 14°C, is pumped and stored in the precooling sump.

Similarly, the surface chill dam feeds chilled water to the underground chill dam situated on Level 29 (29 L). The resulting gravity-fed pressure coupled with auto-compression of the chilled water mean that the water can be passed through a Pelton turbine first to generate electricity before entering the 29 L chill dam.

A Pelton turbine for electricity recovery is used throughout the mine on various levels such as 52 L, 71 L and 92 L. The chilled water is consequently passed through these Pelton turbines and collected in the associated chill dams; however, 71 L is considered as the main underground distribution level.

The waste water, which is at 27°C, is collected and stored in dewatering dams situated on levels 115 L, 100 L, 75 L, 71 L, 52 L and finally 29 L before it is pumped to surface. The refrigeration system's operation is thus a continuous process and the sequence is reinitiated once the water reaches the surface hot dam.

Original control summary

The variable flow DSM initiatives at Mine B had been active for two years before being completely decommissioned at the end of 2012. The initial control philosophies of the associated DSM initiatives are explained below with some photographs to aid in the system definition. It is absolutely crucial in the analysis and synthesis of a performance strategy to state and understand the initial control conditions [32].

Evaporator flow control loop

The evaporator pumps were controlled with VSDs to ensure a constant chilled water dam level of 95%. All back-pass and throttling valves were set to fully open for the control to be used thoroughly.

Three VSDs were installed on the four evaporator pumps, leaving one pump to operate under maximum flow operating conditions. Figure 4-2 illustrates the four evaporator pumps installed at Mine B. Notice the discharge line valves are set to fully open and not throttled.



Figure 4-2: Evaporator pumps

Figure 4-3 illustrates the thermal storage dam where chilled water is stored after passing through the refrigeration machines.



Figure 4-3: Chill dam (surface)

Figure 4-4 illustrates one evaporator VSD (left) and one condenser VSD (right) installed at Mine B. The VSDs are supplied with three-phase power situated in the feeder house next to the refrigeration warehouse. The VSDs are connected to the different control loops as illustrated by Figure 4-1.



Figure 4-4: Evaporator VSD and condenser VSD

Condenser flow control loop

Condenser pumps were controlled to enable a constant temperature rise of 5°C across the condenser side of the refrigeration machines. All throttling valves were set to fully open as explained in Chapter 2.2.2. VSDs were installed on three of the five condenser pumps due to initial project capital constraints. Figure 4-5 illustrates the condenser pumps operating at Mine B.



Figure 4-5: Condenser pumps

The four condenser cooling towers are illustrated by Figure 4-6. During the initial project investigation it was found that the condenser cooling towers had sufficient cooling capabilities and acceptable efficiencies due to regular maintenance and corrective measures.



Figure 4-6: Condenser cooling towers

Figure 4-7 illustrates the thermocouples installed on the condenser water pipes at Mine B. The inlet and outlet water temperatures are measured to determine the temperature rise.



Figure 4-7: Condenser water thermocouple

BAC flow control loop

The BAC return pumps were controlled to maintain a constant BAC outlet air temperature by using a Testo weather station which determined the ambient enthalpy. The control occurred on a linear basis to modulate the flow rate of the pumps to achieve the outlet air temperature set point of 7°C wet bulb. Figure 4-8 illustrates the BAC return pumps and Figure 4-9 the BACs operating at Mine B.



Figure 4-8: BAC return pumps



Figure 4-9: BACs with BAC sumps

Note that only two VSDs were installed in the BAC feeder substation due to budget constraints. The two VSDs were incorporated to control two of the three return pumps to maintain a BAC sump level of 95%. Figure 4-10 illustrates the BAC return pump VSDs, and the Testo weather station that was subsequently used to determine the ambient enthalpy.



Figure 4-10: BAC return pump VSDs and Testo weather station

Figure 4-11 illustrates the original control valves used to control the gravity-fed BAC supply water proportionally, according to the linear enthalpy, as determined by the Testo weather station.



Figure 4-11: BAC water supply control valves

Precooling flow control loop

During the initial project investigation it was found that the precooling towers were irreparably damaged and would not contribute sufficient cooling towards the refrigeration system. Figure 4-12 illustrates the original precooling towers, which employed one fan per cooling set with a total of six fan sets.



Figure 4-12: Previous precooling towers

The mine opted to replace the original precooling towers with new more efficient towers. The towers, as illustrated by Figure 4-13, incorporated more fans per cooling unit and also relied on the larger fill structures for enhanced heat transfer capabilities. The improved design incorporated four small fans as opposed to one large fan per cooling unit.



Figure 4-13: New precooling towers

Refrigeration machines

Figure 4-14 illustrates the refrigeration machine layout found at Mine B. The two parallel-series sets of refrigeration machines are visible in a straight line. The orientation of the machines was specifically designed to have the lead refrigeration machines in the centre with the lag machines situated on the outside. As a result, the operators could quickly shut down the lead machines by closing off the supply valves in the case of an emergency.



Figure 4-14: Refrigeration machine layout

Figure 4-15 illustrates one of the four centrifugal refrigeration machines found at Mine B.



Figure 4-15: Refrigeration machine no. 2

Figure 4-16 illustrates the electric actuator used to control the guide vanes on the refrigeration machine as well as a thermocouple to measure the evaporator water temperature.



Figure 4-16: Electric actuator and thermocouple

Figure 4-17 illustrates valves that have previously been used to manually throttle the flow rate near design conditions. These valves were pointless once the DSM initiatives were implemented, which required the valves to be fully opened during all operating times.



Figure 4-17: Throttling valves

EMS

The original EMS developed for the DSM initiatives incorporated a twin server design as shown by Figure 4-18. The EMS was uploaded on a primary server with a secondary server to serve as a backup, while adding data rigidity to the system. The DSM initiatives on the refrigeration system were therefore controlled by the EMS through the OLE connection with the SCADA system and subsequent PLCs and individual components. Figure 4-19 illustrates the graphical user interface of the EMS.



Figure 4-18: EMS infrastructure



Figure 4-19: EMS graphical user interface

The server rack was installed in a specially designed server room with a unique temperature control to ensure optimum operating conditions. Access to the server room was also controlled precisely to minimise infrastructure losses or cases of vandalism. The graphical user interface, however, was installed at the main control room to indicate the control parameters to the operators and enable ESCO and trained mine personnel to make operational adjustments in case of system changes or emergencies.

It is apparent from the sections above that the initial DSM initiatives and control philosophies employed were inflexible, especially when system alterations were introduced. The versatility of the system coupled with the few operational constraints therefore resulted in a system that could not function properly during operations.

In order to quantify the full effect of the performance strategy implementation, the existing DSM initiatives control are summarised. The most significant alterations are briefly discussed to provide background and thorough knowledge in the existing system definition.

4.2.3 Existing DSM initiatives control summary

According to Groenewald, it is imperative to understand and define the current system operations to make any alterations for system improvement [27]. The developed performance strategy includes a detailed root cause analysis; however, for the purpose of this study, only the most significant alterations are shown and the causes briefly discussed. Table 4-1 illustrates the current control limits employed at Mine B.

Table 4-1: Existing DSM initiatives control summary

Type of control	Baseline	Units
Evaporator flow control loop		
VSD lower limit	43	Hz
VSD upper limit	46	Hz
Condenser flow control loop		
VSD lower limit	50	Hz
VSD upper limit	50	Hz
BAC flow control loop		
VSD lower limit	48	Hz
VSD upper limit	50	Hz

The following discussion is based on a detailed root cause analysis completed on the refrigeration system at Mine B. Table 4-1 and Figure 4-1 can be used as reference material for the underlying discussion.

Evaporator flow control loop

The analysis of the evaporator control loop revealed that only one VSD, which received the control limits presented by Table 4-1, was operational. The other two VSDs were disabled and the two VSD-enabled pumps were running under full-load or maximum speed conditions as a result.

The mine personnel thus reverted to the old practice of throttling valves, which is inefficient and ineffective, to ensure near design flow conditions. The VSD installed on Pump No. 4 was temporarily disabled to receive maintenance while the other VSD installed on Pump No. 2 was broken due to irregular feeder power spikes experienced by the VSD power supply.

Condenser flow control loop

It was found that the first VSD was operational, the second VSD was in maintenance mode, and the last VSD was broken as was the case with the evaporator flow control loop. The VSD installed on Pump No. 3 was broken due to irregular maintenance and a faulty voltage transformer that created a high voltage power surge, overloading the VSD internal electronic board.

The VSD installed on Pump No. 1 was disabled by mine personnel and put in maintenance mode after they experienced frequent refrigeration machine trips. The root cause of the trips can be attributed to the control limits as illustrated by Table 4-1. The start-up conditions led to low condenser flow rates, which in turn resulted in the machines tripping at initial full-load conditions as discussed in Chapter 3.2.3.

BAC flow control loop

Analysing the BAC flow control loop revealed that the VSD installed on Pump No. 1 was operational while the VSD installed at Pump No. 2 was disabled and left in maintenance mode. The root cause of disabling the VSD installed on Pump No. 2 can be attributed to the BAC return Pump No. 2, which was removed for regular maintenance. The pump required new bearings due to bearing brinelling that occurred as a result of poor shaft alignment.

Figure 4-20 illustrates the existing BAC return pumps installed at the Mine B. Note that Pump No. 2 is unavailable as discussed in the previous section.



Figure 4-20: Existing BAC return pumps

After the existing DSM initiatives implemented on the mine refrigeration system have been defined, the next step in the performance strategy would be to determine the feasibility of the proposed solution through a detailed simulation. The feasibility of improving existing DSM initiatives on the refrigeration system of Mine B for sustainable performance is therefore investigated in the next section.

4.2.4 Feasibility of improving DSM initiatives

As part of the performance strategy implementation, a simulation model was developed for Mine B (Appendix E). The simulation model was constructed with the aid of the verified simulation software PTB as discussed in Chapter 3.4.2. The simulation incorporates historical data from the mine's SCADA system. The data includes the original baseline period and latest system operations from the point that the system started to underperform and deteriorate.

The optimised simulation revealed that an electricity reduction of 1.8 MW could be achieved during the course of a typical mining weekday. Furthermore, a reduction of 6.5 MW during peak electricity tariff times was predicted. This would have a simulated electrical cost savings of R12 428 461 per annum with a winter saving of R4 901 496 and a summer saving

of R7 526 965. Figure 4-21 illustrates the simulated power profile and Figure 4-22 the chill dam temperatures after implementation.

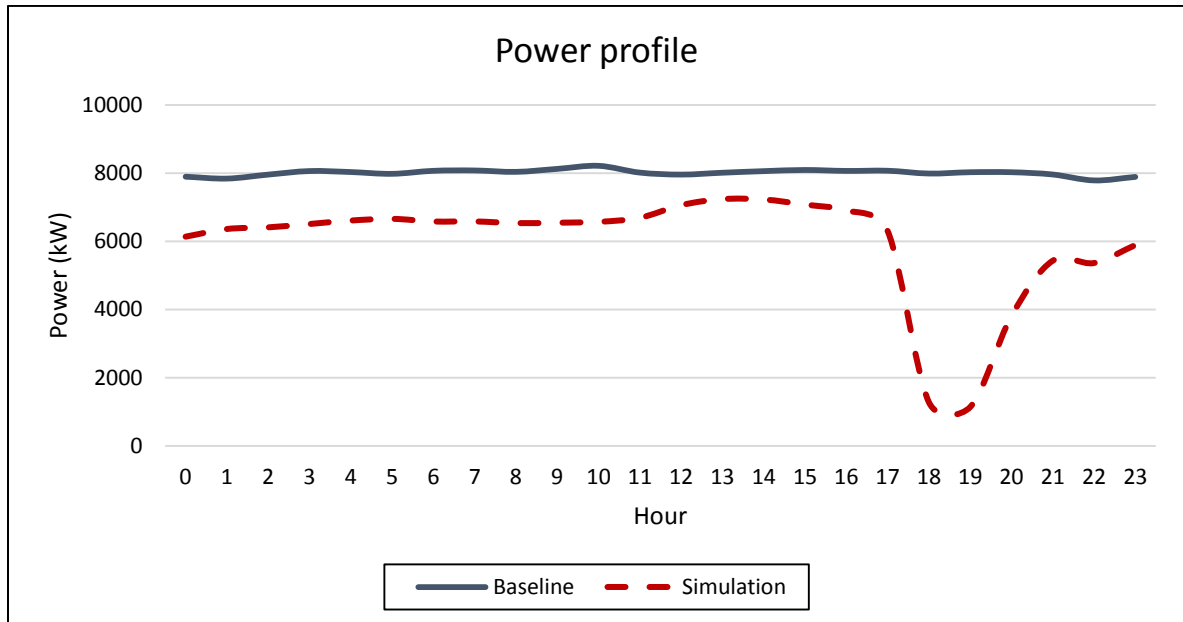


Figure 4-21: Simulated performance strategy power profile

Note the simulation is limited to the existing DSM initiatives employed on the refrigeration system of Mine B. The projected monetary electrical cost savings are therefore conservative and do not include added savings attributed to VSD repairs in the existing system.

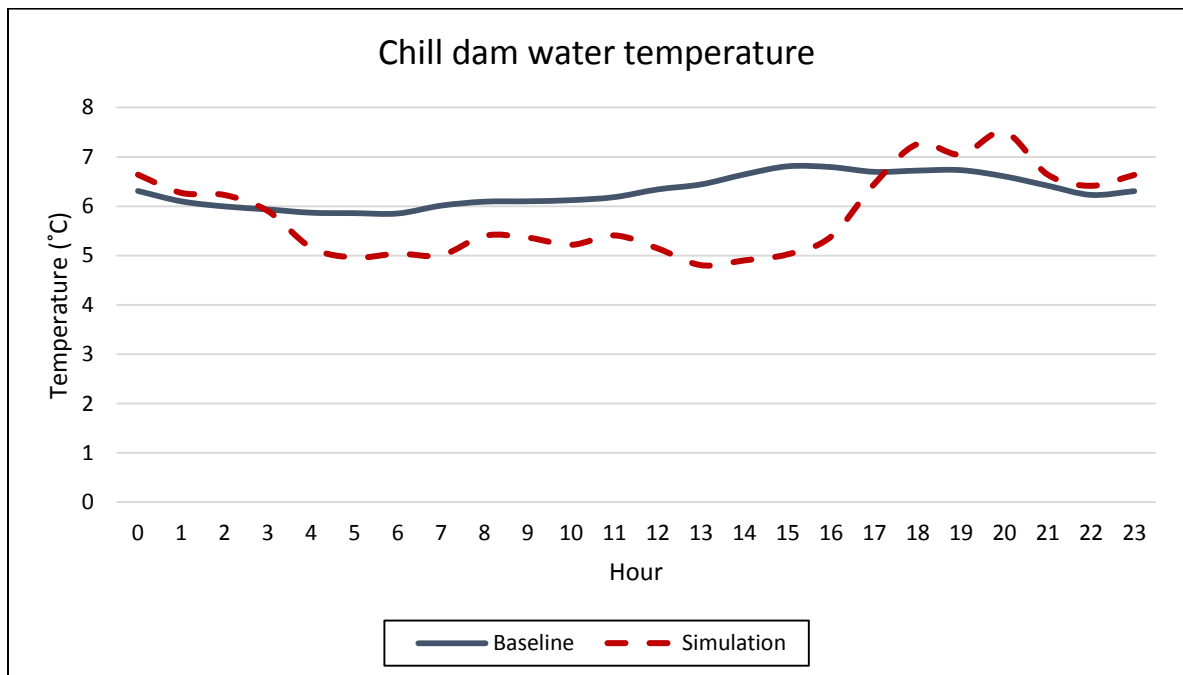


Figure 4-22: Simulated performance strategy chill dam water temperature

Figure 4-23 demonstrates the chilled water flow for underground mining use on Mine B.

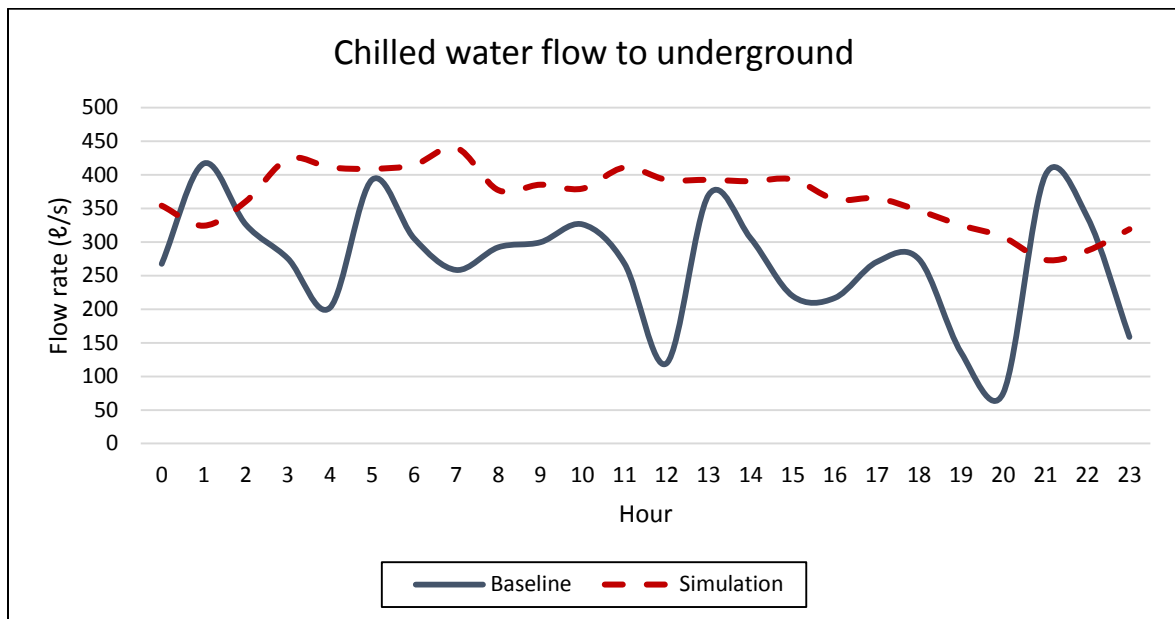


Figure 4-23: Simulated performance strategy chilled water flow

From these figures it is apparent that the performance strategy should improve the existing DSM initiatives on the refrigeration system for sustainable performance. The simulated system exhibits stable conditions to achieve immense electrical cost savings without affecting the production and safety of the mine adversely.

According to the performance strategy developed in Chapter 3.3.2, it is imperative to test the real-world application of the proposed strategy before long-term implementation can commence for sustainable operations. The following section describes the most significant alterations made to improve the existing DSM initiatives on the refrigeration system for sustainable performance.

Performance verification

As part of the performance strategy, the analysis of the existing DSM initiatives control summary defined in Section 4.2.3 was addressed to enable full PID control. The mine's SCADA system was updated and the proposed control philosophy attained from the simulation inserted as the main operational control strategy. The mine, however, requested that the alterations and repairs be made with replacement parts and labour at hand. Furthermore, the proposed alterations should not interfere with normal mining operations and safety.

As a result of the mine's request, the condenser and evaporator VSDs, which were set in maintenance mode, were reconfigured and full PID control established. However, the three broken VSDs were not repaired due to the budget constraints that resulted in one faulty VSD in each control loop.

In order to quantify the tangible effects of the proposed performance strategy, actual verification tests commenced over a typical mining period of one week after implementation. All historical data was incorporated to establish system operational baselines as discussed in the previous sections. Table 4-2 illustrates the most significant alterations implemented during the testing period.

Table 4-2: Improved performance strategy simulation control inputs

Type of control	Baseline	Performance strategy	Units
Evaporator flow control loop			
VSD lower limit	43	36	Hz
VSD upper limit	46	42	Hz
Condenser flow control loop			
VSD lower limit	50	37	Hz
VSD upper limit	50	50	Hz
BAC flow control loop			
VSD lower limit	48	37	Hz
VSD upper limit	50	45	Hz

Note that all VSD lower limits were altered to values below the initial project implementation. The detailed system and operational analysis revealed that frequent overcooling occurred in the system, leaving scope for operations to commence at part-load conditions, subsequently leading to lower frequency limits. The OEM specifications and design parameter specifications were considered before any alterations were made to the existing operations.

Figure 4-24 illustrates the actual power profile realised during the testing period. It is clear that the actual power profile portrays the same profile of that achieved through the simulation. The difference between the actual and simulation model can be attributed to small operational or input changes used to formulate the simulation model.

The performance tests conducted over a one-week period resulted in an average electricity reduction of 1.8 MW over the course of a typical mining weekday. If one considers Figure 4-24, it is clear that an unscaled electricity reduction of 6.9 MW was achieved during the peak electricity tariff times. Note that this was achieved by switching off all surface refrigeration machines. The test data proved that sufficient cooling was realised underground, even though the refrigeration machines were switched off.

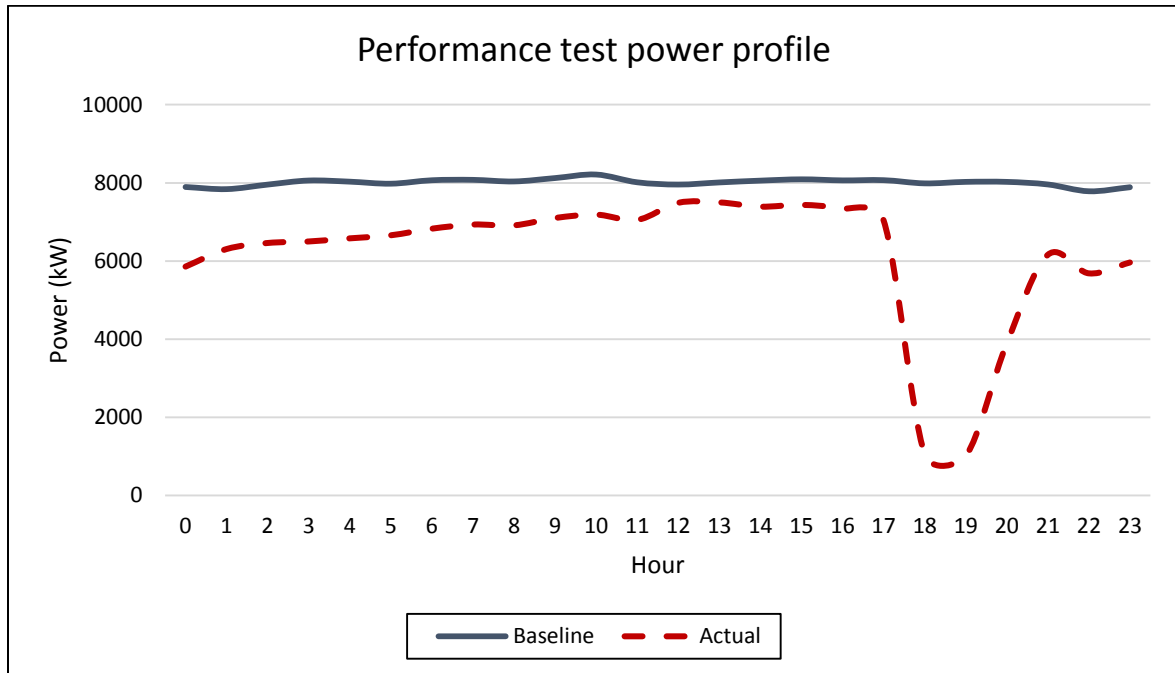


Figure 4-24: Performance test power profile

The recovery period for the entire refrigeration system was shown to be less than three hours from refrigeration start-up. This perfectly coincides with the non-mining period where the fewest mining personnel are present underground during the course of the day. Table 4-3 illustrates the combined effect that the performance strategy had on the existing DSM initiatives for the testing period.

Table 4-3: Mine B performance strategy implementation testing summary

System parameter: Average	Units	Baseline	Actual	Difference
Electric power	kW	8 008.45	6 180.13	22.8%
Chill dam water temperature	°C	6.30	6.77	7.4%
Chilled water flow rate to underground	ℓ/s	240.33	368.59	44.1%

From Table 4-3 it is apparent that the performance strategy did not affect the mining operations adversely. The performance strategy resulted in an electricity reduction of 22.8% with a chill dam water temperature increase of 7.4%. Although the chill dam water temperature experienced an increase during the testing period, the change was still within the specified tolerance limits for mining as expressed by Van der Bijl [72] and Calitz [84].

The performance strategy was therefore implemented on a long-term basis after concluding the performance tests. The assessment of the long-term results is discussed in detail in the following section. The performance strategy's effect on improving existing DSM initiatives on mine refrigeration systems is also encapsulated within the conclusion of the case study on Mine B.

4.3 Achieved electrical cost saving critical analysis

4.3.1 Electrical cost saving overview

In order to quantify the success of the implemented performance strategy, it is necessary to analyse not only the achieved electrical cost savings but also the post-implementation effects on the mining operations and service delivery requirements.

In the preceding sections, the existing DSM initiatives on Mine B were defined fully along with the current operations. Detailed simulation and performance tests furthermore proved the viability of improving the existing DSM initiatives on the refrigeration system to realise an electricity cost saving of 1.8 MW with an associated peak electricity saving of 6.5 MW.

In this chapter, the actual electrical cost savings are determined and discussed in detail. These discussions indicate a measure to determine the effectiveness and viability of the performance strategy to improve existing DSM initiatives on mine refrigeration systems for sustainable performance. Furthermore, the effects on the service delivery requirements are determined and critically analysed. It is imperative that any energy saving interventions do not affect the safety and operations of the mine, and subsequently the mine personnel, adversely [27].

A safety factor was incorporated in the simulation results to leave ample room for operational changes. It was decided that an annual electricity reduction target of 1.5 MW was achievable during the course of a typical mining weekday with a peak-clipping saving target of 5.5 MW after performance strategy implementation.

4.3.2 Performance strategy results analysis

Electrical cost savings

The integrated refrigeration system's electric power consumption after performance strategy implementation is illustrated by Figure 4-25 and Figure 4-26. The power usage was monitored by using the four main feeders supplying the integrated refrigeration system with electricity. The electricity power profile therefore includes the power consumption of the evaporator, BAC and condenser control loops. The discussion is extended by incorporating the nett effects associated with the precooling tower replacement.

The average post-implementation power usage of the refrigeration system is shown by Figure 4-25. During the course of 17 months, an average electricity reduction of 1.62 MW was experienced with a peak-clipping electricity reduction of 6.14 MW. The typical daily average electricity reduction amounts to 21.46% when compared with the scaled baseline.

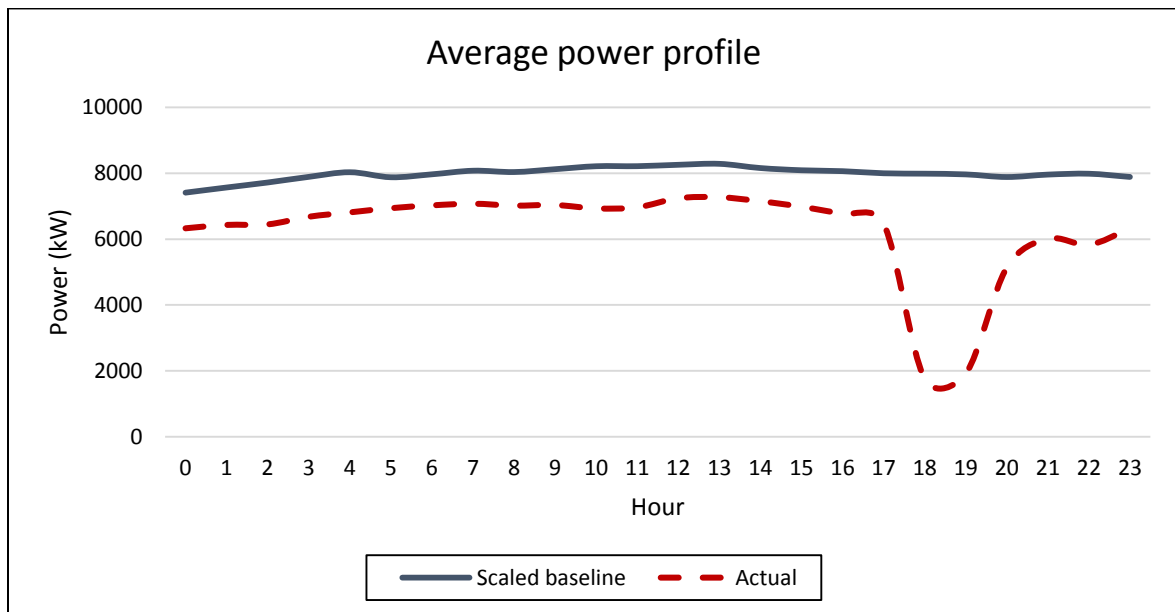


Figure 4-25: Post-implementation average power consumption of refrigeration system

From Figure 4-25 it is clear that a full-load offset is present that can be attributed to the new efficient precooling towers coupled with the evaporator and condenser control loops. The BAC control loop also contributes towards the electricity reduction but to a lesser extent due to the small associated pump capacities.

The evaporator and condenser control loops were used to achieve an electricity reduction by including and operating VSDs. As discussed in Chapter 2.3.2, using water optimally through the VSDs requires that all valves, which were previously used to throttle the water near design conditions, be fully opened.

As a result of using water optimally, a reduction in water flow and subsequently cooling requirements were experienced. The refrigeration machines were therefore used to supply sufficient chilled water to feed the BACs. Additionally, it was redundant to recirculate chilled water to the precooling dam using a back-pass valve to achieve lower inlet temperatures.

The new precooling towers resulted in constant precooling dam water temperatures, lowering the system's cooling requirements. In effect, this reduced the amount of water recirculating in the system, therefore contributing towards the electricity reduction experienced over the course of a typical mining weekday.

In order to evaluate the full effect of the performance strategy, the power usage was analysed separately. This is a result of the varying seasonal operational requirements that need to be accounted for. Figure 4-26 illustrates the average weekday power usage of the refrigeration system experienced during the winter months.

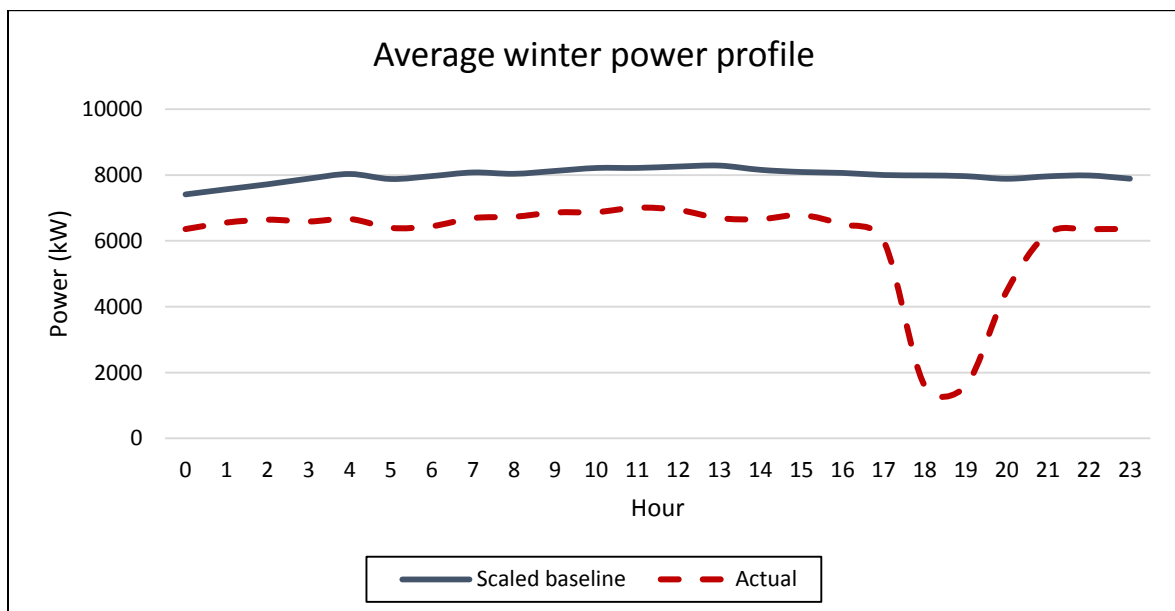


Figure 4-26: Average power consumption of refrigeration system for winter months

Figure 4-27 illustrates the average weekday power usage of the integrated refrigeration system experienced during the summer months.

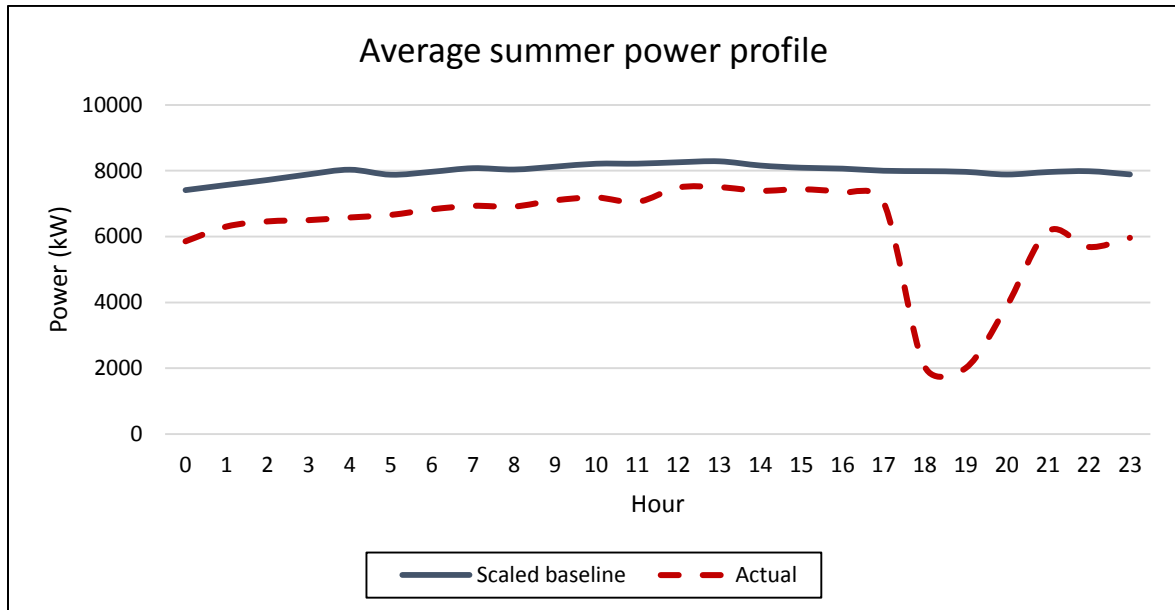


Figure 4-27: Average power consumption of refrigeration system for summer months

From Figure 4-26 it is clear that during the 17-month post-implementation period, an average winter electricity reduction of 1.72 MW was achieved during typical mining weekdays, with a peak-clipping saving of 6.37 MW. The typical summer electricity reduction, as displayed by Figure 4-27, amounted to 1.79 MW with a peak-clipping reduction of 5.94 MW.

It is evident that the electricity reduction remained relatively constant for winter and summer months with the changes attributed to other operational factors (as discussed in Chapter 2.6.3). If one considers the agreed project electricity reduction targets as described in Section 4.3.1, it is apparent that the electricity reduction was far more than the set targets. Hence, the project overperforms on a sustainable basis with the project still in operation at the time that the study was completed. Table 4-4 illustrates the results obtained after implementation commenced.

Table 4-4: Performance strategy results summary

System parameter:	Units	Baseline	Actual	Difference
Average daily power consumption	kW	7 985.23	6 271.65	21.5%

Service delivery

In order to quantify the full effects of the developed performance strategy, one should consider not only the integrated power usage but also the effect on the mine's safety and production through comparable system parameters. Thus, it is extremely important to measure and verify the crucial system parameters before and after implementation to draw a definite conclusion.

The three main factors affecting productivity and safety of mining operations are chill dam water temperature, chilled water flow to underground, and finally the BAC air outlet temperature. Any changes to these parameters should benefit the system, otherwise mining personnel will disable the performance strategy and associated DSM initiatives improvements.

Note that the underground comparable system parameters are also illustrated in the discussions that follow to provide a comprehensive analysis of the service delivery requirements of the mine.

Water operational analysis

The effects of the performance strategy implementation on the water service delivery are illustrated from Figure 4-28 to Figure 4-31. Only comparable boundary system parameters were used pre- and post-implementation. Figure 4-28 illustrates the average daily chilled water temperature and total volume flow sent underground for Mine B.

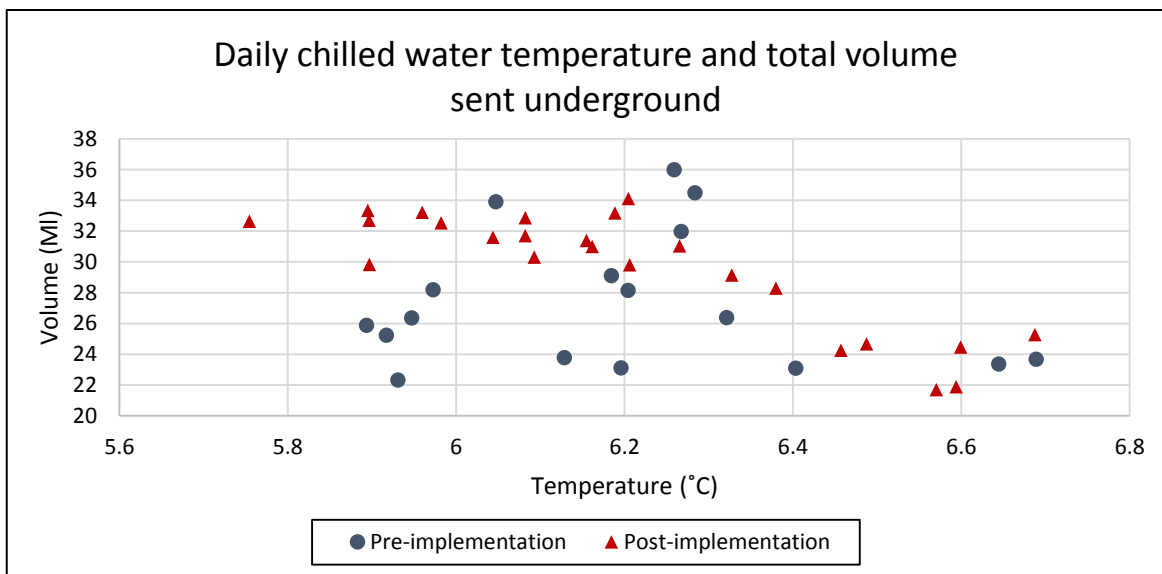


Figure 4-28: Average daily chilled water temperature and tot. volume sent underground

From Figure 4-28 it is clear that the average daily temperature of the chill dam water temperature varied between 5.8°C and 6.8°C pre-implementation with a design point of 6.0°C. Furthermore, the total volume of daily chilled water sent underground varied between 22 MI and 36 MI with a design point of 29 MI. The upper limit of the chill dam water temperature and lower limit of the volume of chilled water sent underground can thus serve as the crucial system parameters in which service delivery must occur.

Figure 4-28 illustrates that the chill dam water temperature post-implementation was maintained within the service delivery limits, with an average of 6.2°C. This negligible temperature increase can be attributed to the reduced evaporator flow rates and subsequent BAC water usage. However, it is apparent that the compressor guide vane control performed as expected – realising the near design outlet conditions with variable flow conditions.

The total daily volume of chilled water, as shown by Figure 4-28, illustrates that the post-implementation volume was maintained above the service delivery requirements, with an average of 29.63 MI. The reduced evaporator flow and BAC water usage did not affect the water supply and mining operations adversely.

Figure 4-29 illustrates the pre- and post-implementation chill dam water temperatures of the surface and underground chill dams.

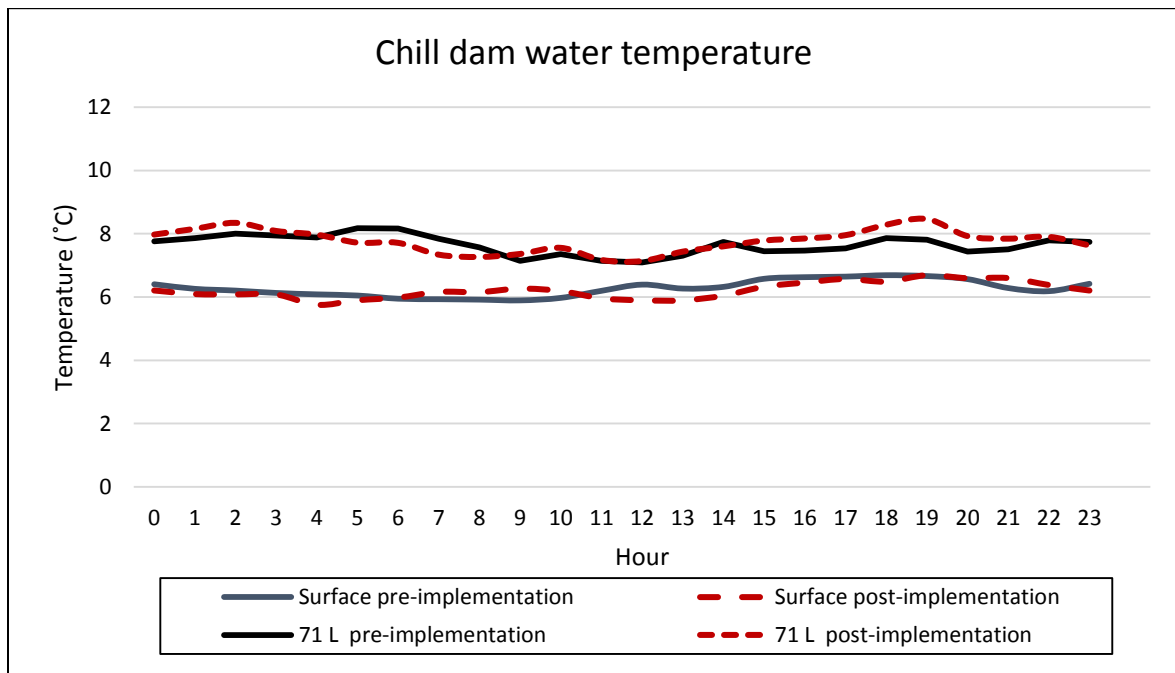


Figure 4-29: Average daily surface and underground chill dam water temperatures

It is apparent from Figure 4-29 that the chill dam water temperatures were maintained within the accepted operational requirements of the mine's service delivery. If one considers the surface post-implementation chill dam temperature, a slight temperature increase during the peak electricity times is visible, which is attributed to the large volume of water required to remain in the dam for longer periods of time.

Figure 4-30 illustrates the average daily chill dam water level before and after implementation.

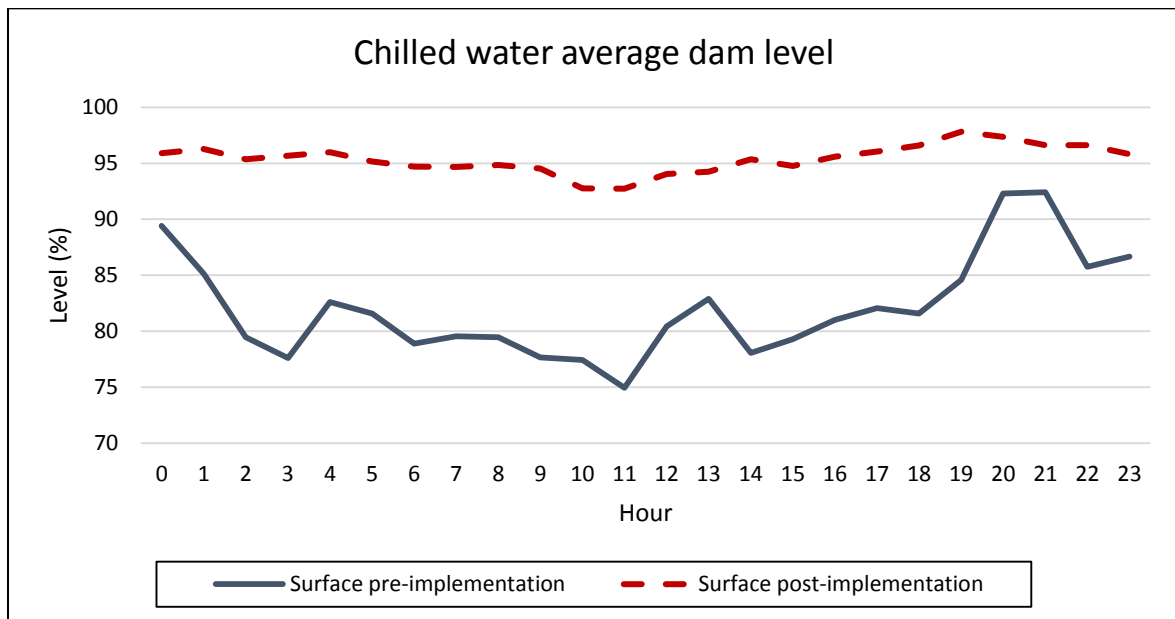


Figure 4-30: Average daily chill dam water level

It is apparent from Figure 4-30 that the daily average chill dam water level improved significantly with less erratic pumping periods. The pre-implementation average dam level was found to be 81.90% with the post-implementation average dam level being 95.37%. Additionally, the post-implementation profile was matched more accurately to the underground demand, which resulted in an increased availability of chilled water, thus improving the service delivery. Considering the evaporator control loop's average dam level set point of 95% and the actual average dam level achieved of 95.37%, the improvements are clear.

Figure 4-30 gives an indication towards the degree of effective control. Some of the benefits associated with the effective evaporator control loop are the reduction in full-load pump operating conditions and a vast reduction in pump cycling.

The typical average chilled water flow sent underground is illustrated in Figure 4-31.

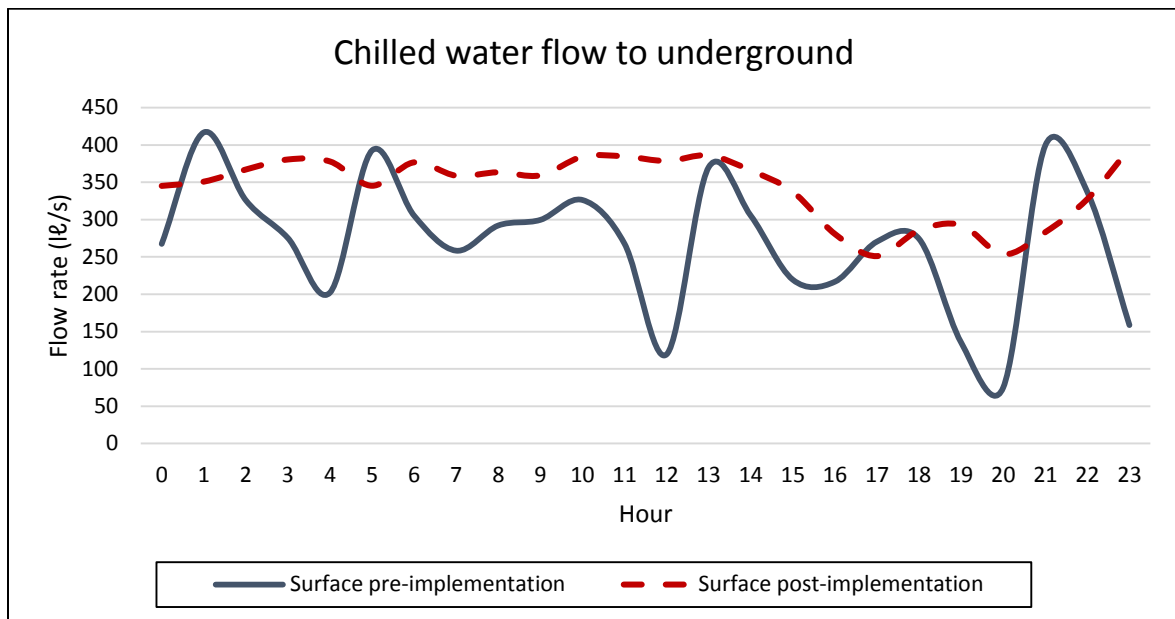


Figure 4-31: Average daily chilled water flow to underground

Considering Figure 4-31, it can be seen that there was no set schedule associated with the underground chilled water flow. Furthermore, the chilled water flow rates changed dramatically and intermittently to satisfy the underground demand. The erratic underground water demand behaviour can be attributed to various thermal storage dams that feed the different underground working areas without any control or scheduling whatsoever. As a result, underground thermal storage dams often required an immense amount of chilled water to replenish the dam level in a short amount of time.

From Figure 4-31 it can be seen that there are two distinctly identifiable trends of surface chilled water pre- and post-implementation. Firstly, the peak chilled water supply flow rates were roughly reduced by 15%. Secondly, the chilled water flow to underground post-implementation illustrates a more stable profile. The reduced flow and well-balanced supply will therefore permit long-term beneficial effects such as improved underground valve control, less frictional losses and improved performance of underground turbines [53].

It is reasonable to conclude that service delivery of chilled water was not affected adversely after implementation. The chill dam water temperature and chilled water flow demand were therefore operating within the acceptable limits. In the following section, a ventilation operational analysis is done to determine the effect of the implementation on the BAC air outlet temperature.

Ventilation operational analysis

The effects of the performance strategy implementation on the ventilation service delivery are illustrated from Figure 4-32 to Figure 4-34. Only comparable boundary system parameters were used in the discussions. It is customary to incorporate the BAC air outlet temperature as the main system parameter in which the effects on ventilation are measured. However, Mine B does not have a temperature or humidity sensor installed on the BAC outlet. Thus, there were no sufficient BAC air outlet temperature or flow data available to be incorporated as baselines.

Upon the mine's recommendation, the historical data of two underground BACs on 102 L situated along the East and West split was incorporated in the analysis. The inlet water flow and temperature conditions were monitored on both BACs. The BACs are situated in one of the mining levels where a wet-bulb area temperature of 27.5°C must not be exceeded [46]. The mine officials reported that the historical data collected ensured sufficient cooling to achieve the designed BAC air outlet temperatures, which comply with mining legislation.

Figure 4-32 illustrates the surface BAC inlet and outlet water conditions before and after implementing the performance strategy.

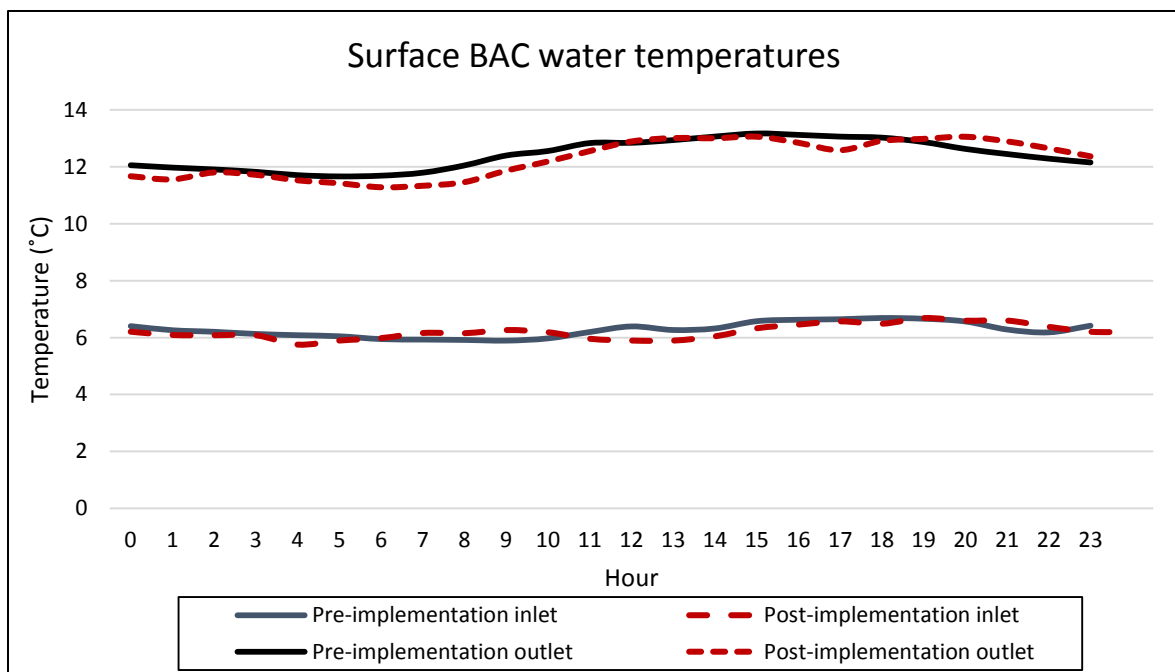


Figure 4-32: Average daily BAC water inlet and outlet temperatures

It was found that the implementation had no adverse effects on the surface BAC water temperatures. If one considers Figure 4-32, it is clear that the pre- and post-implementation inlet water differences of 1.09% and the outlet water difference of 1.15% are negligible. The reduction in surface BAC water flow did not have any significant influence on the cooling capacity of Mine B. The BAC flow control loop is therefore justified.

Figure 4-33 illustrates the inlet water flow and temperature conditions of the BAC situated on 102 L along the East split.

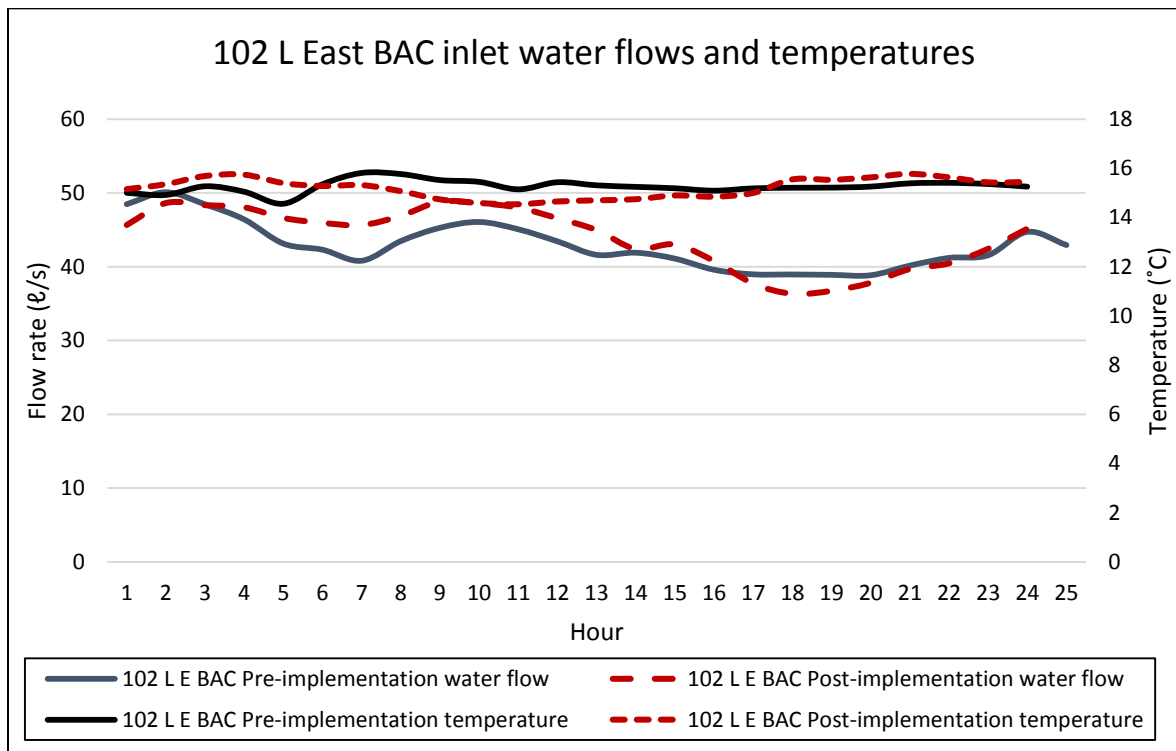


Figure 4-33: Average daily 102 L East BAC inlet conditions

Figure 4-33 illustrates that there were no significant changes to the data points pre- and post-implementation. Furthermore, the average water flow difference of 2.40% and the average inlet water temperature difference of 0.46% are seen as dismissible. The general profiles pre- and post-implementation are also extremely similar with recognisable peaks and declines. The slight increase in average water flow rates can be attributed to various operational parameters that fluctuate according to seasonal changes.

From Figure 4-32 and Figure 4-33 it is apparent that implementing the performance strategy had no effect on service delivery. However, to complete the analysis, the West split BAC

situated on 102 L must be included. Figure 4-34 illustrates the inlet water flow and temperature conditions of the BAC situated on 102 L along the West split.

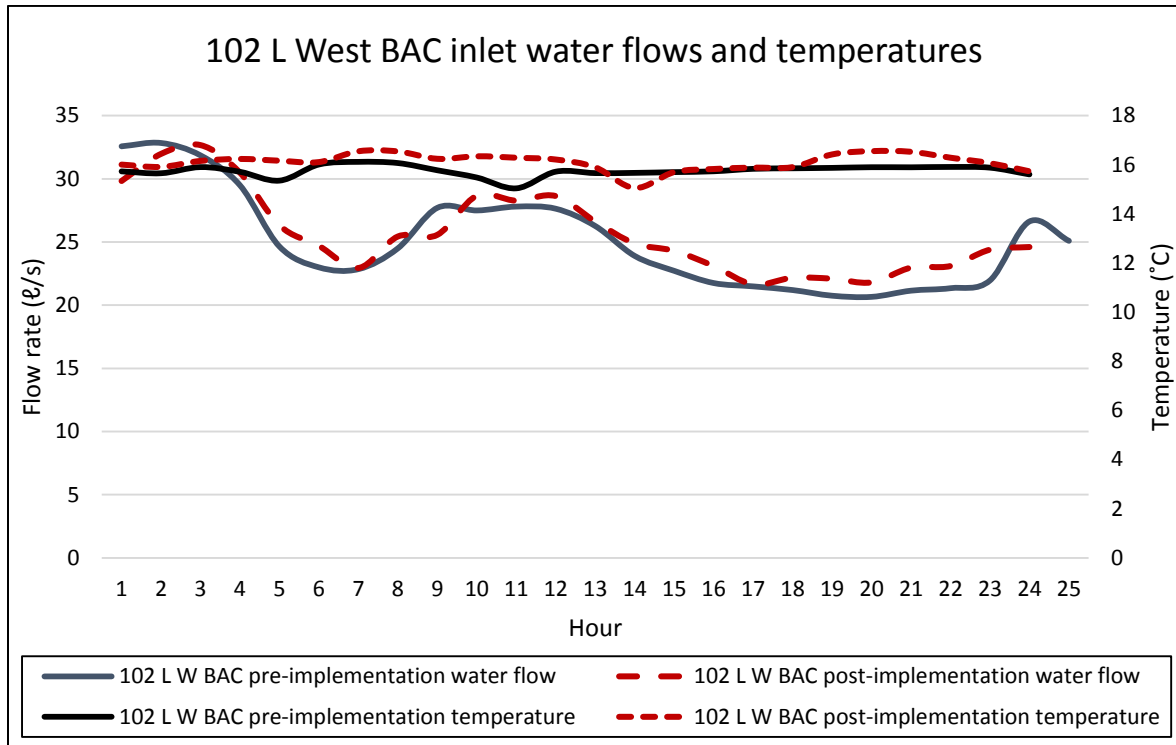


Figure 4-34: Average daily 102 L West BAC inlet conditions

It can be seen in Figure 4-34 that the general profiles of the average BAC water inlet conditions pre-implementation coincide with those experienced post-implementation. The average water temperature difference of 2.25% and average water flow difference of 2.48% are seen as negligible. The minor differences can be attributed to seasonal operational changes as was the case with the East split BAC.

As far as the in-depth analysis into the BAC crucial system parameters is concerned, one can conclude that the BAC outlet temperature remained relatively constant before and after implementing the performance strategy. By considering Figure 4-32 to Figure 4-34, it is clear that both the surface and underground BACs were not affected adversely after implementation.

It is reasonable to conclude that the BAC outlet air temperatures remained constant, contributing towards an environment conducive to safe and productive mining. The performance strategy therefore had no apparent effect on the ventilation requirements of Mine B. The service delivery requirements of Mine B were satisfied for both water and

ventilation operational requirements. The section below illustrates a summary of the key findings revealed by the in-depth analysis on the effects of the implementation.

Service delivery summary

The crucial boundary system parameters before and after implementing the performance strategy are illustrated by Table 4-5.

Table 4-5: Post-implementation effects on the service delivery of Mine B

System parameter (average)	Units	Before (pre)	After (post)	Difference
Chill dam water temp.	°C	6.28	6.20	1.2%
Chill dam water level	%	81.92	95.38	16.4%
Chilled water demand	MI/day	29.12	29.63	1.8%
71 L Chill dam water temp.	°C	7.65	7.77	- 1.6%
Surface BAC inlet water temp.	°C	6.28	6.20	1.2%
Surface BAC outlet water temp.	°C	12.42	12.28	1.1%
102 L East BAC inlet water temp.	°C	15.27	15.20	0.5%
102 L West BAC inlet water temp.	°C	15.76	16.11	- 2.2%
102 L East BAC inlet water flow	ℓ/s	42.94	43.96	2.4%
102 L West BAC inlet water flow	ℓ/s	25.09	25.72	2.5%

Table 4-5 displays a summary of the cumulative effects on the integrated refrigeration system of Mine B after performance strategy implementation. It is apparent that the crucial system parameters remained relatively constant with negligible differences ascribed to seasonal operational changes. However, although the chill dam water temperature and chilled water demand remained relatively unaffected, the water availability increased dramatically as a result of the evaporator flow control loop.

One can conclude that the crucial boundary system parameters of Mine B's refrigeration system were maintained within the acceptable operational limits after implementation. It was shown that the implementation of such a strategy is thus viable without affecting service delivery requirements adversely. The performance strategy can therefore serve as a solution for underperforming projects.

4.4 System performance validation

4.4.1 System performance validation foreword

It was found in the preceding section that implementing the performance strategy resulted in significant electrical cost savings without affecting the service delivery of the mine's refrigeration system adversely. However, it was important to not only analyse the service delivery but also the effects of the performance strategy on the overall system performance. It would therefore be futile if the service delivery requirements were adhered to and significant electrical cost savings were achieved, but the system operational life cycle and efficiency decreased.

In order to evaluate the system's performance, a detailed control analysis had to be completed, including the most significant considerations and crucial system parameters as discussed in Chapter 2 and Chapter 3. As a result, the comprehensive analysis provided a final indication towards the success of improving existing DSM initiatives on mine refrigeration systems for sustainable performance.

4.4.2 Performance strategy control analysis

The proposed control developed by implementing the performance strategy, as discussed in Chapter 3.3.2 and Section 4.2, will be analysed. Furthermore, if the control operates differently than intended, the system's service delivery and sustainable electrical cost saving capabilities might be compromised. Since the control is established on real-time values, typical average daily profiles will be used in the analysis to elaborate on the effects on the operational and performance indicators.

Figure 4-35 illustrates the typical average daily profile of the evaporator control loop. The control loop comprises the average combined VSD AC output frequency, actual dam level and dam level set point. If one considers Figure 4-35, it is clear the actual chill dam level was maintained within the specified control limits, with an average chill dam level of 95.40%. The average evaporator pump VSD frequency was modulated between the premeditated lower and upper limits of 36 Hz and 42 Hz respectively. The real-time PID control logic enabled an average VSD frequency of 38.14 Hz.

Another factor to consider in Figure 4-35 is the relationship between the evaporator VSD frequency and chill dam level. These profiles are seen as opposite reaction curves, which are

to be expected of a system that has to maintain a predetermined set point. As a result, when comparing the profiles, it is apparent that the VSD frequency increases as a result of increased underground or BAC water demand in order for the system to maintain a chill dam level of 95%. The time it takes for the VSDs to be modulated in reaction to a higher demand is defined as the “system response” [32].

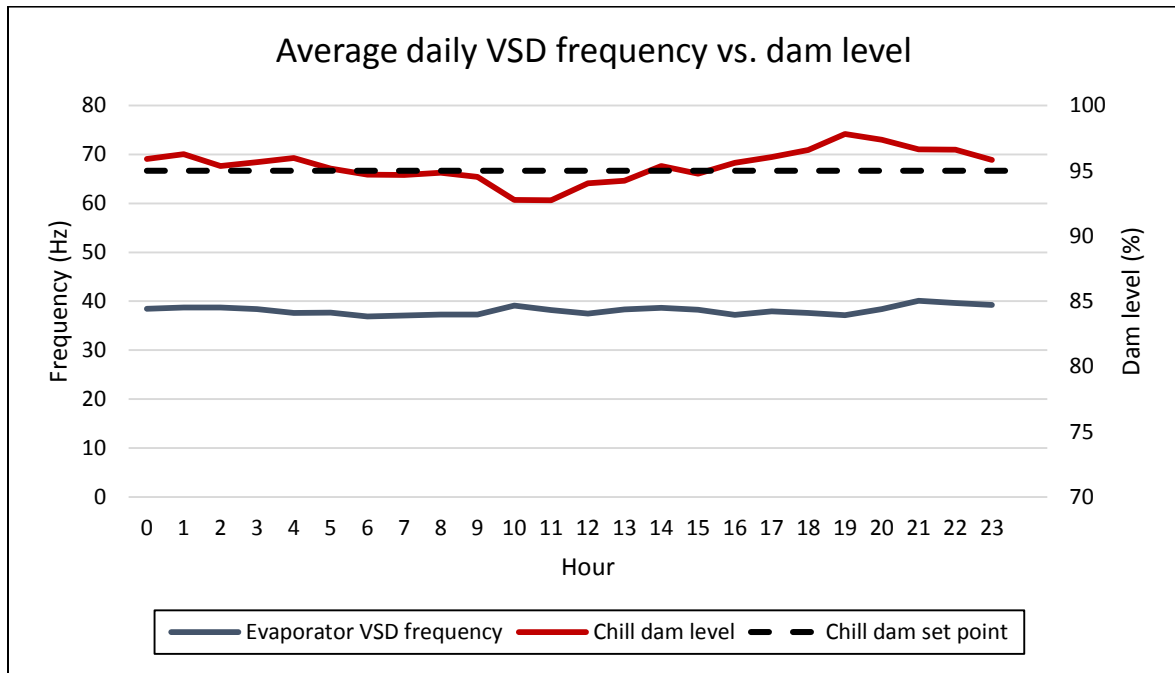


Figure 4-35: Average evaporator VSD frequency as a factor of chill dam level

It can be seen from Figure 4-35 that the average evaporator VSD frequency remained not only within the control limits, but also rarely approached the upper limits of the established control. This confirms the potential of the performance strategy implementation on large industrial refrigeration systems.

Figure 4-36 illustrates the typical average daily profile of the condenser control loop. The control loop includes the combined VSD AC output frequency, condenser temperature rise and delta temperature control set point. It was found that the average combined condenser VSD frequency was maintained between the control limits of 37 Hz and 50 Hz, with an average frequency of 41.54 Hz. The resulting condenser temperature rise was therefore kept between 4°C and 5°C using PID control.

When considering the profile of the condenser temperature rise, two factors are clearly visible. Firstly, the temperature rise across the condenser decreases during the peak

electricity times as a result of shutting down the surface refrigeration machines. The water is left in the dams for longer period of times and the temperature rise decreases with reduced flow rates as described by Saidur *et al.* [78].

Secondly, in contrast to the evaporator control loop, the VSD frequency profile follows the same general curve. If one considers Equation 2-2, it is clear that the temperature rise will increase upon an increase in outlet temperature for a fixed flow rate. Subsequently, the flow rate now compensates through the PID control by increasing the VSD output frequency to maintain a constant temperature rise across the refrigeration machine. Additionally, the opposite occurs when the thermal load of the condenser is decreased.

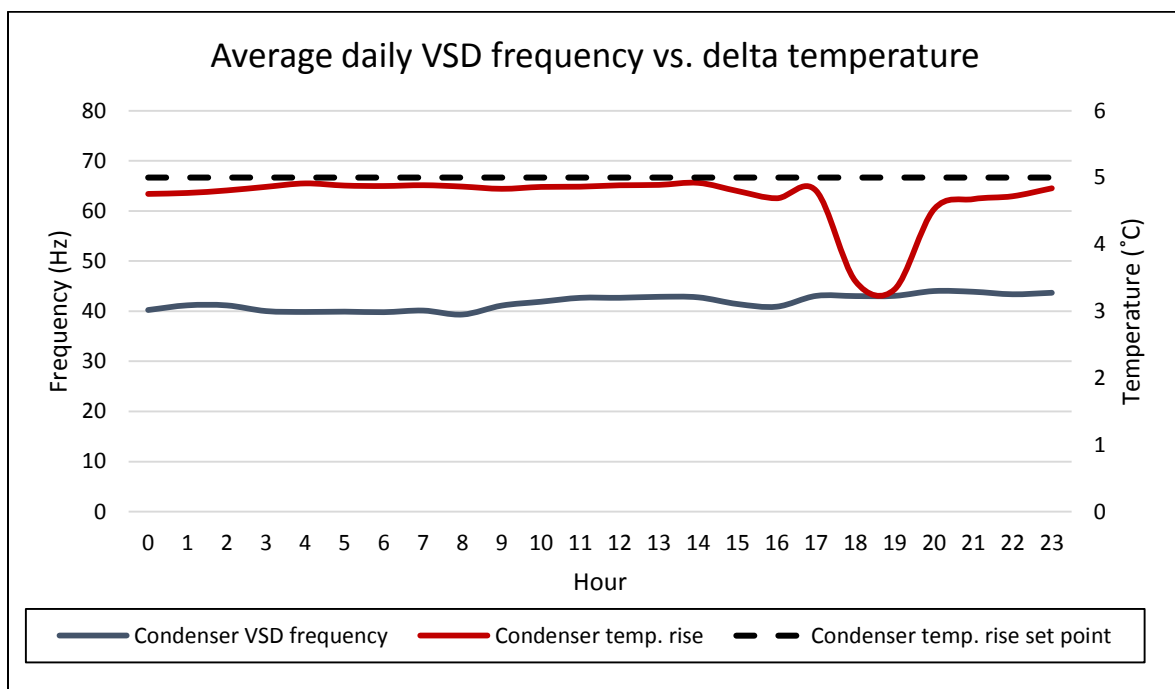


Figure 4-36: Average daily condenser VSD frequency as a factor of temperature rise

The condenser control loop therefore modulated the average condenser VSD AC output frequency to maintain a fixed temperature rise set point of 5°C. It was found that the average condenser rise of 4.7°C was sufficient for the system to operate during typical mining weekdays. Although the temperature rise decreased during the peak electricity times as a result of refrigeration machine shutdowns, it was still within the approved tolerance limits.

Figure 4-37 illustrates the average daily enthalpy and corresponding combined average BAC supply valve position and chilled water flow rate. It was found that the average enthalpy range experienced during the implementation fell within the specified control limits of

20 kJ/kg and 70 kJ/kg. The average ambient enthalpy range of between 40 kJ/kg and 60 kJ/kg was experienced during typical mining weekdays, with an average of 50.69 kJ/kg. From Figure 4-37 it is apparent that the control valves operated as expected, responding proportionally to the ambient enthalpy by varying the valve position to an average open valve position of 32.4%. Additionally, this further elaborates on the forward-loop control response to relative humidity and air temperature changes, defining the ambient enthalpy.

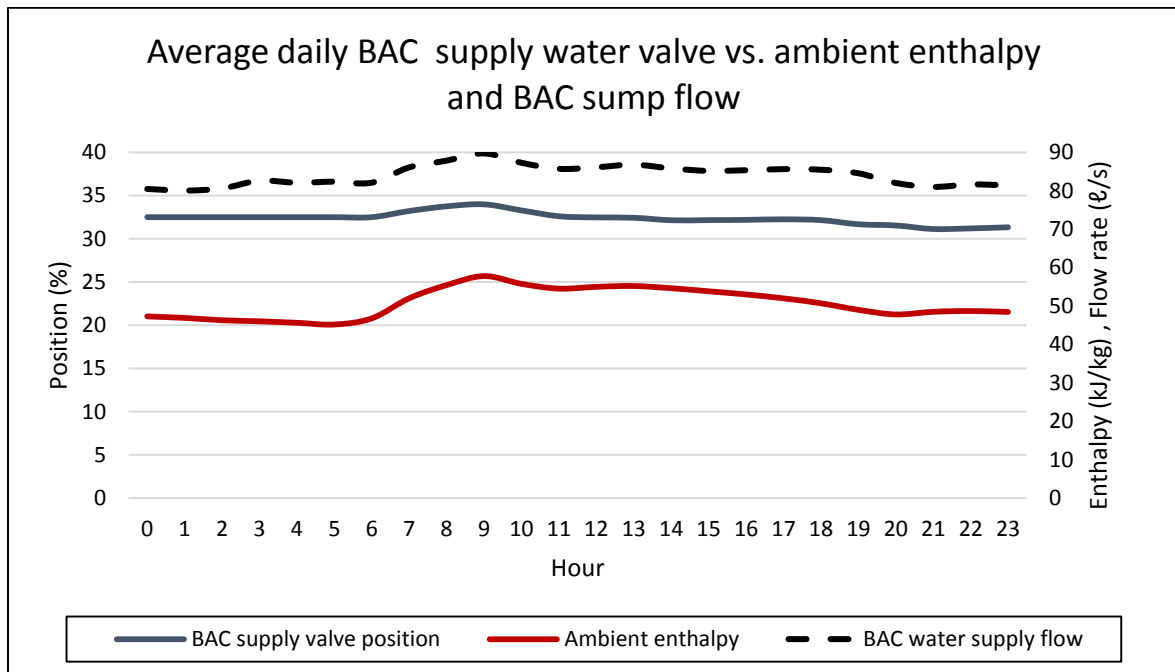


Figure 4-37: Average daily BAC supply valve position vs. enthalpy and flow rate

It can be seen from Figure 4-37 that the BAC water supply flow rate decreased significantly from the original as discussed previously. The reduction in flow can be attributed to the supply valve positions being reduced by an average of 67.6%. Considering that the ventilation service delivery was unaffected by the proposed strategy, the emphasis is once again placed on the redundant use of equipment such as BACs.

As a result of the performance strategy, an average flow reduction of 60 ℓ/s was experienced during typical mining weekdays. Equally, the performance of the BAC control loop can be seen as sufficient by suitably controlling the average water flow to achieve the BAC air outlet temperature set point while reducing the average chilled water flow. The heat transfer is therefore used more effectively by synchronising with the ambient enthalpy.

Figure 4-38 illustrates the average daily BAC return pump AC output frequency as a function of the BAC sump level.

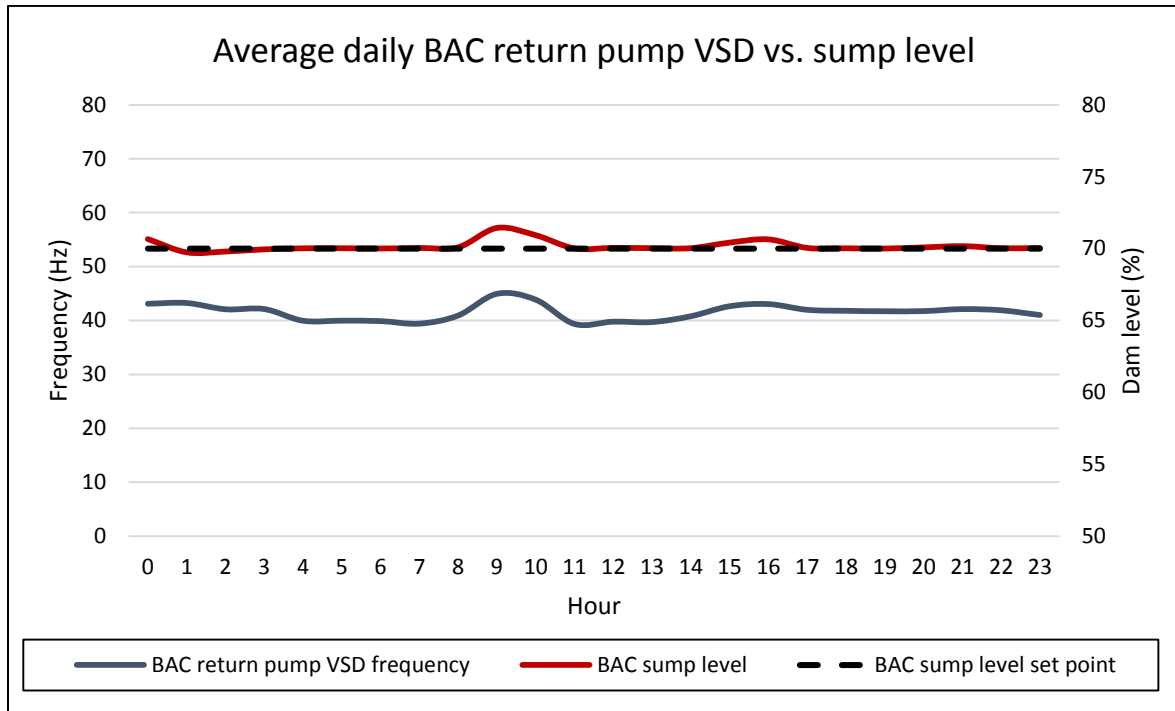


Figure 4-38: Average BAC return pump frequency as a factor of BAC sump level

From Figure 4-38 it is clear that the average BAC return pump AC output frequency followed the fluctuations of the BAC sump level. This is as expected for the BAC control loop, which in contrast with the evaporator control loop drains the water from the BAC sump as opposed to supplying the chilled water to the chill dam and BACs. Furthermore, an average daily BAC sump level of 70.18% was maintained by the BAC control loop. Compared with the set point of 70%, it is clear that the implemented control strategy allows for extremely accurate control.

The accuracy of the control can be ascribed to the comprehensive control strategy that considers both the supply and demand of water in the BACs. Appropriately, there is no delay in the system and the supply and demand can be accurately satisfied by the control loop. Equally, Figure 4-38 illustrates that the average BAC return pump frequency was controlled within the specified control limits realising an average frequency of 41.55 Hz. The average daily BAC return pump AC output VSD frequency, as shown by Figure 4-38, also provides insight into the response of the system, which can be accepted as instantaneous.

It is reasonable to conclude that the BAC control loop performed as expected with an extreme level of accuracy. Furthermore, it is apparent that all of the control loops included in the implementation of the performance strategy performed as expected. Since the service delivery requirements as discussed in Chapter 4.3.2 were satisfied, the control analysis provides the definitive indication towards the success of the performance strategy.

The in-depth analysis revealed that the system performance is not affected adversely by the implementation of the performance strategy, but that the system's performance is ultimately enhanced. Implementing the performance strategy on Mine B therefore only had positive contributions, resulting in significant electrical cost savings with no capital expenditure required. The following section provides a summary of the key findings revealed by the control analysis.

Performance strategy control analysis summary

The average daily crucial control loop parameters after implementing the performance strategy are shown in Table 4-6.

Table 4-6: Control analysis results summary

System parameter (average)	Units	Set point	Actual	Difference
Chill dam level	%	95	95.40	0.4%
BAC sump level	%	70	70.18	0.3%
Condenser temperature rise	°C	5	4.70	6.1%

From the results listed in Table 4-6 it can be concluded that implementing the performance strategy did not affect the refrigeration system and its operations or functionalities at Mine B adversely. The service delivery requirements were satisfied as discussed previously in Section 4.3. The significant electrical cost savings realised proved to be the result of performance strategy implementation.

Table 4-6 illustrates that the control loops included in the performance strategy performed as expected, enhancing the effective use of equipment. The enhanced use has several advantages that include increased system life cycles, reduced maintenance costs and overall improved efficiency. The following section confirms the success of the performance strategy and its overall general application capabilities.

4.4.3 Performance strategy validation results

In order to determine the full effect of the performance strategy implementation, the whole integrated refrigeration system must be analysed. It was proven in the previous sections that implementing the performance strategy does not affect the service delivery of the refrigeration system adversely. Also, the control analysis revealed that the control commenced as planned, which resulted in significant electrical cost savings.

The foremost method used to determine any and all effects on the refrigeration system is to determine the COP, as defined by Equation 2-1 in Section 2.2. The applicable thermal load and electricity consumption include the whole integrated refrigeration system with its accompanying contributors such as pumps, refrigeration machines, fans, motors and BACs. Figure 4-39 illustrates the average daily COP values with the associated refrigeration system electricity consumption before and after performance strategy implementation.

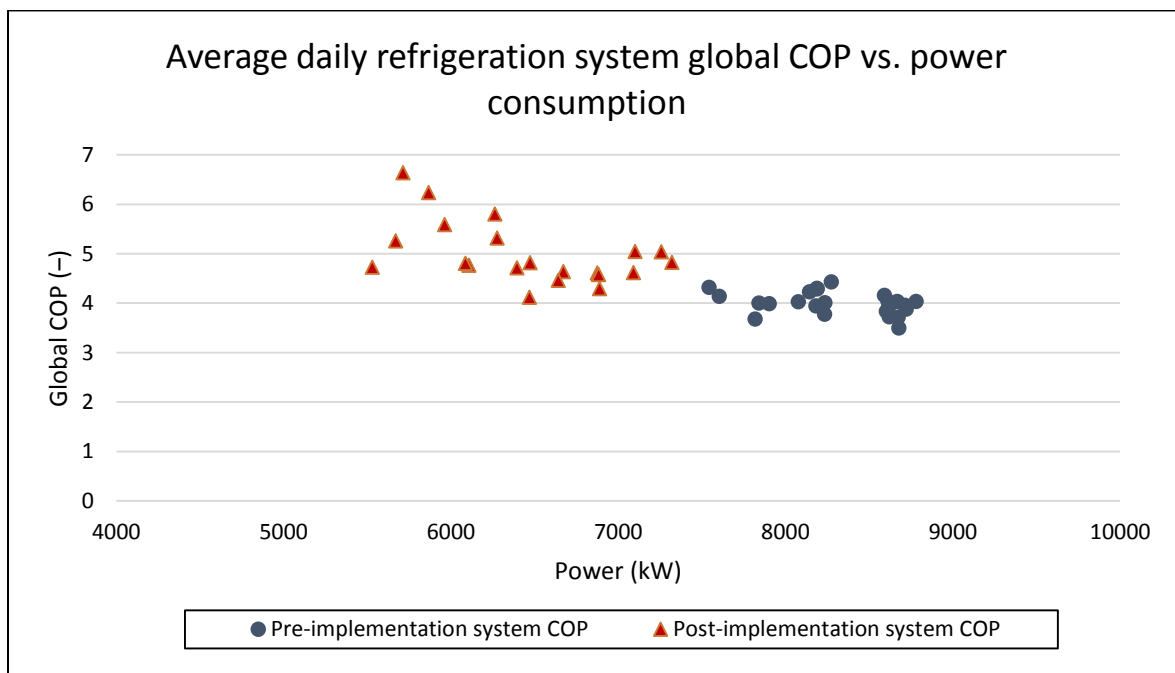


Figure 4-39: Average daily refrigeration system COP as a factor of power consumption

In light of Figure 4-39, it is clear that the average daily global COP increased by approximately 20%. This result serves as a collective summary for the discussions in Section 4.3 and Section 4.4, showing that the control operated as expected without affecting service delivery adversely. In cases where high thermal loads were experienced, the electricity consumption was consequently higher as seen by the pre-implementation profile.

If one considers the post-implementation COP profile for high thermal loads, illustrated by Figure 4-39, the profile values are extremely close to that experienced pre-implementation. The correlation can be contributed to high ambient conditions, high inlet temperatures or large water demands that result in high thermal loads. Larger COP values are, therefore, experienced during lower thermal loadings where the part-load conditions can contribute towards satisfying and controlling the service delivery supply and demand.

It can thus be concluded that the existing DSM initiatives on Mine B's refrigeration system was improved for sustainable performance. The effective use and efficient operation of the integrated refrigeration system contributed towards satisfying the thermal demand with lower electricity inputs required than the norm. The largest COP values were experienced during days where the thermal cooling load was lower than OEM design conditions.

The sustainability of the proposed strategy is directly proportional to the performance of the employed control. One must therefore maintain the refrigeration system to ensure that sustainable practices are promoted and sustainability performance targets are satisfied. Figure 4-40 illustrates the monthly post-implementation performance of the DSM initiatives implemented on Mine B's refrigeration system.

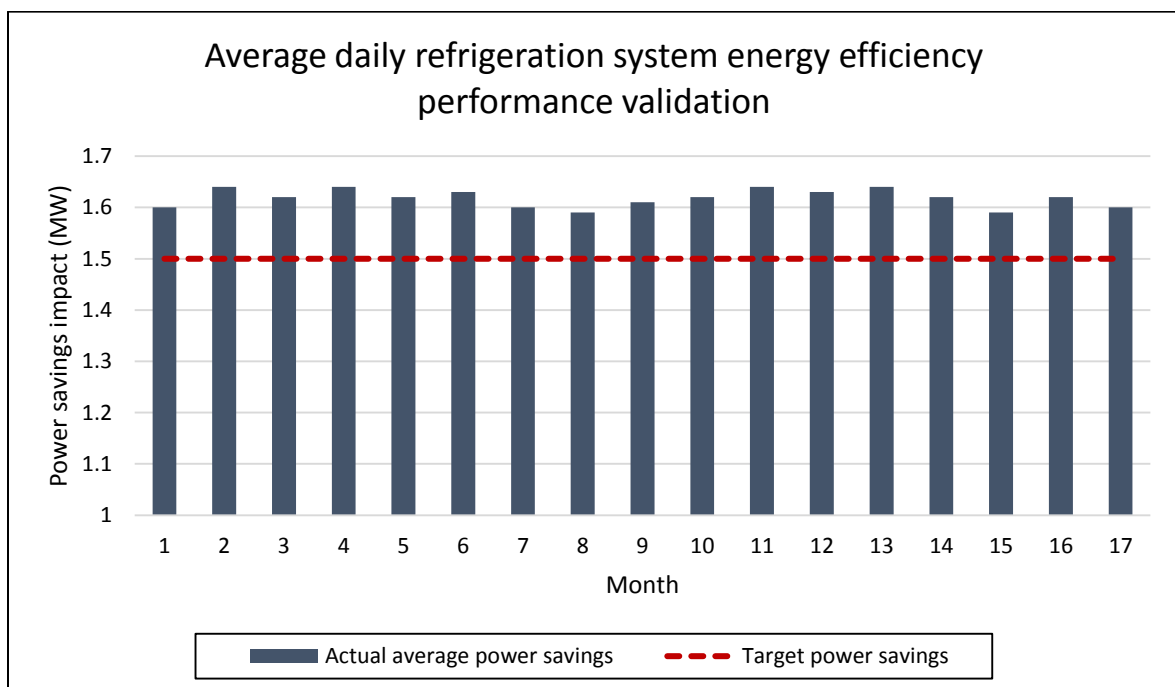


Figure 4-40: Average daily DSM initiative sustainability validation on Mine B

From Figure 4-40 it is apparent the performance strategy can sustainably yield significant electricity cost savings. The general design and comprehensive considerations included in the performance strategy serve as proof of application for implementation on other mines or industrial refrigeration systems. In the next section, a synopsis is displayed of the most significant results obtained from the service delivery and control analysis.

4.4.4 Performance strategy validation results summary

In Chapter 1, a clear unambiguous need for the study was defined with the following hypothesis:

By identifying the factors and challenges that contribute towards project deterioration, a performance strategy can be developed that would improve the sustainability and performance of existing DSM initiatives on mine refrigeration systems through greater realised electrical cost savings without affecting any service delivery requirements adversely.

It follows that in this study, Mine A was identified with deteriorating DSM initiatives on the refrigeration system. Mine A was used for developing the proposed performance strategy to identify the challenges and most crucial system parameters contributing towards sustainable performance. The performance strategy was developed and implemented on Mine A to form part of an in-depth feasibility study. In addition, the performance strategy was implemented on Mine B to illustrate the general application and to serve as further verification and validation.

As a result of the performance strategy implementation on Mine A, a sustainable average electric power saving of 1.8 MW was achieved during the course of 15 months. Implementing the performance strategy on Mine B resulted in a sustainable average electric power saving of 1.62 MW over a 17-month period as discussed in Section 4.3.

It is therefore reasonable to conclude that implementing the performance strategy results in significant sustainable electrical cost savings by improving existing DSM initiatives on mine refrigeration systems. The average electrical cost saving realised on Mine A amounted to R11.9 million and on Mine B to R12.1 million. The performance strategy results summary of Mine B are illustrated by Table 4-7, which demonstrates the combined effects of the proposed strategy when implemented.

Table 4-7: Mine B performance strategy results summary

Service delivery analysis	Units	Before (pre)	After (post)	Difference
Chill dam water temp.	°C	6.28	6.20	1.2%
Chill dam water level	%	81.92	95.38	16.4%
Chilled water demand	Ml/day	29.12	29.63	1.8%
71 L chill dam water temp.	°C	7.65	7.77	- 1.6%
Surface BAC inlet water temp.	°C	6.28	6.20	1.2%
Surface BAC outlet water temp.	°C	12.42	12.28	1.1%
102 L East BAC inlet water temp.	°C	15.27	15.20	0.5%
102 L West BAC inlet water temp.	°C	15.76	16.11	- 2.2%
102 L East BAC inlet water flow	ℓ/s	42.94	43.96	2.4%
102 L West BAC inlet water flow	ℓ/s	25.09	25.72	2.5%
Control analysis	Units	Set Point	After (Post)	Difference
Chill dam level	%	95	95.40	0.4%
BAC sump level	%	70	70.18	0.3%
Condenser temperature rise	°C	5	4.70	4.1%

4.4.5 Increased economic feasibility

Although no large capital expenditure was required to implement the performance strategy on Mine B and significant electricity cost savings were realised, thus justifying the “low-hanging fruit” metaphor used in Chapter 1, the electricity cost savings can be increased dramatically with a minimum expense to the mine. In this section, the increased economic feasibility regarding the repair of the broken VSDs, which would allow for better control and greater electricity cost savings, is illustrated.

It was found by validating the performance strategy that the BAC control loop was controlled sufficiently using only one VSD. As a result, and since the installed capacities of the BAC return pumps were smaller than the evaporator and condenser pumps, they were not included in the feasibility analysis. The focal point was therefore to determine the added economic effect imposed on the performance strategy when the broken VSDs are repaired.

Please refer to Appendix F for the final quotations received for repairing the broken VSDs. The final collective cost of the condenser VSD and evaporator VSD repair amounted to R226 400. Any indication towards client financials and personnel information is privileged

and was hidden on the quotations due to confidentiality reasons. The foremost method in which a project's economic feasibility is determined, is by defining the payback period as described in Section 3.5.

In light of Equation 2-4 in Section 3.5, one requires the capital expenditure and capital electricity cost savings. Hence, on behalf of the client confidentiality, the exact amount of maintenance and operational costs incurred per annum may not be disclosed but was assumed to be R200 000. If one assumes that an average electricity power saving of 2.2 MW would be achieved during typical mining weekdays, with the inclusion of the repaired VSDs in the control loops, it follows that one can evaluate the payback period.

The total capital expenditure for the refrigeration system of Mine B was assumed to amount to R426 400. According to Table 3-4 in Section 3.5, the calculated electricity cost saving per annum would amount to R16.4 million. The payback period is therefore 0.02 months, which is still within the two-year accepted period [78]. Thus, the mine would have saved approximately R4.3 million more over the same implementation period of 17 months. The economic viability far outweighs the involved capital expenditure.

4.5 Further sustainability measures

4.5.1 Sustainability overview

As part of the performance strategy development, as discussed in Section 3.3, it was found that the sustainability of DSM initiatives is directly proportional to the strategy used after project implementation. The performance strategy therefore includes comprehensive monitoring and reporting capabilities to enable the resources and instruments necessary for sustainable operations.

Engineers and mining personnel use these available monitoring and reporting tools for system control and preventative maintenance. If these tools are used effectively as part of daily operations, sustainability can be increased and maintained. The next section's focal points are the measures and techniques that are to be incorporated as part of the performance strategy implementation to ensure increased sustainability.

Note that the emphasis is placed on all related parties to react to and control the system operations according to the relevant project feedback. It is critical for these parties to communicate effectively and work in unison to achieve a common goal. Additionally, if

these parties do not communicate effectively, misunderstandings could lead to production losses, counteraction, and increased component and system failures.

4.5.2 Monitoring, reporting and control

It is imperative for effective and accurate post-implementation monitoring and reporting capabilities that sufficient control and corrective measures for sustained performance are enabled. The equipment as part of existing DSM initiatives should be fully integrated and provide feedback of KPIs.

As a result, KPIs should be used in the monitoring and reporting system to notify the relevant personnel of any system degradation or faults that may occur. The frequency of the reports is also important to ensure that faults are identified well in advance and preventative measures are taken. Typical feedback reports are sent daily, weekly and annually to all relevant parties to act as an added quality assurance system. In the following section the most significant parties involved with the monitoring, reporting and control are identified and the applicable requirements are discussed for each.

ESCO personnel

The new Eskom Energy Efficiency DSM model, implemented from 1 January 2016, ensures that ESCO personnel are only compensated for sustained electrical cost savings [9]. As a result, ESCO personnel are responsible as the main driver behind the different DSM initiatives and subsequent electrical cost savings. In light of the performance-based compensation, the monitoring and reporting systems of the ESCO should include detailed information for preventative and optimisation strategies and procedures.

The reporting system should include the most significant KPIs of the refrigeration system. The report should, for instance, also include control parameters such as the applicable dam levels, chilled water temperatures and VSD frequencies and should not be limited to just service delivery requirements.

A typical example report generated and sent to ESCO personnel can be seen in Appendix G. The example report illustrates a mine with existing DSM initiatives similar to Mine B. If one considers Figure G-1 to Figure G-8, it is apparent that all KPIs are included in the report. The report also illustrates the different control loops, crucial system parameters and relevant

VSD AC output frequencies. The report further incorporates the COPs of the individual refrigeration machines, running statuses and service delivery.

The running statuses table as seen in Figure G-5 is extremely beneficial to ESCO personnel. The table provides an indication towards the level of control employed and the accuracy in which the control philosophy was implemented on the specific day. Additionally, the report supplies information regarding faulty or broken meters. As a result of the outlier values, sudden spikes and/or data loss, the faulty meters can be identified, investigated and repaired. The relevance of such a report is again highlighted when Figure G-4 is considered, illustrating that no surface fridge plants were switched off during the peak electricity times.

Mining personnel

The monitoring and reporting system of mine personnel should only include the main systems with an overall performance summary graph. The reports are typically sent to foremen and engineers who are responsible for the mine's energy consumption. All key personnel have access to all mining systems through the mine SCADA system. As a result, they can retrieve the necessary information if they notice irregularities on the system summary. This would allow mining personnel to investigate system changes and make alterations for repair or improvement.

The mine reports should also include a synopsis of the KPIs and boundary parameters. The system operations can be compared, daily, monthly and annually in order for mine personnel to identify key trends and factors affecting production. Furthermore, mine personnel are more inclined to assist ESCOs and contribute towards sustainable electricity cost savings if the daily savings are quantified. Additionally, the reports can be used in forecast models to determine annual electricity consumptions and quantify the subsequent electricity cost for the system.

In conclusion, mine personnel require summaries of the daily system performance and electrical cost savings realised. Furthermore, mine personnel have the necessary resources and information available through the mine's SCADA system to undertake detailed investigations. As a result, mine personnel can pinpoint system faults or operational changes and together with the ESCO make the necessary alterations or system changes required for system improvement and increased sustainability.

M&V personnel

M&V personnel are appointed to verify the electrical cost savings realised and reported by the ESCO through DSM initiatives. They typically do site visits to verify and document DSM initiatives and associated components or control philosophies. M&V personnel only require data that affects and represents the electrical cost savings realised. As a result, they do not have automated reporting and monitoring systems and rely on the ESCO and mine to provide the raw data.

The personnel therefore require the system power consumption and parameters incorporated in the scaling methodology. Typically, in refrigeration systems, the scaling methodologies include delta condenser temperatures, chilled water temperatures, ambient temperatures and BAC air outlet temperatures, depending on the existing DSM initiatives and control loops employed. As a result, M&V personnel can verify the electrical cost savings reported by the ESCO to Eskom, which form part of a quality assurance plan. In the next section, further sustainability measures are discussed for Mine B as a result of the monitoring and reporting system included in the performance strategy.

4.5.3 Further sustainability measures for Mine B

In this section, the most significant areas of sustainable performance improvement are discussed as a result of the integrated monitoring and reporting system. Furthermore, these areas of potential are categorised according to the capital expenditure required for implementation. Additionally, the possible solutions for the areas of potential can be incorporated directly into the existing performance strategy, increasing performance and sustainability of existing DSM initiatives.

Control philosophy

The first area of potential saving identified is the underground refrigeration machines that form part of the existing overall refrigeration system. The refrigeration machines on 71 L and 100 L are prone to overcool the chilled service water and therefore wastes energy. As a result, there is ample room to switch off two 3.5 MW refrigeration machines on 71 L and one 3.5 MW machine on 100 L during peak electricity times as a peak-clipping initiative.

As is the case with the implementation of the performance strategy on the surface refrigeration system, the underground refrigeration system will require performance testing

to determine the overall effect on the KPIs and boundary conditions. After the performance testing is concluded, the underground refrigeration system can be incorporated into the EMS. As part of a zero-capital initiative, the peak-clipping control can be accomplished by using machine operators, but should ideally only be included as a short-term measure with the main focus of establishing automatic SCADA control.

Infrastructure

The second area of potential identified is the increased sustainability as a result of capital expenditure. The above-mentioned refrigeration machines can be fully automated and incorporated in the control philosophy to increase the electrical cost savings. The capital expenditure will be used for automating the refrigeration machines. Additionally, improved meters and VSD controllers can be installed, which would result in optimised control conditions and a subsequent increase in electrical cost savings.

Installing new meters will increase both the versatility of the system and the number of measuring points. Consequently, the dependence on human control is minimised and fault-finding capabilities are increased simultaneously. Although the proposed infrastructure will increase the electrical cost savings, the lead and lag times of equipment should always be kept in mind before the capital expenditure is classified as feasible. Meters can also contribute towards simplifying the system as seen with the installation of a BAC outlet air temperature meter.

As a final closing to the section, there are still possible areas where further sustainability improvements can be made. The areas were identified as a result of the monitoring and reporting system included in the performance strategy implementation. The next section concludes the energy saving implementation chapter with the most significant outcomes achieved, discussed as a synopsis for each section.

4.6 Conclusion

It was shown that the implementation of the proposed performance strategy resulted in significant electrical cost savings realised for Mine B. The process followed to improve existing DSM initiatives on Mine B's refrigeration system for sustainable performance was presented and analysed through a step-by-step methodology.

After a detailed investigation into the feasibility of improving the existing DSM initiatives on Mine B was completed, a detailed simulation was constructed where the predicted operational effects were analysed. As part of the proposed strategy implementation, performance tests were administered and the effects thereof determined and documented.

As a result of the performance strategy implementation, a sustainable average electricity reduction of 1.62 MW with a peak-clipping electricity reduction of 6.14 MW was realised over the course of 17 months. The typical daily average electricity reduction was calculated as 21.46%, when compared with the scaled baseline.

The post-implementation effects of the performance strategy were determined and analysed in detail through a water operational analysis, ventilation operational analysis and finally a control analysis. The different analysis techniques revealed that implementing the performance strategy did not affect the refrigeration system and its operations or functionalities at Mine B adversely. On the contrary, the analysis revealed that a significant system improvement was achieved with a global COP increase of approximately 20%.

As part of the study validation, the post-implementation electrical cost savings realised on Mine A were also determined. It was found that a sustainable average electric power saving of 1.8 MW was achieved during the course of 15 months. The average electrical cost saving realised on Mine A amounted to R11.9 million and on Mine B to R12.1 million. It is therefore reasonable to conclude that implementing the performance strategy results in significant sustainable electrical cost savings by improving existing DSM initiatives on mine refrigeration systems.

The economic feasibility of improving existing DSM initiatives on mine refrigeration systems further was analysed when capital expenditure was to be made available. It was found that if Mine B had the capital available to repair the two broken VSDs, the mine would

have saved approximately R4.3 million more over the same implementation period of 17 months.

Further sustainability measures and opportunities for increased performance were investigated on Mine B. Additionally, the different monitoring and reporting requirements for each relevant project party were analysed and discussed as part of the performance strategy implementation. The measures specifically identified for Mine B were categorised under the control philosophy and infrastructure headings. The categorisation was a mere result of endeavours requiring no capital expenditure as opposed to added infrastructure requiring large capital. As a result, the economic viability of the strategy was proven to far outweigh the risks, with or without using capital expenditure.

Chapter 5

Conclusions and recommendations



“However beautiful the strategy, you should occasionally look at the results.”

– Winston Churchill

5.1 System summary

South Africa, which forms part of the emerging national economies association better known as BRICS, is critically reliant on unwavering sufficient electricity supply for ongoing economic development. Rapid expansion and industrialisation have led to South Africa having one of the highest energy intensities in the world. The alarming growth rate experienced in the last couple of decades can be attributed to South Africa's resource endowments but also the historically low coal and electricity cost to consumers.

This economic growth pattern is of increasing global concern, especially regarding the management and sustainability of energy resources. South Africa has the largest reserves of coal, gold and platinum in the world. It is apparent that mining is one of the most important, if not the main economic driver in South Africa. The mining sector in South Africa constitutes 14% of Eskom's annual sales distribution and it was identified to boast great potential for DSM initiatives.

Since gold mining is done at great depths in South Africa, the seeming 23% of electricity usage for refrigeration systems comes as no surprise. Although the refrigeration systems are critical for safe and legal mining operations, the general consensus among industry and experts remains that equipment is overdesigned and inefficient. As a result, there were ample opportunities to implement DSM initiatives to not only decrease the electric power consumption but also to optimise the individual systems.

Henceforth, several DSM initiatives have previously been implemented on mine refrigeration systems yielding notable electrical cost savings. Although significant savings had been achieved through these initiatives, project deterioration occurred over time, eroding the viability of sustained electrical cost savings. The opportunity was therefore identified to improve existing DSM initiatives on mine refrigeration systems for sustainable performance with very little capital input required, seen as "low-hanging fruit" to decrease electric power consumption.

As part of an in-depth literature review, the specifications and typical operations of the refrigeration systems and its subsystems were analysed. The analysis established a clear working knowledge into the fundamental theories associated with the evaluation of refrigeration systems and their components. Various optimisation strategies that are

currently employed in industry were scrutinised. The study revealed that although many optimisation strategies and technologies exist, they are rarely applied in deep-level South African gold mines. Furthermore, the literature indicated hidden operational constraints and requirements that are only applicable during strategy implementation.

It was found that integrating VSDs with an EMS is the most effective instrument for achieving electrical cost savings in industry and subsequently in mine refrigeration systems. In mining, VSDs are typically integrated on pumps, compressors, fans, conveyers and winders. Several variable flow energy efficiency strategies exist as part of DSM initiatives on refrigeration systems. The KPIs of such systems, which are directly coupled to environmental health and safety requirements, were identified. The review showed that if the crucial system parameters are kept within an acceptable tolerance range, production will experience no adverse effects.

Finally, previous challenges encountered with DSM initiatives were investigated. It was found that several human and technical factors affect the performance and sustainability of DSM initiatives on mine refrigeration systems. The conclusion to the literature review indicated that there is no documented strategy with the purpose of increasing the sustainability of electrical cost savings on mine refrigeration systems by improving existing DSM initiatives.

The feasibility of improving the existing DSM initiatives was investigated and possible solutions identified. Crucial system parameters and KPIs were used in a detailed root cause analysis of each control loop. The analysis led to the development of a performance strategy, which would theoretically improve existing DSM initiatives on mine refrigeration systems for sustainable performance. The critical performance considerations were summarised for each control loop as part of the performance strategy.

A simulation model was created with the aid of simulation software PTB based on the pioneering work of Du Plessis and Van der Bijl. Actual data from Mine A's refrigeration system was used to verify the accuracy of the proposed performance strategy. The average percentage difference between the actual and simulated values was determined to be 3.74%. The KPIs and critical system parameters of the performance strategy were compared with the actual values attained from a one-month verification test period in which the performance strategy was implemented.

As a result of the performance strategy verification test implementation, an average electricity reduction of 1.4 MW was experienced during the course of a typical mining weekday with a 3.4 MW reduction during the peak electricity period. The improved performance equated to a 26.88% reduction in total refrigeration system electricity costs, which amounted to a value of R388 650 for the month. The performance strategy was therefore verified and further electricity cost savings predicted with the aid of the performance strategy and simulation model.

The economic feasibility revealed that the average daily saving expected is R15 374 for summer tariff months and R23 963 for winter months. The total electricity cost saving per annum would therefore amount to R8 046 935 with a payback period of 0.3 months. It is evident from the payback period that the proposed performance strategy should yield a significant financial contributing with a very high financial saving.

Founded on the preliminary results of improving DSM initiatives on Mine A's refrigeration system, another mine with deteriorating underperforming DSM initiatives was identified and investigated for opportunities. After Mine B was investigated, a detailed simulation was constructed where the predicted operational effects were analysed. As part of the proposed strategy implementation, performance tests were administered and the effects thereof determined and documented.

As a result of the performance strategy implementation, a sustainable average electricity reduction of 1.62 MW with a peak-clipping electricity reduction of 6.14 MW was realised over the course of 17 months. The typical daily average electricity reduction was calculated as 21.46% when compared with the scaled baseline.

The post-implementation effects of the performance strategy were determined and analysed in detail through a water operational analysis, ventilation operational analysis and finally a control analysis. The different analysis techniques revealed that implementing the performance strategy did not affect the refrigeration system and its operations or functionalities at Mine B adversely. On the contrary, a significant system improvement was achieved with a global COP increase of approximately 20%.

As part of the study validation, the post-implementation electrical cost savings realised on Mine A were also determined. It was found that a sustainable average electric power saving of 1.8 MW was achieved during the course of 15 months. The average electrical cost saving

realised amounted to R11.9 million for Mine A and R12.1 million for Mine B. It is thus reasonable to conclude that implementing the performance strategy results in significant sustainable electrical cost savings by improving existing DSM initiatives on mine refrigeration systems.

The economic feasibility of further improving existing DSM initiatives on mine refrigeration systems as “low-hanging fruit” was analysed when capital expenditure was made available. It was found that if Mine B had the capital available to repair the two broken VSDs, the mine would have saved approximately R4.3 million more over the same implementation period of 17 months.

Further sustainability measures and opportunities for increased performance were investigated on Mine B. Additionally, the different monitoring and reporting requirements for each relevant project party were analysed and discussed as part of the performance strategy implementation. The measures specifically identified for Mine B were categorised under the control philosophy and infrastructure headings. The categorisation was a mere result of endeavours requiring no capital expenditure as opposed to added infrastructure requiring large capital inputs. As a result, the economic viability of the strategy was proven to far outweigh the risks, with or without using capital expenditure.

5.2 Conclusions and study objective validation

The study objectives as described in Section 1.4 were satisfied through the following basic process: A detailed analysis into the KPIs and operations of typical deep-level gold mine refrigeration systems indicated the potential of improving existing DSM initiatives for sustainable performance.

As a result, an improved strategy was proposed and developed to satisfy the need for sustainable electrical cost savings. The proposed strategy was verified and refined further to optimise the refrigeration system and its control without affecting the service delivery requirements or production negatively. Health and safety were continuously regarded as top priorities to promote a strategy conducive to safe and productive mining.

After developing the strategy, it was implemented on a mine with deteriorating underperforming DSM initiatives. The KPIs, crucial system parameters, system boundary conditions and service delivery requirements were compared before and after

implementation as part of a detailed analysis. The analysis revealed that all parameters were maintained within the allowable tolerance levels and therefore did not affect the service delivery, production or relevant mineworkers adversely.

In conclusion, the performance strategy was verified and validated by the implementation thereof. The culminating fruits of labour resulted in a sustainable average electric power saving of 1.8 MW for Mine A over the course of 15 months, and 1.62 MW for Mine B over 17 months. The average electrical cost saving realised on Mine A amounted to R11.9 million and on Mine B to R12.1 million.

As a result, the study hypothesis therefore proved that by identifying the factors and challenges that contribute towards project deterioration, a performance strategy can be developed that would **improve the sustainability and performance of existing DSM initiatives on mine refrigeration systems** through greater realised electrical cost savings **without affecting any service delivery requirements adversely.**

5.3 Recommendations

It was found that the performance strategy satisfied the research objective in realising significant sustainable electrical cost savings by improving existing DSM initiatives on mine refrigeration systems. Nevertheless, it is necessary to identify key areas where further improvements can be made, not only in terms of sustainability but also in terms of system performance, reliability and efficiency. The following section is a brief summary of further studies identified that might contribute significantly towards the field.

Firstly, ample room exists to implement and investigate the effect of the performance strategy on industrial cooling applications, specifically large cooling systems found in factories, plants and commercial buildings.

Secondly, it is recommended that possible load-shifting opportunities for BACs on surface and underground are investigated through a detailed water operational analysis. In this study, the negligible effects of service water reductions on the ventilation air temperature were shown.

Thirdly, it is proposed that the necessary dam capacities, which would allow the refrigeration and water reticulation system to be switched off during all peak periods, be investigated.

These systems are usually limited as a result of the limited thermal storage capacity. An increase in thermal storage capacity, especially on surface, not to mention underground, would therefore contribute towards an increase in electrical cost savings.

Fourthly, the use of modern energy efficient equipment deserves further investigation. Integrating new modern equipment will improve overall efficiency, which will improve electrical cost savings further. Equipment such as cooling towers, BACs, pumps, fans or refrigeration machines can be replaced. This strategy can also be implemented on component level; for example, by replacing cooling tower fans or pump VSDs.

Finally, the automation and integration of refrigeration machines can be investigated. Refrigeration machine compressors pose great opportunity for improving existing DSM initiatives, especially when guide vane control is established and optimised.

In conclusion, the above-mentioned recommendations will contribute positively towards advancement of the field. However, the final true evaluation can only be made once industry accepts the paradigm shift from energy intensive to energy efficient operations. It is imperative that the industrial and mining sector promote energy efficiency consciously, and manage it wisely to enhance sustainability. To end in the words of Aristotle, “We are what we repeatedly do. Excellence, then, is not an act, but a habit”.

Chapter 6

References



“We must use time wisely and forever realize that the time is always ripe to do right.”

– Nelson Mandela

6.1 Bibliography

- [1] A. B. Sebitosi, “Is the South African electricity tariff model conducive to an energy efficient economy?,” *Energy for Sustainable Development*, vol. 14, no. 4, pp. 315–319, 2010.
- [2] R. Inglesi-Lotz and J. N. Blignaut, “Electricity intensities of the OECD and South Africa: A comparison,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, pp. 4491–4499, 2012.
- [3] R. R. Kumar, P. J. Stauvermann, N. Loganathan, and R. D. Kumar, “Exploring the role of energy, trade and financial development in explaining economic growth in South Africa: A revisit,” *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1300–1311, 2015.
- [4] M. Kohler, “Differential electricity pricing and energy efficiency in South Africa,” *Energy*, vol. 64, pp. 524–532, 2014.
- [5] E. A. Abdelaziz, R. Saidur, and S. Mekhilef, “A review on energy saving strategies in industrial sector,” *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 150–168, 2011.
- [6] US Department of Energy, “Energy highlights,” Washington, 2005. [Online]. Available: <http://www.eia.doe.gov/>. [Accessed: 13 Oct. 2015].
- [7] R. Inglesi, “Aggregate electricity demand in South Africa: Conditional forecasts to 2030,” *Applied Energy*, vol. 87, pp. 197–204, 2010.
- [8] A. J. Schutte, “Demand side management of a cascade mine surface refrigeration system,” M. Eng. dissertation, North-West University, Potchefstroom, 2007.
- [9] Eskom Holdings Ltd, “Integrated report 2014,” 2014. [Online]. Available: <http://integratedreport.eskom.co.za/pdf/full-integrated.pdf>. [Accessed: 12 Oct. 2015].
- [10] R. Inglesi-Lotz and J. N. Blignaut, “South Africa’s electricity consumption: A sectoral decomposition analysis,” *Applied Energy*, vol. 88, pp. 4779–4784, 2011.
- [11] G. E. Du Plessis, “A variable water flow strategy for energy savings in large cooling systems,” Ph.D dissertation, North-West University, Potchefstroom, 2013.
- [12] Eskom Holdings Ltd, “Interim integrated report,” Eskom Holdings Ltd, Johannesburg, 2014.
- [13] W. Rafey and B. K. Sovacool, “Competing discourses of energy development: The implications of the Medupi coal-fired power plant in South Africa,” *Global Environmental Change*, vol. 21, pp. 1141–1151, 2011.

-
- [14] C. Perfumo, E. Kofman, J. H. Braslavsky, and J. K. Ward, “Load management: Model-based control of aggregate power for populations of thermostatically controlled loads,” *Energy Conversion and Management*, vol. 55, pp. 36–48, 2012.
- [15] P. Maré, “Improved implementation strategies to sustain energy saving measures on mine cooling systems,” M. Eng. dissertation, North-West University, Potchefstroom, 2014.
- [16] H. Winkler, A. Marquard, and M. Jooste, “Putting a price on carbon: Economic instruments to mitigate climate change in South Africa and other developing countries,” in *The 7th Energy Research Centre Conference*, Cape Town, pp. 1–26, 2010.
- [17] E. Vine, “An international survey of the energy service company (ESCO) industry,” *Energy Policy*, vol. 33, no. 5, pp. 691–704, 2005.
- [18] G. Strbac, “Demand side management: Benefits and challenges,” *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, 2008.
- [19] S. Boyle, “DSM progress and lessons in the global context,” *Energy Policy*, vol. 24, no. 4, pp. 345–359, 1996.
- [20] R. Inglesi-Lotz and A. Pouris, “Energy efficiency in South Africa: A decomposition exercise,” *Energy*, vol. 42, no. 1, pp. 113–120, 2012.
- [21] D. Newbery and A. Eberhard, “South African network infrastructure review: Electricity,” University of Cape Town, Cape Town, 2008.
- [22] J. Jeswiet, J. Archibald, U. Thorley, and E. De Souza, “Energy use in premanufacture (mining),” *Procedia CIRP*, vol. 29, pp. 816–821, 2015.
- [23] Statistics South Africa, “National accounts: Mineral accounts for South Africa: 1980–2009,” Environmental Economic Accounts, Pretoria, 2012.
- [24] A. B. Sebitosi, “Energy efficiency, security of supply and the environment in South Africa: Moving beyond the strategy documents,” *Energy*, vol. 33, pp. 1591–1596, 2008.
- [25] K. E. Dupuy, “Community development requirements in mining laws,” *The Extractive Industries and Society*, vol. 1, no. 2, pp. 200–215, 2014.
- [26] Inflation.eu, “Inflation South Africa,” 2015. [Online]. Available: <http://www.inflation.eu/inflation-rates/south-africa/historic-inflation/cpi-inflation-south-africa-2014.aspx>. [Accessed: 21 Oct. 2015].
- [27] H. J. Groenewald, “A performance-centered maintenance strategy for industrial DSM projects,” Ph.D thesis, North-West University, Potchefstroom, 2015.

- [28] C. M. Gomes, J. M. Kneipp, I. Kruglianskas, L. A. B. Da Rosa, and R. S. Bichueti, "Management for sustainability in companies of the mining sector: An analysis of the main factors related with the business performance," *Journal of Cleaner Production*, vol. 84, pp. 84–93, 2014.
- [29] A. S. Berhad, "Harmony Gold Mining Company Ltd integrated annual report 2014," Harmony Gold Mining Company Ltd, Pretoria, 2014.
- [30] D. Struhs, "The energy efficiency series: Towards an energy efficient mining sector," Eskom Holdings Ltd, Johannesburg, 2010.
- [31] R. Els, "Potential for load shifting in ventilation and cooling systems," M. Eng. dissertation, University of Pretoria, Pretoria, 2000.
- [32] A. J. Schutte, "An integrated energy efficiency strategy for deep mine ventilation and refrigeration," Ph.D thesis, North-West University, Potchefstroom, 2013.
- [33] G. Saxon, "Gold mining and processing in South Africa," Anglo American Ltd, University of Cape Town, Cape Town, 2015.
- [34] R. Spence, "The top ten deepest mines in the world," *Mining Technology*, 2013. [Online]. Available: <http://www.mining-technology.com/features/feature-top-ten-deepest-mines-world-south-africa/>. [Accessed: 23 Oct. 2015].
- [35] Department of Minerals and Energy, Directorate: Occupational Hygiene, "South African mines occupational hygiene programme," Pretoria, 2002.
- [36] M. J. McPherson, *Subsurface Ventilation Engineering*, 1st ed., vol. 1. London: Springer, 2015.
- [37] M. Biffi, D. Stanton, H. Rose, and D. Pienaar, "Ventilation strategies to meet future needs of the South African platinum industry," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 107, no. 1, pp. 59–66, 2007.
- [38] F. Lisker, B. Ventura, and U. A. Glasmacher, Eds., *Thermochronological Methods: From Palaeotemperature Constraints to Landscape Evolution Models – Special Publication 324*, London: Geological Society of London, 2009.
- [39] R. C. Hochreiter, "Platinum in South Africa," *Journal of the South African Institute of Mining and Metallurgy*, vol. 85, no. 6, pp. 165–185, 1985.
- [40] J. F. Brune, *Extracting the Science: A Century of Mining Research*, 1st ed. Littleton, CO: Society for Mining, Metallurgy, and Exploration Inc., 2014.
- [41] N. Nattrass, "The crisis in South African gold mining," *World Development*, vol. 23, no. 5, pp. 857–868, 1995.

- [42] G. E. Du Plessis, L. Liebenberg, and E. H. Mathews, “The use of variable speed drives for cost-effective energy savings in South African mine cooling systems,” *Applied Energy*, vol. 111, pp. 16–27, 2013.
- [43] C. Vintró, L. Sanmiquel, and M. Freijo, “Environmental sustainability in the mining sector: Evidence from Catalan companies,” *Journal of Cleaner Production*, vol. 84, pp. 155–163, 2014.
- [44] B. Sütterlin, T. A. Brunner, and M. Siegrist, “Who puts the most energy into energy conservation? A segmentation of energy consumers based on energy-related behavioral characteristics,” *Energy Policy*, vol. 39, no. 12, pp. 8137–8152, 2011.
- [45] U. C. Group, “Mine energy guidelines,” 2015. [Online]. Available: http://conferences.ufs.ac.za/dl/Userfiles/Documents/00000/556_eng.pdf. [Accessed: 7 Nov. 2015].
- [46] F. Varley, “A study of heat stress exposures and interventions for mine rescue workers,” National Institute for Occupational Safety and Health, Spokane, WA, 2004.
- [47] D. Brake, “The application of refrigeration in mechanised mines,” in *The Australasian Institute of Mining and Metallurgy*, vol. 306, 2001.
- [48] J. L. Buys, “Optimising the refrigeration and cooling system of a platinum mine,” M. Eng. dissertation, North-West University, Potchefstroom, 2014.
- [49] M. Karsten and L. Mackay, “Underground environmental challenges in deep platinum mining and some suggested solutions,” *The Southern African Institute of Mining and Metallurgy*, pp. 177–192, 2012.
- [50] J. M. Calm, “Refrigerants for deep mine refrigeration,” in *International Congress of Refrigeration 2011*, Prague, 2011.
- [51] A. J. Schutte, R. Pelzer, and E. H. Mathews, “Improving cooling system efficiency with precooling,” in *The 9th Industrial and Commercial Use of Energy (ICUE) Conference*, Cape Town, 2012.
- [52] D. J. Brake, “Key engineering considerations in the specification and selection of mine refrigeration plants,” in *The Australasian Institute of Mining and Metallurgy*, vol. 306, Brisbane, 2001.
- [53] M. J. McPherson, *Subsurface Ventilation and Environmental Engineering*, 1st ed. London: Chapman & Hall, 1993.
- [54] C. Borgnakke and R. E. Sonntag, *Fundamentals of Thermodynamics*, 7th ed. Hoboken, NJ: John Wiley & Sons Inc., 2008.
- [55] F. Billiard, “Refrigerating Equipment, Energy Efficiency and Refrigerants,” *Bulletin of the International Institute of Refrigeration*, 2005.

-
- [56] S. Anand, A. Gupta, and S. K. Tyagi, “Simulation studies of refrigeration cycles: A review,” *Renewable and Sustainable Energy Reviews*, vol. 17, pp. 260–277, 2013.
- [57] H. W. Stanford, *HVAC Water Chillers and Cooling Towers*, 2nd ed. Basel, NY: Marcel Dekker Inc., 2011.
- [58] K. N. Widell and T. Eikevik, “Reducing power consumption in multi-compressor refrigeration systems,” *International Journal of Refrigeration*, vol. 33, no. 1, pp. 88–94, 2010.
- [59] W. F. Stoecker and J. W. Jones, *Refrigeration and Air Conditioning*, 2nd ed. Austin, TX: McGraw-Hill, 2014.
- [60] UNEP, “Electrical Energy Equipment: Cooling towers,” *Energy Efficiency Guide for Industry in Asia*, 2006.
- [61] R. Ramkumar and A. Ragupathy, “Thermal performance of forced draft counterflow wet cooling tower with expanded wire mesh packing,” *International Journal on Technical and Physical Problems of Engineering*, vol. 3, no. 6, pp. 19–23, 2011.
- [62] J. Van Der Walt and A. Whillier, “Considerations in the design of integrated systems for distributing refrigeration in deep mines,” *Journal of the South African Institute of Mining and Metallurgy*, pp. 109 – 124, 1978.
- [63] E. Rubio-Castro, M. Serna-González, J. M. Ponce-Ortega, and M. A. Morales-Cabrera, “Optimization of mechanical draft counterflow wet-cooling towers using a rigorous model,” *Applied Thermal Engineering*, vol. 31, no. 16, pp. 3615–3628, 2011.
- [64] Z. K. Morvay and D. D. Gvovdenae, “Applied industrial energy and environmental management,” in *Applied Industrial Energy and Environmental Management*, 1st ed., Z. K. Morvay, Ed. Detroit, MI: John Wiley & Sons, 2009, pp. 1–456.
- [65] A. T. Sayers, *Hydraulic and Compressible Flow Turbomachines*. Cape Town: A. T. Sayers, 1990.
- [66] C. Cilliers, “Cost savings on mine dewatering pumps by reducing preparation- and comeback loads,” M. Eng. dissertation, North-West University, Potchefstroom, 2013.
- [67] S. R. Shah, S. V. Jain, R. N. Patel, and V. J. Lakhera, “CFD for centrifugal pumps: A review of the state-of-the-art,” *Procedia Engineering*, vol. 51, pp. 715–720, 2013.
- [68] A. Holman, G. P. Heyns, and R. Pelzer, “Benefits of improved performance monitoring of mine cooling systems,” *Electricity and Control*, 2014.
- [69] C. B. Jacobsen, “Research and technology: The centrifugal pump,” Bjerringbro, 2008.

- [70] M. Koor, A. Vassiljev, and T. Koppel, “Optimization of pump efficiencies with different pumps characteristics working in parallel mode,” *Advances in Engineering Software*, 2015.
- [71] M. Šavar, H. Kozmar, and I. Sutlović, “Improving centrifugal pump efficiency by impeller trimming,” *Desalination*, vol. 249, no. 2, pp. 654–659, 2009.
- [72] J. Van Der Bijl, “Sustainable DSM on Deep Mine Refrigeration,” Ph.D thesis, North-West University, Potchefstroom, 2007.
- [73] J. A. Mathews, “Designing energy industries for the next industrial revolution,” *Organizational Dynamics*, vol. 39, no. 2, pp. 155–164, 2010.
- [74] R. Pelzer, E. H. Mathews, D. F. Le Roux, and M. Kleingeld, “A new approach to ensure successful implementation of sustainable demand side management (DSM) in South African mines,” *Energy*, vol. 33, no. 8, pp. 1254–1263, 2008.
- [75] J. Ralston, D. Reid, C. Hargrave, and D. Hainsworth, “Sensing for advancing mining automation capability: A review of underground automation technology development,” *International Journal of Mining Science and Technology*, vol. 24, no. 3, pp. 305–310, 2014.
- [76] South African National Energy Development Institute (SANEDI), “12L energy efficiency tax incentive frequently asked questions,” Johannesburg, 2014.
- [77] N. Khalid, “Efficient energy management: Is variable frequency drives the solution,” *Procedia Social and Behavioral Sciences*, vol. 145, pp. 371–376, 2014.
- [78] R. Saidur, S. Mekhilef, M. B. Ali, A. Safari, and H. A. Mohammed, “Applications of variable speed drive (VSD) in electrical motors energy savings,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 543–550, 2012.
- [79] P. Fonseca, S. B. Nielsen, and D. Both, “VSDs for electric motor systems,” Brussels, 2001.
- [80] W. L. Lee and F. W. H. Yik, “Framework for formulating a performance-based incentive-rebate scale for the demand-side-energy management scheme for commercial buildings in Hong Kong,” *Applied Energy*, vol. 73, no. 2, pp. 139–166, 2003.
- [81] Y. Yao, Z. Lian, Z. Hou, and X. Zhou, “Optimal operation of a large cooling system based on an empirical model,” *Applied Thermal Engineering*, vol. 24, no. 16, pp. 2303–2321, 2004.
- [82] M. Kleingeld, A. Fourie, R. Pelzer, and M. Slade, “Optimising control of a combined mine pumping and refrigeration system,” in *The 5th Industrial and Commercial Use of Energy (ICUE) Conference*, Cape Town, 2008.

-
- [83] D. Lee and C. C. Cheng, “Energy savings by energy management systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 760–777, 2016.
- [84] J. Calitz, “Research and implementation of a load reduction system for a mine refrigeration system,” Ph.D thesis, North-West University, Potchefstroom, 2006.
- [85] L. Mackay, S. Bluhm, and J. Van Rensburg, “Refrigeration and cooling concepts for ultra-deep platinum mining,” in *The 4th International Platinum Conference*, pp. 285–292, Cape Town, 2010.
- [86] I. G. Boake, “A strategy for electrical load management in the South African mining industry,” Ph.D thesis, Rand University, Johannesburg, 2003.
- [87] P. A. De Villiers, R. P. Coetzee, and L. J. Grobler, “Measurement and verification methodology for industrial compressed air load management on a mine,” in *The 6th Industrial and Commercial Use of Energy (ICUE) Conference*, Cape Town, 2009.
- [88] T. Matlala, “Industrial demand side management in South Africa,” in *The Industrial and Commercial Use of Energy (ICUE) Conference*, Cape Town, 2004.
- [89] C. A. Van Der Merwe and L. J. Grobler, “Applying and evaluating the baseline energy consumption model for calorifiers for measurement and verification purposes,” in *The 12th Industrial and Commercial Use of Energy (ICUE) Conference*, 2015.
- [90] H. Winkler, R. Spalding-Fecher, S. Mwakasonda, and O. Davidson, “Sustainable development policies and measures,” *Options for Protecting the Climate*, World Resource Institute, Washington, DC, 2002.
- [91] H. Z. Abou-Ziyan and A. F. Alajmi, “Effect of load-sharing operation strategy on the aggregate performance of existed multiple-chiller systems,” *Applied Energy*, vol. 135, pp. 329–338, 2014.
- [92] G. P. Heyns, “Challenges faced during implementation of a compressed air energy savings project on a gold mine,” M. Eng. dissertation, North-West University, Potchefstroom, 2014.
- [93] A. Fay, B. Vogel-Heuser, T. Frank, K. Eckert, T. Hadlich, and C. Diedrich, “Enhancing a model-based engineering approach for distributed manufacturing automation systems with characteristics and design patterns,” *Journal of Systems and Software*, vol. 101, pp. 221–235, 2015.
- [94] Eskom Holdings Ltd, “Eskom tariffs & charges 2015/16,” Eskom Holdings Ltd, Johannesburg, South Africa, 2016.
- [95] Eskom Holdings Ltd, “Eskom tariffs & charges 2016/17,” Eskom Holdings Ltd, Johannesburg, South Africa, 2016.

Appendix A:

Eskom tariff structures

As part of Eskom's condonable efforts to satisfy the electricity supply, different tariff and billing structures were developed for the various electricity consumers. Several tariff structures were developed to specifically suit the requirements of the electricity consumers and was therefore classified according to the usage. Consumers with a notified maximum demand (NMD) exceeding 1 MVA are classified in the Megaflex tariff structure. Subsequently, most of the South African deep-level gold mines are exorbitant energy users with a NMD far exceeding 1 MVA and are therefore classified as part of the Megaflex tariff structure [95].

Figure A-1 illustrates the different active energy charges used by Eskom as part of the Mageflex tariff structure. Notice, the Megaflex tariff is a time-of-use (TOU) structure which varies according to low and high demand seasons but also according to peak, standard and off peak period.

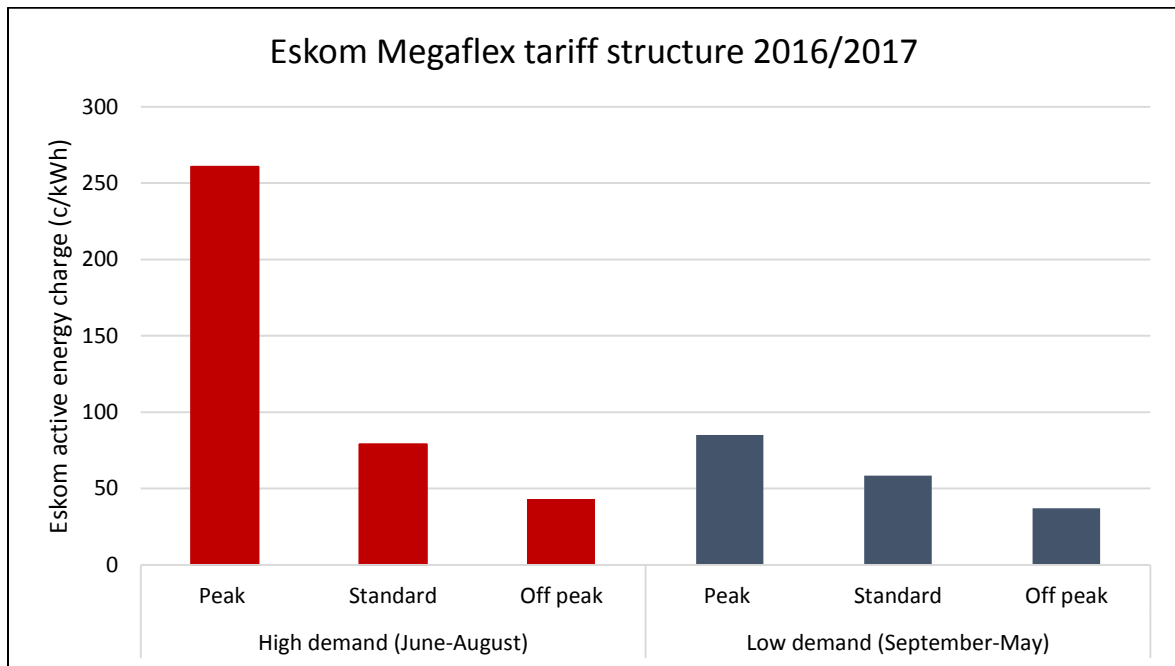


Figure A-1: Eskom Megaflex tariff structure 2016/2017 [95]

Figure A-2 illustrates the different TOU periods included in the Megaflex tariff structure for 2016/2017.

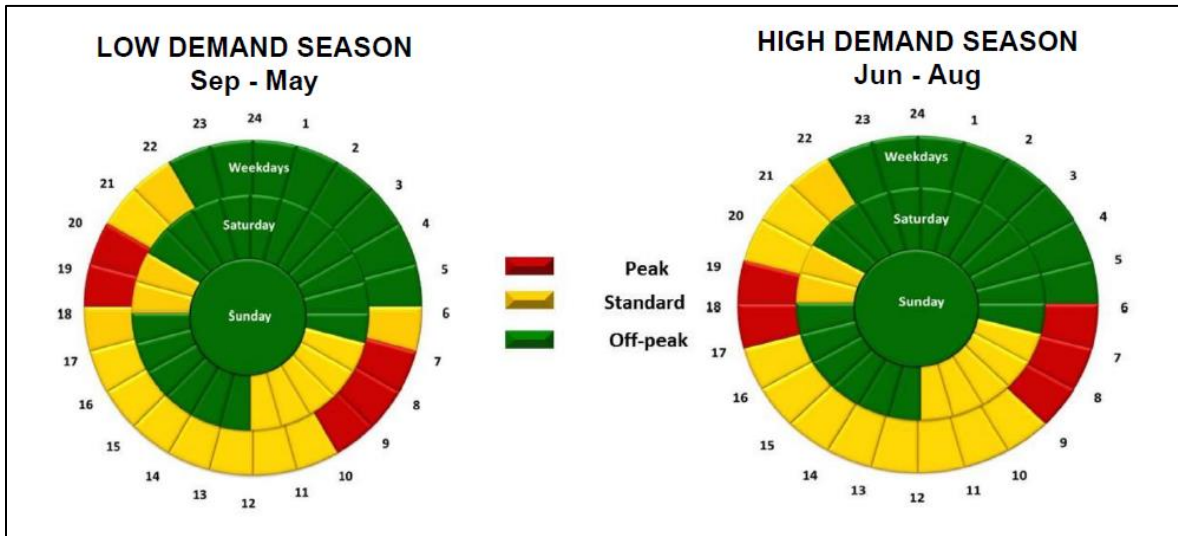


Figure A-2: Eskom Megaflex TOU tariff [95]

Appendix B:

Mine A system specification

Table B-1: Mine A refrigeration machine specification

Refrigeration machines	
Number of fridge plants	6
Make	York
Compressor type	Centrifugal
Refrigerant	R134a
Voltage (V)	6600
Cooling capacity (kW)	6500
COP	5.5
Evaporator outlet temperature (°C)	3
Condenser inlet temperature (°C)	27
Evaporator water flow (kg/s)	250
Condenser water flow (kg/s)	450
Evaporator pump motor rating (kW)	110
Number of evaporator pumps	6
Condenser pump motor rating (kW)	160
Number of condenser pumps	6

Table B-2: Mine A condenser cooling tower specification

Condenser cooling towers	
Number of cooling towers	6
Water inlet temperature (°C)	31
Water outlet temperature (°C)	27.5
Water flow (kg/s)	450
Air inlet wet-bulb temperature (°C)	22

Table B-3: Mine A precooling tower specification

Precooling towers	
Number of cooling towers	2
Water inlet temperature (°C)	30
Water outlet temperature (°C)	24
Water flow (kg/s)	360
Air inlet wet-bulb temperature (°C)	22
Pump motor rating (kW)	70
Number of pumps	4

Table B-4: Mine A BAC cooling tower specification

BAC cooling towers	
Number of BACs	3
Water inlet temperature (°C)	3
Water outlet temperature (°C)	9
Water flow (kg/s)	250
Airflow (kg/s)	250
Air inlet wet-bulb temperature (°C)	18
Air outlet wet-bulb temperature (°C)	7
Pump motor rating (kW)	75

Table B-5: Mine A control philosophy specification

Evaporator flow control loop	
Maintain a constant chill dam level	90%
Condenser flow control loop	
Maintain a constant temperature rise across condenser	5°C
BAC flow control loop	
Control VSDs according to ambient enthalpy	30-70 kJ/kg
Precooling tower flow control loop	
Maintain a constant precooling sump level	90%
Maintain a constant hot dam level	90%

Appendix C:

Mine A simulation

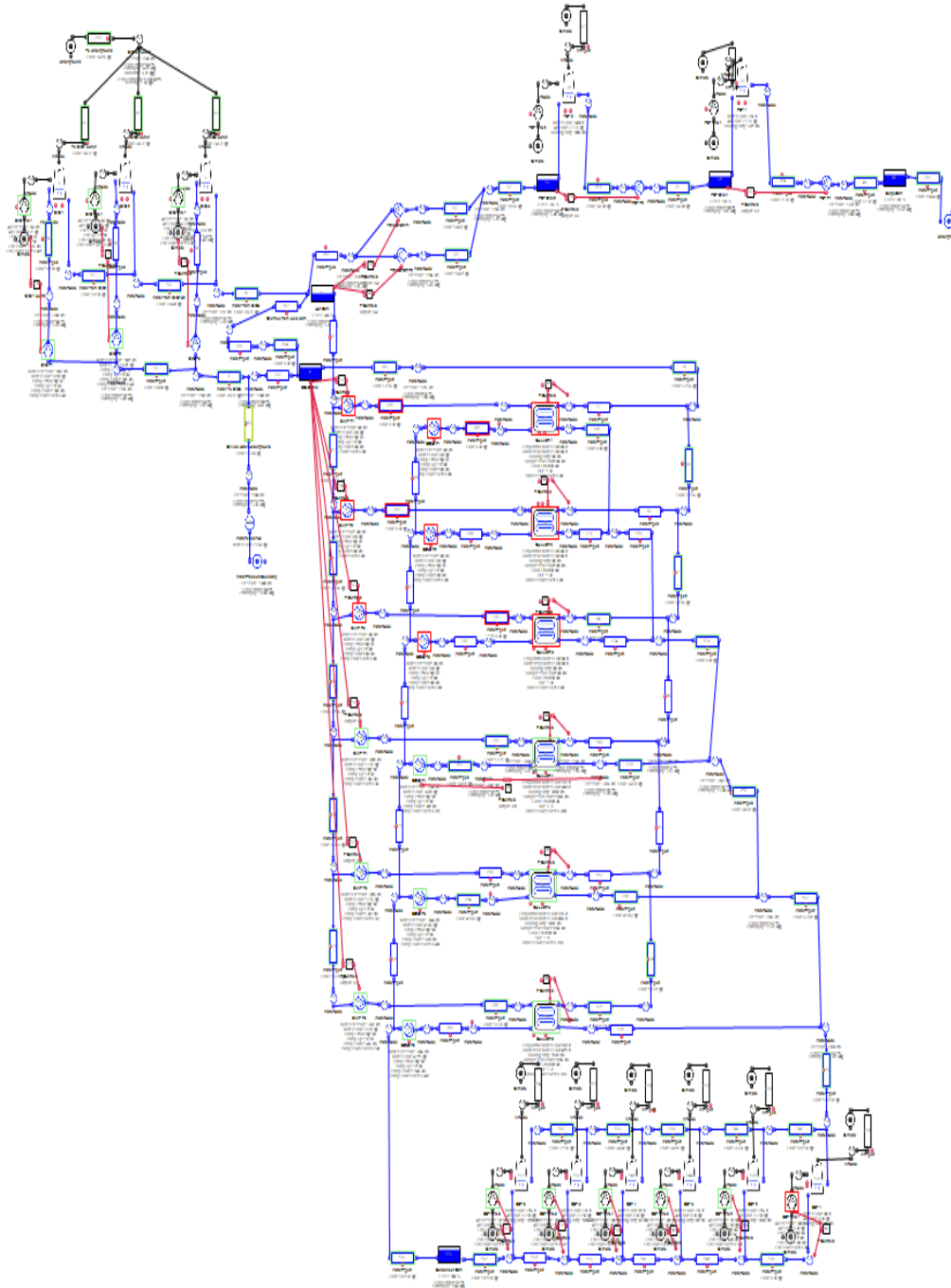


Figure C-1: Mine A PTB simulation

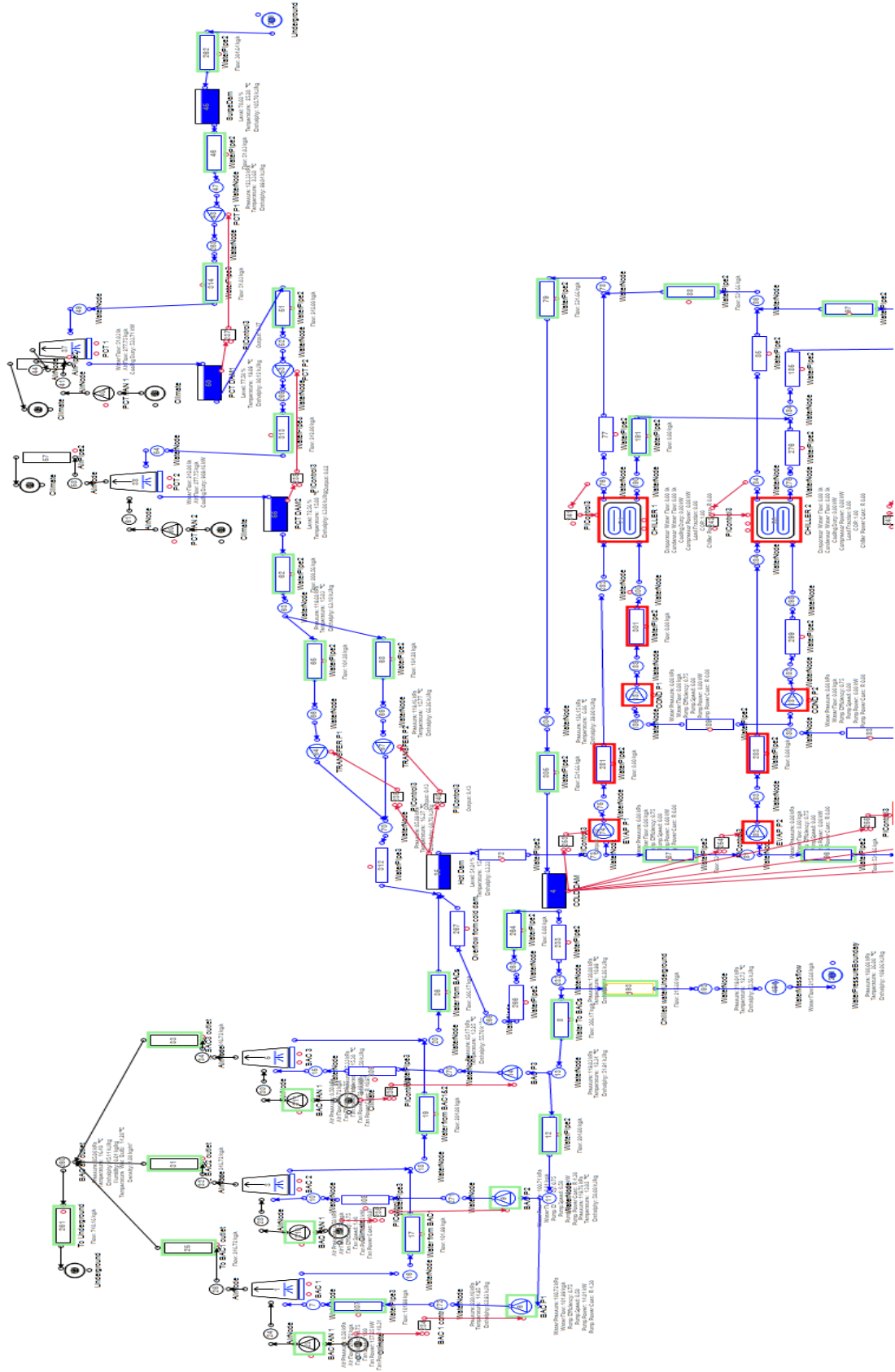


Figure C-2: Mine A PTB simulation detail part 1

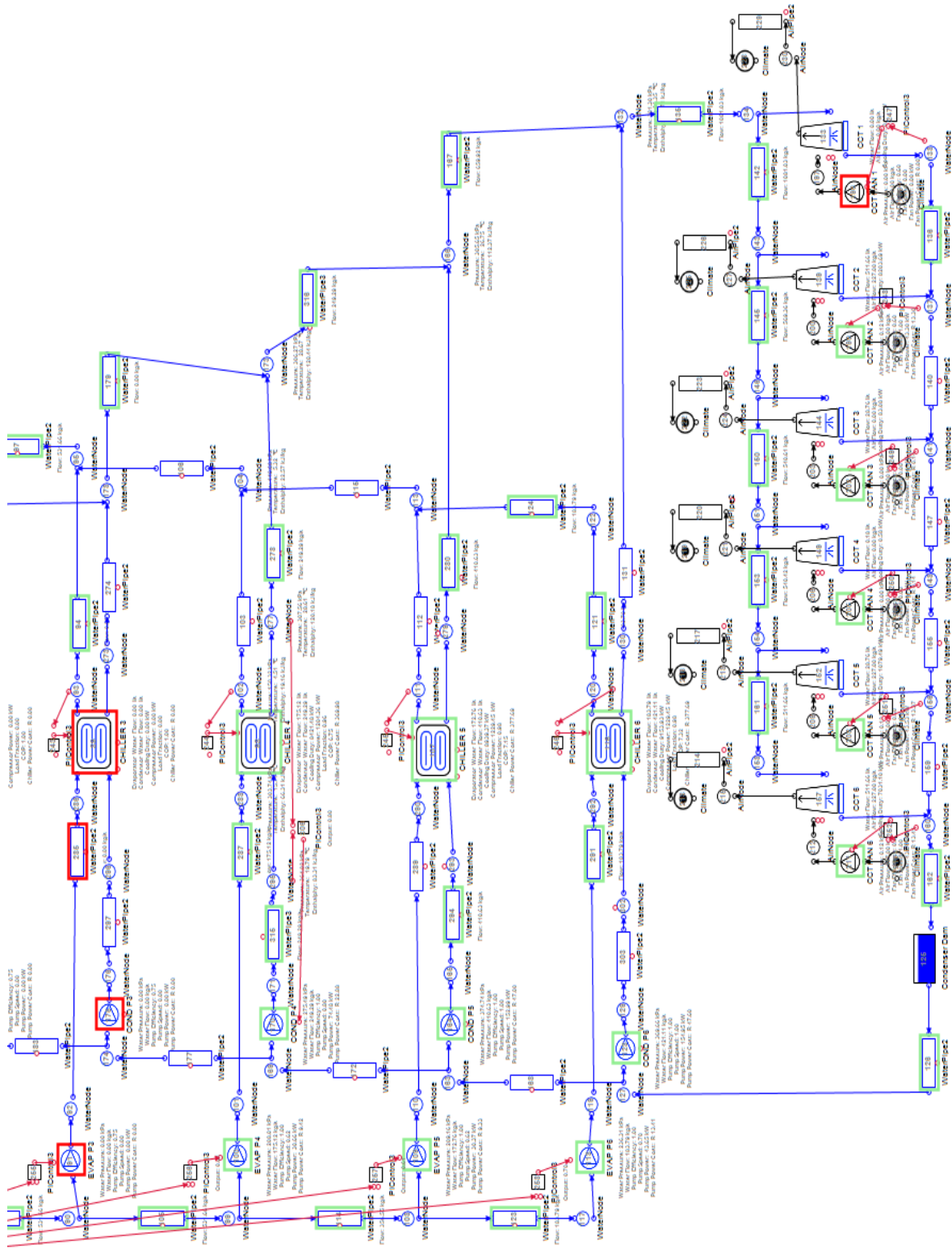


Figure C-3: Mine A PTB simulation detail part 2

Appendix D:

Mine B system specification

Table D-1: Mine B refrigeration machine specification

Refrigeration machines	
Number of fridge plants	4
Make	Hitachi
Compressor type	Centrifugal
Refrigerant	R134a
Voltage (V)	6600
Cooling capacity (kW)	2900
COP	6.65
Evaporator outlet temperature (°C)	5.9
Condenser inlet temperature (°C)	18.5
Evaporator water flow (kg/s)	300
Condenser water flow (kg/s)	600
Evaporator pump motor rating (kW)	90
Number of evaporator pumps	4
Condenser pump motor rating (kW)	185
Number of condenser pumps	5

Table D-2: Mine B condenser cooling tower specification

Condenser cooling towers	
Number of cooling towers	4
Water inlet temperature (°C)	32
Water outlet temperature (°C)	27.5
Water flow (kg/s)	670
Air inlet wet-bulb temperature (°C)	22

Table D-3: Mine B precooling tower specification

Precooling towers	
Number of cooling towers	8
Water inlet temperature (°C)	28
Water outlet temperature (°C)	24
Water flow (kg/s)	300
Air Inlet Wet-Bulb Temperature (°C)	7
Pump motor rating (kW)	75
Number of pumps	2

Table D-4: Mine B BAC cooling tower specification

BAC cooling towers		
Type of fans equipped	Main surface	Rock vent
Number of BACs	2	1
Water inlet temperature (°C)	3	3
Water outlet temperature (°C)	14	14
Water flow (kg/s)	150	150
Airflow (kg/s)	225	230
Air inlet wet-bulb temperature (°C)	18	18
Air outlet wet-bulb temperature (°C)	7	7
Pump motor rating (kW)	75	75

Table D-5: Mine B control philosophy

Evaporator flow control loop	
Maintain a constant chill dam level	95%
Condenser flow control loop	
Maintain a constant temperature rise across condenser	5°C
BAC flow control loop	
Control VSDs according to ambient enthalpy	20-70 kJ/kg
Precooling tower flow control loop	
Maintain a constant precooling sump level	90%
Maintain a constant hot dam level	90%

Appendix E:

Mine B simulation

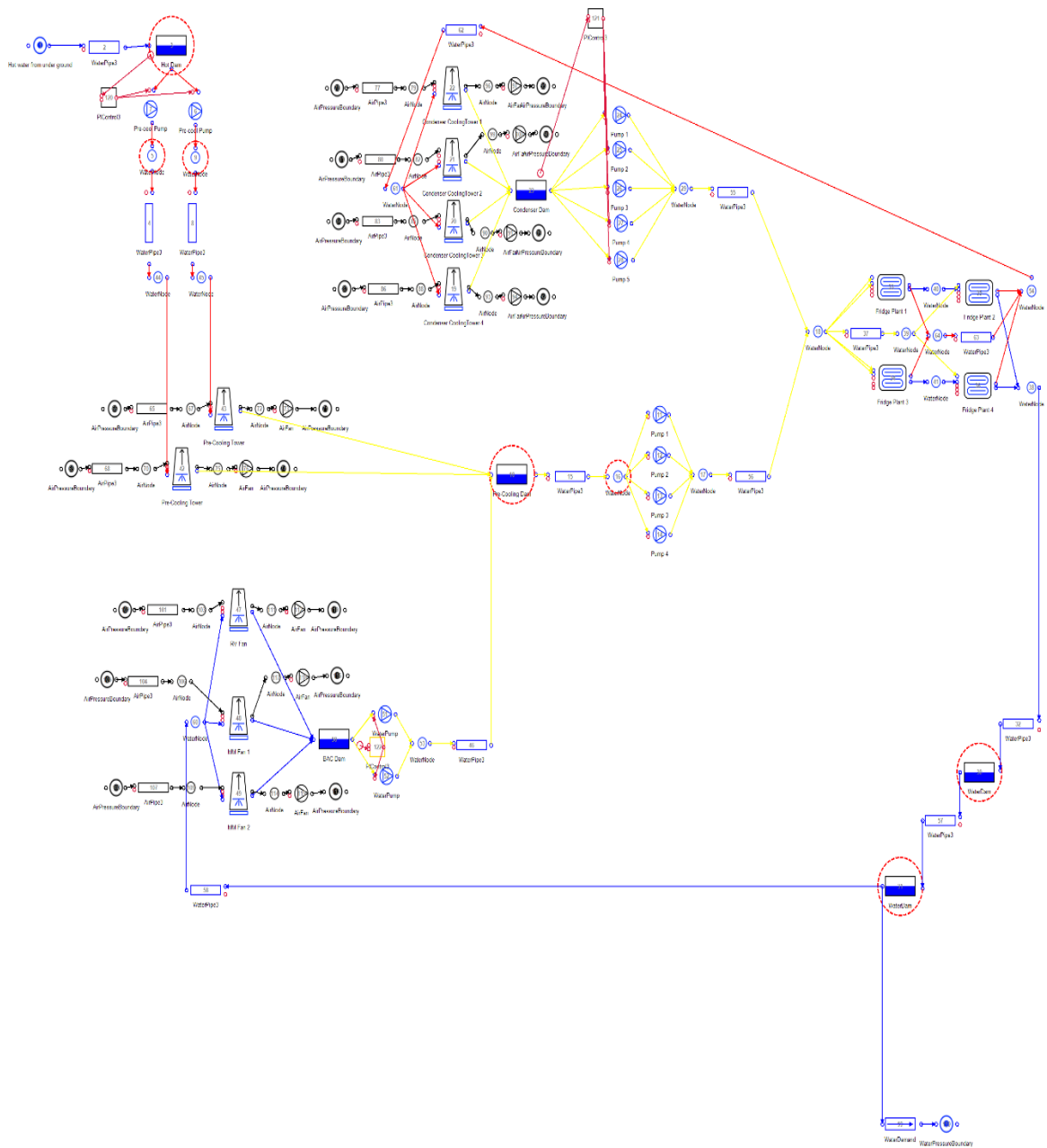


Figure E-1: Mine B PTB simulation

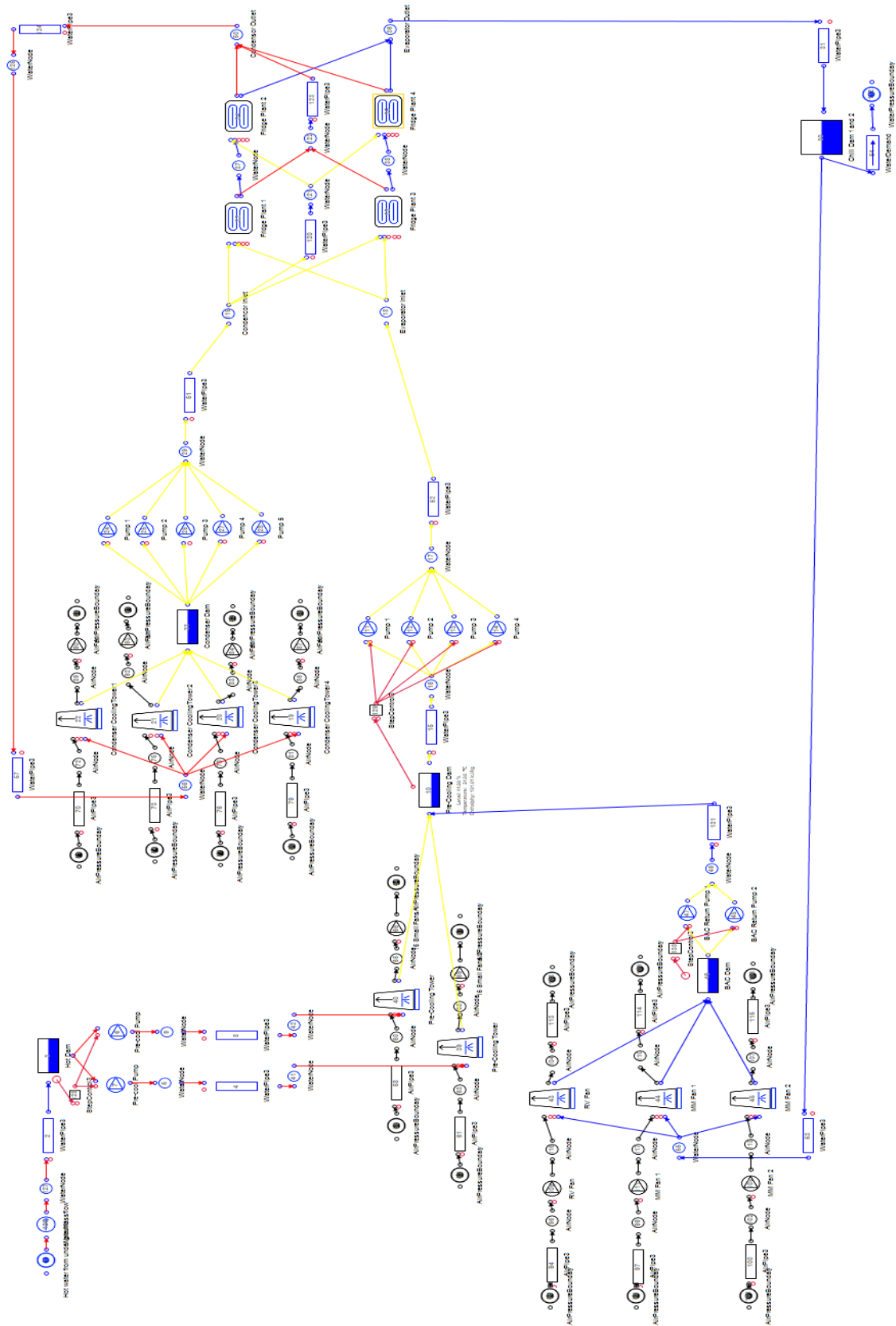


Figure E-2: Mine B PTB simulation detail

Appendix F:

Mine B VSD quotations

We thank you for your valued request to strip and quote, and herewith provide you with our quotation:-

ITEM	QTY	DESCRIPTION	PRICE EACH	TOTAL
A		<u>Normal Repair Cost</u>		
	2	VARIABLE SPEED DRIVE ATV61 FOR REPAIR.		
		MAKE: Schneider Altivar 61 PART No.: <u>ATV61HC25Y</u>		
	a)	VSD BODY SERIAL No.: # 881131000005	B.E.R.	B.E.R.
		Labour: R 13 300.00 Spare Parts: R 120 645.54		
		B.E.R: <i>The above serial no. was scrapped due to the Hardware spares the ETA of the import spares. (4-6 Weeks). Warranty on replacement spares 3 Months. Thus the unit was found beyond economical to repair.</i>	R 133 945.54	
1	a)	<u>Offer:</u> Service Exchange Unit Offer Replaced PNo.: ATV61HC25Y (ZZASRV-16YG) ** Replacement Serial No.: # Delivery = 1 Week/ prior to your order.	R 136 500.00	R 136 500.00
	b)	MAKE: Schneider Altivar 61 PART No.: <u>ATV61HC13Y</u> VSD BODY SERIAL No.: # 881123000086		
		Labour: R 13 300.00 Spare Parts: R 118 217.39		
		B.E.R: <i>The above serial no. was scrapped due to the Hardware spares the ETA of the import spares. (4-6 Weeks). Warranty on replacement spares 3 Months. Thus the unit was found beyond economical to repair.</i>	R 131 517.39	
1	b)	<u>Offer:</u> Service Exchange Unit Offer Replaced PNo.: ATV61HC13Y (ZZASRV-16YG) ** Replacement Serial No.: # Delivery = 1 Week/ prior to order.	R 89 900.00	R 89 900.00

Figure F-1: Mine B VSD quotation part 1 of 2

We thank you for your valued request to strip and quote, and herewith provide you with our quotation:-

ITEM	QTY	DESCRIPTION	PRICE EACH	TOTAL
		<p>██</p> <p>██</p> <p>██</p> <p>██</p> <p style="text-align: center;">Repair ONo.: ORD.: 205330-ELK Workshop Order.: HPR. 585969 Radio Clear Cert.: No.: Ext Wayb. 810716</p>		
A. 1		PERCENTAGE VALUE OF NEW UNITS TO REPAIR COST:	51%	
DISCOUNT:		NETT		
V.A.T.:		EXCLUDED		
DELIVERY:		1 WEEKS/ SUBJECT TO PRIOR ORDER (Service Exchange Offer)		
			TOTAL:	R 226 400.00
WARRANTY:		3 MONTHS ON REPAIRED UNITS/ 12MNTHS ON SERVICE EXCHANGE		██
VALIDITY:		14 DAYS FROM THE DATE HEREON		██
R.O.E:		ALL PRICES QUOTED ARE SUBJECT TO CHANGES AND VARIANCES IN THE RATE OF EXCHANGE.		

Figure F-2: Mine B VSD quotation part 2 of 2

Appendix G:

Mine B example report

1.2 Cooling Auxiliaries

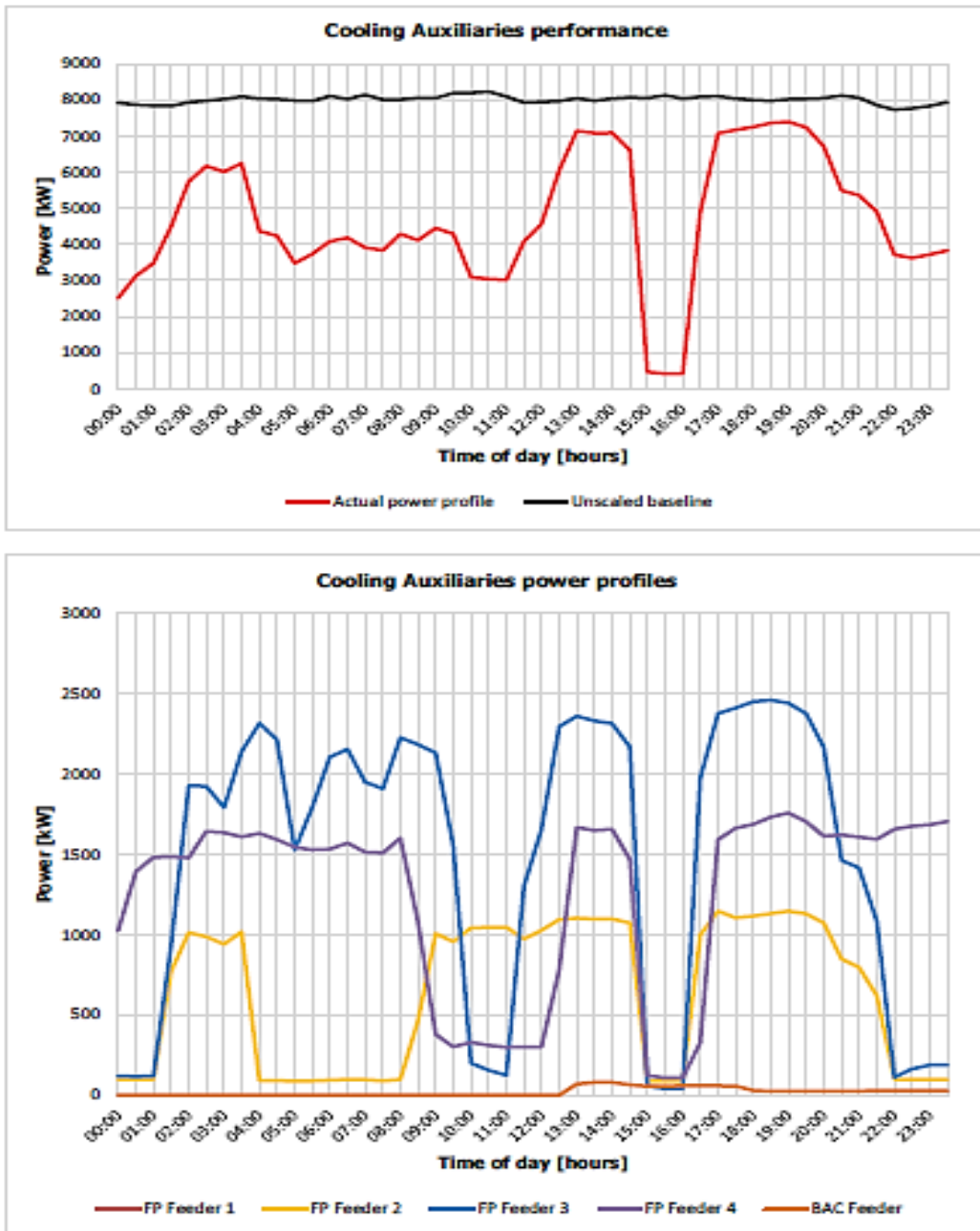


Figure G-1: Example report part 1 of 8

Table 1-3: Evaporator pumps min and max frequency limits

Pump	Min	Max
1	37.00	45.00
2	36.00	46.00
4	38.00	41.00

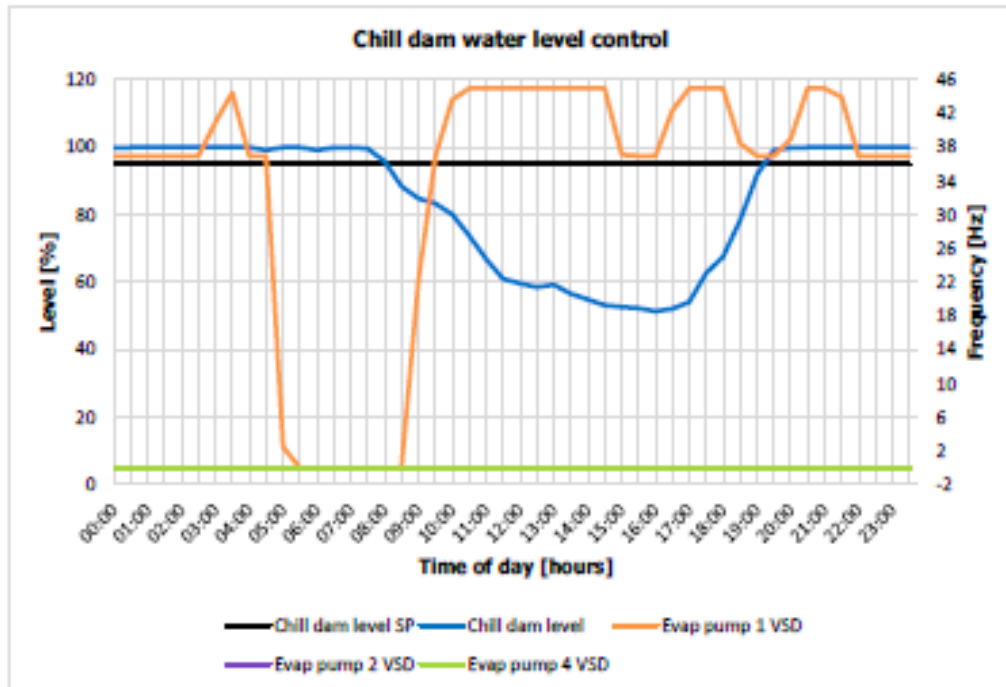


Table 1-4: BAC return pumps min and max frequency limits

Pump	Min	Max
1	38.00	45.00
2	40.00	50.00

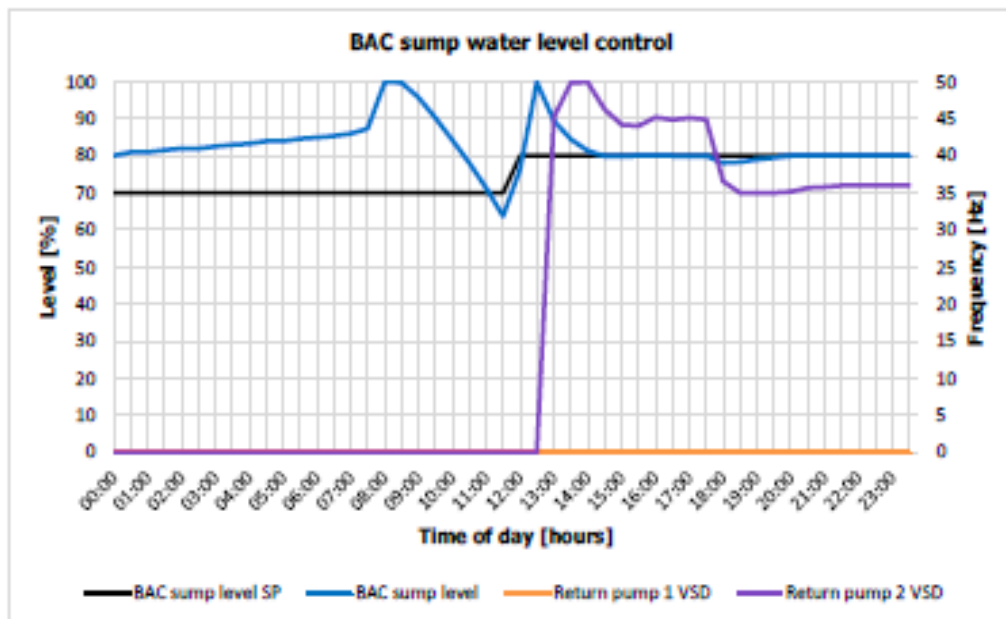


Figure G-2: Example report part 2 of 8

Table 1-5: Condenser pumps min and max frequency limits

Pump	Min	Max
1	42.00	48.00
2	37.00	50.00
3	38.00	45.00

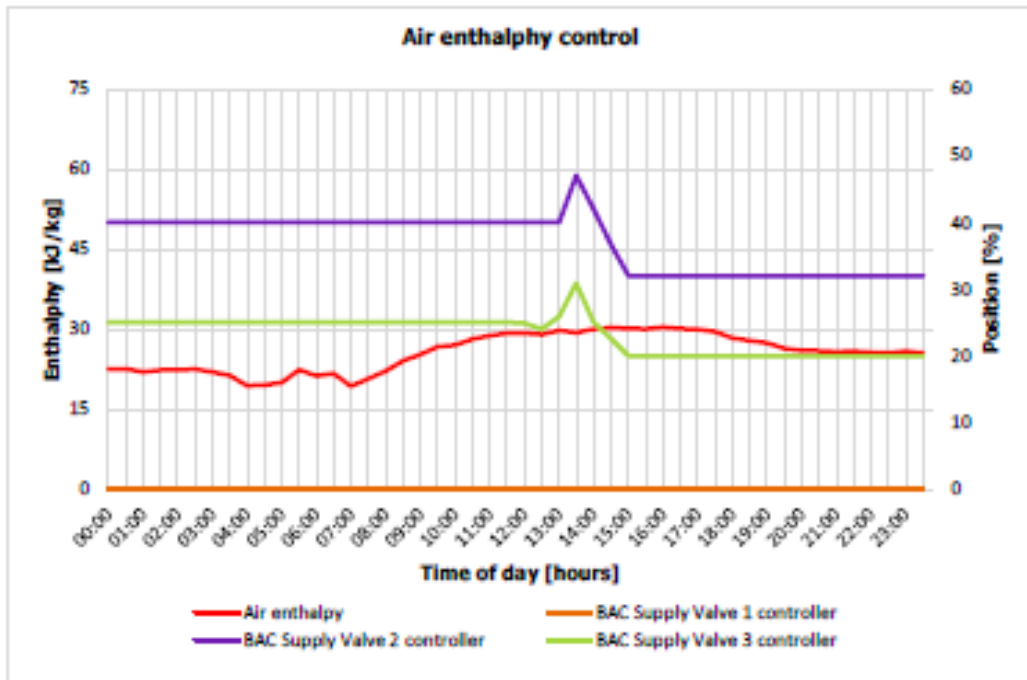
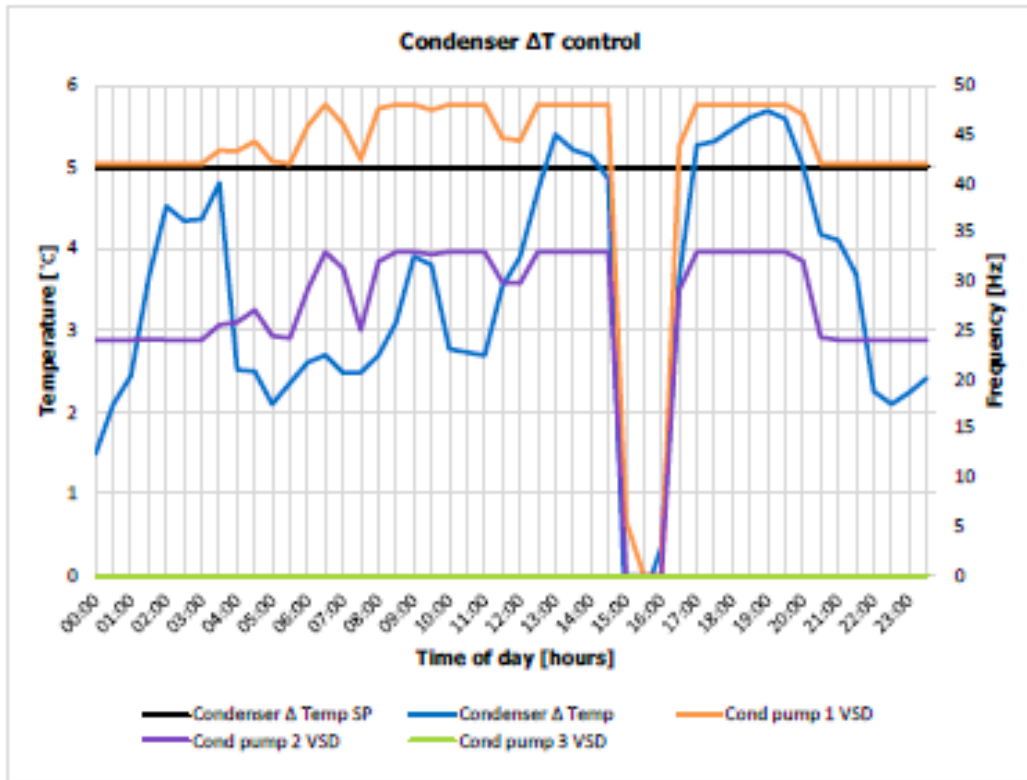


Figure G-3: Example report part 3 of 8

1.3 Fridge plant

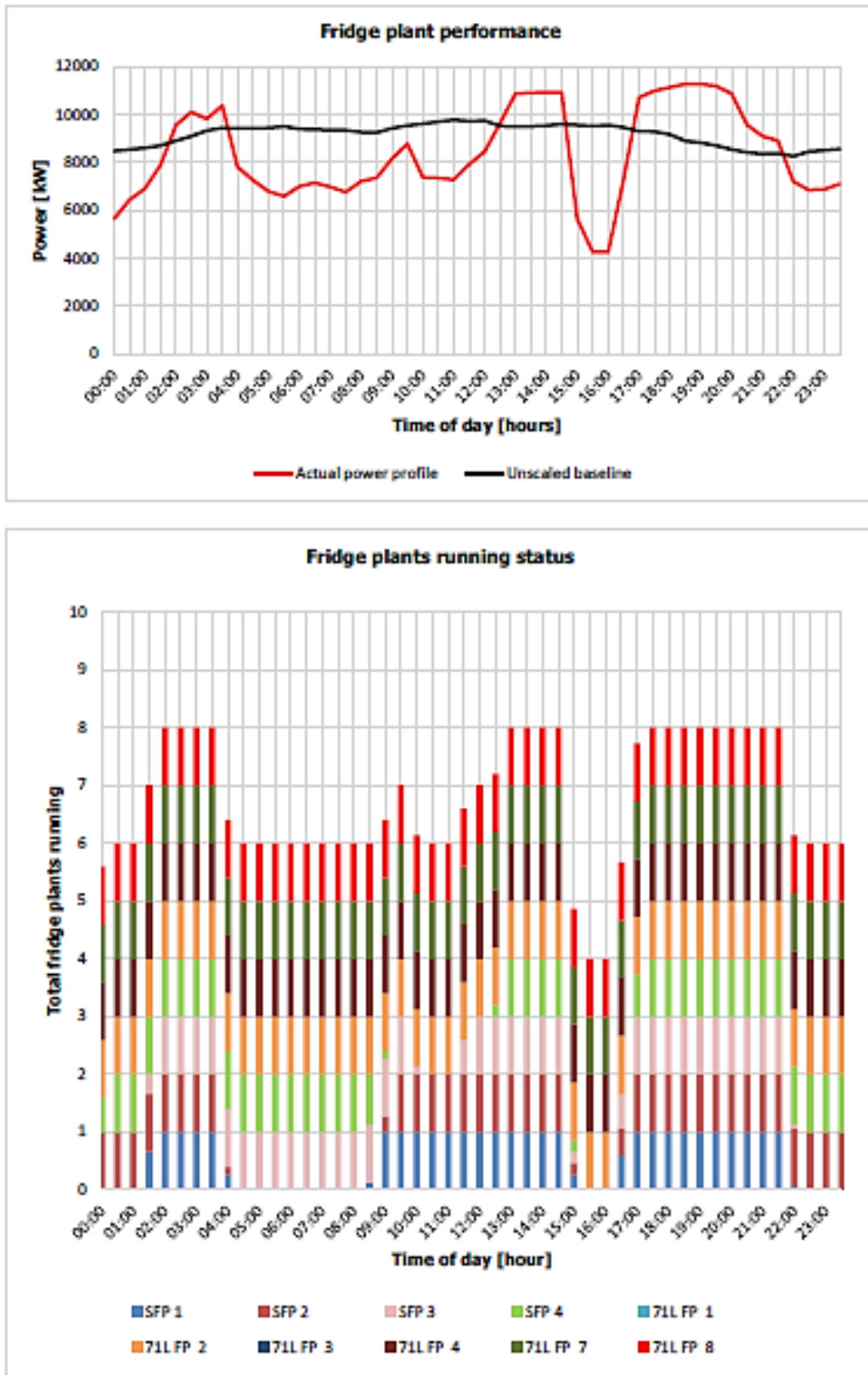


Figure G-4: Example report part 4 of 8

Table 1-6: Fridge plants running statuses

Time	SFPs				71L FPs					
	1	2	3	4	1	2	3	4	7	8
00:00	1.0	0.0	0.0	0.6	0.0	1.0	0.0	1.0	1.0	1.0
00:30	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
01:00	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
01:30	1.0	0.7	0.3	1.0	0.0	1.0	0.0	1.0	1.0	1.0
02:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
02:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
03:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
03:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
04:00	0.1	0.3	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
04:30	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
05:00	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
05:30	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
06:00	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
06:30	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
07:00	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
07:30	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
08:00	0.0	0.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
08:30	0.0	0.1	1.0	0.9	0.0	1.0	0.0	1.0	1.0	1.0
09:00	0.3	1.0	1.0	0.1	0.0	1.0	0.0	1.0	1.0	1.0
09:30	1.0	1.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
10:00	1.0	1.0	0.1	0.0	0.0	1.0	0.0	1.0	1.0	1.0
10:30	1.0	1.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
11:00	1.0	1.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
11:30	1.0	1.0	0.6	0.0	0.0	1.0	0.0	1.0	1.0	1.0
12:00	1.0	1.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
12:30	1.0	1.0	1.0	0.2	0.0	1.0	0.0	1.0	1.0	1.0
13:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
13:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
14:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
14:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
15:00	0.2	0.3	0.2	0.2	0.0	1.0	0.0	1.0	1.0	1.0
15:30	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
16:00	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0
16:30	0.5	0.6	0.6	0.0	0.0	1.0	0.0	1.0	1.0	1.0
17:00	1.0	1.0	1.0	0.7	0.0	1.0	0.0	1.0	1.0	1.0
17:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
18:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
18:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
19:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
19:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
20:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
20:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
21:00	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
21:30	1.0	1.0	1.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
22:00	1.0	0.1	0.1	1.0	0.0	1.0	0.0	1.0	1.0	1.0
22:30	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
23:00	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0
23:30	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0

Figure G-5: Example report part 5 of 8

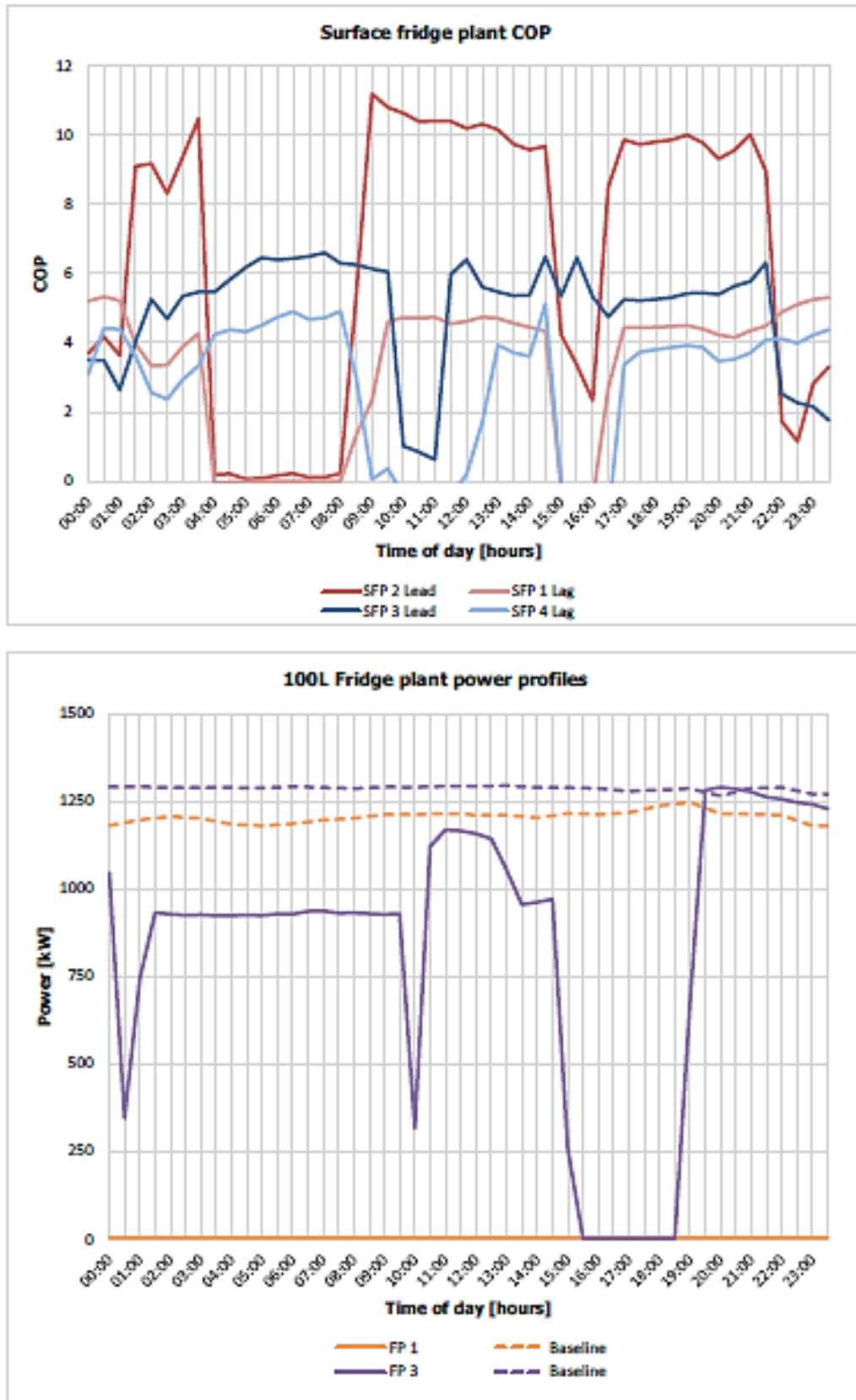


Figure G-6: Example report part 6 of 8

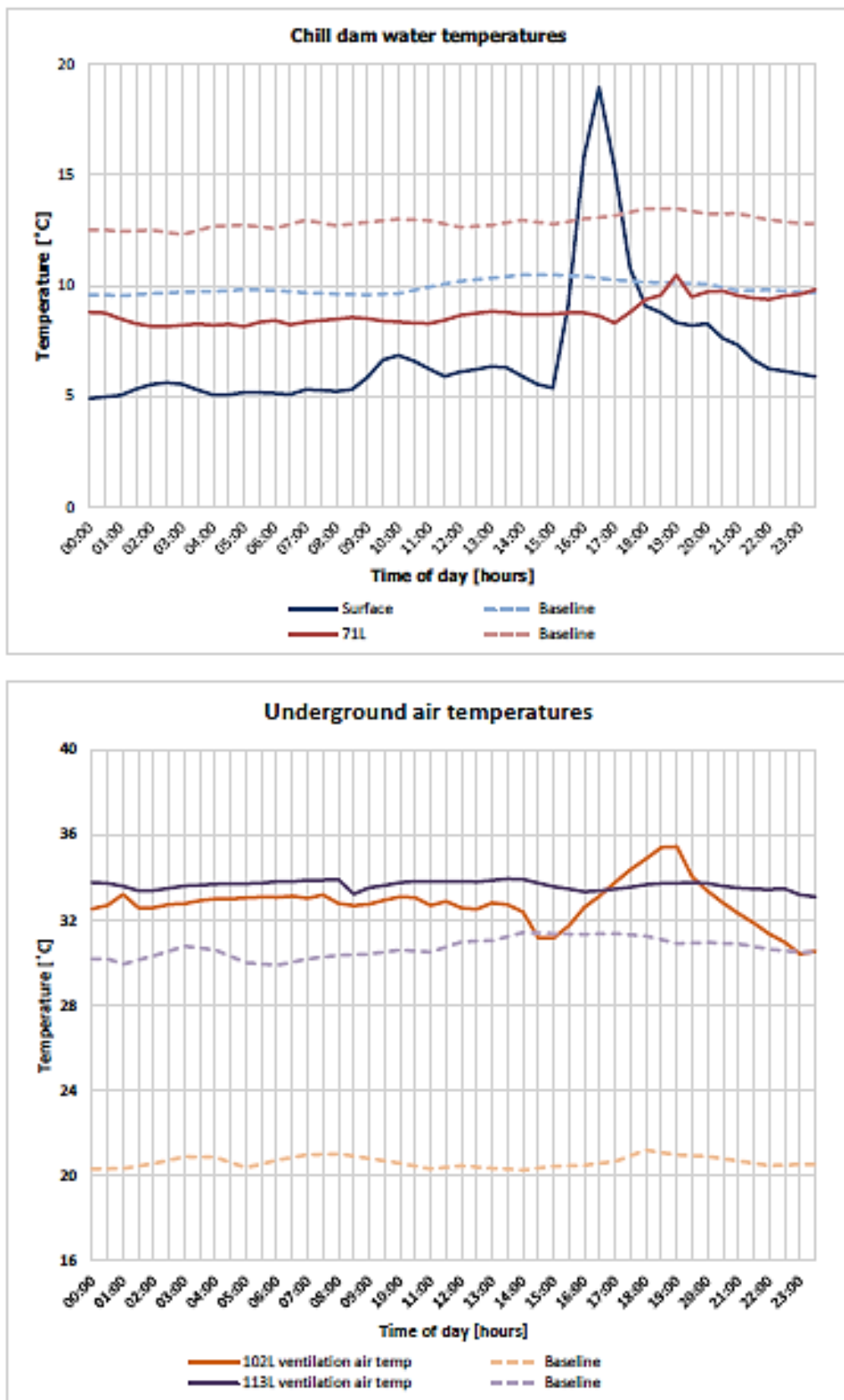


Figure G-7: Example report part 7 of 8

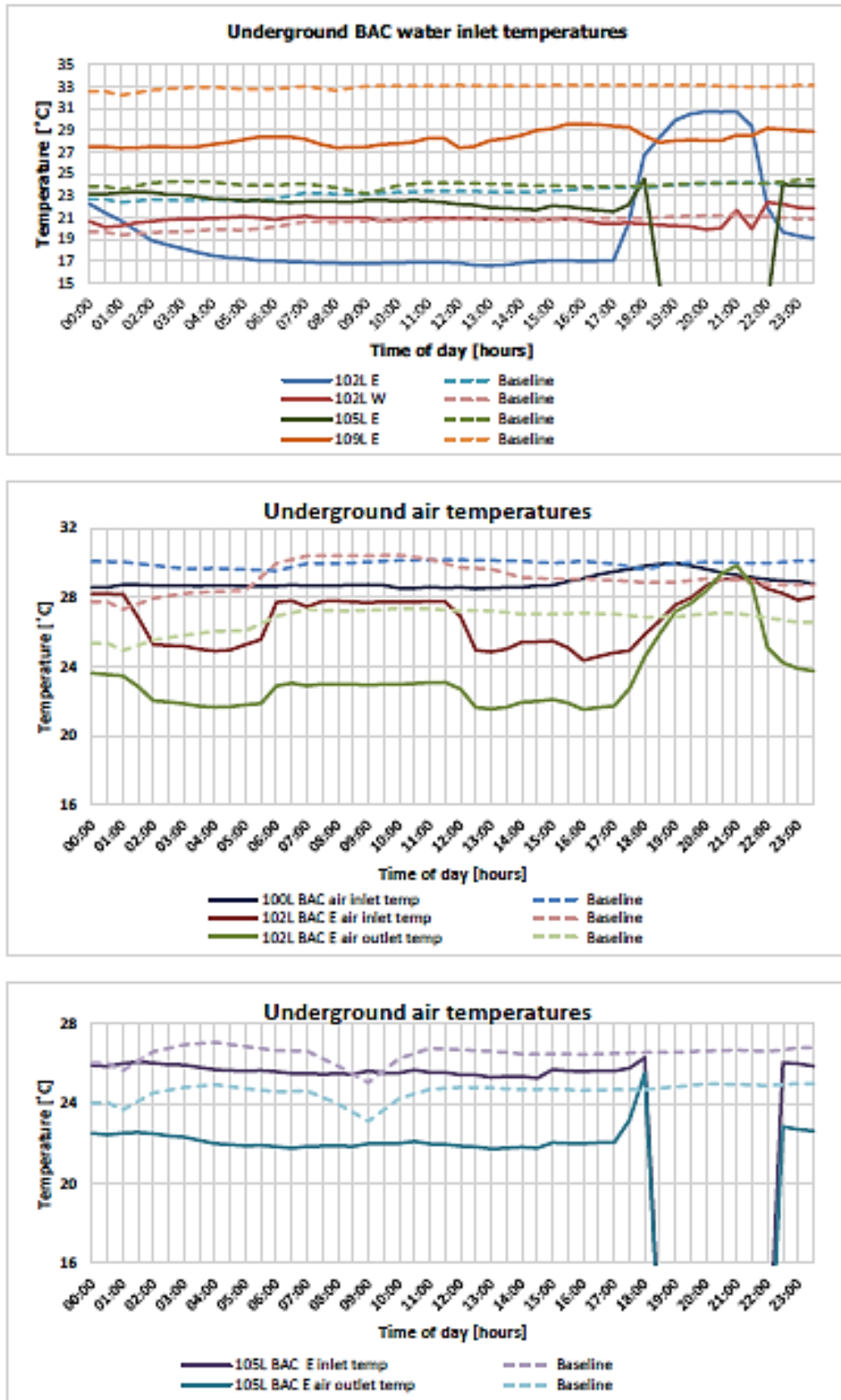


Figure G-8: Example report part 8 of 8