Cost effective control of a platinum mine cooling system using combined DSM strategies

J. Engles

21681872

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

Supervisor: Dr. M. Kleingeld

November 2015

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT ®

It all starts here ™

Field Cod

ABSTRACT

Title: Cost effective control of a platinum mine cooling system using combined DSM strategies

Author: J. Engles

Supervisor: Prof. M. Kleingeld

Keywords: Electrical energy saving, Demand Side Management (DSM), refrigeration plants, Energy Services Company (ESCO), Eskom

The platinum mining industry in South Africa faces various challenges. Increasing labour and energy costs as well as dropping commodity prices threaten the sustainability of the industry. Reducing energy usage and cost will aid the sector in remaining profitable. Refrigeration and cooling of mines are, among others, users of large amounts of energy. Implementation of Demand Side Management (DSM) strategies at these cooling systems will aid in both reducing energy usage and improving system efficiency.

A background of platinum mine ventilation and cooling systems were covered to determine the required system parameters that must be adhered to. Existing DSM strategies were studied to determine possible shortfalls of the approaches and likely energy savings. The energy efficiency DSM strategies place a focus on average power usage reduction. Load shifting DSM strategies place focus on the shifting of load from the evening peak to off peak periods.

A case study was carried out at a platinum mine with appropriate cooling systems and requirements. Simulations of both independent and combined strategies were carried out to determine the feasibility of implementation. All required hardware and software additions were included in the feasibility study. Simulated savings and control alterations were compared to the proposed cost of implementation to determine viability.

Power usage prior to implementation was quantified in order to accurately calculate post-implementation energy savings. Installations were carried out, including hardware and software updates. Initially a single strategy was implemented with the second strategy implemented at a later stage. This was due to a delay in approval from the mine as well as funding requirements. Upon completion of implementation, the actual acquired savings were compared to the simulated savings.

The Combined implemented strategy yielded a daily energy saving of more than 44 MWh. The corresponding cost savings were R 22,400 daily. Comparing these values with the simulated savings results showed for an over performance of approximately 25%. As a result, the viability and success of the combined strategy is proven.

ACKNOWLEDGEMENTS

The Lord for giving me the ability and opportunity to do great deeds in His name.

Prof. Eddie Matthews, Dr. Marius Kleingeld, TEMM International (Pty) Ltd and Enermanage (Pty) Ltd for both the opportunity and financial assistance to complete this study

Dr. Lodewyk van der Zee, Dr. Kobus van Tonder and Dr. Johan Marais for providing guidance and advice throughout the study.

Riaan Deysel, Leon Buys and Janco Vermeulen for assistance with investigations as well as data gathering whenever it was needed.

My family Scott, Isabel and Michael Engles, for endless words of encouragement and support.

My wife Engela Engles, for always being there for me, and pushing me to succeed.

All of my friends and family for kind words, support and prayers.

Field Cod

TABLE OF CONTENTS

Field Cod

LIST OF TABLES

LIST OF FIGURES

Field Cod

LIST OF EQUATIONS

NOMENCLATURE

Unit	Description
%	Percentage
$/oz	Dollar per ounce
MW	Megawatt
MWh	Megawatt hour
kW	Kilowatt
kWh	Kilowatt hour
°C	Degrees Celcius
ℓ/s	Litres per second
Mℓ	Megalitres
Hz	Hertz
R	Rand
V	Voltage

ABBREVIATIONS

AC	Alternating Current
BAC	Bulk Air Cooler
BIC	Bushveld Igneous Complex
COP	Coefficient Of Performance
DSM	Demand Side Management
EE	Energy Efficiency
EMS	Energy Management System
ESCO	Energy Services Company
GDP	Gross Domestic Product
LS	Load Shift
NPSH	Net Positive Suction Head
PGM	Platinum Group Metals
PLC	Programmable Logic Controller
PTB	Process Toolbox
SA	South Africa
SCADA	Supervisory Control and Data Acquisition
SSM	Supply Side Management
US	United States
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive

1. INTRODUCTION

1.1 PLATINUM MINING IN SOUTH AFRICA

As of 2002 South Africa (SA) held 87.7% of the world's known reserves of platinum group metals [1]. As a result of this, SA accounts for more than 70% of platinum production worldwide [2]. The mining sector contributes significantly towards the country's gross domestic product (GDP). Platinum mining in particular produced over four million ounces of material in 2013, accounting directly for 1.4% of the SA GDP in that year [2], [3].

Figure 1 shows the mining sector's contribution to the SA GDP year by year. It is clear that the mining sector's economic contribution has shrunk drastically. The sector decreased in size by 4.17 billion United States (US) dollars between 2012 and the second quarter of 2014. This is a decrease of more than 19% [4].

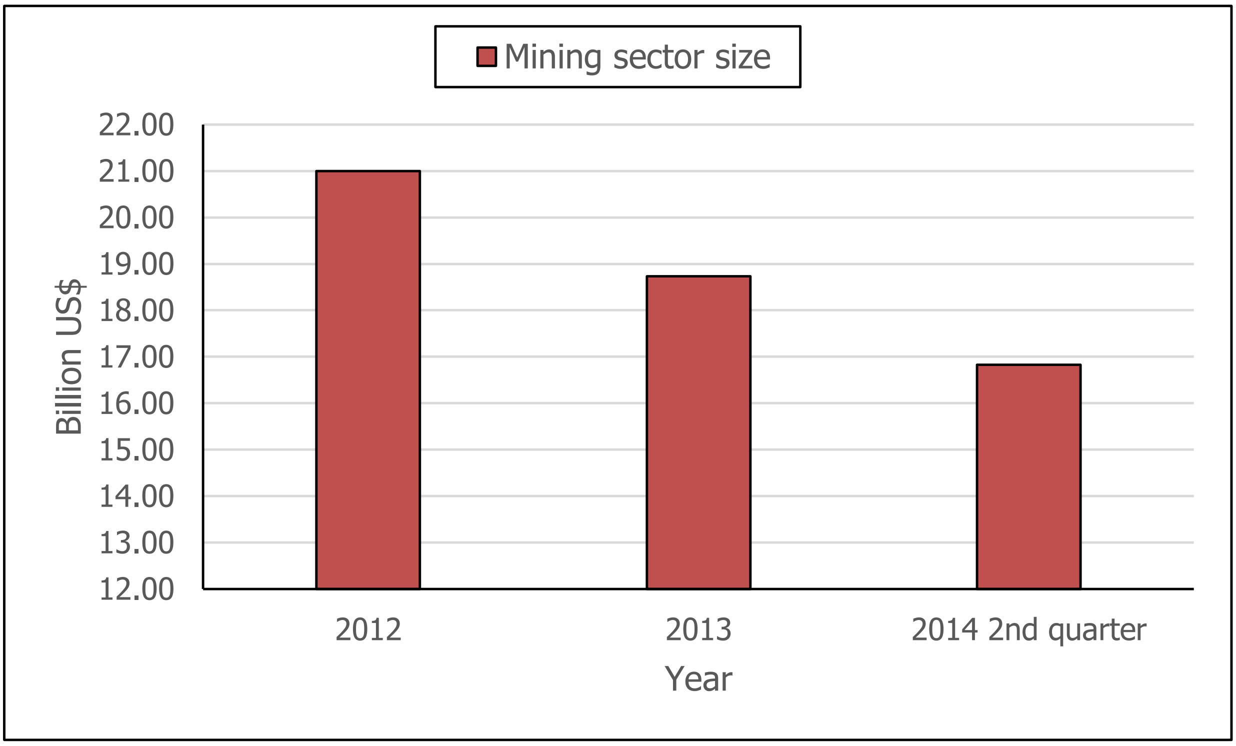


Figure 1: Mining sector contribution to the SA GDP year by year [5]

In recent years, the South African mining sector has experienced increasing pressure due to various factors. Mine closures, labour strife and reduced ore quality have been the major factors involved [6]. Further impeding progress in the sector is the declining platinum price, as shown in Figure 2.

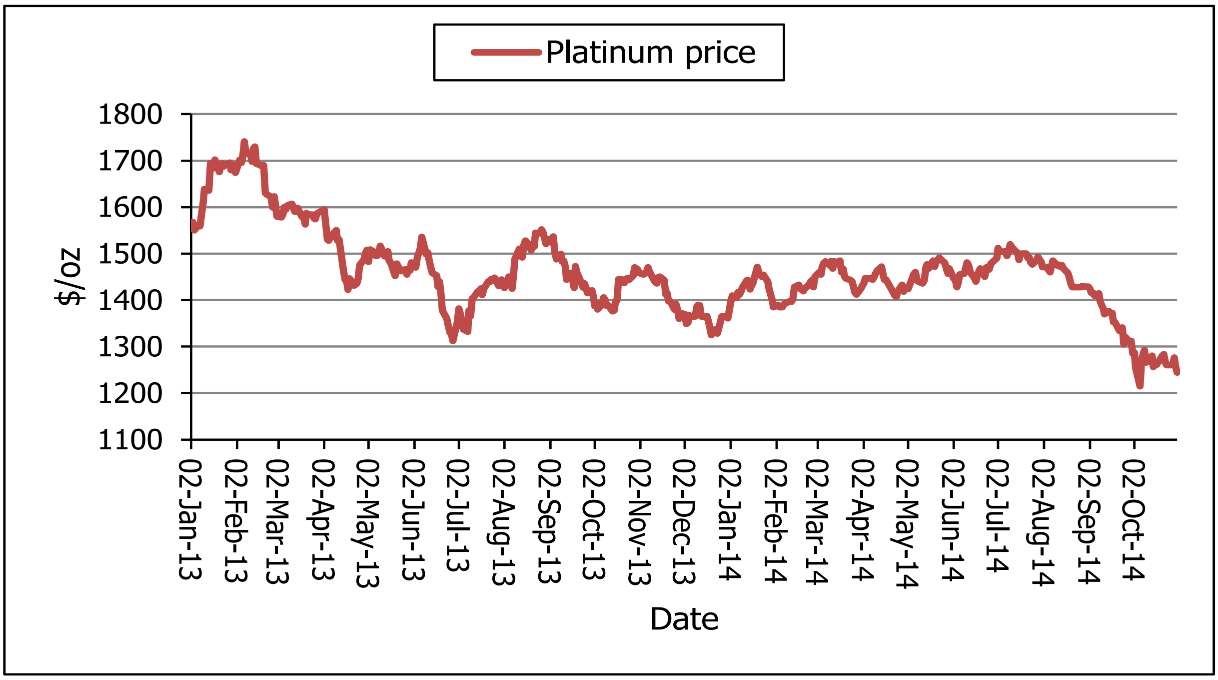


Figure 2: Platinum price per ounce 2013-2014 [7]

The selling price of platinum has seen a steady decline between January 2013 and October 2014. The average selling price for January 2013 was 1646.73 $/oz, compared to 1267.17 $/oz for October 2014. This is a drop of approximately 23% in the platinum price over 22 months. Furthermore, the period between July 2014 and October 2014 showed a price drop from a maximum 1520 $/oz to a minimum 1214 $/oz. This is a drop of over 20% in a period of four months [7]. The cost of platinum is thus showing a downward trend, dropping the profit per kg produced. This in turn places greater strain on Platinum Group Metals (PGM) mines.

Labour relations at SA mines also adversely affect operations. Protected and unprotected strike actions have increased dramatically. This lead to severe losses, downtime, increased training costs and loss of morale in mining companies. Platinum mines in particular have experienced crippling strikes, severely cutting efficiency [8].

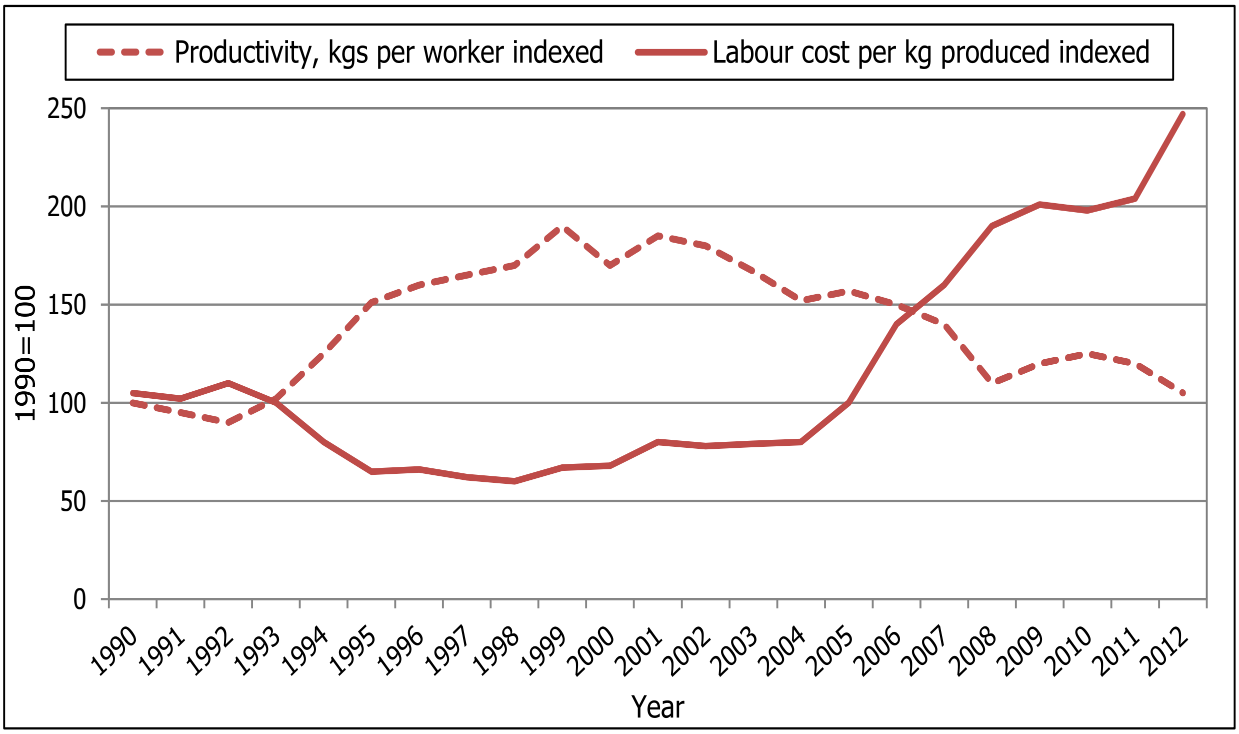


Figure 3: Productivity vs Labour cost at SA mines [8], [9]

Figure 3 shows the correlation between productivity and labour cost at SA mines since 1990 (base scaled to 100). As can be seen, productivity has shown a constant decline whilst the cost of labour has sharply risen in recent years. Growing disparity between mine management, unions and workers also costs the platinum mining sector [10].

As a result of the factors discussed above, the platinum mining sector must strive to become more cost effective. Baxter states that inflation of input costs has had a drastic impact on the mining sector. The major inflation areas are electricity prices, PGM mining costs, diesel, reinforced steel, labour costs and structural steel. All of these factors experienceding inflation of more than 10% from 2007 to 2012 [11].

It is clear that the SA mining sector, and particularly platinum mines, must seek methods of increasing profitability.

1.2 PLATINUM MINE ENERGY USAGE

As discussed in the previous section, there are various input costs that currently influence the platinum mining sector. Electricity presents the largest inflation of all input costs, as Eskom continually strives to restore generation capacity. To do this, the utility must increase consumer electricity costs to allow greater capital expenditure [12]. The increase in electricity costs directly affects all electricity consumers, including mines.

SA mines consume approximately 15% of all power produced locally. The platinum mining sector accounts for 33% of this [13]. This is indicative of the dependence of the SA economy on minerals and mining. As SA holds the majority of the world's PGM reserves, it is clear that supplying this sector with a stable power supply is crucial [1]. The financial well-being of mines as well as that of all stakeholders depends heavily on this.

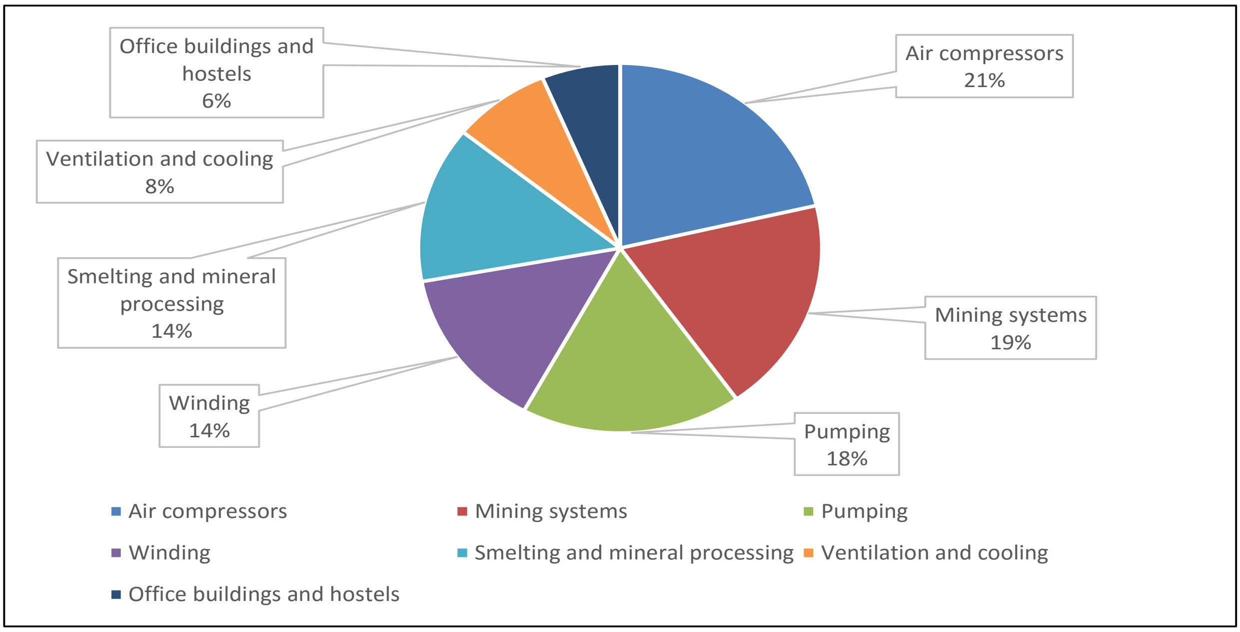


Figure 4: Mining auxiliaries electricity consumption [14]

Figure 4 shows the energy consumption breakdown of a typical SA mine. Various opportunities exist for cost saving through increased Energy Efficiency (EE) [15].

Ventilation and cooling of mines are crucial components of any underground mining operation. The majority of SA mines make use of chilled water to satisfy this need. The chilled water is used to provide cool ventilation air, as well as aiding in the proper functioning of mining equipment. The safety and well-being of underground personnel is crucial and proper cooling is also key to satisfying this need [16].

Cooling and ventilation are crucial for deep underground mining operations. Heat radiates from the rock surface and drives up surrounding air and equipment temperatures. Figure 5 shows the underground Virgin Rock Temperatures (VRT), by depth, of SA mining areas. The majority of SA platinum mines are situated within the Bushveld Igneous Complex (BIC). It is clear that the BIC presents higher VRT values by depth than areas containing much deeper gold mines. The cooling requirements of platinum mines in SA is therefore proportionally higher than that of other mines [17].

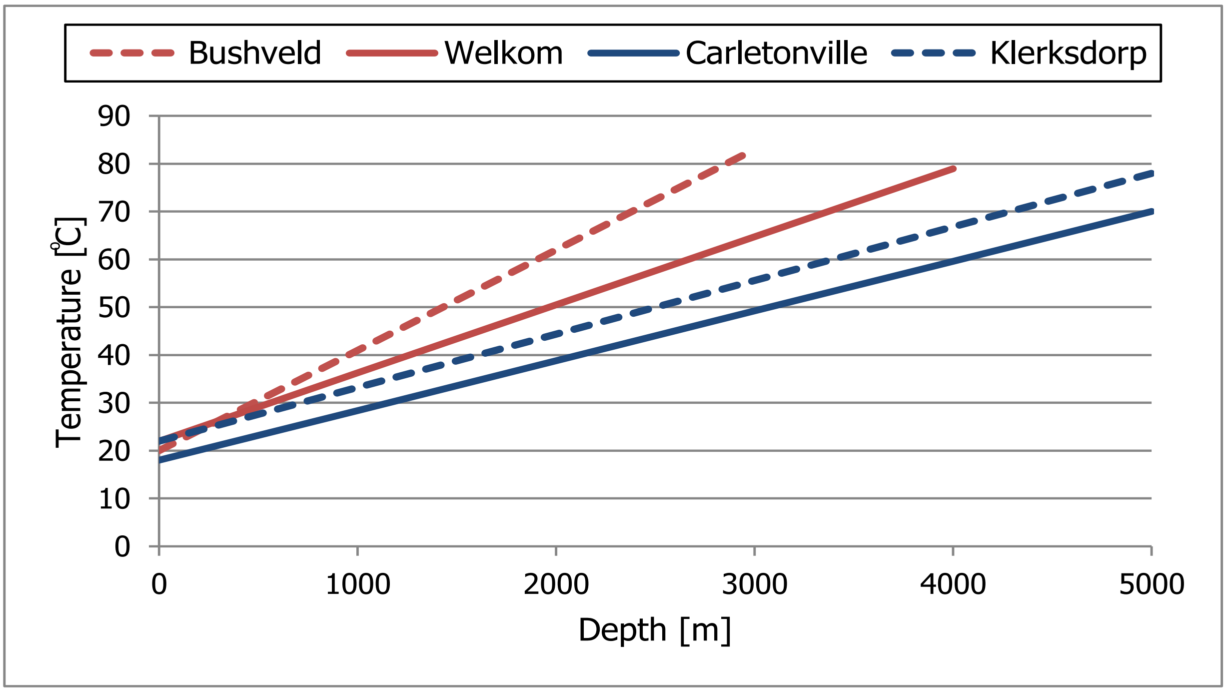


Figure 5: Virgin rock temperatures for SA mines [17]

A small portion of the mine water reticulation system can be attributed to refrigeration and cooling systems. When EE is considered, the service water distribution network, as well as water reticulation systems can be combined. This will yield a larger overall energy saving, whilst allowing greater control [16]. The supply as well as demand of chilled service water will then be controlled more effectively. The potential EE savings can be improved if both surface and underground equipment areis considered.

In order for deep level mines in SA to mitigate the increased cost per kg of material mined, they must effectively manage input costs, of which electricity is the largest. Optimisation strategies and equipment, implemented effectively, will drastically improve control of costs. The platinum mining industry must implement such strategies in order to remain profitable, whilst maintaining adequate underground ventilation and cooling [18]. Effective and efficient ventilation and cooling will thus decrease operational costs, all the while maintaining a safe and efficient work environment.

In order to effectively identify and implement EE initiatives, the safety of personnel and equipment must also be considered. Underground VRTs can rise to levels exceeding 60℃ [19]. Mining practice however, dictates that an underground working temperature of no greater than 27.5 °C wet-bulb is permitted [18]. An increased work environment temperature leads to a drastic loss in worker effectivity as shown in Figure 6.

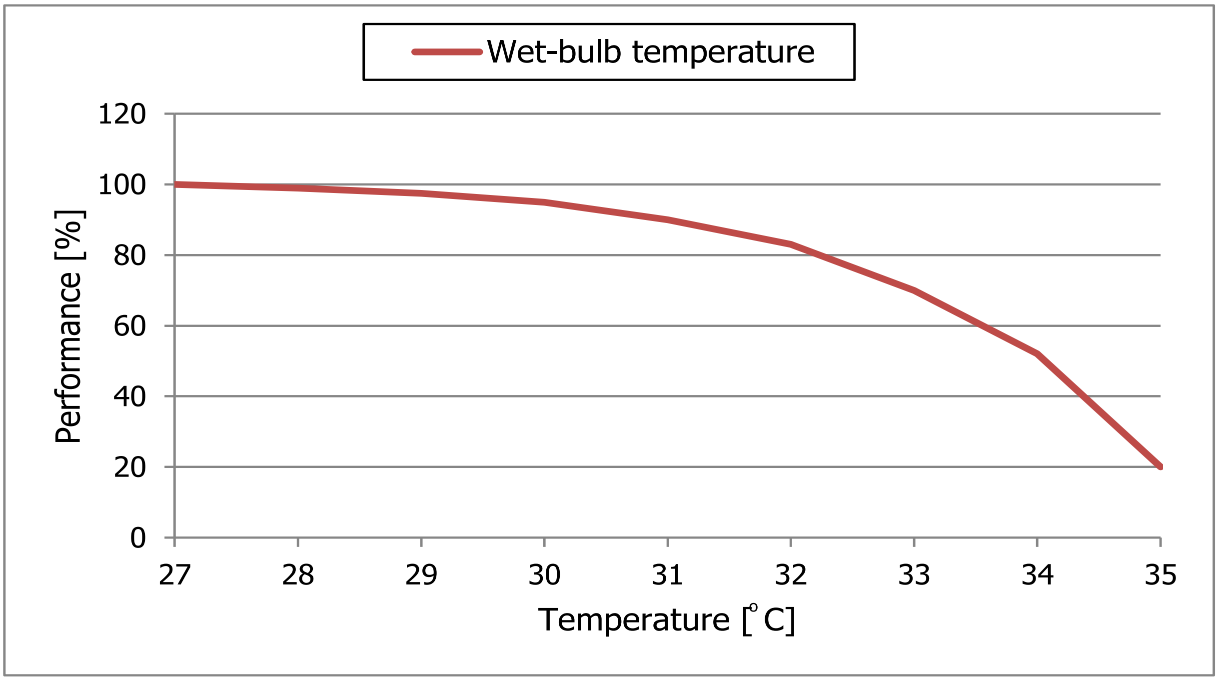


Figure 6: Underground worker performance related to temperature [20]

Platinum mines make use of surface refrigeration plants, aided by ventilation fans and secondary underground cooling equipment. The load on these cooling systems is dictated by ambient and underground conditions, as well as mining process factors such as working shifts and fluctuating machinery demands. The load on the refrigeration and cooling systems therefore varies throughout any given 24 hour period and will also be seasonal [21].

Mining activities are the primary drive behind load fluctuations related to refrigeration and cooling. Underground mine workers work according to shifts which define periods of increased chilled air demand. Seasonal weather also plays a critical role, increased demand being pertinent in summer with the winter having a lesser demand for chilled water and air. This is due to the much lower ambient wet-bulb temperatures associated with winter time [22].

These fluctuations in cooling demand present opportunities for cost saving through energy management. Reduced load conditions present the greatest opportunity to reduce energy demand and increase effectiveness. SA platinum mines generally make use of aged systems and equipment. This equipment was generally installed prior to the rapid inflation of electricity costs experienced in recent years. As a result there is generally scope for improved efficiency of these systems as energy efficiency was not a primary driver at the time of installation [16], [22].

Daily shift-specific demands can also be used to determine the cooling requirements of a mine. Afternoon blasting shifts for instance, require very little cooling as the mine is cleared of personnel [21]. This period thus presents a dramatically reduced load on the cooling system, as only critical equipment requires cooling. Load control for this period is not implemented at present and also presents opportunity for electricity cost savings.

The primary method of control currently in place at most SA platinum mines is varying the amount of refrigeration machines in operation to match cooling requirements [22]. Through previous studies, it can be shown that some mines make use of valve throttling to match demand. The inefficiency of this method of control becomes apparent when frictional losses and pressure drops are analysed [23]. The use of Variable Speed Drives (VSDs) can eliminate these losses however. The speed reduction that VSDs are capable of, renders this valve control obsolete [16].

Partial and reduced load conditions present a great opportunity for EE savings. Old, outdated and inefficient equipment is also present at most SA mines. The control systems and strategies in place to manage these systems are generally similarly outdated. This combination of inefficient equipment and outdated control strategies and systems presents substantial opportunity for Demand Side Management (DSM) project implementation [24].

Refrigeration and cooling constitute a large percentage of increasing costs of mining platinum. Old, inefficient control, coupled with outdated systems and lack of systems control in partial and reduced load conditions exacerbates the issue. This is then compounded by outdated and inefficient equipment. All of the abovementioned factors present ample opportunity for cost saving through DSM project implementation. These projects are then able to focus on increasing efficiency of control systems and strategies as well as increasing efficiency of, or replacing, inefficient and costly equipment [25].

1.3 DEMAND SIDE MANAGEMENT (DSM) OPPORTUNITIES

As discussed, a strategy must be developed to effectively match the supply and demand of electricity to consumers in SA. Supply Side Management (SSM) will not be as effective when implemented in SA. As Eskom is already experiencing financial as well as electricity supply issues, SSM will prove too time consuming to be effective [15]. DSM focuses on consumer electricity usage. DSM projects implementation focuses on identifying inefficient process elements such as outdated control systems or equipment and replacing or managing these elements in an energy efficient manner [26].

DSM projects focus on reducing the energy consumption of selected, high consumption, users. Key to the strategy is effectively maintaining acceptable production output for the user as well as maintaining satisfaction levels with the service provider, namely Eskom. Cost savings in the form of reduced electricity costs for users are also a benefit of DSM projects. Secondary cost savings in the form of tariff decreases and reduced transmission costs are also possible [27].

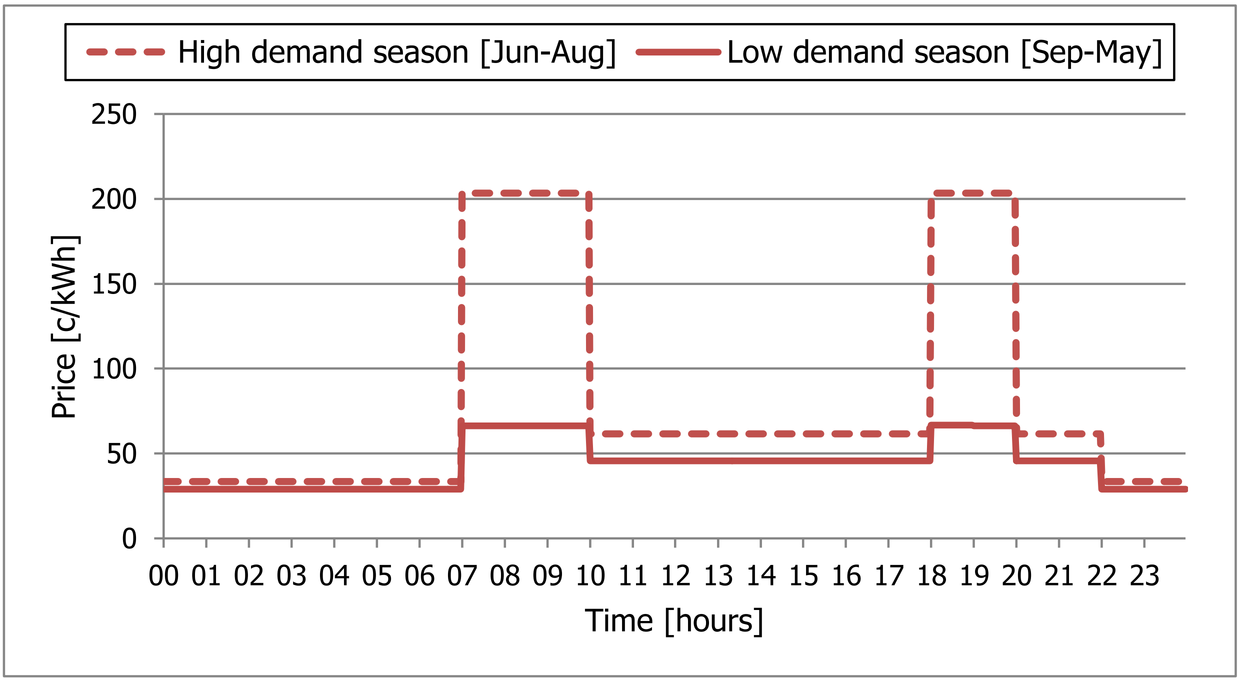


Figure 7: Megaflex weekday tariff structure [28]

Figure 7 shows the weekday structure of the Megaflex tariff. This is applied to industrial users connected to the medium and high voltage grids [28]. As can be seen, the peak periods (07:00-10:00 and 18:00-20:00) are substantially more expensive periods to operate electrical machinery. The main objective of DSM projects is to reduce energy usage during the Eskom peak billing periods, reducing strain on the national grid [22].

Most DSM projects are run as part of the Eskom Industrial Demand Management program. The main purpose of this program is to reduce energy usage, with a focus on saving during the peak periods [29]. Many strategies exist to achieve this. For the purpose of this study, there will be a focus on Load Shifting (LS) and EE strategies as discussed below.

Eskom evening peak demand period

As discussed above, the primary purpose of DSM project implementation is the reduction of energy consumption during the Eskom peak demand period. LS is one of the strategies available to achieve this. The main purpose of LS is to reduce electricity usage during the peak period and shift this to fall outside of the Eskom peak demand period [30], [31]. The purpose of this strategy is not to reduce the overall energy consumption of the consumer, but for the power supplier to regain generated capacity in the peak demand period [32].

Figure 8 shows a 3.1 MW evening load shit. The total average power of both the baseline and actual profiles is the same, the peak load is merely shifted to the remaining 22 hours. The total energy shifted is 6.2 MWh.

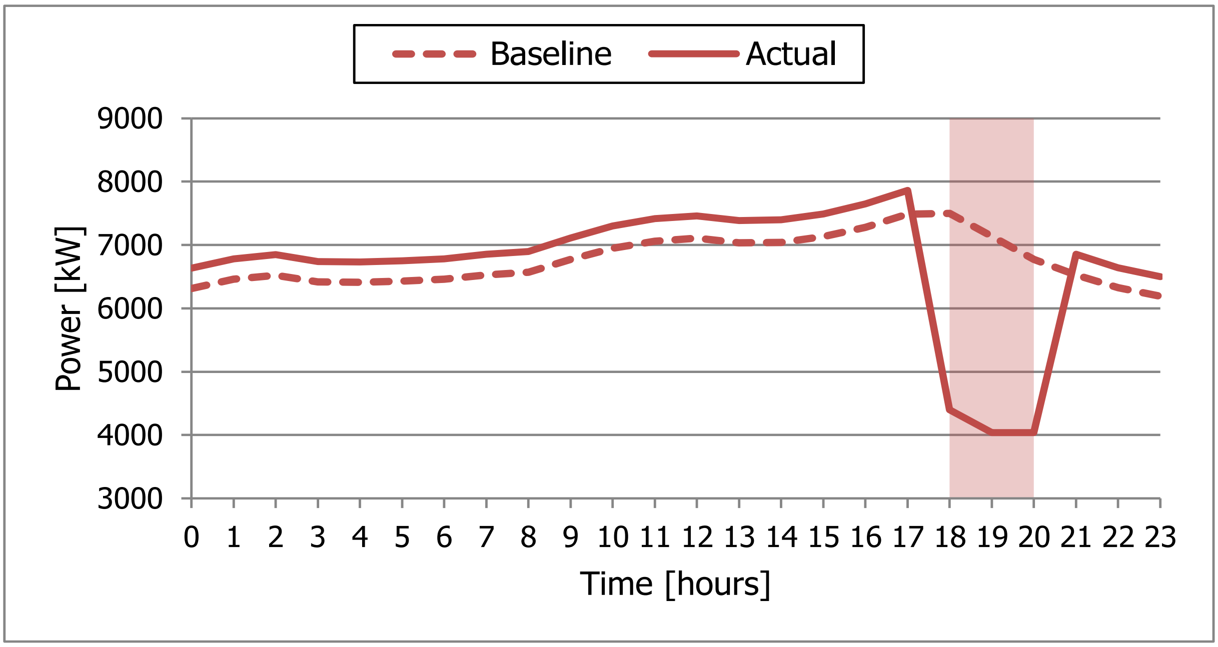


Figure 8: Load shifting power profile

Energy Efficiency (EE)

An EE strategy focuses on reducing the client's electricity consumption on a constant basis. Increasing the efficiency of processes is then key, as no load is shifted using this strategy. A 24-hour reduction in electricity consumption is thus the aim [33]. Figure 9 shows an EE power profile. A 24-hour reduction in electricity consumption of 720 kW is shown. This yields a 17.3 MWh saving per day.

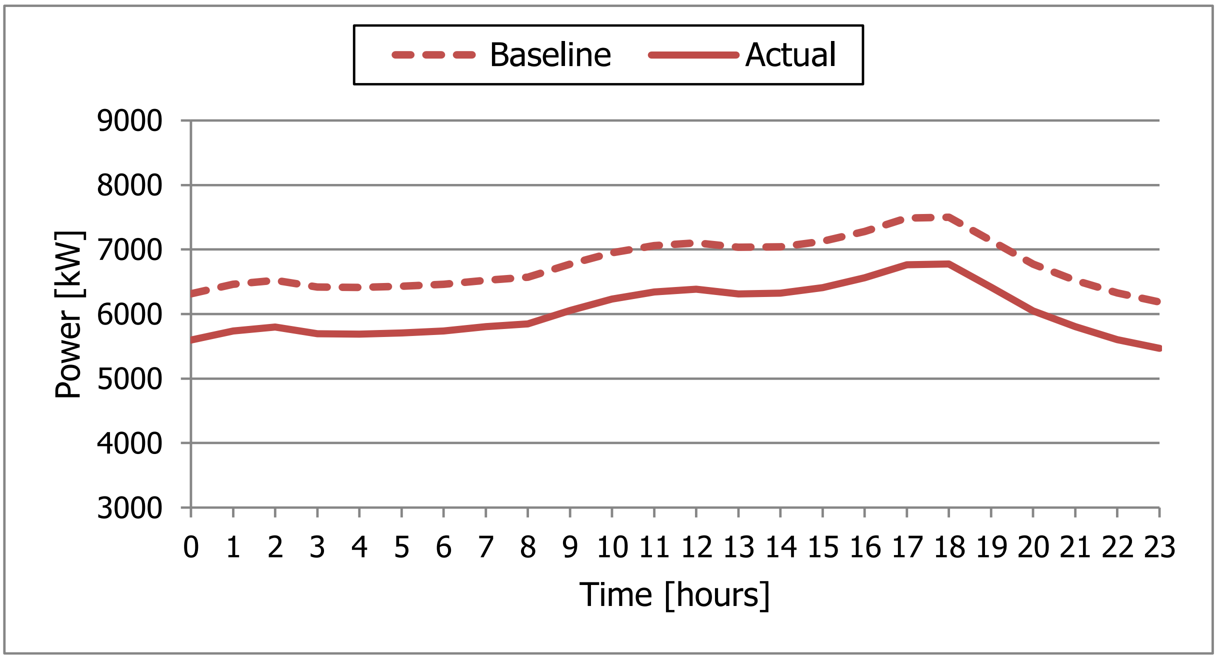


Figure 9: Energy efficiency power profile

1.4 PROBLEM DEFINITION

As discussed in the preceding sections, it is clear that there exists an opportunity for cost savings at platinum mines in SA. The management of input costs is the most effective method of saving costs. Input cost management has an immediate effect on mining operations and efficiency. It is for this reason that efficient and safe strategies must be implemented.

Electricity costs have experienced inflation greater than any other input cost associated with platinum mining in SA. DSM projects place focus on reducing the client electricity usage and cost, while maintaining safe mining practice and product output. The strategies implemented by DSM therefore benefit both the client and Eskom.

The electricity demand of ventilation and cooling systems of platinum mines presents great opportunity for the implementation of cost saving measures through DSM. Not only will this grant cost savings to the client, it will also allow the power supplier (Eskom) to regain generated capacity and furthermore supply a stable power grid.

The cooling demand of PGM mines situated within the BIC is relatively high considering the depths mined. Effective management of cooling via both chilled water and air will be extremely beneficial. A previous study has been carried out to determine the effect of EE DSM projects implementation at a PGM mine [34].

To further expand on the work carried out in previous studies, the effect of combined DSM projects implemented at a single PGM mine refrigeration plant will be investigated [34]. Both EE and LS projects will be investigated, implemented and quantified to determine the efficacy and co-effects of the strategies.

1.5 STUDY LAYOUT

Chapter 1

This chapter serves as an introduction. The current economic climate surrounding SA platinum mines is discussed. Uncertainty in the local labour market as well as dropping platinum prices are also outlined. This coupled with ever increasing electricity prices and reduced generation capacity are outlined as the research problem. The scope and layout of the document is also defined.

Chapter 2

This chapter will investigate platinum mine refrigeration plants. DSM projects implementation at refrigeration plants will also be investigated. Both EE and LS DSM strategies will be investigated. The fundamental concepts of the required infrastructure and implementation requirements will also be given.

Chapter 3

In this section, the feasibility of implementing multiple DSM strategies at a single refrigeration plant will be investigated. Simulations of a refrigeration plant will be designed. Simulated results of implementing both strategies separately as well as simultaneously will be analysed.

Chapter 4

This chapter will cover the implementation, control and assessment of the combined DSM strategies. Any hindrances experienced during implementation will be briefly covered. Performance of the strategies will also be covered and compared to results obtained from the simulations carried out in Chapter 3 in order to verify the results.

Chapter 5

This will serve as the conclusion of the document. The feasibility and success of implementing the combined DSM strategy will be discussed as the validation of this study. Control and efficiency factors will be briefly covered. Recommendations for future work will also be included.

2. PLATINUM MINE REFRIGERATION AND COOLING SYSTEMS

2.1 PREAMBLE

As discussed in Chapter 1, underground heat loads are the primary requirement for refrigeration and cooling systems at mining operations. These heat loads are generated by VRTs present underground. The majority of SA platinum mines require large cooling and refrigeration systems to account for the relatively high VRTs present.

The need for SA platinum mines to decrease operational costs is becoming increasingly apparent. The platinum mining sector is experiencing ever-increasing pressure due to strained labour relations, increasing operations costs and dropping platinum prices, as discussed in Chapter 1.

Refrigeration and cooling systems at platinum mines present great opportunity for cost savings through systems optimisation. This optimisation can be achieved through the implementation of DSM strategies that lead to reduced electricity usage. This chapter will expand upon this, with a focus on energy intensive equipment.

Platinum mine systems operations must be investigated in greater detail, in order to identify the pertinent constraints and requirements of such systems. A literature survey will be carried out to achieve this. The development of a combined DSM strategy must adhere to all requirements identified by such a survey. Should this not be achieved, production losses and safety hazards could occur.

The focus of this chapter will provide background and expand upon the workings of platinum mine refrigeration and cooling systems. Surface cooling systems will be focused on, as the majority of SA platinum mines use this configuration. The definition of a large cooling system, as defined by ASHRAE (American Society of Heating and Air-Conditioning Engineers), is any cooling system that contains one or more refrigeration plants with a cooling capacity of 1050 kW or more [35].

Platinum mine cooling systems will be the focus of discussion. How these systems form an integral part of the mine water reticulation systems at most platinum mines will also be briefly discussed. Particular emphasis will ~~also~~ be placed on equipment and systems identified to have high electricity demand.

Energy management systems and equipment already in place in similar applications will also be investigated. These systems will be investigated for possible adaption for use at platinum mines.

2.2 VENTILATION AND COOLING SYSTEMS BACKGROUND

As discussed in Chapter 1, underground temperatures rise dramatically with depth. This is particularly true for SA mines in the BIC area. High geothermal heat ingress and auto compression of air lead to large heat loads that must be relieved in order to provide a safe working environment [16].

Large surface cooling systems are commonplace at all mines in SA. The basic cooling methods and equipment required are the same for most systems. Each mine will differ in configuration, as requirements such as underground operations and cooling needs differ. These systems form a crucial part of a mine water reticulation system. Figure 10 shows a simplified mine water reticulation and cooling system layout.

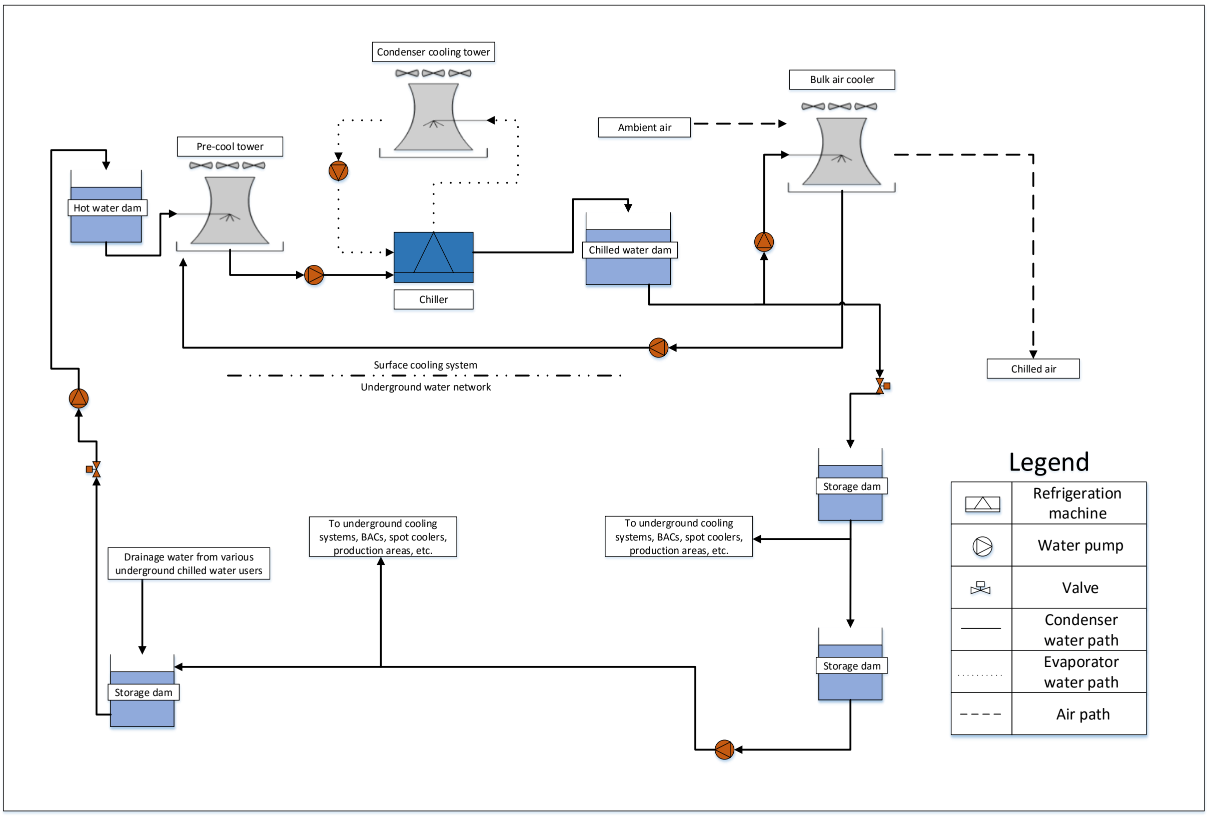


Figure 10: Typical mine water reticulation and cooling schematic [16]

As can be seen in the layout water is supplied, on average between 3 °C and 6 °C, via the water reticulation network to the end users. This network is a semi-closed loop system as the majority of water used is recycled [36]. This supply of chilled water is used for air cooling through surface bulk air coolers as well as underground spot coolers.

Chilled water is also used for the cooling of machinery used in underground operations [37]. After use, the water is at a temperature of approximately 30 °C to 35 °C. This hot water is stored in various underground and surface storage dams. The surface refrigeration plant is supplied with water for the evaporator circuit from these hot water storage dams [16].

Hot water is pumped from the hot water surface dam to the pre-cooling tower. After passing through the pre-cool tower the water is stored in a pre-cool dam. Water is pumped from this dam through the chiller machines, where it passes the evaporator heat exchanger section of the machine [16]. The specific arrangement of the chiller machines will vary according to the specific requirements of the application.

The chilled water passes out of the chiller machines and is stored in the surface chill dam. From this dam it is fed underground via the water reticulation network. The time-specific demand for chilled water is generally regulated using an actuated valve. Mine specific water usage will differ with each application, but flow rates are typically between 100 ℓ/s and 600 ℓ/s totalling approximately 10 Mℓ to 40 Mℓ per day [38].

Chilled water fed from the chillers is also routed to pass through the Bulk Air Cooler (BAC). The primary purpose of the BAC is dehumidification and temperature reduction of ventilation air. The chilled air, typically at a temperature of about 7 °C, is fed to the mine using a system of ventilation fans [38].

The condenser circuit of the refrigeration plant serves the purpose of cooling the chiller machines. These machines are typically water cooled and make use of a closed loop condenser circuit to achieve this. Hot water, typically flowing at double the evaporator flow rate, passes through the condenser heat exchanger. A water temperature increase of approximately 5℃ to 7℃ occurs. The hot water then flows out of the chiller and is pumped through the condenser cooling towers where it is cooled. These towers are similar in design and operation to the pre-cool tower [35].

The demand for chilled water can vary dramatically as a result of the various requirements of the network of end users. The purpose of water storage dams in the system is to provide capacity for these fluctuations [38]. This allows for a degree of demand matching. Flow fluctuations can also be accounted for through the use of storage dam water capacity. Seasonal demand fluctuations are more drastic and as a result this demand is met by varying the number of chiller machines in operation [22].

A typical refrigeration plant will operate at a fixed design flow through the evaporator heat exchanger. The most common method to achieve this flow is through the use of a variable opening valve. When the chilled water dam reaches the maximum desired level, the water is bypassed to the pre-cool sump/dam. This bypassing will continue until chilled water demand increases. It is common practice for continuous bypassing of the chilled dam to take place [23].

Mine water reticulation systems make use of large networks of equipment in order to deliver chilled water underground and return hot water to the surface. This water is transported by means of a system of pumps, valves and dams. The majority of these systems are outdated and as a result, are extremely energy intensive and make use of outdated control strategies [16]. A brief background of the various components included in a platinum mine cooling system will be given below.

Chiller machines

Mine cooling systems primarily make use of chiller machines that are based on either the vapour compression or ammonia absorption refrigeration cycles [39]. When a liquid is boiled at a constant temperature and pressure, latent heat is extracted from the surrounding medium. If this vapour is then compressed to a higher temperature pressure, condensation can occur. This in turn ~~r~~ejects the heat produced by condensation to the surroundings. Refrigeration cycles, such as the vapour-compression cycle, rely on this principle [38].

The temperature range specific pressure-temperature relationships are the primary factors to be considered when a refrigerant fluid is to be chosen. For the purposes of cooling water for use in mines, the input and output temperatures are about 30 °C and 3 °C respectively. Both ammonia and R134a are suitable for these ranges. Ammonia is extremely efficient and economical, with high efficiency. The corrosiveness and toxicity however, limit~~s~~ its use to surface applications [40].

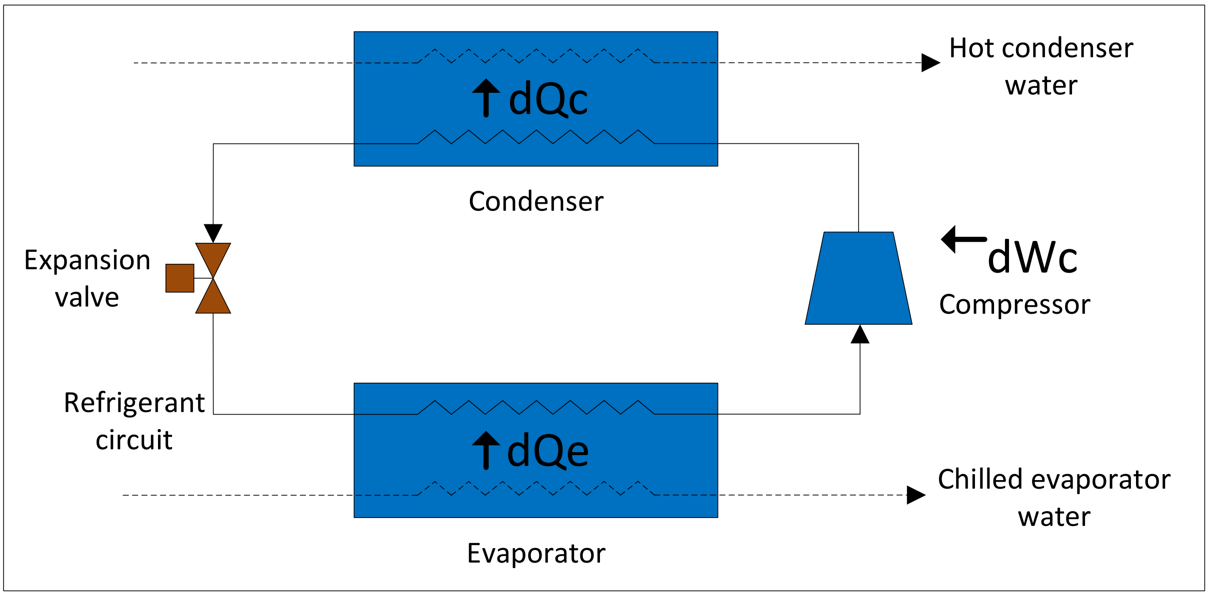


Figure 11: Chiller vapour compression refrigeration cycle

Figure 11 provides a simplified schematic of a vapour compression cycle as used in mine cooling system chiller machines. The main components, as shown, are the evaporator, condenser, compressor and expansion valve. Shell-and-tube heat exchangers are the most prominent type of evaporator and condenser, although plate-type exchangers are used in some cases where space constraints are present [41].

Shell-and-tube heat exchangers generally operate in such a manner that refrigerant flows in the shell with water flowing inside the tubes. Due to evaporation, latent heat is present in the refrigerant as it passes through the evaporator. This is used to transfer heat from the water, chilling it in the process. The heat transferred to the refrigerant is once more passed to water in the condenser. Shaft work is required to compress the refrigerant vapour in the compressor [39].

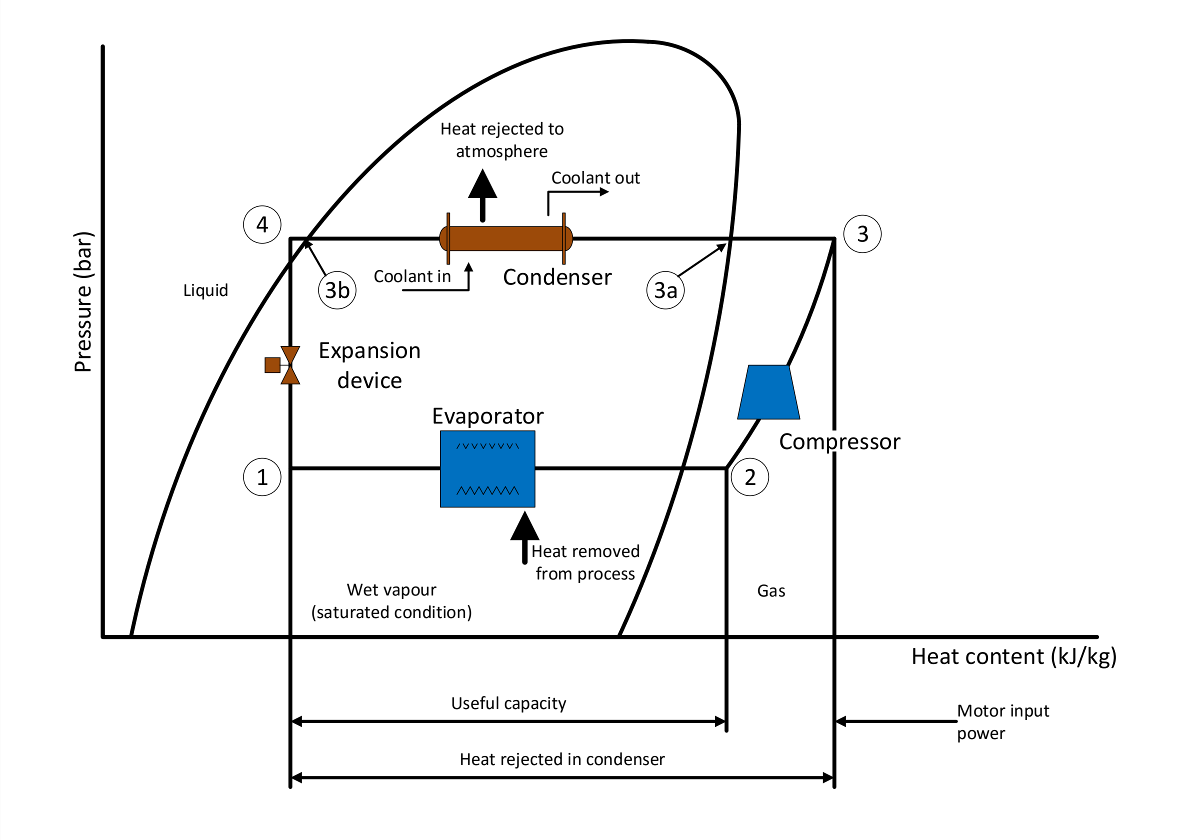


Figure 12: Pressure-enthalpy diagram for a vapour compression cycle (adapted from [42])

Figure 12 shows the pressure-enthalpy diagram that summarises the thermodynamic principles of the vapour compression refrigeration cycle. Firstly the refrigerant is heated to a higher pressure and temperature (2-3). The heat of the refrigerant is then reduced to below the super-heated region at a constant pressure in the condenser (3-4). The temperature and pressure values are then lowered by passing the fluid through the expansion valve (4-1). Before the compressor entrance, the refrigerant is evaporated at constant pressure in the evaporator (1-2) [39].

A number of mine cooling systems make use of the ammonia absorption process as opposed to the vapour compression cycle. The basic principles of operation, as described, of these two cycles are broadly similar. The compression method differs slightly, however. A pump, absorber, compressor, liquid receiver and surge drum are used to achieve absorption, compression and evaporation of low pressure ammonia into water. This cycle is advantageous, as less energy is required to achieve a similar cooling output to the vapour compression cycle [39], [41].

The most common form of compressors in use at mine cooling systems are centrifugal and screw compressors, for use with vapour-compression and ammonia cycles respectively. Screw compressors make use of slide valves to control cooling loads, with centrifugal compressors making use of guide vanes to achieve this [43]. A set evaporator outlet water temperature is maintained through throttling of the refrigerant compressors. This allows for the complete control of refrigerant flow rate affecting latent heat transfer as well as capacity [44].

The performance of a chiller machine is commonly measured in terms of the cooling capacity of the chiller. That is, the efficiency as defined by the ratio of cooling capacity versus input shaft power. This value is defined as the Coefficient of Performance (COP) of the compressor. Large chiller machines have a COP value of approximately 6 with this value dropping to around 3 for small- to medium-sized chillers (1050 kW or lower). The COP is defined below.

$$COP = \frac{\dot{Q}_e}{\dot{W}_c}$$

With $\dot{Q}_e = \dot{m}_w c_{pw}(T_{wi} - T_{wo}) = \dot{m}_r \Delta h_r$

$$\dot{Q}_e + \dot{W}_c = \dot{Q}_c + \dot{Q}_{loss}$$

Equation 1: Definition of coefficient of performance [39]

As the evaporator outlet water temperature is to be held constant, the COP value will vary as changes in cooling demand and compressor input power occur [44]. Equation 1 states that the evaporator cooling load is affected by a number of factors. Any change in the water flow rate or inlet temperature will have an effect on the cooling load and influences the COP value.

The capacity control of a compressor also allows for the control of variation in the COP. Any changes in the cooling load induced on the chiller by the water side heat loads will require capacity control changes to maintain a constant COP value. In theory, a thermally balanced chiller should make allowance for cooling load variations and maintain a constant COP value. In practice however, the COP value will always vary somewhat.

In some cases, it has been observed that a reduction in evaporator water flow rates leads to an increase in the COP. Inversely, a reduction in condenser water flow will lead to a reduction in the chiller COP [45], [46]. When changes in water flow rate occur, compensation for optimal load conditions must be accounted for. This must be done in conjunction with compressor power control for the greatest efficiency [47]. So, efficient water flow control depends heavily on the control strategy.

The mechanical performance of a chiller machine must also be considered, as this directly affects cooling efficiency. A reduction in performance of a chiller machine will be observed as either a reduction in the COP over time, or the shutting down, or 'tripping', of the machine due to fail-safe control. Various factors, among which are dirty process water or low water flow rates, can lead to chiller degradation [41]. Compressor surges may also become more frequent as a reduction in evaporator water inlet temperature is present [44]. As a result, when implementing an energy saving strategy, compensation for chiller machine health as well as for efficiency must be made.

Pumps

The majority of water pumps in use at mine cooling systems are of the centrifugal type that operate at a fixed speed. These pumps are used to distribute condenser and evaporator water as well as supply coolers and dams. The configuration of a specific set of pumps depends on the application with associated pressure and flow requirements. Pump power generally ranges from 45 kW to 400 kW.

The impeller of a pump is rotated by an electric motor. The rotation of this component forces the passing liquid into a circumferential path. The velocity of the liquid leaving the impeller is translated into pressure. Casing and impeller design are the factors that most influence the efficiency of a pump.

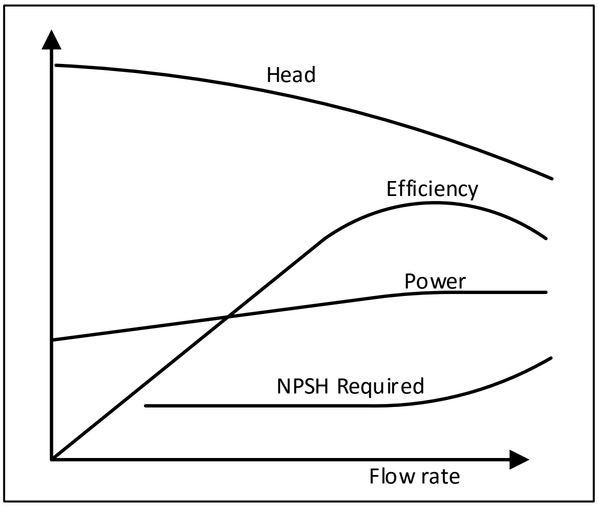


Figure 13: Characteristic curves of a centrifugal type pump (adapted from [48])

Figure 13 shows a typical example of the characteristic curves of a centrifugal type pump. This is a gauge of the performance of the pump [48]. These characteristic curves plot the delivered head, pump efficiency, motor power and Net Positive Suction Head (NPSH) in terms of the pump's flow rate. Ideally a pump is selected such that it would operate in the optimum efficiency range. This point lies at the intersection of the pump characteristic curve and system resistance curve, with axes of head (required pressure) and system flow rate [49].

The characteristic curves of a centrifugal pump are associated with a fixed impeller speed. This is as a result of the affinity law. This states that flow rate and rotational speed are proportional, an increase in head is proportional to rotational speed squared and input power is proportional to rotational speed cubed [49]. System changes such as valve throttling alter the system resistance which in turn affects the pressure and flow requirements.

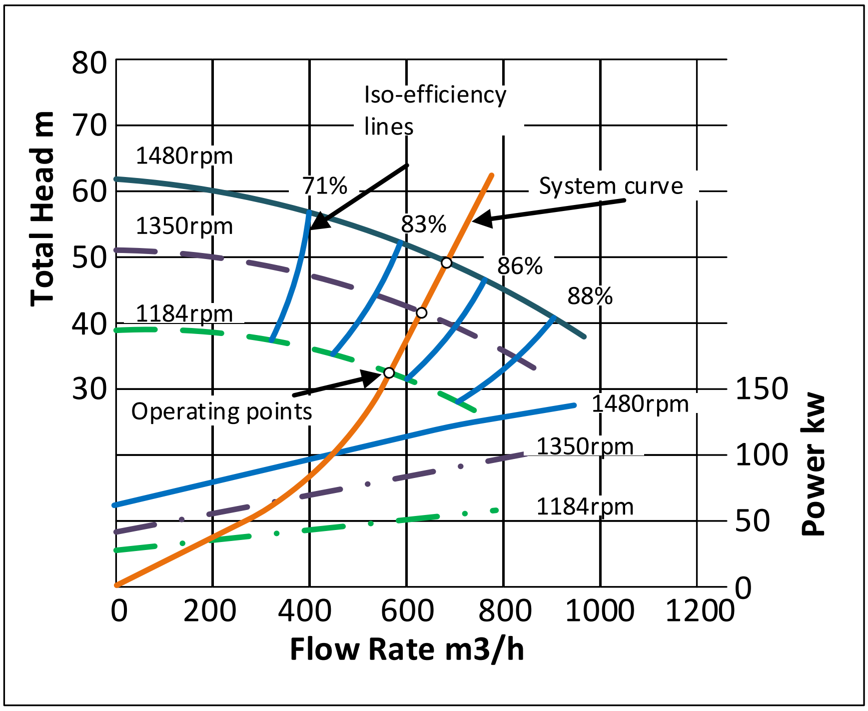


Figure 14: Typical effects of a VSD on the characteristic curves of a pump (adapted from [50]**)**

When the operating speed of a pump is altered, various changes take place regarding the associated pump curves, as shown in Figure 14. A system that is dominated by frictional pressure will display a curve similar to that displayed. Generally, these systems have pressure requirements that are dictated by system components such as heat exchangers and cooling towers. It should be noted that a reduction in pump speed causes the operating point to move lower on the iso-efficiency line. This shows that a reduction in pump speed will reduce pump power while maintaining efficiency [16].

Another consideration that must be accounted for is the ~~associated~~ increase in pump wear associated with lower frequencies. A balance between speed reduction and pump maintenance must be adhered to. Speed reduction control must also account for a sufficient NPSH to prevent cavitation. Starting and stopping methods must also be carefully managed to allow for safe starting and stopping of pumps to prevent undue wearing of pump components [50].

Cooling towers

As shown in Figure 10, cooling towers are used for two similar purposes namely, cooling condenser circuit water and pre-cooling water supplied from underground working areas. These cooling towers are generally of the forced draught design where air flow is achieved through the use of a fan installed in the tower. Evaporative cooling is used to drop the temperature of the water passing through the tower. Evaporation is achieved because the ambient air is at a lower temperature than that of the process water [51].

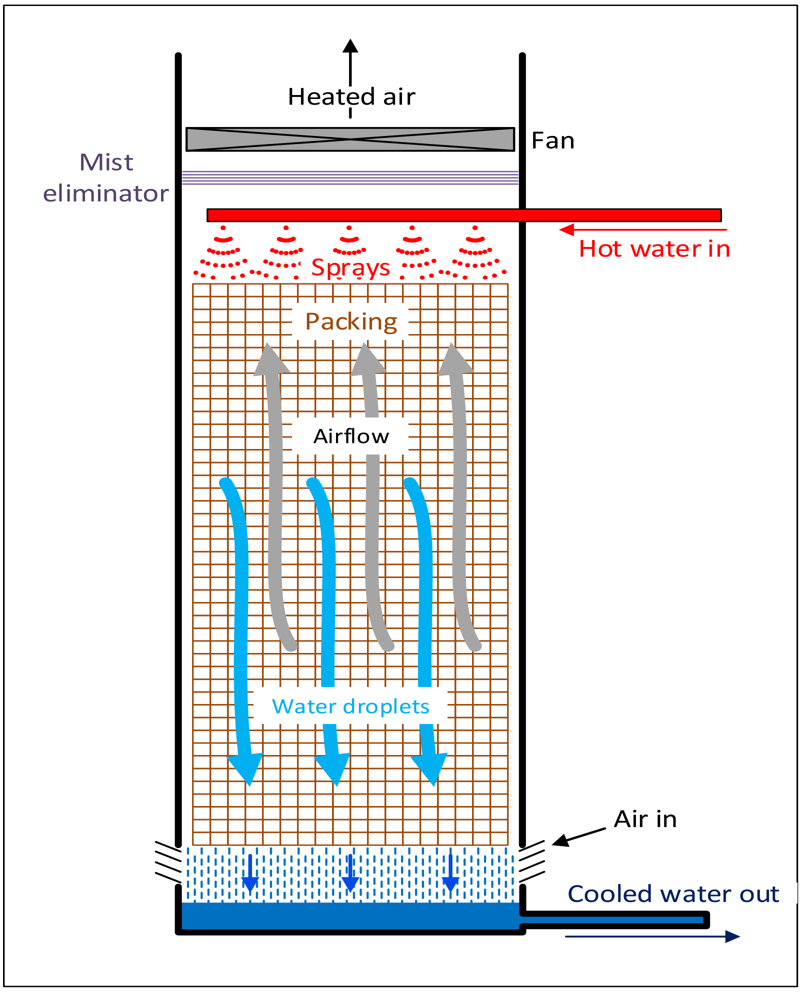


Figure 15: Typical layout of a cooling tower (adapted from [38])

As shown in Figure 15, hot water is pumped~~flowed~~ into the tower in the upper section. Air flow is forced upward through the tower by the fan, causing the air and water to flow in opposite directions. Packing material is in place throughout the tower. This allows for the greatest amount of contact time between the hot water and ambient air. The packing also distributes water flow evenly through the tower. PVC, galvanised steel or polypropylene are the most commonly used materials in cooling tower packing [16].

A combination of methods allows for heat transfer between the ambient air and process water. The first process is convection, or the heat transfer as a result of the temperature difference between the water and air. The second process is~~Secondly,~~ evaporation, or the latent heat transfer resulting from the changing of phase of the water. This cooled water is then pumped to the desired component or end-user. A small degree of evaporation is present (approximately 0.2% of total flow), but this is easily accounted for by adding water [52].

Various factors influence cooling tower performance, namely inlet water temperature and flow rate, air flow and psychrometric attributes and the duration of the water-air contact [38]. Cooling tower performance is measured through various means including water- and air-side efficiencies as well as the cooling tower effectiveness and factor of merit. These measurements are all influenced by the factors mentioned [53].

$$Range = T_{wi} - T_{wo}$$
$$Approach = T_{wo} - T_{ai(wb)}$$
$$\eta_w = \frac{\dot{Q}_{actual}}{\dot{Q}_{ideal}} = \frac{T_{wi} - T_{wo}}{T_{wi} - T_{ai(wb)}}$$

Equation 2: Heat transfer efficiency calculation of a cooling tower [38]

When only water side and inlet air conditions are known, the simplest method to calculate cooling tower efficiency is through the use of Equation 2. This considers the range, approach and water side-efficiency of the cooling tower. A low approach and high efficiency value indicates effective operation. The range quantifies the water side temperature drop and is viewed relative to the approach to aid in determining efficiency [38].

When operating under steady-state conditions, the energy rejected as heat by the cooling tower is equal to the energy transferred to the system by either underground operations or the condenser heat exchanger. The rate of heat rejection is thus not dependent on the cooling tower efficiency. The steady-state water outlet temperature is directly influenced by changes in the cooling tower efficiency. This is because changes in efficiency will alter the temperature reduction that the tower is able to deliver.

The effectiveness of a cooling tower is directly influenced by controllable factors such as water and air flow rates. For example, inadequate flow and pressure will cause a conventional fixed orifice nozzle to provide uneven wetting of the packing material, leading to inefficiencies. Any dry areas within the cooling tower that result from this will show increased scaling and wear. Various other factors such as damage to the packing material or spray nozzles will result in reduced efficiency [54]. When developing control strategies that will alter flow values or halt flow through the cooling towers, all of the abovementioned factors must be taken into account.

Bulk air coolers

The majority of mines, in particular platinum mines, make use of BACs to cool air flowing into the mine. The main advantage of BACs is their relatively low cost. No equipment needs to be lowered into or assembled within the mine. Relatively simple designs allow BACs to remain in use for many years. Another advantage of the use of BACs is the reduced need for pumping chilled water underground [55].

$$Q = \dot{m}_{air}(S_{out} - S_{in})$$

Equation 3: Energy absorption of a BAC [39]

Equation 3 provides the energy absorbed in a BAC. Simply, the measurement of air flow is required relative to the change in entropy. With this, and associated power consumption and process values, the efficiency of the BAC can be determined [39]. Another advantage of the use of BACs is the dehumidification of the ventilation air, leading to a reduced wet-bulb air temperature value. Equation 4 shows the rate of dehumidification of a BAC.

$$X_{H_2o} = \dot{m}_{air}(W_1 - W_2)$$

Equation 4: Rate of water removal by dehumidification of a BAC [56]

As shown in the equation, the change in humidity ratio is directly proportional to the dehumidification rate of the BAC [56]. The two factors mentioned above are directly impacted by BAC operation and efficiency. Additionally, BACs make use of chilled water that would otherwise be required for underground cooling equipment. This yields an indirect energy saving as the pumping requirement for this water is greatly reduced [22].

The basic operation of a BAC, which acts as a large evaporative spray chamber, is directly opposite to that of cooling towers, as previously discussed. The main difference being that the heat transfer takes place in such a manner that the air is cooled and water heated, directly inverse to a cooling tower [16]. Unlike cooling towers, BACs are generally not required during winter months (June – August in the Southern hemisphere);, this is due to the greatly reduced ambient air temperature [57].

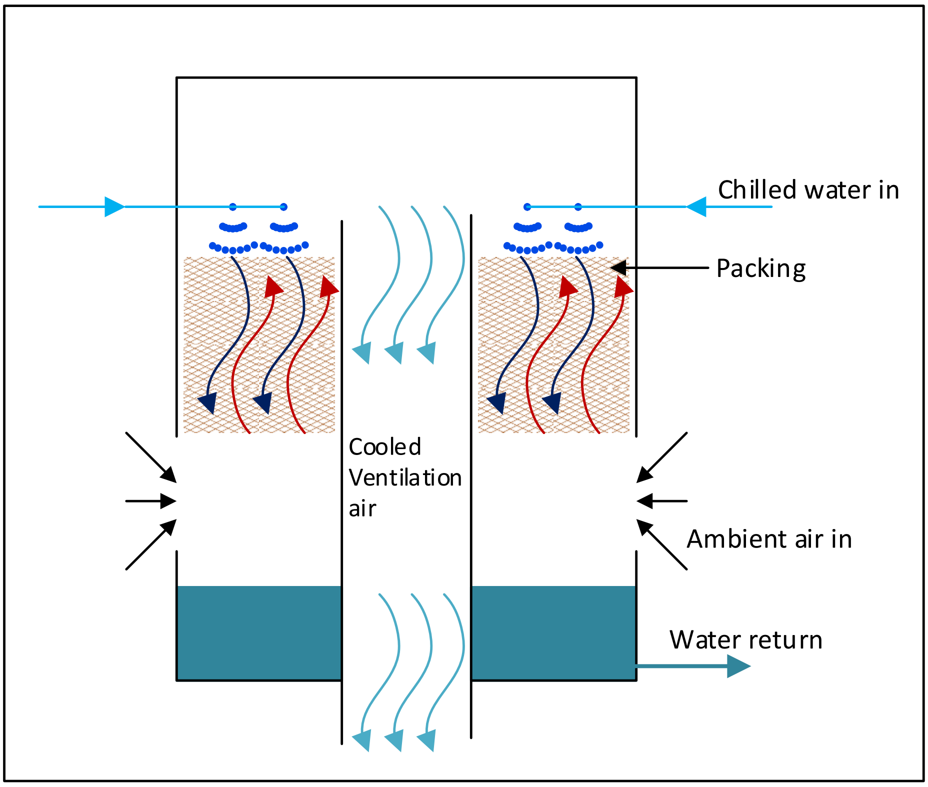


Figure 16: Typical vertical Bulk Air Cooler design (adapted from [38])

Figure 16 shows the design and layout of a typical vertical BAC as used in mine cooling systems. Like a cooling tower, water is sprayed evenly over a packing material filling. The key difference being that the water flowed into the tower is cooler than the ambient air. Air flow is either forced using mechanical fans, or induced through mine ventilation with fans being located elsewhere in the network [38].

Air flowing through the BAC must always be kept below acceptable temperature levels. Any control systems that influence the water temperature and flow through the BAC must allow for adequate water flow to ensure adequate wetting of the packing and ensure that input water temperature levels are kept low enough that safe operation is ensured.

2.3 EXISTING ENERGY EFFICIENCY (EE) STRATEGIES

As discussed in Chapter 1, an EE strategy focuses on reducing overall power usage. So, no load is shifted as the overall energy consumption is reduced while maintaining product output. The key to EE strategies is the identification of inefficient, energy intensive equipment. This equipment is either replaced or altered, to achieve reduced power consumption, while maintaining acceptable performance [16], [21].

Numerous studies have shown that the most appropriate approach to EE DSM strategies on mine cooling systems involves the installation of VSD technology [21], [58], [23]. VSDs are installed in order to accurately control the rotation speed of water pumps. In order to properly carry out development and implementation of a system comprising partly of an EE strategy, a brief overview of VSDs is given below.

Variable speed drives

A VSD can either be electrical or mechanical, with both types varying the speed of some form of rotating equipment [59]. Electrical VSDs have a broad range of potential for installation. This is due to the desirability of controlling the speed at which most forms of rotating machines operate. This has made the installation and operation of VSDs extremely popular, further showing their worth as effective and reliable components [58], [60].

In essence, a VSD operates through the usage of solid state electronic devices by varying the frequency of alternating current (AC) voltage (V) that is supplied. VSDs operate by maintaining a fixed Volt/Hertz (V/Hz) ratio;, that is if the component controls both supplied voltage and supplied frequency. When a fixed V/Hz ratio is maintained, the output torque of a connected motor remains similar to that of full speed conditions. Altering this ratio with motor speed will thus result in a change in motor torque output [61].

Adaptability for a number of different applications means that currently inefficient systems can be retrofitted with VSDs. A reduction in mechanical losses is represented when systems are integrated with VSDs, making installation all the more attractive. The ability to vary the speed of rotating equipment allows for superb load-matching capability. This is an obvious advantage in terms of EE as loads are reduced while maintaining output [62].

Further, VSDs also allow for greater process control, as both supply and output can be accurately controlled. Reduced start-up voltages and built in diagnostics allow for improved reliability of machinery as less strain is placed on equipment, and maintenance can be more thoroughly controlled. Multiple motors can be controlled using VSDs, allowing for parallel control across a number of motors. VSDs represent the most viable option for variable flow control of a mine cooling system. Increased reliability, monitoring and control of systems result in an improvement in energy usage as well as more accurate control of cooling output.

Implementation considerations

A number of different control applications are available for VSDs. Cooling systems in particular comprise of a number of electrical motors fitted to various types of rotating machinery. Fans, pumps and chillers are all powered by motors. The sizes of these motors vary from less than 50 kW to over 1000 kW [23]. The cost of VSDs across this range varies dramatically and as a result careful consideration must be given to which motors are most viable in terms of electrical cost savings.

Chillers machines represent a possible reduction in energy usage of between 12% and 24% [63]. However, the prohibitively high costs associated with medium voltage VSDs in SA means that possible savings are not sufficient enough to offset the initial financial costs of implementation. At best, a payback period of approximately 4 years can be achieved when chiller loads can be substantially reduced. Due to the high cooling demand of SA mines, a payback period of more than 15 years is to be expected [23]. This would mean that, for cost-effective DSM, chillers would not be appropriate for VSD implementation.

Unlike with chillers, as discussed above, a payback period of less than a third of expected motor life should be considered adequate [64]. As this is the case, low-voltage electric motors show a far greater affinity to VSDs as their payback period is typically less than two years [65]. Payback periods of just more than 1 year have been reported when pump and fan motors have been integrated with VSDs [66], [67].

A case study was carried out that included air-cooled centrifugal chillers. This case study presented an annual energy usage reduction of between 16% and 21%. Control was focussed on achieving the most efficient condenser temperature differential as well as evaporator output temperature. Control was varied according to ambient conditions and cooling demand [60]. This case study showed that the VSD operation should be limited such that a minimum flow is accounted for. This is done to prevent freezing of water inside the chiller heat exchanger tubes

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

Table 1: Simplified variable water flow control strategy (adapted from [16])

A previous study specifically developed a variable-flow control strategy that is applicable to the vast majority of large mine cooling systems [24], [68]. The result of this study was a model that can be used as a basis for the control of any large mine cooling system that makes use of VSDs for water flow control. Table 1 shows the basic control elements of the strategy developed.

A gold mine was used as the basis for the development of this strategy as well as being the subject of the case study. As proof of previously asserted COP tendencies regarding water flow, the case study showed that a reduction in condenser flow had a negative effect on the chiller COP, where a decrease in evaporator flow has the opposite effect [45], [69], [70].

During this case study, variation of the COP value of the chillers was limited to 1.5% of the value prior to implementation. In order to achieve this it was observed that implementing both the condenser and evaporator control strategies simultaneously are crucial. Another noteworthy observation of the study was that, although cooling loads remained similar, the combined COP value of all combined plants increased by 33% [68].

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

Table 2: Savings summary of case studies using variable flow strategy (adapted from [16], [58], [71]**)**

Table 2

~~Table 2~~ shows the results of the implementation of the abovementioned variable flow strategy at multiple mines. The average daily reduction in power usage was recorded as 1 540 kW. This translates to an average energy reduction of 35% with an average repayment period of 8.3 months with 17 months being the maximum. This definitively proves that the strategy is viable for implementation at a wide variety of mine cooling systems.

Relating directly to the repayment period and implementation cost is the cost of VSD installation. This directly affects the success of a variable flow DSM strategy as it will alter the repayment period of the strategy. An increase in VSD power rating is observed to have an inverse effect on the cost-effectiveness of supply and installation of the VSD. The cost/power (R/kW) ratio becomes more favourable as VSD size increases [16].

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

Table 3: VSD cost of supply and installation by size (adapted from [34])

A previous study found that a decrease in VSD size was directly associated with diminished savings potential and an increased R/kW ratio. Table 3 shows the costs of typical VSDs in SA based on November 2013 exchange rates. These costs are inclusive of typical requirements such as cabling, PLC programming, communication network adaptation and equipment commissioning [34].

Typical VSD implementation costs					
Mine	Proposed saving [kW]	Evaporator pumps [kW]	Condenser pumps [kW]	BAC pumps [kW]	Project costs (excl. VAT)
A	1150	2 x 300	4 x 275	3 x 132	R3 093 801
B	700	3 x 250	3 x 275	-	R1 991 470
C	1440	2 x 400 1 x 200	5 x 400 2 x 250	-	R3 443 816

Table 4: Typical VSD installation costs at a number of mines (adapted from [34])

Table 4

~~Table 4~~ shows the typical costs of implementation of a variable flow strategy using VSDs at a number of mines. Basic plant information is also provided. An Energy Services Company (ESCO) determined the feasibility of the displayed savings values through an energy audit. Site specific requirements are apparent, as each site will have varying pumping requirements [34].

As shown above, typical variable flow EE strategies depend heavily on the use of VSDs. This is the most appropriate manner in which an EE strategy should be approached, as costs and savings are most effective.

2.4 INVESTIGATING LOAD SHIFTING INITIATIVES

A number of studies have investigated the implementation of LS strategies of ventilation and cooling systems at mines [71] – [73]. The cooling load placed on mine cooling systems is directly linked to underground operations, as chilled water is used for underground equipment. As a result, the focus of this study will be to shift load from the evening peak billing period (18:00 to 20:00) to standard and off-peak periods [36], [73].

The primary method of shifting load from the evening peak period is to make use of thermal storage. This is the practice of ensuring that an ample amount of chilled water is stored during the off-peak and standard periods. Any cooling requirements that are dependent on chilled water can then be satisfied without the use of cooling equipment [36].

Control requirements

One of the many advantages of implementing an LS strategy is the relatively low equipment requirement. As discussed above, mine refrigeration systems supply either chilled water or chilled air. A combination of these two requirements is also apparent in some instances. The equipment required for various system configurations will differ slightly [36], [74].

An open loop cooling system, that makes use of surface chiller machines to provide only chilled water to underground mining and cooling equipment, was assessed in a previous study. The advantage of this system is that control can be focused on chilled dam level and chilled dam temperature, while controlling active chiller machines [36].

The abovementioned strategy made use of an early version of currently available energy management systems (EMSs). Plant control requirements are dam level and temperature monitoring, chiller stop/start control and water flow measurements. As was the case with this particular study, no equipment was required apart from control components such as servers, Supervisory Control and Data Acquisition (SCADA) alterations and PLC upgrades [36].

Another study, to develop a versatile LS control system, briefly assessed the impact of implementing an LS strategy on multiple closed loop configuration mine cooling systems. Closed loop systems supply only chilled air to underground working areas by means of a BAC [24]. The primary control element of these systems is the outlet temperature of the BAC, which must be kept within safe boundaries [74].

In both of the closed loop LS implementations only basic monitoring equipment, such as underground and BAC outlet temperature probes and control equipment as for the open loop system above, was required. An open loop system with an included BAC was also assessed to have similar requirements to that of the open and closed loop systems [74].

The basic operations of the LS controller used in the above case studies comprise of monitoring a combination of BAC outlet/underground temperatures and chilled water dam levels and temperatures. A maximum prescribed level is set for the BAC outlet/underground and chilled dam temperatures. The chilled water dam level is controlled according to a minimum value, as chilled water supply is crucial and may not cease [36], [74].

Fridge plant load shifting control (18:00 to 20:00)	
Fridge plant control	Control requirements
Shut down fridge plant	BAC output/underground temp. safe Chill dam level above set boundary Chill dam temp. below set boundary
Start fridge plant sequence	BAC output/underground temp. high
Start fridge plant sequence	Chill dam level below set boundary
Start fridge plant sequence	Chill dam temp. above set boundary

Table 5: Simplified load shifting controller parameters (adapted from [74])

These pre-set conditions dictate when, and if, a set of chillers can be shut down during the evening period. Table 5 shows the control parameters according to which the LS strategy controller operates. As can be seen, all cooling machinery that can be safely shut down is stopped during the evening peak period. Should any safety parameter move outside of the safe operating zone defined, the plant is started. The controller also allows for only a single start/stop sequence per day to reduce machinery wear [74].

Implementation considerations

In order to successfully implement an LS strategy at a mine, certain constraints outside of control must be accounted for. These include considerations as mentioned above for the EE strategy. Other considerations of health and safety must be considered, as LS strategy focuses on shutting down plants and limiting the available cooling capacity. This has the potential to create unsafe working environments, which cannot be allowed [72]. Adequate control of output temperatures and plant parameters is therefore a fundamental requirement.

Typical load shift strategy implementation costs		
Mine	Proposed savings (kW)	Installations cost (excl. VAT)
A	3200	R3 080 000
B	6300	R6 340 000
C	4200	R4 160 000
D	3200	R1 165 000

Table 6: Typical load shifting strategy implementation costs (adapted from [75])

A previous study carried out implementation of an LS strategy at a number of mines. Table 6 shows the typical implementation costs of an LS strategy at a mine. For this study, full plant control was implemented in all instances. As can be seen in the table, the relative costs associated with an LS strategy vary drastically [75]. This is due to the varying state of automation of mines throughout SA.

As discussed, for the implementation of any form of LS strategy on a mine cooling system, special attention must be given to the safety of operations. Detailed costing and assessment of plant automation must also be carried out prior to commencement of implementation. The cost of implementation will vary drastically depending on the level of plant maintenance, control and monitoring.

2.5 CONCLUSION

As discussed, cooling and ventilation systems installed at mines are set up very similarly. Plant layout, configuration, power usage and cooling output are all factors that are dependent on the application. The basic premise of operation and heat exchange is standard and as such, can be taken advantage of in order to carry out standard energy saving procedures through DSM.

Electric motors are extremely prevalent at mine cooling systems. These motors also present the greatest opportunity for cost saving through energy reduction by means of EE. Chiller machines are fitted with the largest of these motors, but are not feasible for VSD implementation as initial costs outweigh the possible savings that can be achieved. Pump motors and fans however, present the greatest opportunity for EE savings through VSD installations.

VSD installations on plant water pumps in particular present great opportunity for cost savings. This is because VSDs allow for excellent control of water pumps which would otherwise be carried out via extremely inefficient means. Numerous studies have also shown that the installation of VSDs at mine cooling system pumps has proven extremely effective at returning an EE saving.

Chiller machines, cooling towers and BACs show an affinity to LS strategy implementation, as cooling load can be accurately controlled using these components. Stop/start control of chillers allows for immense savings potential while maintaining cooling output. BACs, cooling towers and pumps, used in conjunction with chillers, can also be shut down as the underground thermal capacity of mines is immense and allows for periods of little to no cooling supply.

Studies in LS strategy implementation at mine fridge plants have proven that, even with relatively large input costs, the strategy is feasible. Complete assessment of plant operations, automation and monitoring must be carried out in order to ensure that total control of cooling supply during shut down periods is maintained.

A combined strategy must balance the requirements of both the EE and LS strategies in order to deliver sufficient EE as well as LS savings. This must be done while maintaining safe plant operations in the form of machinery health. Human health and safety in the form of safe underground working temperatures must also be maintained in order to ensure strategy success as well as safety.

3. OPTIMISED REFRIGERATION PLANT CONTROL THROUGH COMBINED DSM STRATEGIES

3.1 PREAMBLE

As outlined in the previous section, EE and LS strategies implemented at refrigeration plants are extremely effective at improving control as well as delivering a cost saving. In order to adequately investigate the impact of various strategies running simultaneously, simulations will be used.

Process simulation software, Process Toolbox (PTB), will be used to simulate a typical platinum mine refrigeration plant. Comparison between the simulations and an operational refrigeration plant will be used to increase accuracy. Deviations from actual running conditions will be accounted for to allow for simulated testing of the various DSM strategies.

Upon completion of an accurate refrigeration plant simulation, the various DSM strategies will be simulated separately. This will yield independent results to show the feasibility of both strategies independent of each other. Simulation of simultaneous implementation of the strategies will also be carried out. This, coupled with the independent simulations, will yield an indication of lost savings or inadequate process control.

An EE strategy will be investigated in order to determine the most efficient combination of control and savings. The focus of this strategy will be to increase plant efficiency, leading to an overall reduction in power usage. This must be done whilst maintaining acceptable output levels.

The LS strategy will be investigated in a similar manner to that of the EE strategy. The key difference is the focus on a reduction in peak billing period power usage. The disadvantage of an LS strategy implemented in tandem with an EE strategy is a possible shifting of load. The savings gained in the peak period may be translated to an increase in off peak demand. This may adversely affect the savings achieved by an EE strategy.

In conclusion, a baseline simulation will be developed using actual plant and process data. This baseline will then be altered to simulate both EE and LS strategies. A combination of EE and LS strategies will then be compiled. The combined strategy will be compared to the independent simulations to determine if any loss of savings or process efficiency exists. If the combined strategy is shown to be feasible, implementation may commence.

3.2 CONTROL PHILOSOPHY DEVELOPMENT

3.2.1 Equipment and control specifications

In order to accurately simulate the effects of various DSM strategies on a refrigeration plant, a typical plant setup must be used. A plant making use of both variable flow and variable temperature control can accurately represent this. Multiple pumps, fans, cooling towers and chiller machines will be included to complete the simulation.

The primary requirement for accurate simulation of a refrigeration plant is adequate input data. A case study was carried out at a mine near Northam in the Limpopo Province in South Africa (Mine X). This specific plant layout will be used for simulation. Process variables will be used as input data in order to match simulated values to actual process output data.

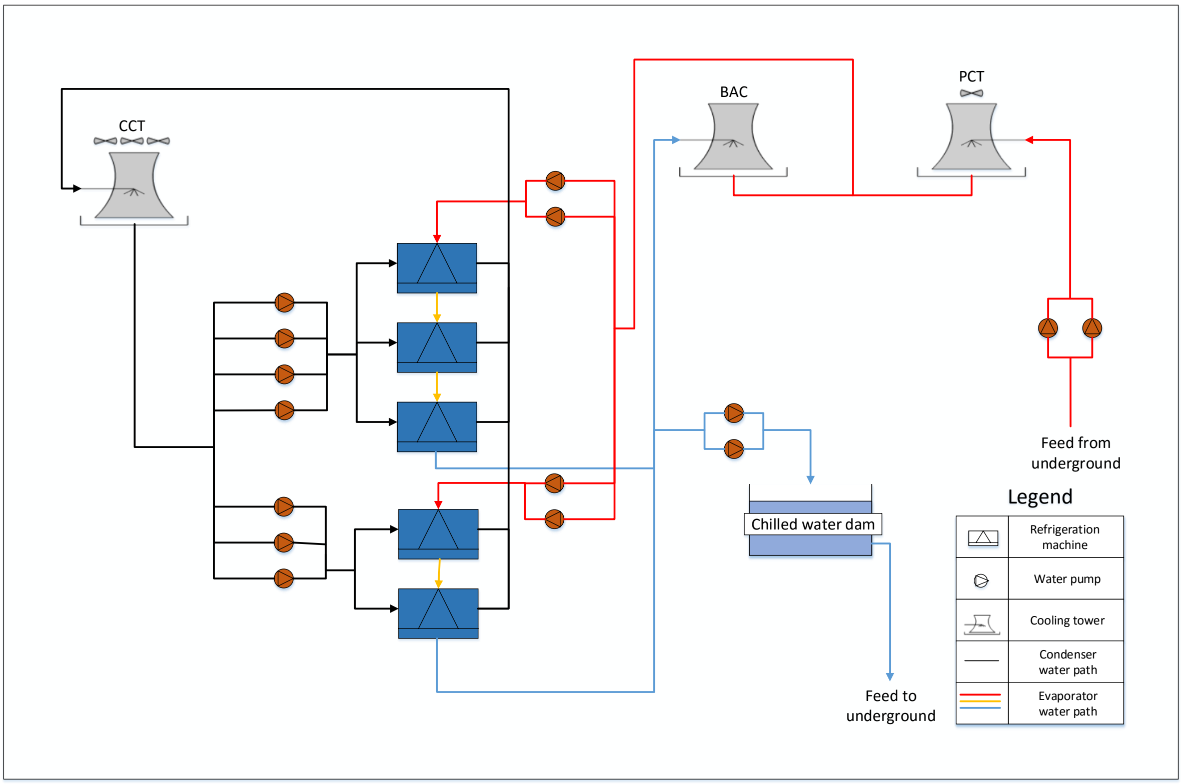


Figure 17: Mine X refrigeration plant layout

Figure 17 shows the refrigeration plant layout of Mine X. The various components present at the refrigeration plant will be discussed in this section.

Chiller machines

Cooling of water and, secondarily, air is the primary purpose of a refrigeration plant. In order to achieve this, large scale heat exchange must take place. Chiller machines are used to achieve this. As discussed in Chapter 2, ammonia chillers are generally installed.

Chiller machines can be configured in various ways. As detailed in Chapter 2, chiller machines can be configured in parallel, series or a combination of both. Mine X makes use of two plants coupled in parallel on both evaporator and condenser circuits. Plant 1 makes use of three chillers coupled in parallel on the condenser circuit and series on the evaporator circuit. Plant 2 is configured in a similar manner albeit with two chillers.

The two plants act in parallel, with the number of plants running varied to achieve the required cooling. Both condenser and evaporator circuits are independent for each plant. The exception to this being the condenser cooling towers, BAC water feed and surface chilled water dam feed. Both plants draw water from the condenser cooling tower sump. Both evaporator circuits draw hot water from the pre-cool tower and feed to the BAC and surface chill dam.

In order to compensate for flow and temperature demands, the number of plants run at each plant is varied. Plant 1 is run as a base load with the number of plants running varied to account for temperature variations. Should a greater evaporator outlet flow be required, plant 2 is started. Flow requirements are accounted for by means of valve throttling.

Plant 1 and plant 2 differ in calibration. The design of machines differs between the two plants, and as a result the plants have different COP values. The differing cooling capacities of the plants also results in a varied flow requirement. Table 7 provides the chiller specifications for both plant 1 and plant 2.

Chiller machines		
	Plant 1	Plant 2
Number of chiller machines	3	2
Machine type	Stal-Astra	York
Cooling capacity per machine	6532	6455
Evaporator inlet temperature [˚C]	12	12
Evaporator outlet temperature [˚C]	1	1
Condenser inlet temperature [˚C]	24	24
Condenser outlet temperature	28.5	28.5
Evaporator water flow rate [ℓ/s]	425	280
Condenser water flow rate per machine [ℓ/s]	385	440
Machine COP	5.02	4.97
Refrigerant	Ammonia	Ammonia
Compressor type	Screw	Screw
Compressor rating [kW]	1300	1300

Table 7: Fridge plant chiller machines specifications

Pumps

Moving large quantities of water is crucial to the operation of refrigeration plants. Both evaporator and condenser circuits of a refrigeration plant make use of water to achieve cooling. Various sizes of water pump are used in order to move water as required by the refrigeration plant. Specific flow requirements will vary from plant to plant.

The condenser circuit of the refrigeration plant makes use of water to chill ammonia. The water is pumped at a rate of approximately 450 ℓ/s through the condenser heat exchangers and condenser cooling towers. In order to achieve the specified flow, pumps are generally run in parallel. The pumps must also be adequately sized. As a result, most pumps in use at mines are over-spec.

Similarly, the evaporator circuit passes hot water through the evaporator heat exchanger. At this point the water is cooled and fed to either the BAC or directly to surface chilled water storage dams. This water flow, typically half the condenser flow rate, is large enough to also necessitate the use of relatively large pumps.

Mine X makes use of a number of pump sizes as well as configurations, as shown in Figure 17, to achieve required flow rates. Table 8 provides the specifications of the water pumps in use at Mine X. Plant 1 makes use of three chiller machines while plant 2 makes use of two. The number of pumps needed to provide the required flow rates is representative of this.

Water pumps		
	Plant 1	Plant 2
Evaporator pumps		
Number of pumps	2	2
Pump motor rating [kW]	400	200
Pump water flow rate [ℓ/s]	425	250
Pump pressure [kPa]	400	530
Condenser pumps		
Number of pumps	4	3
Motor rating [kW]	400	250
Water flow rate [ℓ/s]	370	390
Pump pressure [kPa]	400	400

Table 8: Fridge plant water pump specifications

In addition to the refrigeration plant water pumps, the system also makes use of transfer pumps. These pumps are used to provide the evaporator circuit with hot water via the pre-cooling tower. Another crucial role is to provide chilled water to the surface dam. Table 9 provides the specifications of these pumps.

Transfer pumps	
Return pumps	
Number of pumps	2
Pump motor rating [kW]	75
Pump water flow rate [ℓ/s]	150
Pump pressure [kPa]	280
Feed pumps	
Number of pumps	2
Motor rating [kW]	75
Water flow rate [ℓ/s]	150
Pump pressure [kPa]	280

Table 9: Fridge plant transfer pump specifications

Bulk Air Cooler

One of the primary purposes of the refrigeration plant is to provide a safe underground working environment. This is achieved by providing chilled ventilation air to underground working areas. This is done through various means, with BACs and spot coolers being the most prominent. The refrigeration plant at Mine X makes use of a single above-ground BAC.

The BAC in place at Mine X is used to chill ventilated air supplied to a single shaft. Secondary underground cooling equipment is present at other shafts at the same mine. These underground cooling systems make use of the chilled water supply to cool air. As the demand for these secondary systems is represented by the chilled water demand, they will not be directly included in this study.

The BAC in place at Mine X is of the induced draught design. The flow of air through the BAC is being induced by ventilation fans at various locations throughout the mine. A curtain of chilled water is created within the BAC. Ventilation air is forced to travel through this curtain of water before passing underground. The heat exchange that takes place in the BAC provides the necessary cooling.

Table 10

~~Table 10~~ provides the specifications of the BAC in place at Mine X.

Bulk air cooler	
Number of bulk air coolers	1
Air flow per cell [kg/s]	420
Water inlet temperature [°C]	2
Water outlet temperature [°C]	12
Water flow rate [ℓ/s]	425
Sump capacity [Mℓ]	0.6
Air outlet wet-bulb temperature	8

Table 10: Fridge plant BAC specifications

Condenser cooling towers

The chiller machines in use at Mine X make use of condenser circuit water to chill heated ammonia. The water is pumped from the condenser cooling tower sump to the condenser heat exchanger of the chiller. At this point the water is heated and passes out of the chiller. In order for the chiller to work effectively, this water must be chilled before passing through the heat exchanger once more.

The condenser cooling towers operate by pumpingflowing water into the top of the tower. The water then falls and is dissipated into smaller droplets using a packing material. Fans are used to increase the air flow through the towers, thus increasing the amount of heat exchanged.

Formatte

Table 11

Table 11 provides the specifications for the condenser cooling towers in place at Mine X.

Condenser cooling towers	
Number of condenser cooling towers	3
Air flow per cell [kg/s]	420
Water inlet temperature [°C]	2
Water outlet temperature [°C]	12
Water flow rate [ℓ/s]	425
Sump capacity [Mℓ]	0.6
Condenser cooling tower fan rating [kW]	90

Table 11: Fridge plant condenser cooling tower specifications

Pre–cool tower

Chilled water that is passed underground is used to chill the rock face, as well as in the operation of cooling equipment. After use, this water, along with discarded ground water, is at a temperature of approximately 28 °C. This water is pumped above ground and serves as the supply for the refrigeration plant evaporator circuit.

In order to increase the effectivity of the plant, a pre-cooling tower is used to drop the temperature of the water supplied to the evaporator circuit before use. This cooling tower makes use of a fan to induce air flow. The specifications of the pre-cool tower are provided in Table 12.

Pre-cool tower	
Number of pre-cool towers	1
Tower fan rating [kW]	75
Air flow per cell [kg/s]	265
Water inlet temperature [°C]	28
Water outlet temperature [°C]	23
Water flow rate [ℓ/s]	200
Sump capacity [Mℓ]	0.6

Table 12: Fridge plant pre-cool tower specifications

3.2.2 Mine cooling requirements

Cooling for underground operations is carried out using two different methods. The first method of cooling is the direct supply of chilled air. This chilled air is supplied by the BAC. The second method is through the supply of chilled water. This chilled water is used to cool the virgin rock face. Chilled water is also fed to secondary underground cooling equipment.

Underground cooling requirements must be thoroughly understood and quantified. If this is achieved, surface supply control can be more accurately developed. Quantifying the underground chilled water demand can be achieved through monitoring the supply via the surface chilled water storage dam. The chilled air supply is permanent during the summer months and generally not monitored.

Underground virgin rock temperatures are relatively high for the majority of SA platinum mines. Figure 5 shows the increase in temperature by depth. Heat radiates from the rock face and heats up the air in the surrounding work areas. Chilled air from the BAC is used to reduce this effect. The effect of this chilled air must be quantified.

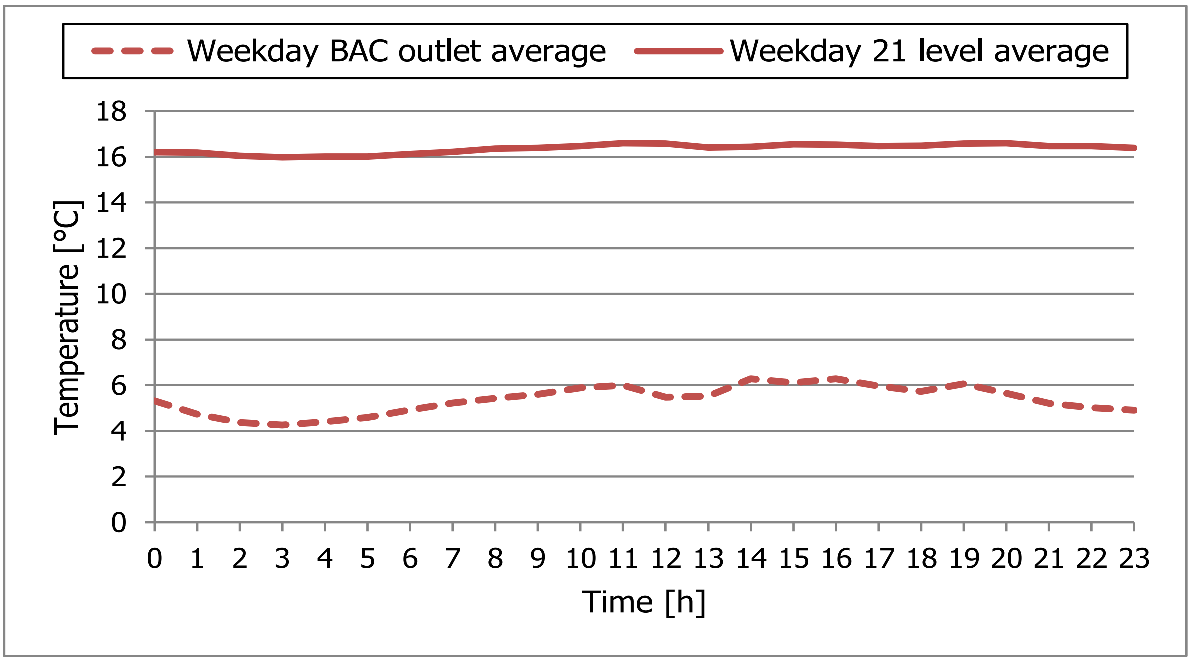


Figure 18: BAC vs 21 level average air temperature

Figure 18 shows the summer weekday average for the BAC outlet air temperature and 21 level air temperature. The 21 level average temperature is used for calculations as the level is the deepest and hottest level that is fed by the BAC. The temperatures in this figure are dry-bulb values.

The underground temperature is approximately three times higher than the BAC outlet. The maximum underground working temperature permitted is 37.5 °C dry-bulb [18]. The maximum value currently is below 17 °C. As a result, under standard operating conditions, the BAC cooling capacity is sufficient.

In order to quantify underground thermal capacity accurately, drop testing must take place. To do this the surface fridge plant must be shut down for a period. The evening peak period was selected for this. The results are then appropriate for the LS strategy control. Once the surface refrigeration plant was shut down, the underground working levels were allowed to heat up marginally. No personnel were underground during testing.

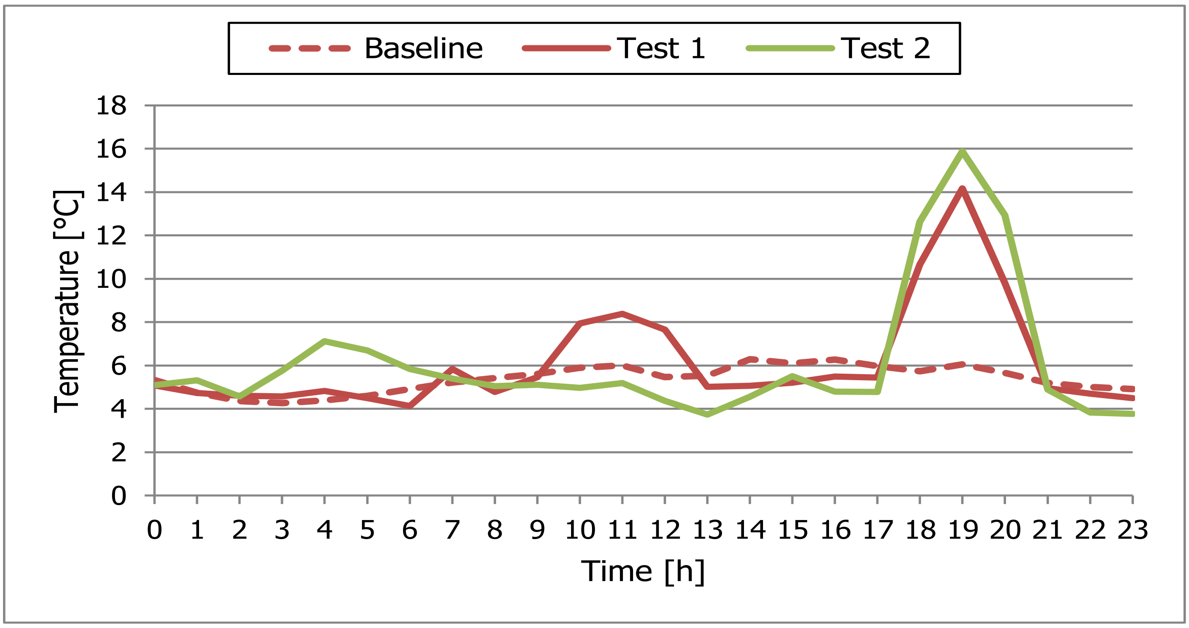


Figure 19: Drop test BAC outlet temperatures

Figure 19 shows the BAC outlet temperature for an average weekday as well as two drop tests carried out during the same measuring period. As can be seen, the outlet temperature dramatically increases if the plant is shut down. The maximum temperature achieved is just below 16 °C dry-bulb. This is well below the accepted 37.5 °C dry-bulb. The underground temperature reacts at a slower rate than the BAC outlet due to the thermal capacity of the mine.

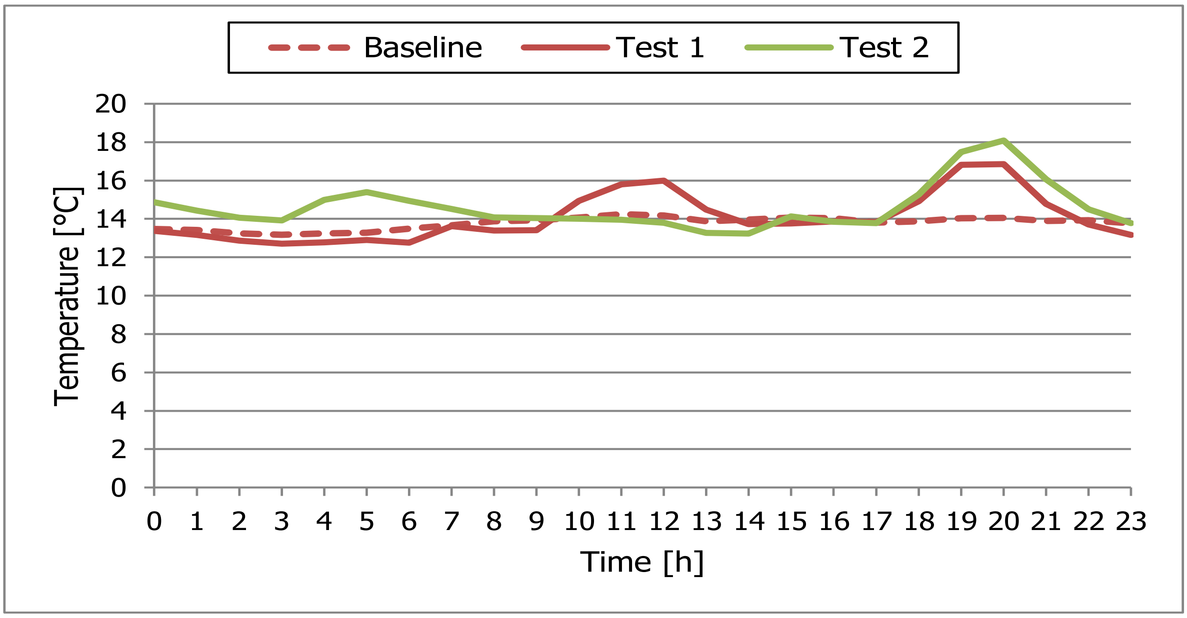


Figure 20: Drop test 21 level temperature

Figure 20 shows the average wet-bulb temperature for 21 level. The values for the first and second test are also included. As can be seen, the increase in temperature is not as dramatic underground as on the surface. A correlation can be derived for the BAC outlet and 21 level wet-bulb temperature. This will allow for accurate surface control without the need for costly underground monitoring.

$$\boldsymbol{T_{21L} = 0.367T_{BAC} + 0.075T_{amb} + 0.016H_{amb} + 9.249}$$

Equation 5: 21 Level wet-bulb temperature

Equation 5 shows the calculation used to determine the 21 level wet-bulb temperature. The variables; T_{21L}, T_{BAC}, T_{amb} and H_{amb} represent 21 level wet-bulb temperature, BAC outlet temperature, ambient dry-bulb temperature and ambient relative humidity respectively. The correlation co-efficient of the equation is 0.66. This equation can be used throughout control implementation to ensure safe underground operations.

The chilled water requirement of the mine is capacitated by the surface chilled water dam. The control of this level is carried out through the starting and stopping of transfer pumps. These pumps are controlled according to the current surface dam level. Control is currently in place at these pumps. As a result, this aspect of the cooling requirements will require no alterations but will be monitored.

3.2.3 Hardware requirements

In order to gain full control of the refrigeration plant, certain hardware requirements must be met. This is as a result of most plants being fairly old and requiring updating, repair and alteration to allow for the improved control. Each type of DSM project will have a number of requirements unique to that project. A brief discussion will follow that will detail the requirements of both EE and LS projects as covered in this study.

Energy efficiency strategy

The primary control requirement of the EE strategy is the ability to reduce the running frequency of the plant water pumps. This can be achieved through the use of VSDs. Purchasing and installing VSDs can however be costly. As a result, only those pumps that will return the greatest power reduction should be fitted with VSDs.

Figure 21: Water pumps installed at Mine X[1]

Formatte

Table 8

~~Table 8~~ and Table 9 detail the specifications of the pumps in use at Mine X. As shown, the largest of the transfer pumps is 90 kW. This size of pump is not viable for VSD installation as the pump will not return a saving large enough to warrant the costs involved. The condenser and evaporator circuit water pumps, as shown in Figure 21, display ample opportunity for energy savings.

[1] Photo taken at Mine X by the author with the mine's permission.

In order to determine the cost of VSD installations, quotes from various appropriate contractors were obtained. The contractor displaying the most appropriate skill set as well as cost effectiveness will be selected to carry out the required work. The contractors were supplied a brief to quote for VSD installation on all circuit water pumps. All ancillaries required were also included.

Quotations	
Contractor 1	R 11,497,926.58
Contractor 2	R 5,188,587.89
Contractor 3	R 4,019,683.00
Contractor 4	R 3,443,815.85

Table 13: EE project infrastructure quotes

Table 13

~~Table 13~~ shows the prices quoted by various contractors for the installation of VSDs at Mine X. These prices serve to outline the large costs associated with VSD installations. It must be determined if the payback period of the EE project is short enough to warrant the initial cost. The EE simulation, as detailed in section3.3, will be used to calculate the payback period as a result of savings achieved.

EE project bill of quantities		
Nr	**Item**	**Quantity**
1	**Equipment:**	
1.1	400 kW / 570 A Allen Bradley Variable Speed Drive	6
1.2	250 kW / 310 A Allen Bradley Variable Speed Drive	2
1.3	200 kW / 260 A Allen Bradley Variable Speed Drive	1
1.4	Panel for 400 kW / 570 A Allen Bradley VSD	6
1.5	Panel for 250 kW / 310 A Allen Bradley VSD	3
1.6	Panel for 200 kW / 260 A Allen Bradley VSD	2
1.7	Weather station	1
2	**Instrumentation / communication equipment:**	
2.1	Profibus cable	225
2.2	Profibus D-Sub 9-pin attached vertical connector	4
2.3	6GK1503-3CB00 - Siemens OLM Multi Mode	2
3	**Cables:**	
3.1	70 mm earth cable	220
3.2	300 mm 3 core cable	220

3.3	2.5 mm 3 core PVC SWA power supply cable	25
3.4	BT-FIB-F016 - 4 core MM HDD fibre	100
3.5	BT-FIB-F080 - Multicoupler	4
3.6	BT-SPLICE - Splice & OTDR	4
3.7	BT-FIB-F176 - 1 meter unjacketed pigtail	8

Table 14: EE project bill of quantities

Table 14

Table 14 shows the bill of quantities for the EE project infrastructure. As can be seen, one pump on both the evaporator circuit and condenser circuit is not to be fitted with a VSD. These pumps will serve as a backup in the unlikely case of a failure of the VSDs. The inclusion of a weather station is also required in order to constantly monitor ambient conditions.

Load-shifting strategy

The sole requirement of the load-shifting strategy control is the ability to safely stop and start the entire refrigeration plant. In order to do this, slight alterations to the plant infrastructure are required. A site investigation was carried out with the aid of on-site personnel in order to determine what infrastructure would be required to safely stop and start the refrigeration plant.

The plant starting and stopping procedure is already in place. There are however, certain procedure requirements that will require alteration. Currently no control is in place for the centralised starting and stopping of the condenser cooling tower fans. Condenser circuit valves are also manual. Should these valves not be closed when the plant is shut off, the condenser circuit experiences unnecessary or reversed flow.

Figure 22: Load shifting strategy: proposed condenser circuit valve location[2]

Installation of automated water valves on the condenser circuit water lines will be required. Figure 22 shows the proposed position of the water valve. Installation of communications and PLCs will be required for the starting and stopping of the condenser cooling tower fans. Contractors were approached to quote for the work required.

Quotations	
Contractor 1	R 1,135,530.86
Contractor 2	R 926,837.22
Contractor 3	R 990,204.33

Table 15: LS project infrastructure quotes

When compared with the EE project, the LS project is very cost-effective. However, the savings achieved by the LS project are in the peak period only. The result of this is a reduced cost saving. The simulations in section 3.4 will be used to determine if the LS project is cost effective in terms of payback from savings achieved.

[2] Photo taken at Mine X by the author with the mine's permission.

LS project bill of quantities		
Nr	**Item**	**Quantity**
1	**Chilled water valve installation**	
1.1	Slimline 450mm PN16 cast iron butterfly type valve	3
1.2	Yellow Asi cable (roll E74100)	1
1.3	Black Asi cable (roll E74110)	1
1.4	Asi splitter (used to extend cable) (AC3000)	3
1.5	Asi Air Box 2 in 2 out (AC5227)	3
1.6	Wirable M12 Plug (E11504)	6
1.7	Asi cable end glands (E70413)	1
1.8	Asi fly leads	6
1.9	Air Pipe to Valve	100
2	**Condenser cooling tower fan control**	
2.1	600x600x210 S/S enclosure	1
2.2	Trunking, din rails, fixtures &misc	1
2.3	Terminals, double with fuse module	12
2.4	Glands (existing temp plus 3 spare for vid switches)	12
2.5	Glands (multi core)	2
3	**Transfer pump control**	
3.1	1000x1000x300 S/S enclosure double door	1
3.2	Trunking, din rail, fixtures &misc	1
3.3	Terminals, double with fuse module	80
3.4	Panel wire assorted colours	2
3.5	220v-110v - control transformer	1
3.6	Mini circuit breaker 1 pole supply (in 220v DB)	1
3.7	Mini circuit breaker 2 pole incomer	1
3.8	Mini circuit breaker 1 pole control transformer input	1
3.9	Mini circuit breaker 1 pole control transformer output	1
3.10	Mini circuit breaker 1 pole profibus adaptor	1
3.11	Mini circuit breaker 1 pole IO rack	1
3.12	Mini circuit breaker 1 pole fiel 110v	1
3.13	Cable tray - wire mesh	1
3.14	Glands (power supply and comms)	4
3.15	Glands (multicore to buckets)	1
3.16	Tray fixings	1
3.17	6ES7390-1AE80-0AA0 - DIN rail 480 mm	1
3.18	6ES7153-1AA03-0XB0 - IM 153-1 for ET 200M, PROFIBUS DP	1
3.19	6ES7321-1EL00-0AA0 - Digital input 32DI, 120V AC; isolated	1
3.20	6ES7392-1AM00-0AA0 - Front connector, 40-pin, with screw contacts	1
3.21	6ES7307-1EA01-0AA0 - Load current supply PS 307; AC 120/230V, DC 24V, 5A	1
3.22	6ES7322-1FL00-0AA0 - Digital output 32DO, 120V AC, 1A; isolated	1
3.23	6ES7392-1AJ00-0AA0 - Front connector, 20-pin, with screw	1

	contacts	
3.24	6ES7331-7KF02-0AB0 - Analog input 8AI; 14-bit; 20ms; isolated	1
3.25	Profibus Plug	2
4	**BAC temperature probe**	
4.1	Asi splitter (used to extend existing cable) (AC3000)	1
4.2	Asi IO 2 DIN, 2 DOU, 1 AIN, 1 AOU (AC5230)	1
4.3	Wirable M12 Plug (E11504)	2
4.4	Wirable M12 Socket (E11508)	2
4.5	Temperature Sensor	1
4.6	Asi fly leads	2
4.7	Clamp Fitting (E30025)	1

Table 16: LS project bill of quantities

Formatte

Table 16

~~Table 16~~ provides the bill of quantities required to achieve full control of the refrigeration plant at Mine X. No monitoring is currently in place at the BAC outlet. As a result a dry-bulb temperature monitor is added. This, coupled with Equation 5 and the weather station specified in Table 14, will allow for the calculation of the 21 level wet-bulb temperature.

3.2.4 Energy efficiency control philosophy

The effective return on investment of the combined strategies depends heavily on the order in which the projects are implemented. Certain control elements of one strategy can heavily influence the control of another. Greater control will allow for greater savings to be achieved. To this end, the first strategy that is implemented must be selected with the goal of maximising savings and minimising costs.

The EE strategy is the most appropriate strategy to implement initially. The cost savings allowed for through an EE strategy are far greater than an LS strategy. The control elements of the EE strategy, namely pump speed control, can be used to the benefit of the LS strategy. Another benefit of this is that the savings of the EE strategy can be used to offset the initial cost of the LS strategy.

The initial control philosophy is focused on the EE strategy. An energy management system (EMS) program will be used to control the system. The control of this strategy includes monitoring certain process parameters and adjusting pump speeds accordingly. The EMS system will connect with the plant SCADA via an OPC connection to achieve this. The condenser and evaporator circuits of the plant are controlled independently of each other.

Condenser circuit control

The control of the condenser circuit water flow will be as follows:

- Starting and stopping of pumps is still controlled by the plant SCADA. After a pump has started, and is running, the EMS control will assume control.
- EMS will write a set-point value for the temperature differential across the chiller machine condensers. The SCADA will control the VSD frequency as required to achieve the required set-point.
- The PLC will be coded in such a manner that a minimum flow may not be exceeded. A minimum frequency will be associated with a fixed flow. This minimum VSD frequency will then be set to the PLC.

Figure 23 graphically represents the communications of the system. Should either the SCADA or the EMS systems fail, the PLC will revert back to a standard operating frequency. This frequency will be fixed to the value under which the pumps currently operate, namely 50 Hz.

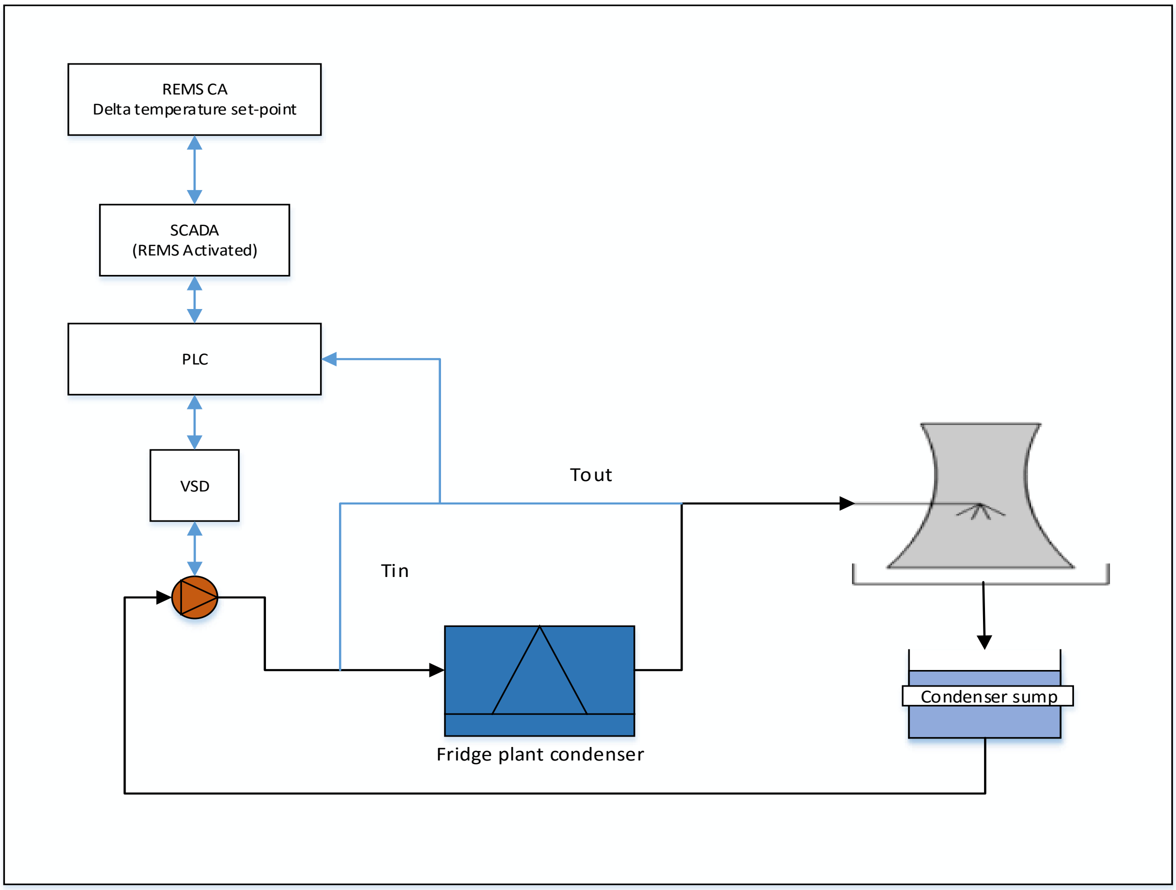


Figure 23: Energy Management Software Condenser control

Evaporator circuit control

The control of the evaporator circuit water flow will be as follows:

- Starting and stopping of pumps is controlled by the plant SCADA. After a pump has started, and is running, EMS will assume control.
- EMS will write a set-point value for the output temperature of the fridge plant evaporators. The SCADA will control the VSD frequency as required to achieve the required set-point.
- The minimum temperature and flows will be associated with a minimum VSD frequency. This frequency will be set to the PLC.

Figure 24 provides a graphic representation of the communications of the system. Should either the SCADA or the EMS systems fail, the PLC will revert back to a standard operating frequency. This frequency will be fixed to the value under which the pumps currently operate, namely 50 Hz.

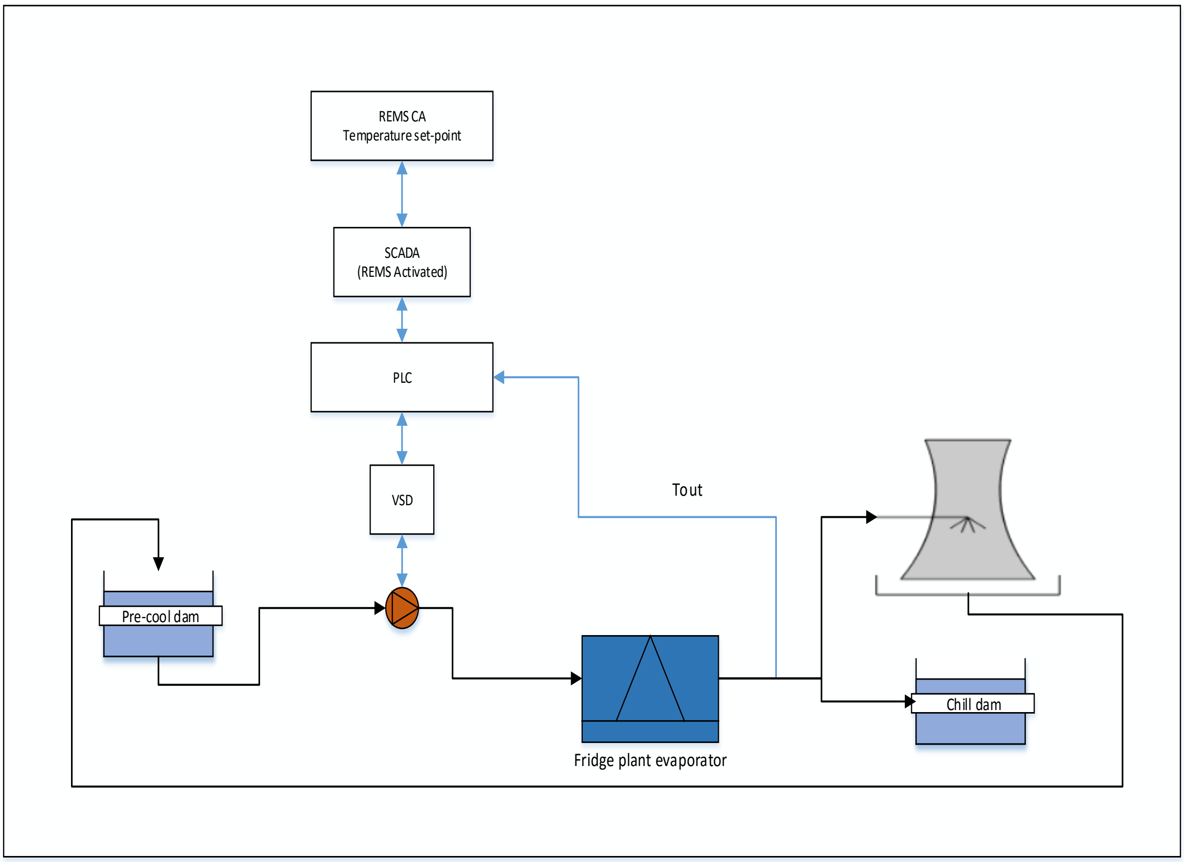


Figure 24: Energy Management Software Evaporator control

The temperature set-points required by the system will be determined during implementation. Performance testing of the strategy will also take place. This will be carried out upon completion of implementation. The installations required for this strategy are basic and costing is complete. The economic viability of the strategy is to be determined in section 3.4.

3.2.5 Combined control philosophy

After implementation, testing and evaluation of the initial control philosophy, the final control philosophy of the combined strategies can be implemented. The combined control philosophy will include the previously implemented EE strategy. Alterations will be made to the strategy to account for shutting down the refrigeration plant during the evening peak.

As detailed in section 3.2.3, infrastructure will be required for the control of the condenser cooling tower fans, transfer pumps and condenser circuit water valves. Upon completion of the infrastructure upgrades, control of the system can be implemented. Unlike the EE strategy control, the LS control will be time based. This is to allow for the stopping of the plant during the evening peak.

The evaporator circuit control of the plant will be as follows:

Combined strategy evaporator circuit control			
Time period	**Item**	**Monitor**	**Procedure**
00:00-16:00	Refrigeration plant	-	EE strategy normal control
16:00-18:00	Surface chilled water dam	Dam level	Raise minimum start level for transfer pumps to raise dam level
18:00-20:00	BAC	BAC air temperature	Maintain safe temperature
	Surface chilled water dam	Dam level	Maintain above safe level
	Fridge plants	-	Shut down
	Surface chilled water dam feed pumps	-	Shut down
	Evaporator water pumps	-	Run only one evaporator pump
20:00-00:00	Refrigeration plant	-	EE strategy normal control

Table 17: Load shifting control philosophy evaporator control

The condenser circuit control of the plant will be as follows:

Combined strategy condenser circuit control			
Time period	**Item**	**Monitor**	**Procedure**
00:00-18:00	Fridge plants	-	EE strategy normal control
18:00-20:00	Fridge plants	-	Shut down
20:00-00:00	Fridge plants	-	EE strategy normal control

Table 18: Load shifting control philosophy condenser control

This system will allow for the control of the EE strategy, with the improved savings of shutting down the plant for the evening period. The final control philosophy combines the EE and LS strategies. This will allow for an EE energy saving as well as an evening peak period LS energy saving. A more detailed explanation of the various control components to be implemented is discussed in the following sections.

3.3 SIMULATING A COMBINED CONTROL STRATEGY

3.3.1 Simulation requirements

In order to accurately simulate plant operations, applicable process data must be acquired. A typical summer day operation of the plant will be used. The period from which this process data is acquired will also be used to determine an electricity usage baseline. The use of a summer day profile will ensure that the plant is running at the highest possible ambient temperatures, and as a result consuming the most power.

A typical summer period will be assessed. The required process data will be drawn from this period. The average ambient temperature of the period will be used as the first requirement, this will ensure the heat load on the system is depicted accurately. After assessment, average process data was chosen as the most appropriate depiction of typical ambient temperatures. Figure 25 shows the average ambient temperature for the period compared to the selected assessment data.

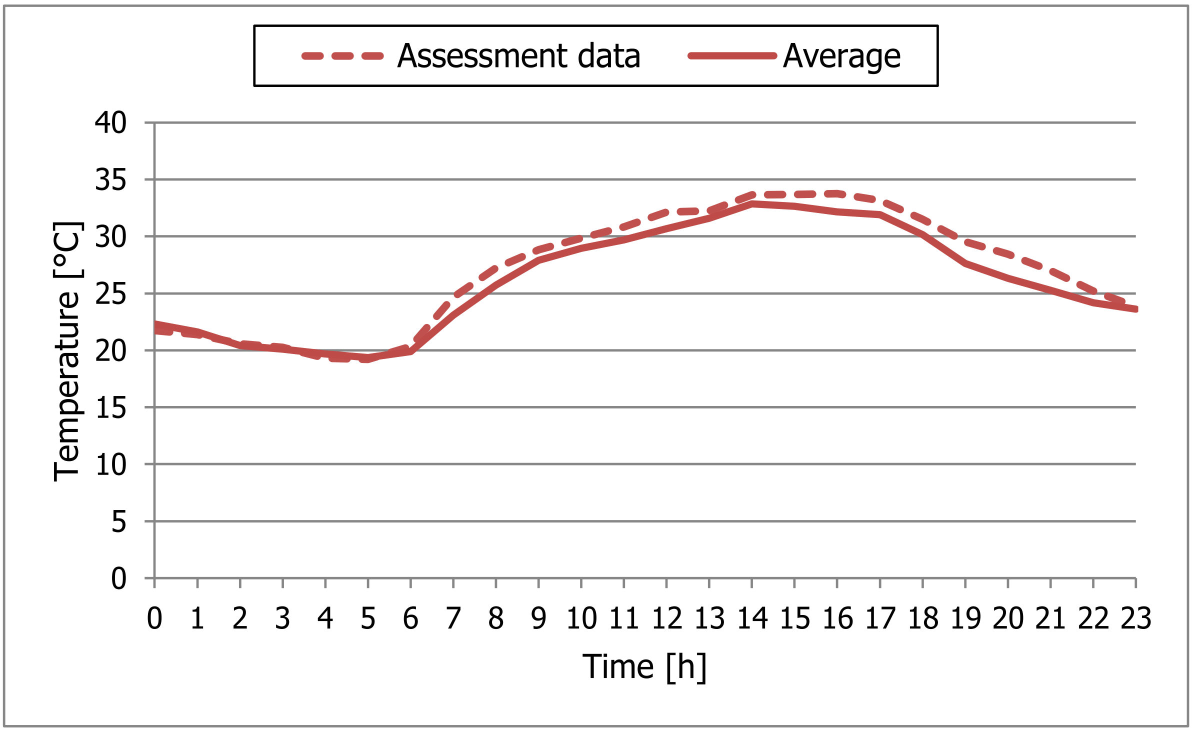


Figure 25: Summer period average ambient temperature vs. assessment data

The correlation coefficient for the temperatures is 99%, so the assessment data is an accurate depiction of ambient conditions during summer. In order to accurately assess power consumption and cooling demand, all users dependant on the refrigeration plant must be quantified. The chilled air demand can be accurately depicted according to ambient conditions.

Chilled air supply is one of two demands the refrigeration plant must meet. The second supply from the refrigeration plant is chilled water. This water is drawn from the evaporator circuit and is fed directly to a surface water storage dam. This water flow directly represents the chilled water demand on the refrigeration plant. Figure 26 shows the chilled water flow to the surface dam.

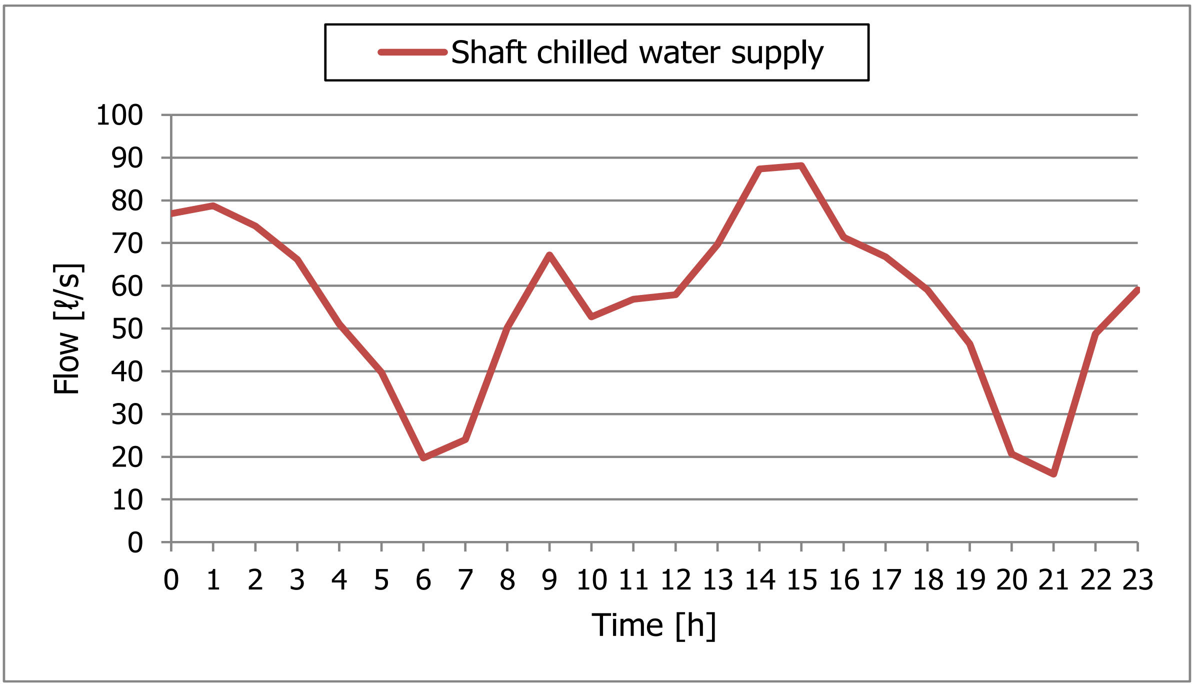


Figure 26: Chilled water supply to shaft for the assessment period

Finally, the measured power consumption of the refrigeration plant must be acquired. This measurement is crucial in order to determine the accuracy of the simulated power data. This data will be used as the primary comparison between the simulated data and actual operating conditions. Figure 27 shows the power profile of the refrigeration plant for the assessment period.

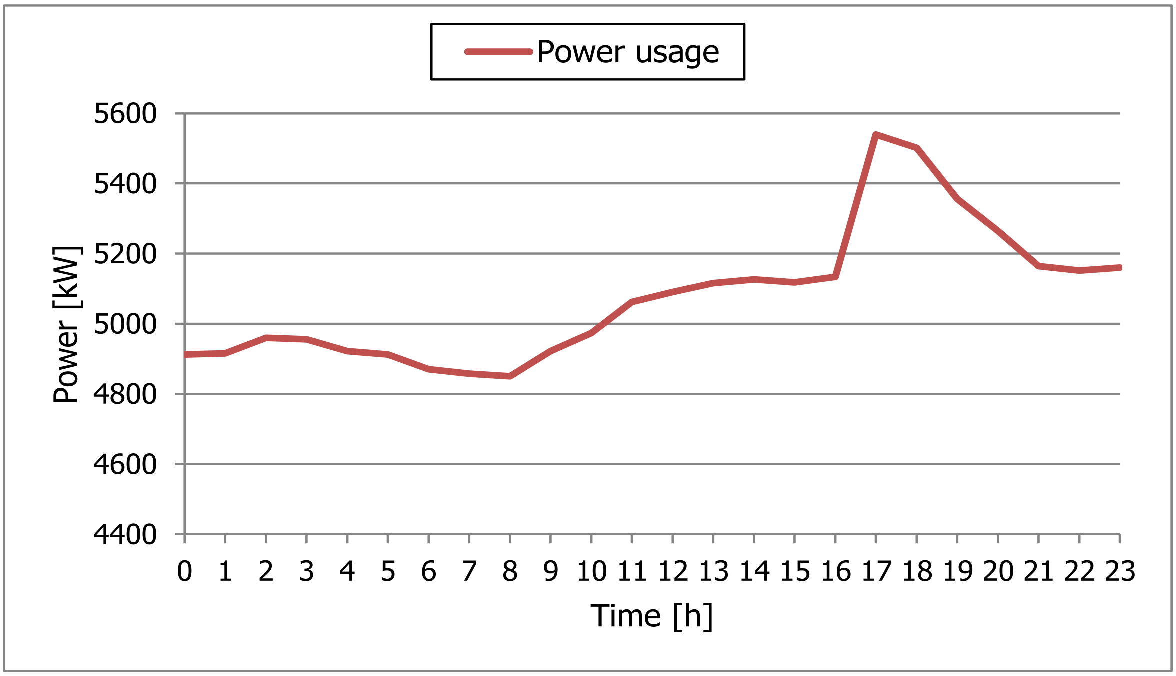


Figure 27: Refrigeration plant power consumption for the assessment period

3.3.2 Baseline simulation

In order to determine the feasibility of implementing the various DSM strategies at a platinum mine refrigeration plant, simulations will be used. The primary advantage of developing an accurate plant simulation is the dramatically reduced cost compared to immediate implementation. This allows for accurate assessment of DSM strategies without risking damage to costly equipment or personnel safety.

The first simulation to be carried out is a baseline simulation, the layout of which can be found under Appendix A. The baseline simulation will serve two purposes. Firstly the simulation will be used to determine the accuracy of the simulation by comparing simulated data to actual plant performance data. Secondly, the simulated process data will then be used as a baseline for comparison to the simulated DSM strategy control.

As discussed in the previous section, the process and power data of a fixed assessment period is used to develop and assess the baseline simulation. Ambient conditions, chilled water demand and equipment schedules will all be incorporated into the simulation to accurately represent plant operations. Figure 28 shows the actual refrigeration plant power vs. the simulated power usage.

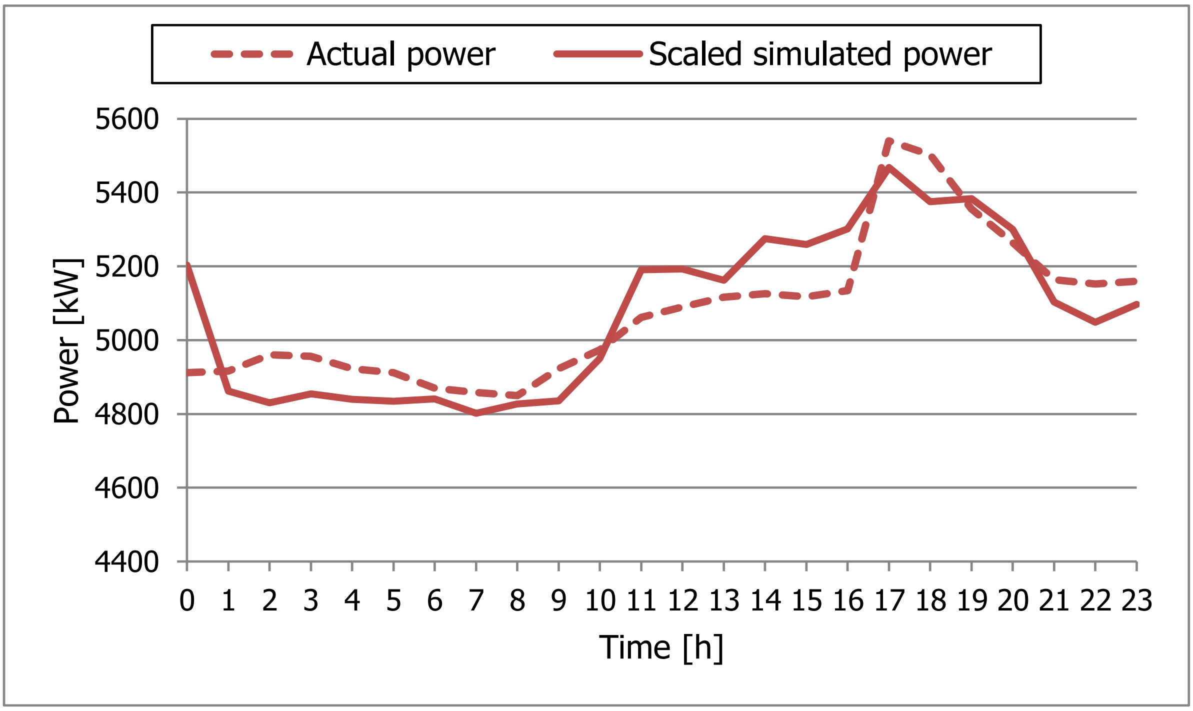


Figure 28: Actual refrigeration plant power vs. simulated power for the assessment period

A scaling factor of 1.19 is used to scale up the simulated power usage. This factor is used as the measured actual power data includes equipment not related to the refrigeration plant operation. This equipment comprises primarily of fans, which are run constantly and can be ignored if an applicable scaling factor is used. The correlation coefficient of the data is 0.75;, this is acceptable as the simulated data cannot account for factors such as plant deterioration and efficiency variations.

3.3.3 Energy Efficiency (EE) simulation

The focus of the EE strategy is the temperature based speed control of evaporator and condenser circuit water pumps. This is generally achieved through the use of VSDs. The EE control simulation, with layout found under Appendix B, is based on the baseline simulation. Speed control of water pumps is included in the simulation to represent EE control of the refrigeration plant.

The chiller machines at Mine X make use of slide valve control. This allows the chiller machines to be run at partial load conditions. Under partial load, the ammonia compressors of the chiller machines consume less power. Reducing the condenser and evaporator pump speeds allows the chillers to run at optimum flow rates. As a result, the controlled water flow rates also allow the chiller compressors to run optimally.

In order for the system to be effective it must reduce the overall energy consumption of the plant. This is achieved by dropping the average power consumption for the refrigeration plant for a full 24 hour day. The EE control simulation runs according to all parameters as discussed above. Figure 29 shows the power consumption profile for the refrigeration plant simulation.

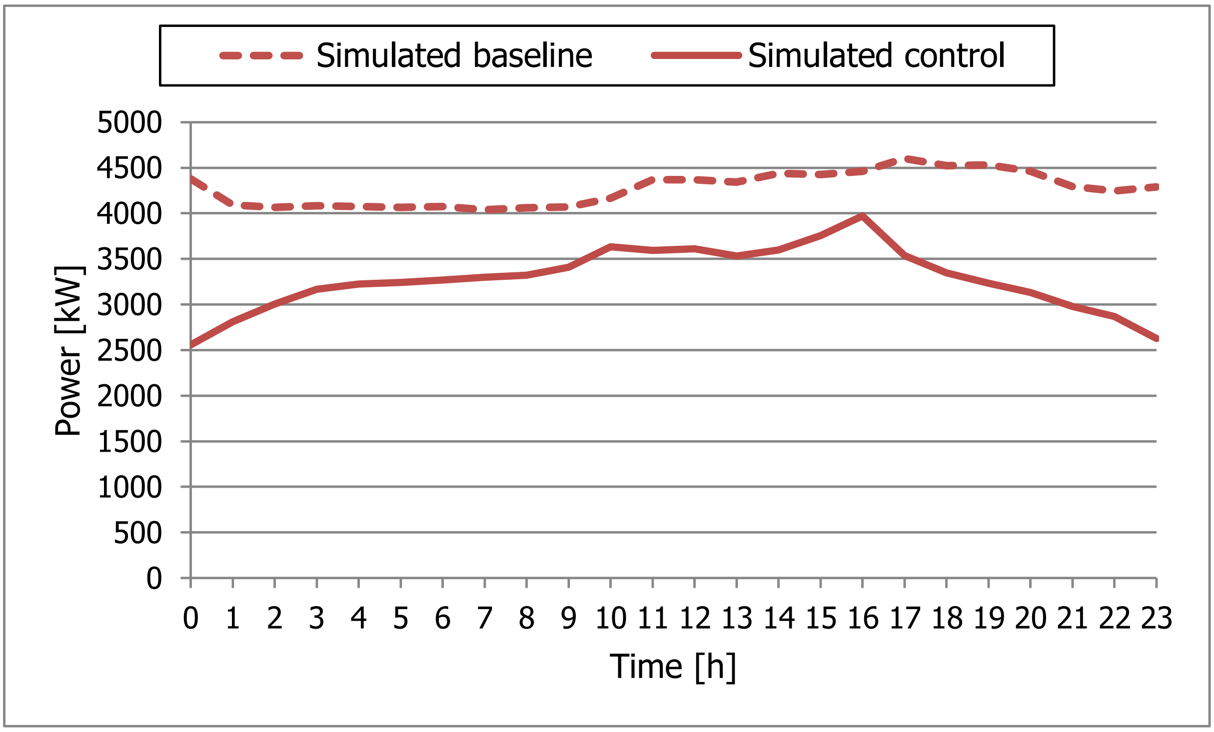


Figure 29: Energy efficiency control simulation power profile

The power profile yields an overall average saving of 992 kW for the 24 hour period. This results in a cost saving of R 11,000 per day. This is a cost reduction of over 22%. As can be seen, the plant operates at a lower energy consumption as opposed to the baseline operations. The reduced power usage of the plant must be balanced by equal, or improved, plant efficiency.

The primary control measurement for the EE strategy control is differential temperature. The condenser circuit yields a water temperature increase. The inverse is true for the evaporator circuit. If the condenser temperature differential is decreased, the plant is running at a lower efficiency with the control implemented. The inverse is true for an increase in temperature differential, indicating increased efficiency.

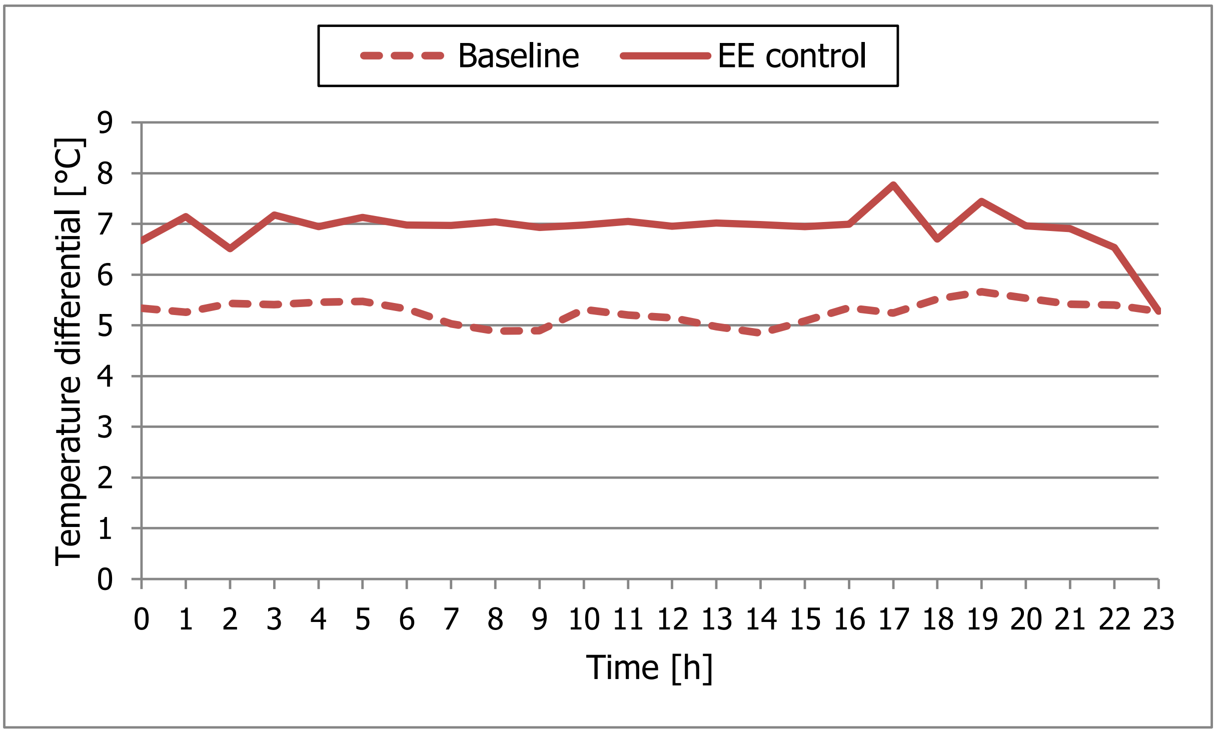


Figure 30: Energy efficiency control simulation condenser temperature differential

Figure 30 shows the temperature differential for both the baseline and EE control simulations. The average increase in the differential is 1.65 °C. This shows that the condenser circuit of the refrigeration plant will run at a reduced power consumption while increasing the plant efficiency.

The refrigeration plant evaporator circuit yields a temperature decrease. If this temperature differential can be increased along with the condenser circuit, the plant efficiency is drastically improved. Figure 31 shows the evaporator temperature differential. It is clear that the EE control shows a dramatic increase in the temperature differential, showing an increase in efficiency.

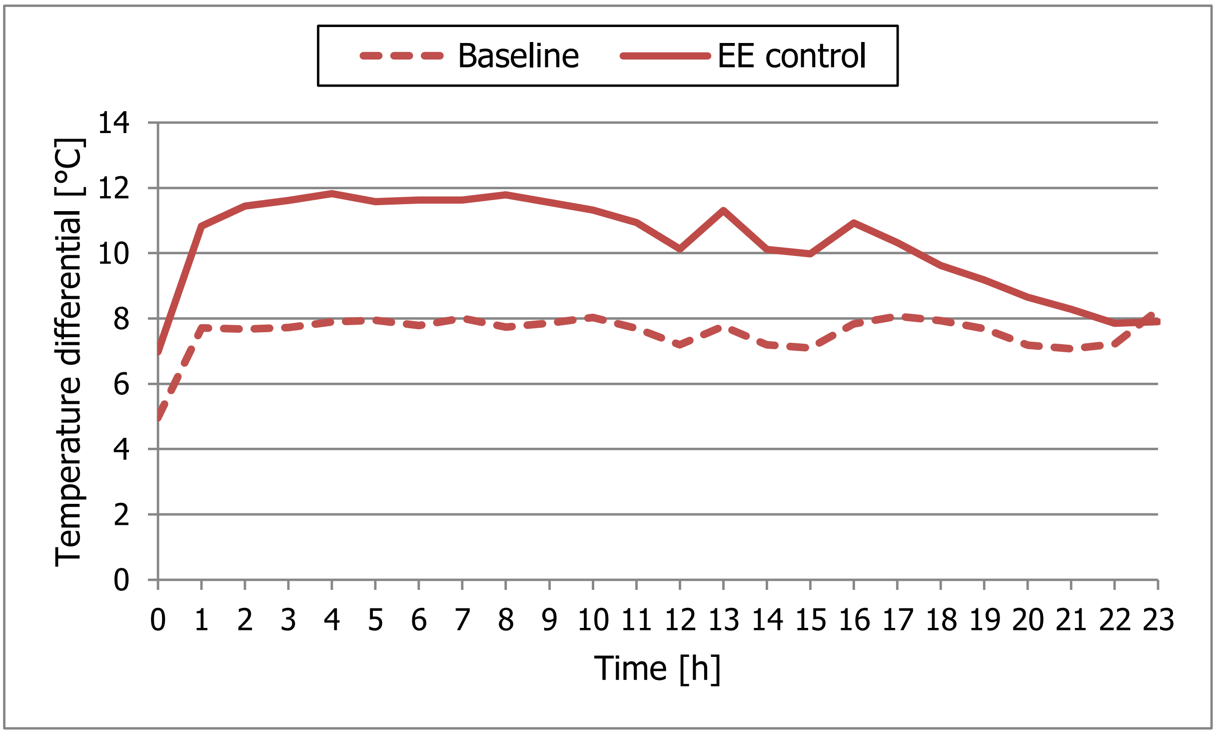


Figure 31: Energy efficiency control simulation evaporator temperature differential

As shown above, power consumption is reduced and plant efficiency is increased through implementation of an EE strategy at the refrigeration plant at Mine X. The simulated cost savings the project is capable of will result in a very short payback period relative to strategy lifetime and cost. Section 4 will further investigate the cost of implementation and resulting payback period.

3.3.4 **Load Shift (LS) simulation**

The focus of the LS strategy simulation is the reduction of load in the evening peak period. This is achieved through shutting down the refrigeration plant for this period. Cooling demand during this peak period is dramatically reduced as this coincides with the evening blasting period.

The evening peak billing period presents a drop in the ambient temperature as shown in Figure 25. This drop in ambient temperature corresponds to a drop in the BAC load. This combination of reduced water consumption coupled with dropping ambient temperatures presents the perfect opportunity for the implementation of an LS strategy. The LS simulation is based on a variation of the baseline plant simulation. The key difference being a scheduled shut down of the plant from 18:00 until 20:00.

During the shutdown period the system will monitor both the surface chill dam level and BAC outlet air temperature. The system will account for an increase in BAC air temperature by starting chiller machines and pumps as required. The chill dam level will be controlled by means of the transfer pumps. For simulation purposes the chill dam level of the shaft will not be simulated, the flow to the shaft will be accounted for however.

The simulation is run according to the abovementioned parameters. All other plant operations remain the same as the baseline simulation with the exception of the evening shutdown. The layout for the LS simulation can be found under Appendix C. Figure 32 shows the power profile for the LS control simulation.

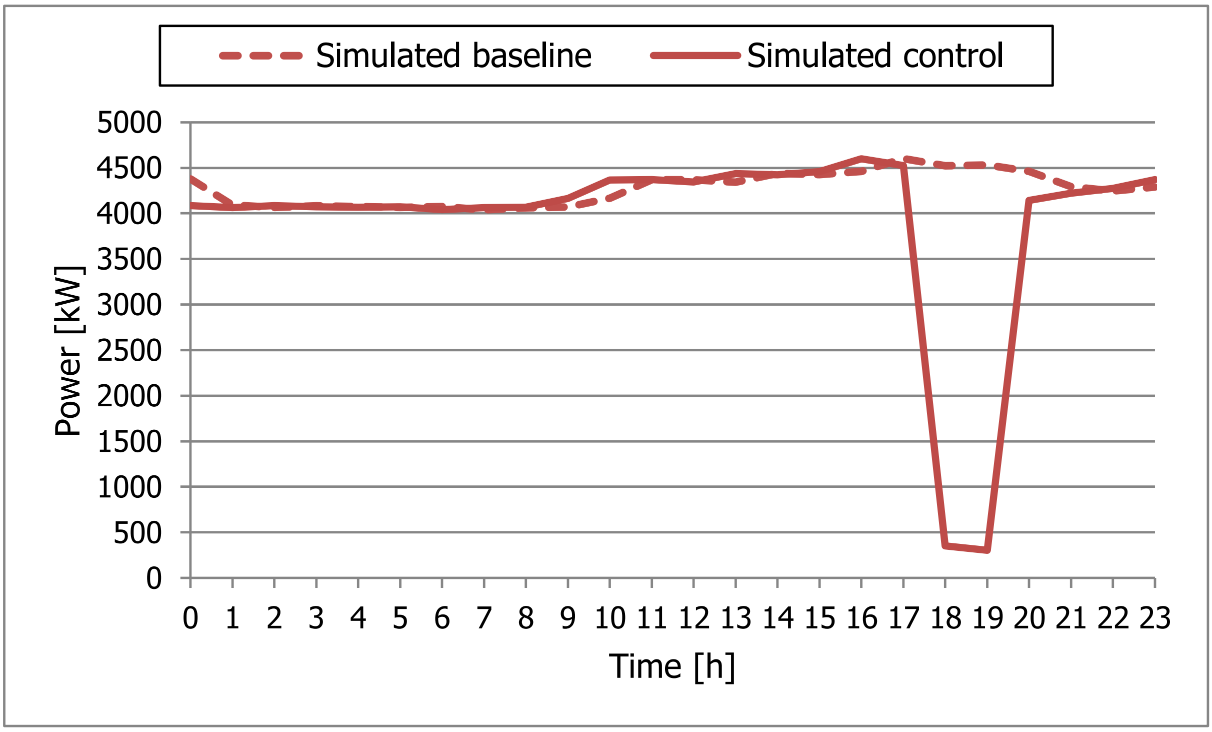


Figure 32: Load shifting control simulation power profile

The LS control power profile shows an evening load reduction of 4 200 kW. This translates to a daily cost saving of R 6,000, a daily cost reduction of over 12%. The savings presented by the LS strategy are less than those of the EE strategy. The key advantage of the LS strategy is the advantage of increased evening capacity for the power supplier. Another advantage of this strategy is increased maintenance opportunity. The evening shutdown can be used as an opportunity to carry out routine maintenance in place of a scheduled shutdown.

As discussed above, the primary control parameter for the LS strategy is the outlet air temperature of the BAC. Shutting down the chiller machines of the refrigeration plant results in an increase in the BAC water feed temperature. The maximum safe underground dry-bulb temperature is 37.5 °C. The underground thermal capacity of a large mine is extremely large, and the average ambient temperature will rise very slowly. This will be exploited to ensure safe operation.

The simulated BAC outlet air temperature for the LS control simulation is shown in Figure 33. The maximum outlet temperature is 13.1 °C. The corresponding 21 level wet-bulb temperature is 16.7 °C. This is well within the safe operation parameters of the refrigeration plant.

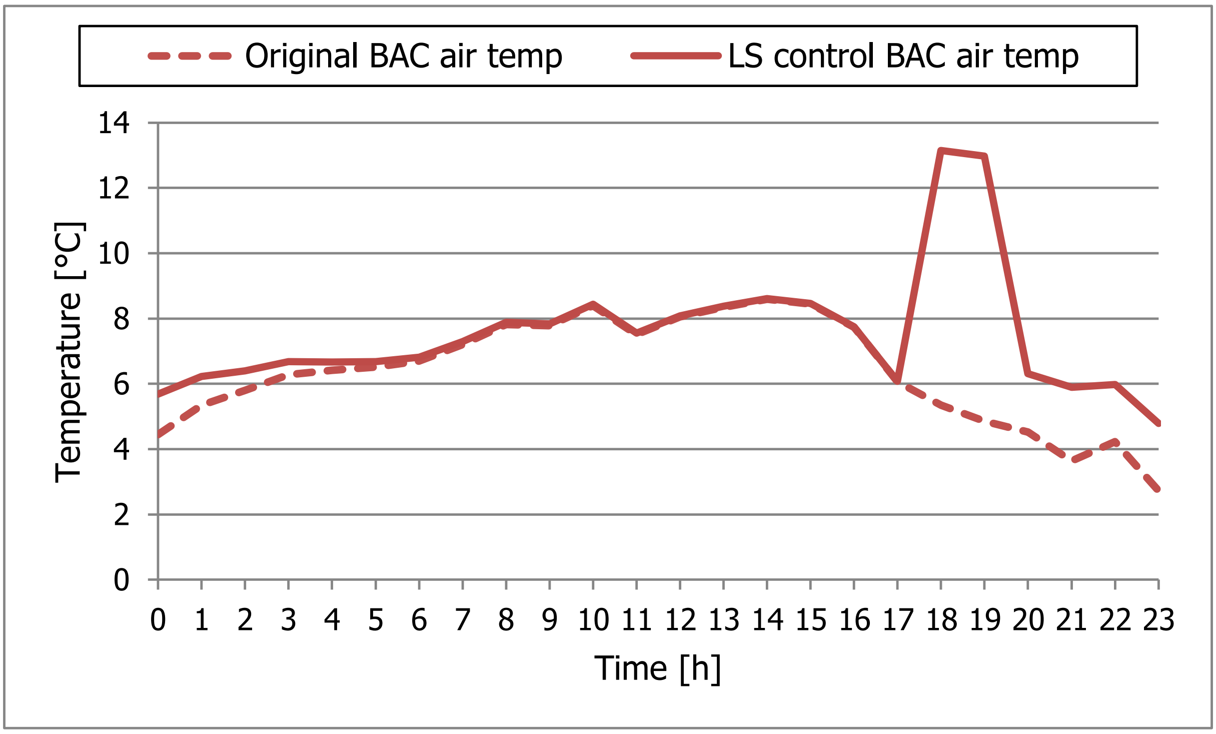


Figure 33: Load shifting control simulation BAC outlet air temperature

3.3.5 Combined strategy simulation

The combined strategy focuses on drawing the greatest advantage from combining the EE and LS strategies. In order to effectively do this, the strategy must deliver viable savings in terms of both LS and EE. The combined strategy is based on the final combined control philosophy discussed in section 3.2.5.

The combined strategy simulation will operate in a similar manner to the EE strategy. The only exception to this is the chill dam feed control and evening peak shut down. The evening peak shut down is used to achieve the LS energy saving. Figure 34 shows the simulated power profile for the combined control simulation compared to the baseline simulation. The combined simulation layout can be found under Appendix D.

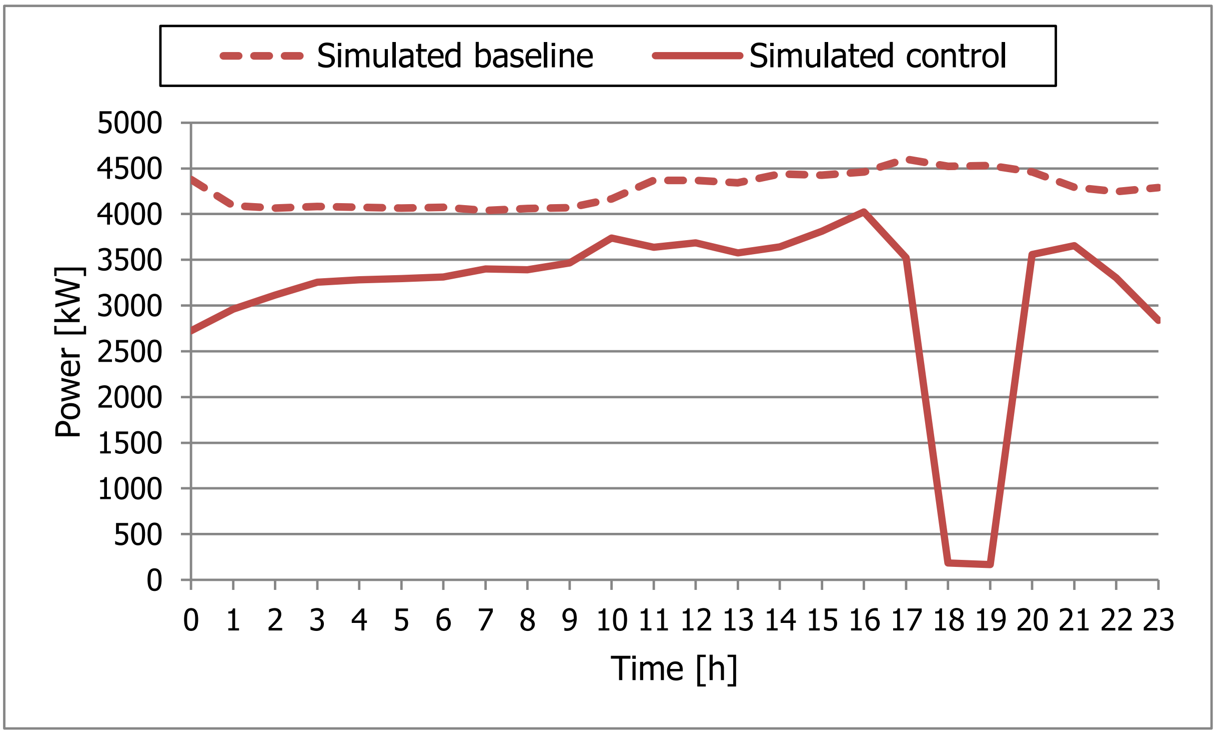


Figure 34: Combined control simulation power profile

The combined strategy yields savings in two forms, namely EE and LS energy savings. The EE saving for the strategy, excluding the evening peak period, is an average daily reduction of 830 kW. The LS savings for the strategy, calculated only during the evening peak period, are~~is~~ 4 350 kW. The combined saving achieved, calculated according to the Megaflex tariff structure, yields a daily cost saving of R 13,000. This is a daily cost reduction of over 28%.

The combined strategy must be assessed in a similar manner to both the LS and EE strategies. The combined strategy must yield a more effective condenser and evaporator temperature differential, in order for the control to be effective. A safe BAC outlet temperature must also be maintained. Both of these requirements must be met in order for the strategy to be deemed viable.

The temperature differential across both evaporator and condenser circuits must be higher than the baseline values. This is to ensure that the combined strategy not only yields a cost saving, but allows the chiller machines to be run more effectively. Figure 35 shows the condenser temperature differential for the combined control strategy.

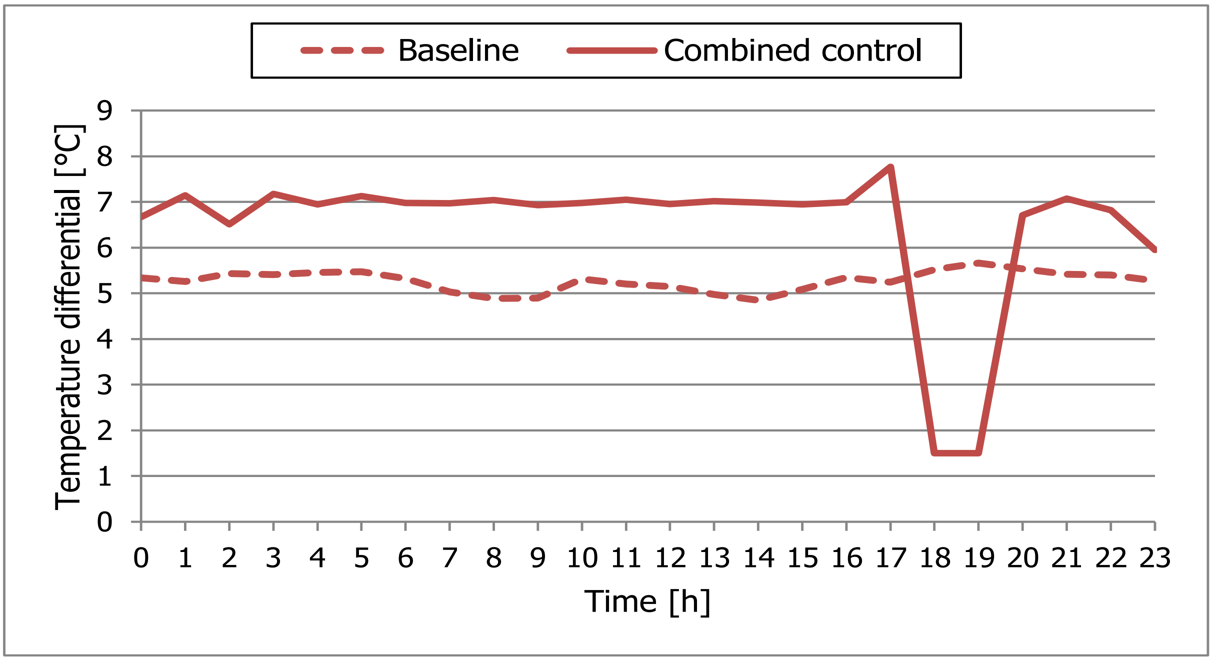


Figure 35: Combined control simulation condenser temperature differential

The condenser circuit temperature differential for the combined strategy is very similar to that of the EE control strategy shown in Figure 30. A clear drop in the temperature differential is present during the evening peak, this is due to the shutting down of the fridge plant. This is allowable, as some latent cooling is present. Figure 36 shows the evaporator temperature differential for the combined control strategy.

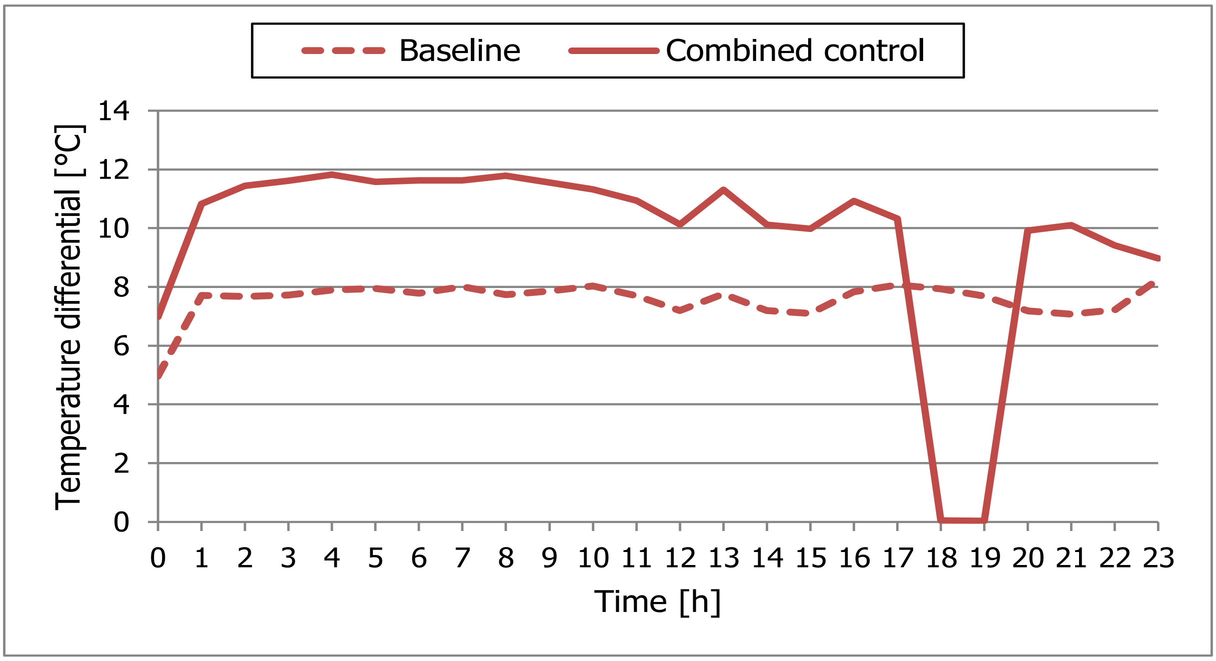


Figure 36: Combined control simulation evaporator temperature differential

As expected, the evaporator circuit also shows a dramatic drop in the temperature differential across the chillers. This is directly representative of an associated increase in the BAC outlet air temperature. The BAC outlet temperature will be assessed separately however, as it is another criteria of the effectivity of the combined control strategy. Should the underground working temperature be within safe levels, the drop in temperature differential will be acceptable.

In order for the strategy to be viable, the underground air temperature may not exceed 27.5 °C wet-bulb. To determine this temperature, Equation 5 will be used. Figure 37 shows the BAC outlet air temperature for the combined control strategy simulation.

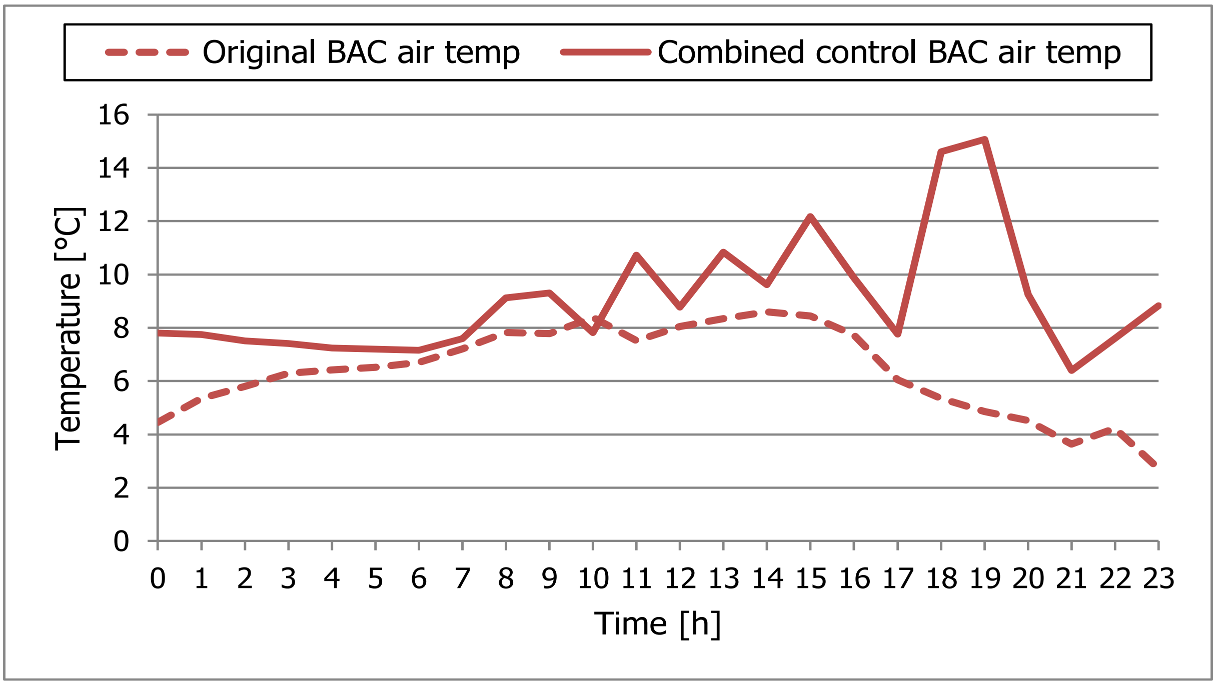


Figure 37: Combined control simulation BAC outlet air temperature

As shown in Figure 37, the BAC outlet air temperature fluctuates dramatically. This is as a result of the evaporator and condenser circuit water pumps speed control. The maximum outlet air temperature achieved is 15.07 °C. The associated wet-bulb temperature for 21 level underground is 17.51 °C. This is well below the permitted maximum underground temperature of 27.5 °C wet-bulb.

As discussed above, the combined strategy falls well within required limits for both BAC outlet air temperature and temperature differentials. The savings yielded by the strategy are also substantial. As a result, the combined strategy yields appropriate savings when fridge plant efficiency is considered. In the following section, cost based feasibility of the strategies will be discussed.

3.4 VERIFYING THEORETICAL APPROACH

As shown in the previous section, both EE and LS strategies yield ample cost and electricity savings. The combined strategy also yields positive results in this regard. In order to determine the feasibility of the combined strategy, it must be compared to both the EE and LS strategy. Power savings, cost savings and hardware costs will all be compared and discussed to determine the viability of the combined strategy.

Firstly, cost of implementation for the strategies must be assessed. The total cost of the combined strategy is equal to the sum of the LS and EE strategies. This is because the combined strategy makes use of all equipment and alterations as required for the individual strategies. Table 19 shows the costs of the independent strategies as well as the combined strategy.

Strategy implementation costs		
Energy Efficiency strategy	R	3,443,815.85
Load Shift strategy	R	926,837.22
Combined strategy	R	4,370,653.07

Table 19: Strategy implementation cost comparison by strategy

As shown in the table, the cost of implementation of the EE strategy is substantially higher than that of the LS strategy. As a result, the majority of costs incurred to implement the combined strategy will be associated with the EE strategy. In order to determine the feasibility of the abovementioned costs, the payback period from electricity cost savings must be calculated. Table 20 provides the proposed daily costs savings achieved by each project, according to the simulations in section3.3.

Daily cost savings:		
Energy Efficiency strategy	R	10,894.25
Load Shift strategy	R	5,963.23
Combined strategy	R	13,987.77

Table 20: Daily cost savings by strategy

As can be seen in the table, the total cost saving achieved by the combined strategy is not the sum of the independent strategies savings. The payback period of the projects must then be compared to determine cost feasibility of the combined strategy compared to the independent strategies. Table 21 shows the payback period of each strategy in days.

Payback period in days:	
Energy Efficiency strategy	316
Load Shift strategy	155
Combined strategy	312

Table 21: Payback period by strategy

As can be seen, the payback period for the EE strategy is almost double that of the LS strategy. The combined total payback period of the two independent strategies is 471 days. The payback period of the combined strategy however, is less than that of the EE strategy. This is due to the combined and EE strategy both having a daily cost saving to implementation cost ratio of approximately 0.32%. So, the feasibility of the combined strategy in terms of cost is equal that of the EE strategy.

As discussed above, the feasibility in terms of cost of the combined strategy is greater than that of the EE strategy, giving a marginally shorter payback period, with increased savings. As covered in sections 3.3.3, 3.3.4 and 3.3.5, the efficiency of the refrigeration plant system is substantially improved through the implementation of the independent strategies.

The combined strategy offers the greatest compromise between strategies, improving temperature differentials outside the evening peak period. During the evening peak period, the combined strategy improves upon the savings achieved by the LS strategy. This is achieved while still providing ample cool air to maintain safe underground operations.

3.5 CONCLUSION

In order to determine the effectivity of the various control philosophes detailed in section 3.2, a feasibility study was carried out. Factors such as cost, payback period, viable savings and control improvements were assessed. Both LS and EE strategies were individually assessed. The combined strategy was also assessed for comparison with individual control strategies.

The initial implementation costs of both the EE and LS strategy are relatively high. This is due to costly equipment and control elements. The high initial costs of both strategies can be shown to be viable. The payback period for both projects is relatively short. This will allow for the recuperation of costs incurred in a short period. Since the high initial costs are offset by electricity cost savings, the improved control allowed for by the strategies can be seen to be advantageous.

The combined strategy's implementation cost is equal to the sum of the individual strategies, due to the same equipment being required. The savings achieved by the strategy are, however, much greater than the individual strategies. This in turn leads to a marginally shorter payback period than the EE strategy. Thus, for a shorter payback period, greater savings and control can be achieved through implementation of the combined strategy.

Implementation of the various strategies will be detailed in the following chapter.

4. COMBINED STRATEGY IMPLEMENTATION AND ASSESSMENT

4.1 PREAMBLE

In the previous chapter, the feasibility of the EE and LS strategies was shown. The combined strategy was shown to be extremely effective at providing electricity cost savings and improved control. This section will detail the implementation of the individual strategies as well as assess the results obtained compared to the simulated values.

Mine X was approached to implement the strategy. The EE strategy was selected for initial implementation. This is due to the greater savings provided by the EE strategy when compared to the LS strategy. As a result, the EE strategy may yield cost savings earlier and aid in subsidising the LS strategy implementation.

As a result of this, the LS strategy will be implemented after the EE strategy is already in place. The resultant savings obtained by the LS strategy will then be the same as the combined strategy. Adjustments will be made to determine the individual savings and effectivity of the LS strategy. A baseline drawn before the implementation of the initial control strategy will thus be used to determine the savings achieved by all three strategies.

4.2 PRE-IMPLEMENTATION POWER USAGE

4.2.1 Baseline period selection

To obtain the most accurate results possible, an extended period must be used to develop an energy usage baseline. The baseline period will be based in summer months, as this is when the strategies are to be implemented. A winter baseline will be derived by scaling the summer baseline to account for reduced load.

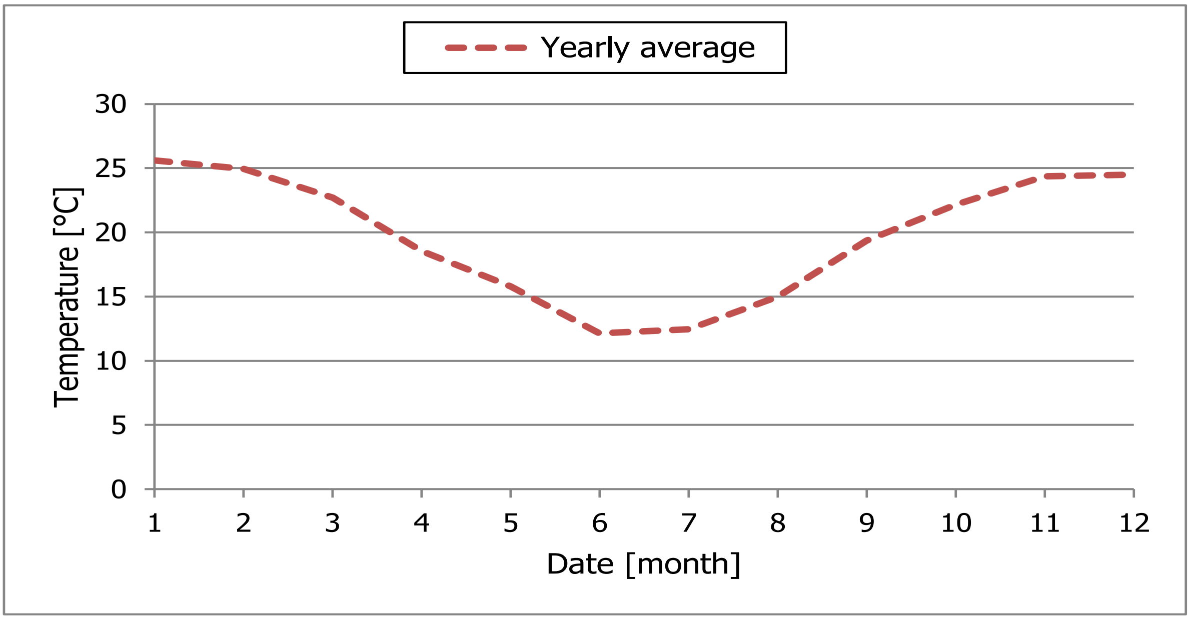


Figure 38: Northam average temperature by month

For this study, a month with an average temperature of 22 °C or higher will be considered as summer. Figure 38 shows the average monthly temperature of the Northam area, where Mine X is based. As shown in the graph the months of January, February and March as well as October, November and December are appropriate for baseline derivation.

Measurement and verification (M&V) of the baseline will be carried out by a third party to ensure validity and quality of the baseline data. The baseline will act as a representation of how the plant would perform if no DSM was in place. As a result, all process elements must be assessed for the period in order to draw an accurate baseline to determine savings.

The baseline should also include all operating cycles of the plant. Measurement of the baseline must also account for lost data, either by extension of the measurement period, or by substitution of appropriate data. Ambient, production and performance conditions must all be taken into account to determine their effect on plant performance.

The baseline will be drawn from the period immediately prior to implementation in order for the plant conditions to closely match those present during and after implementation. A regression model will be calculated, where necessary, to determine the baseline scaling factor required to calculate savings.

A three month period during the aforementioned summer months will be monitored to acquire the baseline. Raw data will be acquired from the existing on site SCADA systems. The most complete data that most accurately represents plant cycles and operations will be selected.

In closing, a three month summer period will be selected to determine the baseline. The power and plant process data should accurately represent full plant cycles and operations. The power profile will be represented as a 24 hour profile. A scaling factor will be calculated using plant and ambient parameters to accurately calculate achieved electricity savings.

4.2.2 **Baseline derivation**

A three month summer assessment period was selected for the baseline selection. The baseline was drawn from a period immediately prior to commencement of installations. During this period the refrigeration plant was run according to standard operations procedures. No alterations to control or hardware were included in this period.

The basic power profile used for the EE, LS and combined strategies will be the same. The exception to this, is the scaling applied to the baseline profile to account for the different strategies. The combined strategy savings will be calculated by determining the individual strategies savings separately. This is because the combined strategy yields both EE and LS based savings.

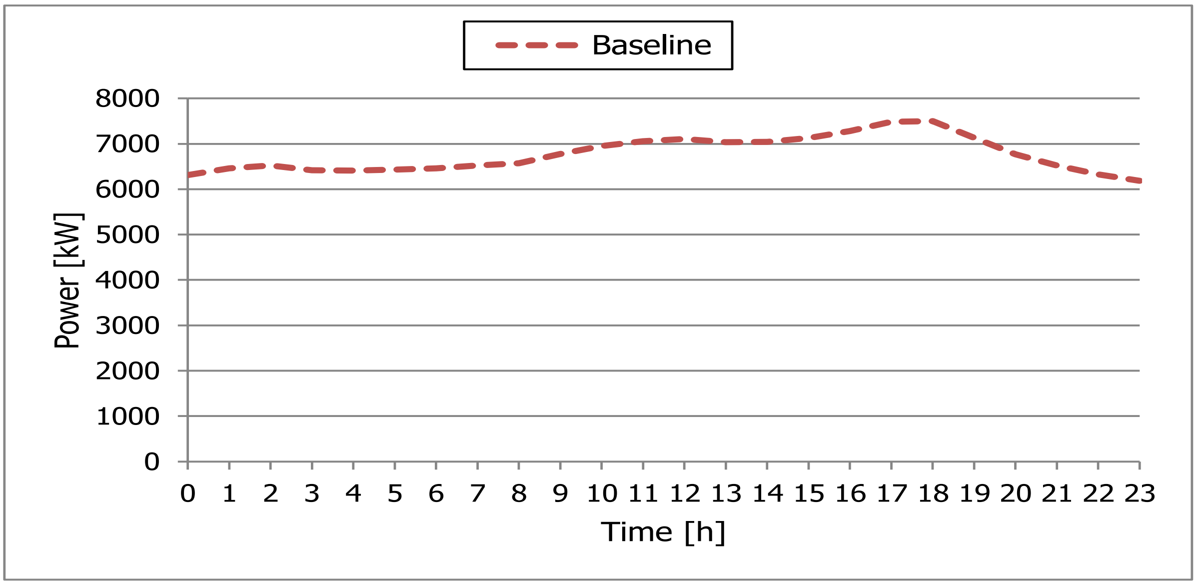


Figure 39: Mine X refrigeration plant weekday power baseline

Figure 39 shows the basic weekday power profile that will be used to carry out savings calculations. The total energy consumption for the baseline is 162 MWh with an average 24 hour cost of R 77,000. Scaling will however, alter these figures as required for calculations. A weekend baseline will also be derived for the purpose of calculating the EE strategy weekend savings. The LS strategy control will not be in place over weekends.

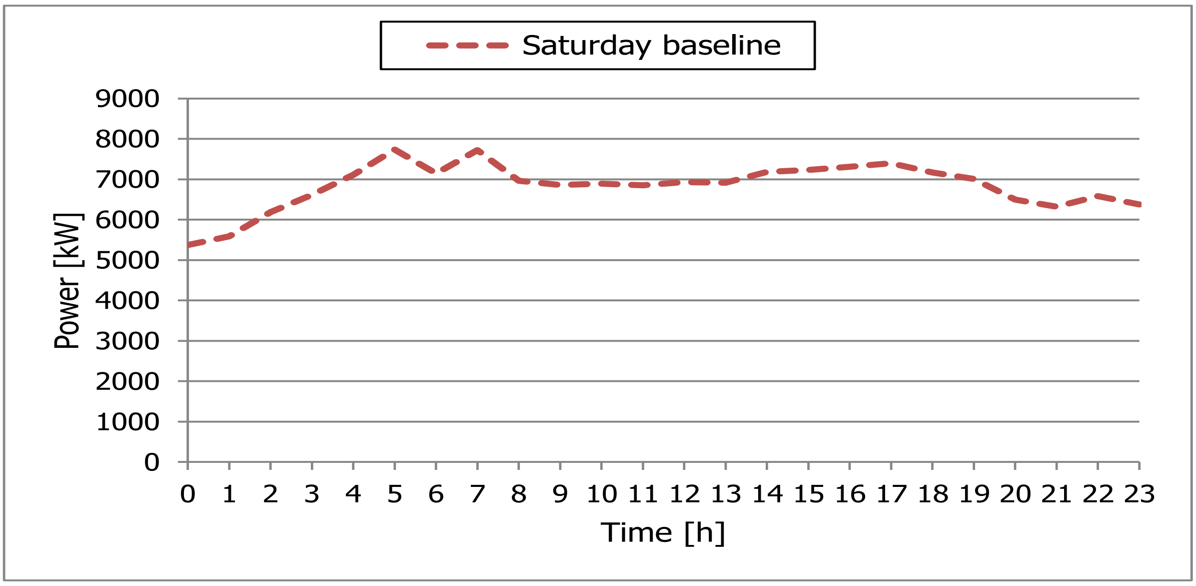


Figure 40: Mine X refrigeration plant Saturday power profile

Figure 40 shows the basic Saturday power profile that will be used to carry out EE savings calculations. The total energy consumption for the baseline is 164 MWh with an average 24 hour cost of R 67,200.

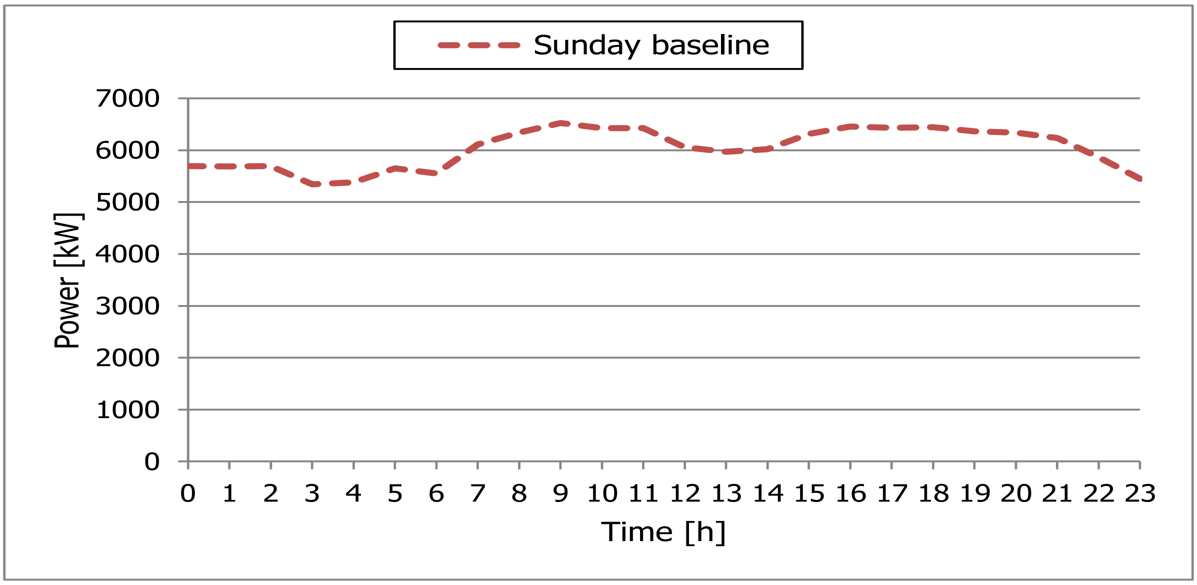


Figure 41: Mine X refrigeration plant Sunday power profile

Figure 41 shows the basic Sunday power profile that will be used to carry out savings calculations. The total energy consumption for the baseline is 145 MWh with an average 24 hour cost of R 50,000. Scaling of these baselines must be carried out in a manner that will ensure accuracy of measurement. Both the LS and EE strategies have different scaling requirements. These will be detailed in the following sections.

4.2.3 **Energy efficiency baseline scaling**

The primary purpose of the EE strategy is to achieve a reduction in the overall energy consumption of the refrigeration plant. This will be achieved by reducing the average power consumption over a 24 hour period. Plant operations vary slightly according to ambient as well as production conditions. The baseline power profile must therefore be scaled to allow for these variations.

Five variables will be used to determine the scaling factor for the baseline. In order to determine the water demand the shaft chilled water dam temperature and supply flow will be used. The ambient load on the system will be accounted for through the refrigeration plant hot water supply and ambient dry-bulb temperature. Finally, the BAC water supply flow will be included, as no BAC outlet temperature reading will be available before implementation.

$$P_{\text{calc}} = 65.4 + 51.3T_{amb} + 147.6T_{hdam} + 190.9T_{cdam} + 0.4V_{sflow} + 3.5V_{Bflow}$$

Equation 6: EE profile weekday calculated power

Equation 6 provides the equation for the calculated power profile of the EE strategy. The variables T_{amb}, T_{hdam}, T_{cdam}, V_{sflow} and V_{Bflow} are representative of ambient temperature, supply dam temperature, chilled water storage dam temperature, shaft supply flow and BAC supply flow respectively. The calculated power profile will be used to determine the scaling factor for the baseline profile.

$$P_{\text{calc}} = 517.3 + 71.6T_{amb} + 67.5T_{hdam} - 287.6T_{cdam} + 0.7V_{sflow} + 6.6V_{Bflow}$$

Equation 7: EE profile Saturday calculated power

$$P_{\text{calc}} = 3100.7 + 54.3T_{amb} + 2.9T_{hdam} - 662.3T_{cdam} + 0.4V_{sflow} + 6.0V_{Bflow}$$

Equation 8: EE profile Sunday calculated power

Equation 7 and Equation 8 provide the calculated power equations for a Saturday and Sunday profile. As with the weekday profile, these will be used to determine the scaling factor for the baseline profile. The post-implementation, calculated and baseline power profiles will be used to determine the actual savings achieved by the EE strategy. The correlation coefficient of the above equations is no lower than 80% when compared to the baseline period.

In order to determine the scaling factor for the baseline power profile, the calculated power profile must be obtained. The average value of the calculated profile will be divided by the average of the baseline profile to obtain a scaling factor. The hourly baseline values will then be multiplied by the scaling factor. This scaled baseline average will then be compared to the actual power profile average to quantify the savings achieved.

4.2.4 Load shifting baseline scaling

The savings to be achieved by the LS strategy are primarily focused on the evening peak billing period. As a result of this, the remainder of the 24 hour cycle energy consumption outside this period will remain the same. Because of this, the scaling of the LS strategy is simpler than that of the EE strategy.

The baseline power profile for the LS strategy is identical to that of the EE strategy. In order to scale this profile up or down, a scaling factor must be calculated. The periods outside of the evening peak billing period will be used to calculate this factor. The average power usage of the scaled baseline profile and the actual usage must match, outside of the evening peak.

The average power usage of the actual hourly profile will be divided by the baseline profile value. This will yield a scaling factor. The hourly baseline profile values will then be multiplied by the scaling factor, yielding a scaled baseline. The average difference between the baseline and actual profiles during the evening peak period will represent the achieved savings.

4.2.5 Combined strategy baseline scaling

The combined strategy baseline will comprise of both EE and LS baselines in conjunction. The combined cost saving from this will then be calculated as a total. The total energy saved will also be calculated. There are a number of differences to the individual calculations that will be discussed briefly.

The LS strategy savings will be reduced due to the effect of the EE strategy. The reduction in the average power consumption of the plant will cause the average energy usage outside of the evening peak to be reduced. This in turn will drop the scaled LS baseline and reduce the savings achieved by the system.

The EE savings will be calculated as normal, as the scaling of the profile is not affected by the LS strategy control. The overall savings achieved will be reduced however, as EE savings can no longer be calculated during the evening peak shut down period. As a result the EE savings will only be calculated for the hours of 00h00 to 18h00 and 20h00 to 24h00.

The slight reduction in savings achieved by the individual strategies must be assessed in comparison with the overall increase in savings allowed for by the combined strategy. This will be done by comparing energy consumption and electricity costs, as power usage is evaluated differently for each strategy. The success of the combined strategy will be indicated by an overall increase in savings.

4.3 PHASE 1: ENERGY EFFICIENCY STRATEGY

4.3.1 Hardware installations

As described in section 3.2.3, VSD installations were required at the refrigeration plant. The VSDs allow for the reduction of pump power usage through frequency control. These VSDs and their ancillaries were installed at Mine X to facilitate control. The installation process will be briefly discussed.

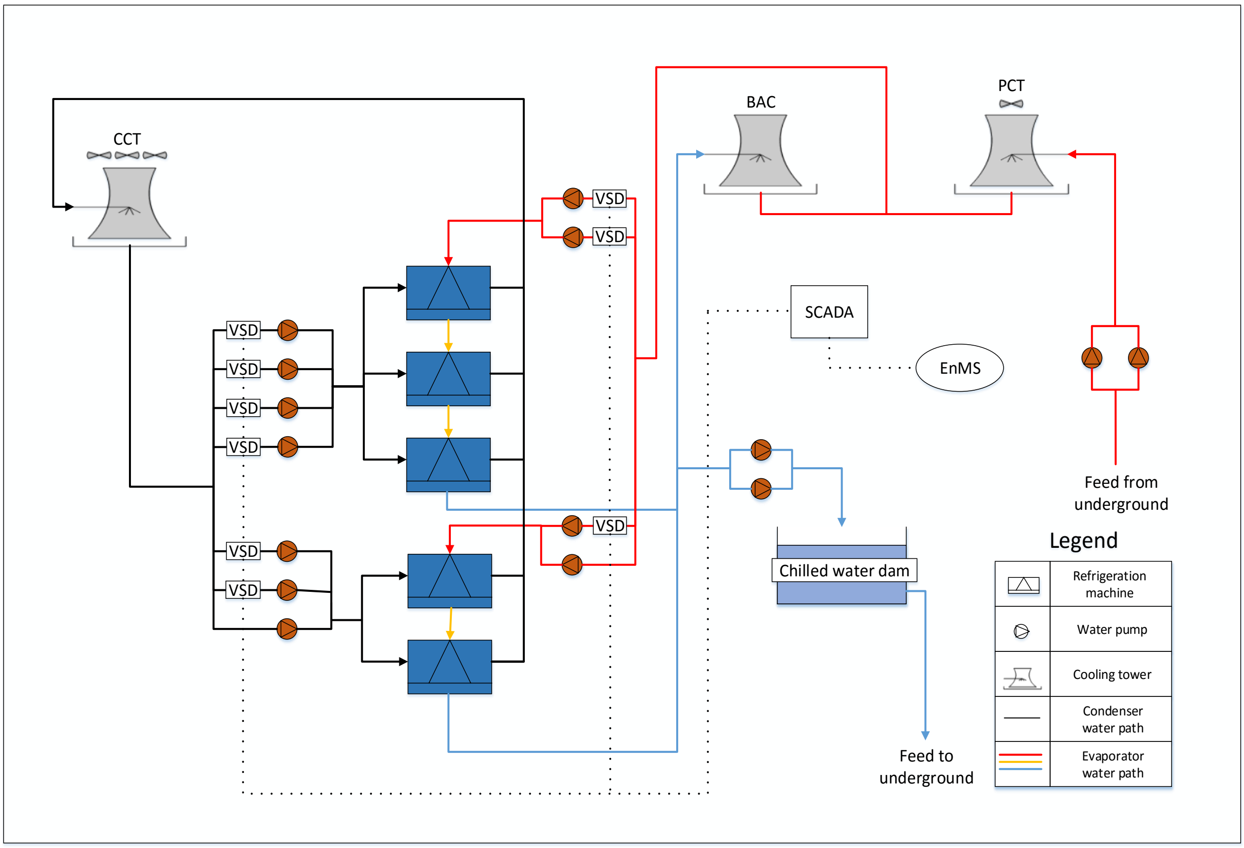


Figure 42: Refrigeration plant layout with proposed energy efficiency hardware

Figure 42 shows the layout of the refrigeration plant including the required VSDs and communications. One condenser and one evaporator pump were not fitted with VSDs. This is due to cost constraints. These pumps will also serve as a backup in the unlikely case of a malfunctioning VSD.

Figure 43: VSDs during installation[3]

[3] Photo taken at Mine X by the author with the mines permission.

During the process of installations, it was found that the earth cables fitted to the water pump motors were incorrectly installed. The wiring of the water pump motors was such that each motor was fitted with two cables run from the supply substation to the pump. The third, earth cable, was connected directly to the cable rack. The cable rack was then earthed within the substation.

This incorrect fitment of the water pump earth cables led to a delay. New earth cables were installed with each VSD directly connected to the corresponding water pump. During this process it was found that, as the plant had been in operation for many years, much of the plant wiring had deteriorated, further slowing installation progress.

Figure 44: VSD bus coupler showing lightning damage[4]

During commissioning of the installed VSDs and associated pumps, a lightning storm was experienced in the area. Upon investigation it was found that three VSDs had experienced damage, as displayed on the bus coupler in Figure 44. These VSD units were replaced by the sub-contractor responsible for the installations.

[4] Photo taken at Mine X by the author with the mine's permission.

Once all VSDs were installed, and the aforementioned setbacks overcome, final commissioning and testing of the VSDs was carried out. In conjunction with the hardware installations, software upgrades were also required at the plant.

4.3.2 Software installations

Prior to the VSD installations all pumps at the refrigeration plant made use of liquid soft starters for starting. The addition of VSDs necessitated the integration of upgraded SCADA software. The new software allows for the starting of pumps via a gradual increase in running frequency.

The new software also included the ability to vary the running frequency of the water pump motors. Maximum and minimum frequency values are variable with this system. This allows for the adjustment of the minimum frequency value to match the minimum flow requirements of the plant.

4.3.3 Control implementation

Upon completion of all hardware and software installations, the EMS was commissioned. Flow testing took place to determine the minimum frequency associated with the minimum flow for each water pump. These values differ according to the number of chillers in operation, but all chillers in each plant have the same individual requirements.

As described in section 3.2.4, the condenser and evaporator frequencies are separately controlled. A minimum evaporator water outlet water temperature of 1 °C was included in the control requirements to prevent freezing of water at the evaporator heat exchanger. Thus, the control requirements of the plants are as follows:

VSD control parameters		
	Plant 1	Plant 2
Evaporator circuit		
Minimum flow rate [ℓ/s]	180	200
Minimum outlet temperature [°C]	1	1
Condenser circuit		
Minimum flow rate [ℓ/s]	300	320

Table 22: Energy efficiency strategy VSD control parameters

Table 22

~~Table 22~~ shows the control parameters of the plant. These are the boundaries of the VSD control. Upon completion, the EE strategy made use of the evaporator outlet temperature and condenser temperature differential. Upon installation of the LS strategy equipment, the evaporator circuit control would be altered to allow for control with the BAC outlet air temperature as reference.

4.3.4 Process values

The simulation in section 3.3.3 indicated that both savings and an increase in efficiency of the plant could be achieved through the implementation of the EE strategy. Although savings remain the primary goal of the strategy, a decrease in efficiency would negatively impact the viability of the strategy.

The condenser as well as evaporator circuit temperature differentials will be considered. The baseline for these values was derived from the same period as the power baseline. This is to ensure that the baseline values are derived from a period immediately prior to installations. The baseline operation conditions will thus emulate similar conditions to those under which the implemented strategy operates.

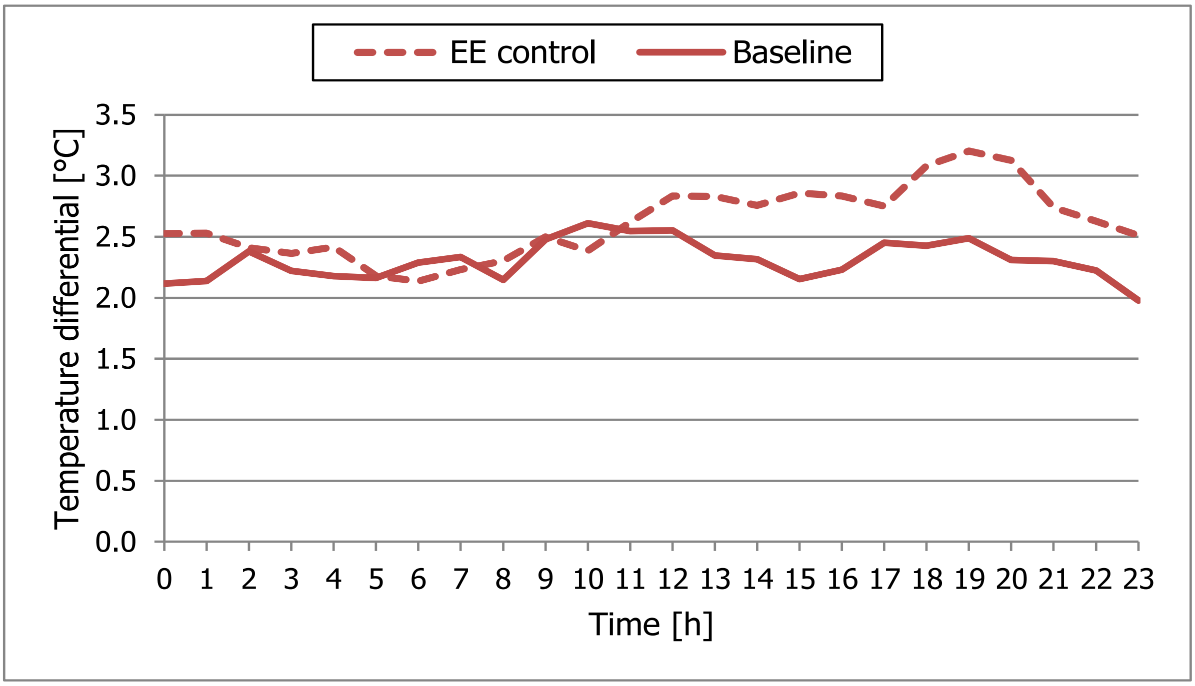


Figure 45: Energy efficiency strategy post-implementation evaporator temperature differential

When compared, the post implementation evaporator temperature differential remains broadly similar to that of the baseline. The implemented strategy temperature differential is 13% greater than that of the baseline. Considering Figure 45 however, it is clear that the increase in the temperature differential is not as great as previously anticipated.

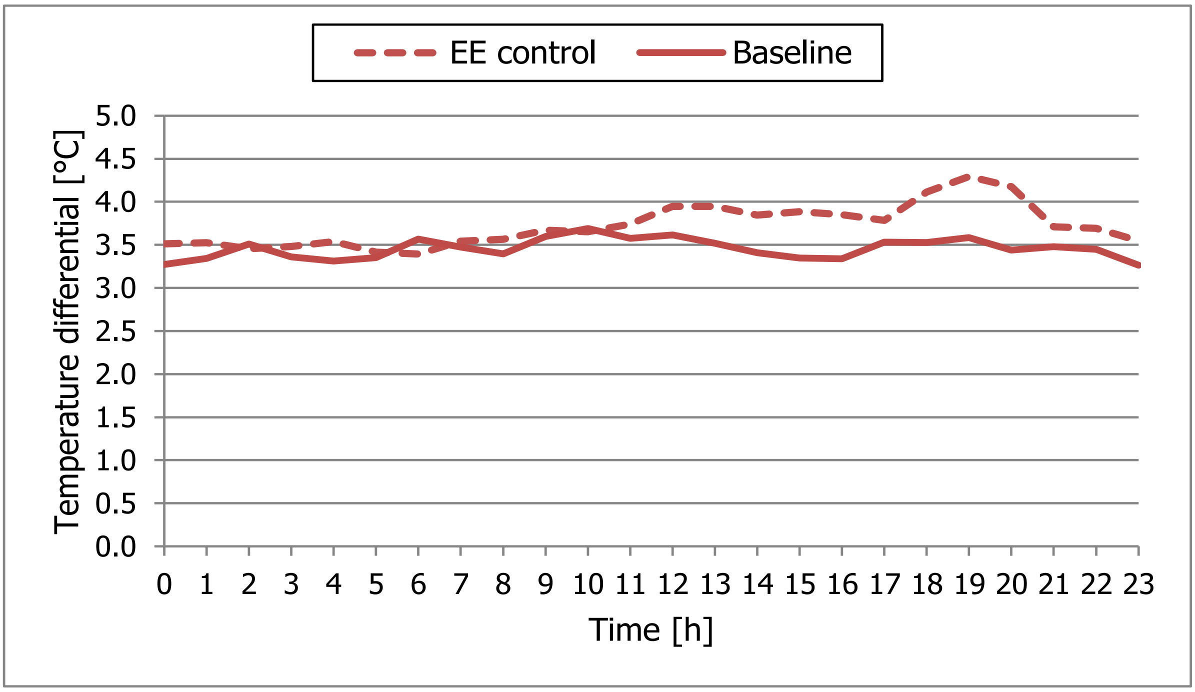


Figure 46: Energy efficiency strategy post-implementation condenser temperature differential

Figure 46 shows the condenser temperature differential for both the baseline and post-implementation periods. Similar to the evaporator circuit, the condenser circuit shows a very small increase of only 8%. This is not as high as the simulated values would indicate. Thus, the implementation of the strategy has not had a large impact on plant performance.

Should savings still be achieved by the strategy, the marginal increase in efficiency will be satisfactory, as machinery will still be run at specified temperatures and speeds. As a result, the plant, although running at a similar thermal efficiency, will run at a lower power usage value and so will represent an increase in electrical efficiency.

4.3.5 Savings

Similar to the measurement of the baseline power profile, the post-implementation assessment period was three months. This period was within the summer periods as previously defined. Power as well as plant monitoring were carried out in an identical manner to the baseline period.

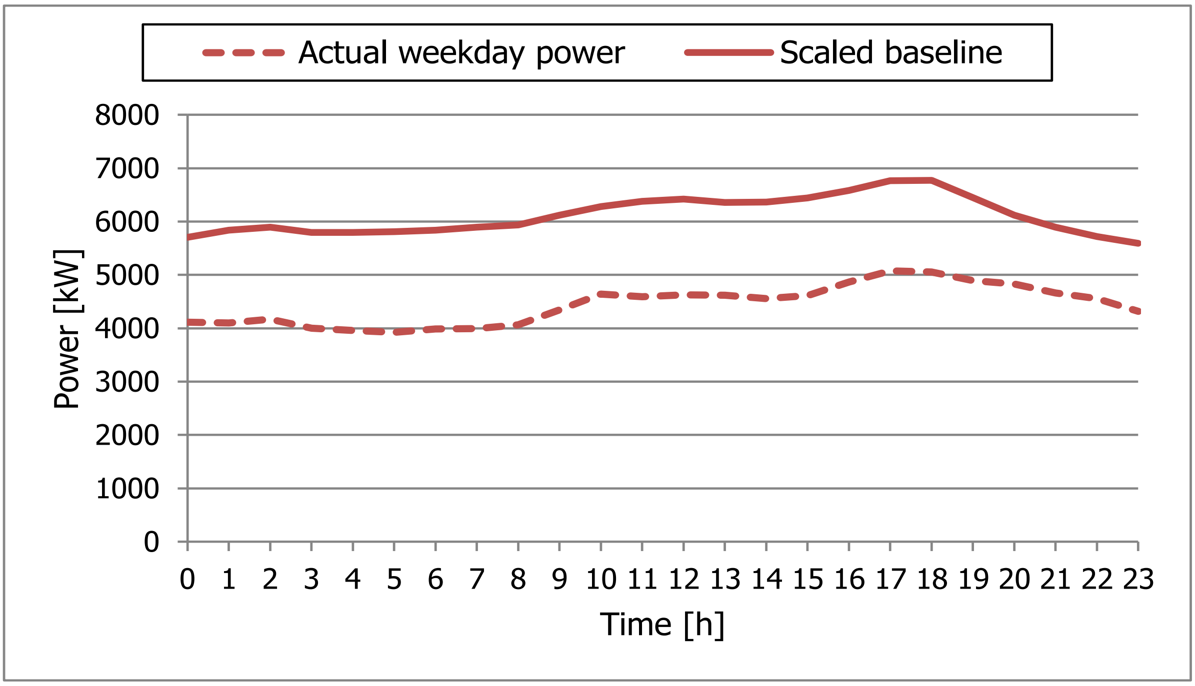


Figure 47: Energy efficiency strategy post-implementation power profile

Figure 47 shows the savings achieved by the EE strategy. The average power reduction achieved by the strategy is 1.6 MW. The total average energy savings per day is 40 MWh with a corresponding cost saving of approximately R 19,200. The EE strategy simulation produced a savings figure of 1.2 MW with a daily cost reduction of R 14,000 and energy saving of 29 MWh. The simulated values are calculated using a scaling factor of 1.19. The actual savings achieved are then 25% greater than the simulated values.

4.4 PHASE 2: EVENING PEAK LOAD REDUCTION

4.4.1 Hardware installations

Unlike the EE strategy, the LS strategy requires relatively few hardware installations. For this reason, the LS strategy was implemented after the completion of the EE strategy. So, the results of the LS strategy implementation will be analogous to the combined strategy. As discussed previously, the plant required the addition of chilled water dam feed pump control, BAC outlet air temperature monitoring and condenser cooling tower fan control.

The EE control as previously implemented will also be controlled as normal outside the evening peak. The chilled water dam feed pumps were previously run constantly, with the excess chilled water being pumped~~flowed~~ to the hot water supply dam. With the implementation of the LS strategy, chilled water savings will also be achieved, as the dam level will be monitored with existing equipment, allowing for the control of the chilled water feed pumps.

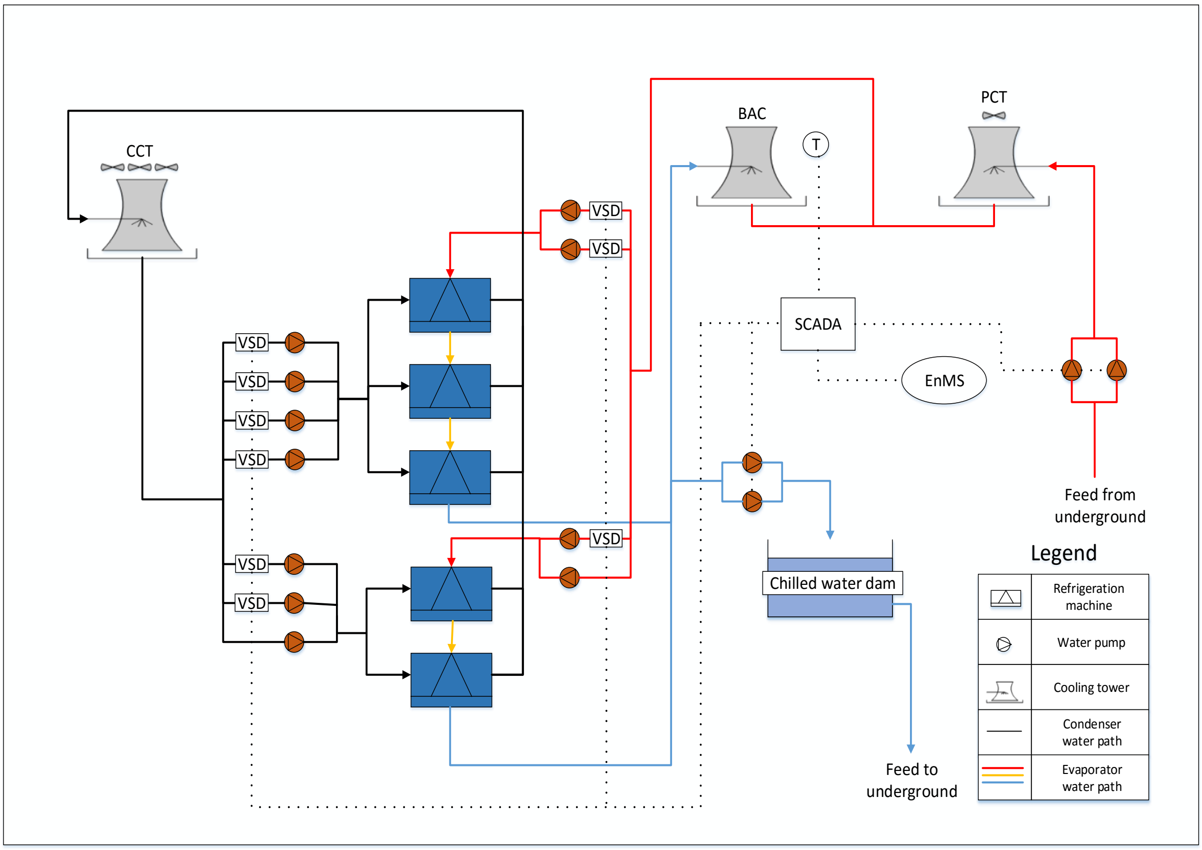


Figure 48: Refrigeration plant layout with proposed LS hardware

Figure 48 shows the refrigeration plant layout with additional equipment and communications. Not shown is the existing equipment for the starting and stopping of the pre-cool tower fan and fridge plants. As shown in the figure, the EMS will operate on a single platform to control the plant. Scheduling will be used to determine which of the systems is given priority.

Figure 49: BAC temperature probe location[5]

Figure 49 shows the location of the temperature probe inside the BAC. The probe is situated at the entrance to the underground airway. The ambient air travels into the BAC, passing through the chilled water spray and into the underground airway. This placement of the BAC temperature probe also allows for the accurate calculation of the underground wet-bulb temperature, as well as for the control of the plants.

Figure 50: Condenser cooling tower fan inlets[6]

[5] Photo taken at Mine X by the author with the mine's permission.

[6] Photo taken at Mine X by the author with the mine's permission.

Figure 50 shows the outlets of the condenser cooling tower fans. These fans were previously run on a constant basis. With the new control, the fans can be run in sequence allowing for more accurate control. This also allows for the fans to be shut down during the evening peak, as no condenser flow will be present.

Although minimal, the installations also required software alterations and control implementation.

4.4.2 Software installations

The addition of control of the condenser cooling tower fans and chilled water feed pumps necessitated a minor upgrade to the fridge plant SCADA system. The BAC outlet air temperature monitoring was also incorporated into the SCADA. Though the SCADA does not make use of the BAC outlet temperature, it was required, as the EMS system requires this value to maintain safe operations.

4.4.3 Control implementation

Upon completion of the hardware and software installations, control implementation could commence. Start/stop testing was carried out on each individual chiller machine. Sequence running was then implemented on each separate plant. This allows for the starting and stopping of plants as required according to water demand and ambient temperatures.

Fridge plant control parameters	
BAC	
Maximum outlet air temperature [°C]	12
Shaft chilled water storage dam	
Minimum level [%]	60
Maximum level [%]	80

Table 23: Load shifting strategy control parameters

Table 23

~~Table 23~~ provides the control parameters for the refrigeration plant during the evening peak period. The dam level limits are adhered to outside the evening peak, in order to match plant conditions to shaft water requirements. Should any of the above limits be exceeded during the evening peak, the plant will be started and will continue to run as normal. The plant may only be shut down once per day to prevent possible equipment damage.

4.4.4 Process values

The primary control value of the LS strategy is the BAC outlet air temperature. The maximum outlet temperature, as shown above, is 12 °C. Using the maximum outlet temperature, the maximum recorded ambient temperature (47 °C) and 100% humidity, an underground wet-bulb temperature of 18.6 °C is provided by Equation 5. As such the maximum value is well within the safe operations range.

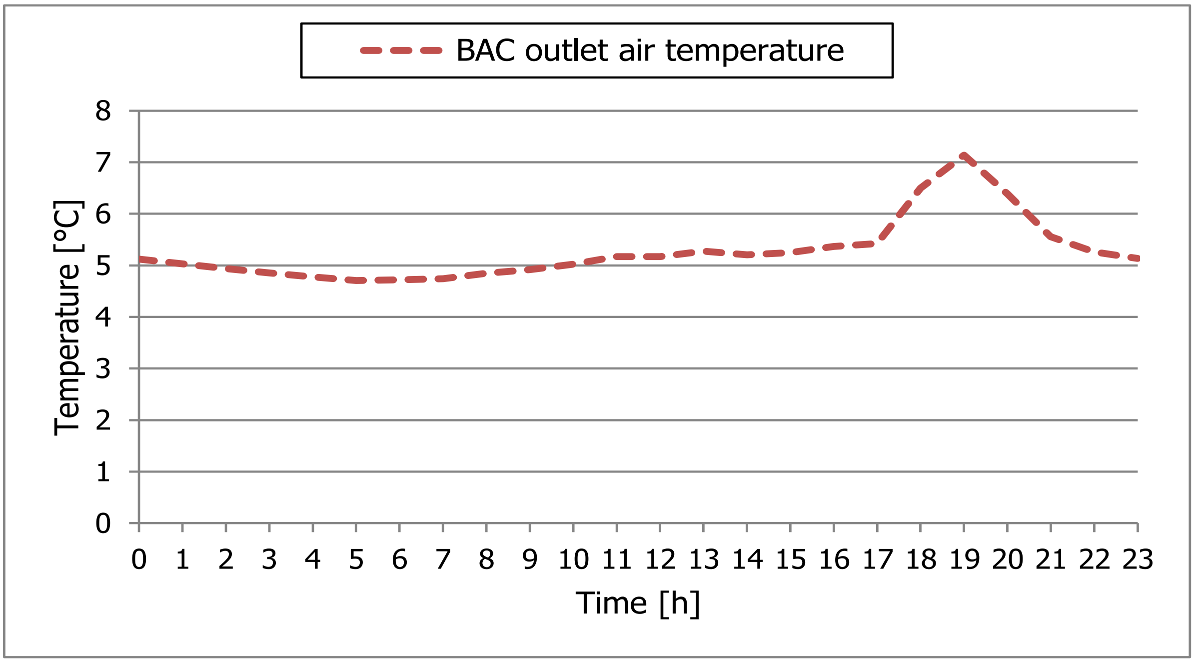


Figure 51: Load shift strategy post-implementation BAC outlet air temperature

Figure 51 shows the average weekday BAC outlet air temperature after implementation of the LS strategy. As can be seen, the outlet air temperature of the BAC for this period falls well within the acceptable range. The maximum outlet temperature for the duration of the assessment period is 11.7 °C. Thus, from the gathered data, it can be determined that the plant remains within operating limits during the evening shutdown.

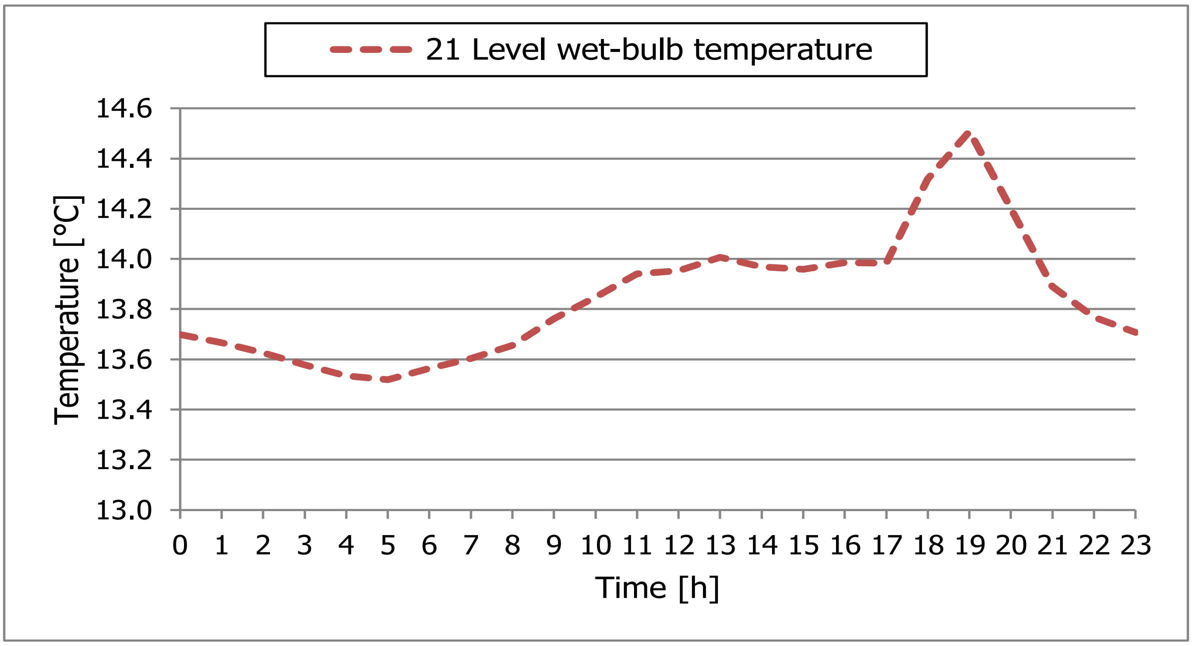


Figure 52: Load shift strategy post-implementation 21 level wet-bulb temperature

Figure 52 shows the average calculated 21 level wet-bulb temperature with ambient and BAC outlet temperatures as well as ambient humidity as reference. The maximum value for this period is 19 °C wet-bulb. This is well below the required maximum value of 27.5 °C wet-bulb. As shown in both graphs above, the operations of the plant are well within stipulated safety guidelines.

4.4.5 Savings

Two forms of savings need to be calculated after the implementation of the LS strategy. Namely, EE and LS savings. The LS savings presented in this section are therefore the savings achieved by the combined strategy. The savings will be calculated separately for both strategies with the combined energy and cost savings representing the total savings achieved by the combined strategies.

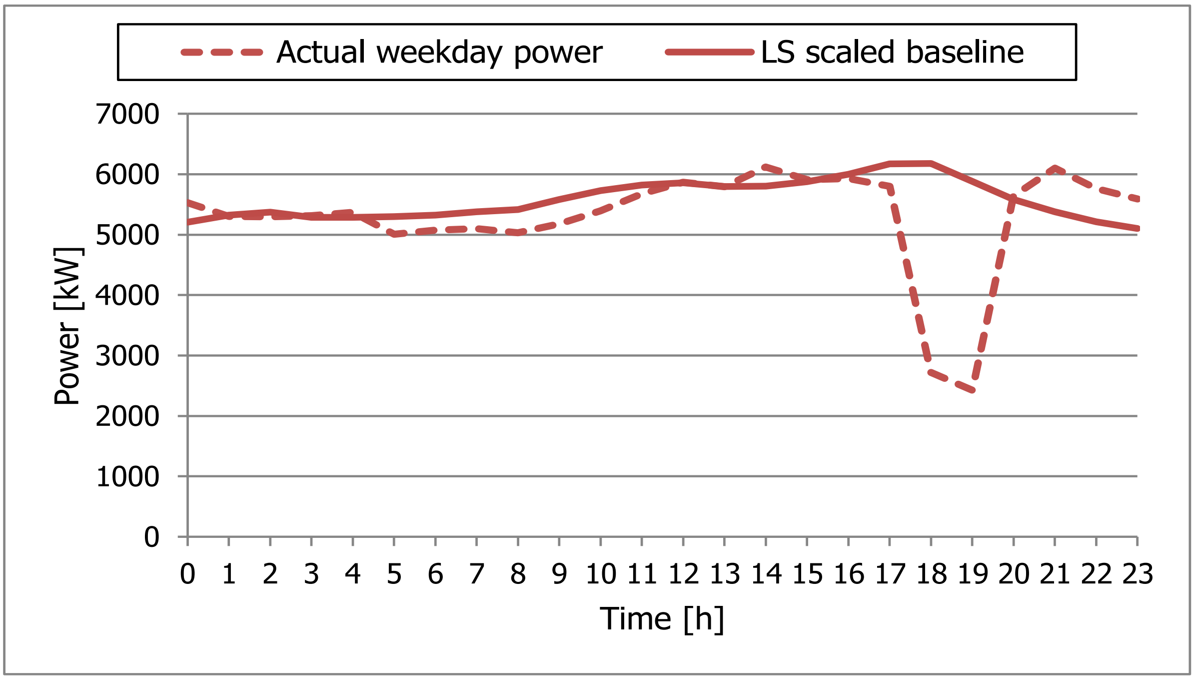


Figure 53: Combined strategy post-implementation load shifting power profile

Figure 53 shows the power profile for the combined strategy compared to the baseline scaled for the LS strategy. The average power reduction for the evening peak is 3.5 MW. This translates to a total energy saving of 6.9 MWh per day with a total cost saving of approximately R 4,900. The baseline is scaled in a manner that the average of both the actual usage and the baseline is the same outside the evening peak period.

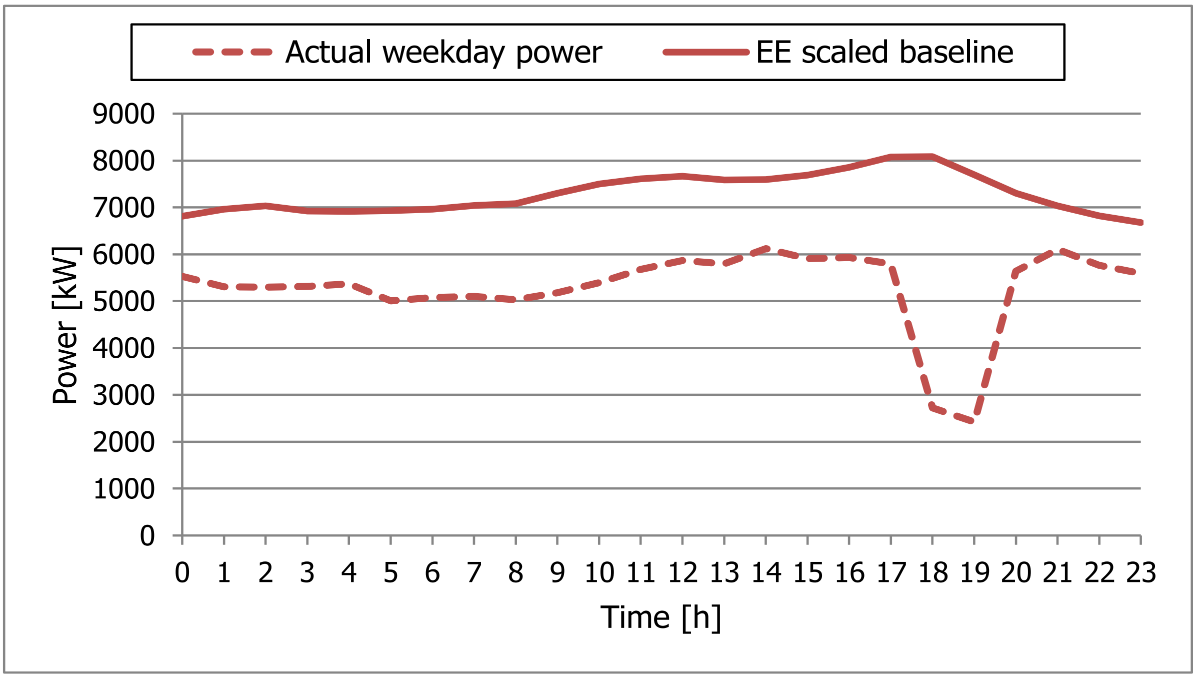


Figure 54: Combined strategy post-implementation energy efficiency power profile

Figure 54 shows the combined strategy power profile compared to the baseline scaled according to the EE strategy. The average reduction in power usage is 1.7 MW. The total energy saved per day is 37.6 MWh with a total cost saving of approximately R 17,500. No savings are calculated for the evening peak. All averages and costs also exclude the evening peak period.

As can be seen, although the average reduction in power usage for the combined strategy is greater than that of the EE strategy, the combined strategy yields a lower energy saving. This is due to the lack of EE savings in the evening peak. The sum of savings between the strategies however, is much greater. The total energy saving of the combined strategy is 44 MWh with a daily cost saving of approximately R 22,400. ~~The combined strategy gave a daily energy saving of 32 MWh and a cost saving of R 17,000.~~

4.5 CONCLUSION

As displayed in this section, both LS and EE strategies can be implemented safely on a platinum mine refrigeration and cooling system. Cost considerations in this particular case study meant that the combined strategy consisted of a two-phase implementation process. As a result, only the EE and combined strategy savings could be accurately calculated.

The baseline for the implementation of both strategies was calculated prior to implementation in order to accurately calculate all savings achieved according to the operation of the plant under circumstances where no DSM was in place. Scaling of the baselines for both the LS and EE strategy were also crucial as this allowed for the accurate calculation and comparison of savings achieved.

Some hindrances were experienced during the implementation of the EE strategy. As these incidents occurred during installation, a solution was sought that had no financial implications for the mine or ESCO carrying out implementation. No major instances occurred during the implementation of the LS strategy.

The post-implementation savings achieved by the EE strategy were enough to return a cost saving that is sufficiently higher than that of the simulations carried out. The combined strategy also performed better than anticipated. As such, the combined strategy will have a shorter repayment period than previously suspected. So, the success of both the EE and combined strategies can be deemed successful in terms of both cost and energy savings.

5. CONCLUSION AND RECOMMENDATIONS

5.1 PREAMBLE

This section will serve as the conclusion of the dissertation. In the previous sections control development was carried out. These control strategies were assessed for implementation according to the parameters of an appropriate platinum mine refrigeration system. Simulations were used to determine the efficiency and viability of implementation of both individual strategies as well as the combined strategy.

Appropriate equipment was installed at a mine that would serve as the case study for implementation. The EE strategy was implemented initially due to financial as well as component constraints. The LS strategy was implemented with the EE strategy already in place. As a result, the LS strategy could not be assessed individually. Only the EE and combined strategies have comparable results. As the combined strategy is the focus of this study this is appropriate.

5.2 COMBINED STRATEGY AT A SINGLE PLANT

The total cost of the combined strategy as implemented is R 4,370,653.07. As discussed in section 4 the cost of implementation of the individual strategies is not influenced if more than one strategy is implemented. This value does exclude project management, simulation and consultancy costs, as these were covered by an agreement between the mine and Eskom. As a result, when implementing a combined strategy, there is little influence on previously implemented strategies. Small scale control alterations may be required.

In the case of Mine X, the implementation of the EE strategy initially required software upgrades to the plant SCADA. These upgrades were found to be beneficial to the implementation of the LS strategy, as stop/start control of the motors was improved. When implementing multiple strategies at a single plant, it is therefore prudent to investigate previously implemented strategies. Control elements in particular can be taken advantage of, in order to improve control.

5.3 COMBINED STRATEGY SAVINGS

The savings delivered by the EE strategy prior to implementation of the combined strategy are available. The average power usage reduction is 1.6 MW, translating to a daily energy saving of 40.2 MWh. The average daily cost savings achieved by the strategy are R 19,200. This serves as proof of the effectivity of the implementation of an EE strategy alone.

The combined strategy, after implementation of the LS strategy, returned an EE saving of 1.7 MW with a daily energy saving of 37.6 MWh and cost saving of approximately R 17,500. This increase in average power reduction but reduction in energy savings is as a result of the evening peak period being devoted to the LS strategy. The LS savings delivered by the combined strategy are a 3.5 MW evening peak period power reduction. This gives a daily energy saving of 6.9 MWh with a cost saving of approximately R 4,900.

As a result the combined strategy delivers an average daily energy reduction of 44.5 MWh, an increase of 4.5 MWh over the initially implemented EE strategy. The average daily cost reduction of the combined strategy is approximately R 22,400. This is an increase over the EE strategy of R 3,200 daily. The plant performance results show clearly that a combined strategy returns the greatest savings, whilst maintaining or improving plant control.

5.4 RECOMMENDATIONS FOR FUTURE WORK

In the case of Mine X, underground water flow requirements could not be controlled or monitored in real time. As a result, the evening peak plant shut down was interrupted on a number of occasions, as chilled water levels stored at the surface were not sufficient. As a result, chilled water supply could not be halted until sufficient chilled water dam levels were attained. This was caused by a pumping schedule discrepancy caused by operator error.

~~.~~ A further expansion of the combined strategy to Include~~ing~~ automated control of underground equipment such as return pumps or dam supply line valves will greatly improve achievable savings, particularly during the evening peak period~~control~~. Existing control systems and strategies exist for this express purpose. Integration of these systems with the combined strategy discussed in this dissertation will expand control capability immensely. Large underground pump systems will also allow for marginal load shifting, returning greater savings.

6. REFERENCES

Field Cod

[1] M. Economics, “PLATINUM-GROUP METAL MINES IN SOUTH AFRICA,” 2003.

[2] Chamber of mines, “Platinum Mining in South Africa | Mining Industry | Chamber of Mines SA.” [Online]. Available: http://chamberofmines.org.za/mining-industry/platinum. [Accessed: 12-Nov-2014].

[3] Trading economics, “South Africa GDP charts.” [Online]. Available: http://www.tradingeconomics.com/south-africa/gdp. [Accessed: 12-Nov-2014].

[4] StatisticsSA, “Statistical release Gross Domestic Product,” no. February, 2014.

[5] StatisticsSA, “FACT SHEET Contributions of the annualised percentage change in seasonally adjusted real value added by industry to the annualised percentage change in seasonally adjusted real GDP,” no. August, p. 2014, 2014.

[6] L. Bloxham, S. Brown, L. Cole, A. Cowley, P. Duncan, M. Fujita, J. Jiang, J. Li, O. Meara, R. Raithatha, and E. Zadoff, “platinum 2 013.”

[7] Johnson Matthey, “Price charts - Platinum.” [Online]. Available: http://www.platinum.matthey.com/prices/price-charts. [Accessed: 17-Nov-2014].

[8] Chamber of mines, “Chamber of mines SA.” Chamber Of Mines Building, 5 Hollard St, Johannesburg, 2014.

[9] StatisticsSA, “Statistics SA.” 170 Thabo Sehume Street, Pretoria, 2014.

[10] A. England, “South African mining: Stuck in the past,” *The Big Read*, The big read, Apr-2014.

[11] R. Baxter, “The South African mining sector – Challenges and opportunities,” in *African Iron Ore Conference*, 2014, p. 59.

[12] R. Inglesi and A. Pouris, “Forecasting electricity demand in South Africa: a critique of Eskom’s projections,” *S. Afr. J. Sci.*, vol. 106, no. 1–2, pp. 50–53.

[13] Eskom, “The energy efficiency series.” Megawatt Park, Sunninghill, Sandton, 2157, South Africa.

[14] H. Le Roux, “Energy-consumption reduction challenge,” *Mining weekly*, 2005.

[15] R. Inglesi-Lotz and J. N. Blignaut, “South Africa’s Electricity Consumption: A Sectoral Decomposition Analysis,” Pretoria, 2011.

Field Cod

[16] G. E. du Plessis, "A variable water flow strategy for energy savings in large cooling systems," 2013.

[17] C. A. Nixon, A. D. S. Gilliest, and M. J. Howes, "Analysis of Heat Sources in a Large Mechanized Development," pp. 109–117, 1992.

[18] W. Marx, "Providing acceptable working environment in ultra-deep mines," *J. Mine Vent. Soc. South Africa.*, 1990.

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

[20] W. L. Le Roux, "Le Roux's notes on mine environmental control," *Mine Vent. Soc. South Africa*, 1990.

[21] A. J. Schutte, M. Kleingeld, and L. van der Zee, "An integrated energy efficiency strategy for deep mine ventilation and refrigeration," *Proc. 11th Ind. Commer. Use Energy Conf. Cape T.*, 2014.

[22] J. Vosloo, L. Liebenberg, and D. Velleman, "Case study: Energy savings for a deep-mine water reticulation system," *Appl. Energy*, vol. 92, no. 1, pp. 328–335, Apr. 2012.

[23] G. E. Du Plessis, L. Liebenberg, and E. H. Mathews, "The use of variable speed drives for cost-effective energy savings in South African mine cooling systems," *Appl. Energy*, vol. 111, pp. 16–27, 2013.

[24] G. E. Du Plessis, L. Liebenberg, E. H. Mathews, and J. N. Du Plessis, "A versatile energy management system for large integrated cooling systems," *Energy Convers. Manag.*, vol. 66, pp. 312–325, 2013.

[25] A. Grein and M. Pehnt, "Load management for refrigeration systems: Potentials and barriers," *Energy Policy*, vol. 39, no. 9, pp. 5598–5608, Sep. 2011.

[26] T. Nortje, "South Africa's demand side management program: a savings opportunity," in *International Pump User Conference 2005*.

[27] Eskom, "Energy efficiency and Demand Side Management Program Evaluation Guideline Proposal." Eskom Ltd, Megawatt Park, Sunninghill, Sandton, 2157, South Africa, 2011.

[28] Eskom, "Schedule of standard prices." Megawatt Park, Sunninghill, Sandton, 2157, South Africa, 2014.

Field Cod

[29] Eskom, “Eskom Integrated Demand Management.” Megawatt Park, Sunninghill, Sandton, 2157, South Africa, 2014.

[30] R. Pelzer, E. . H. Mathews, D. F. 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, Aug. 2008.

[31] B. Matthews and I. K. K. Craig, “Demand side management of a run-of-mine ore milling circuit,” *Control Eng. Pract.*, vol. 21, no. 6, pp. 759–768, Jun. 2013.

[32] A. Pina, C. Silva, and P. Ferrão, “The impact of demand side management strategies in the penetration of renewable electricity,” *Energy*, vol. 41, no. 1, pp. 128–137, May 2012.

[33] J. T. Cousins, “Using time of use (TOU) tariffs in industrial, commercial and residential applications effectively,” TLC Engineering Solutions, Bryanston, 2009.

[34] L. Buys, “Optimising the refrigeration and cooling system of a mine,” M.Eng. dissertation, Dept. Mech. Eng., NWU, 2014.

[35] ASHRAE, *Fundamentals Handbook*. Atlanta: American Society of Heating, Refrigeration and Air conditioning Engineers: American Society of Heating, Refrigeration and Air conditioning Engineers, 2001.

[36] A. J. Schutte, “Demand-side energy management of a cascade mine surface refrigeration system,” M.Eng. dissertation, Dept. Mech. Eng., NWU, 2008.

[37] H. Wagner, “The management of heat flow in deep mines (part 2),” *Geomech Tunn.*, vol. 4, no. 2, pp. 157–163, 2011.

[38] M. J. J. McPherson, *Subsurface ventilation and environmental engineering*. London: Chapman and Hall, 1993.

[39] R. E. Sonntag, C. Borgnakke, and G. J. Van Wylen, *Fundamentals of Thermodynamics*. New York: J. Wiley & Sons, 2003.

[40] Z. Crepinsek, D. Goricanec, and J. Krope, “Comparison of the performances of absorption refrigeration cycles,” *WSEAS Trans. Heat Mass Transf.*, vol. 4, no. 3, pp. 65–76, 2009.

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

[42] Energy Research Institute and Energy Research Centre, “How to save energy and money in refrigeration.” Department of Mechanical Engineering, University of Cape

Field Cod

Town, South Africa, 2007.

[43] K. N. Widell and T. Eikevik, “Reducing power consumption in multi-compressor cooling systems,” *Int. J. Refrig.*, vol. 33, pp. 88–94, 2010.

[44] M. International, “WSC/WDC-4 Centrifugal Compressor Water Chiller Catalogue,” *Verginia*. 2005.

[45] J. M. Gordon, K. C. Ng, H. T. Chua, and C. K. Lim, “How varying condenser coolant flow rate affects chiller performance: thermodynamic modeling and experimental confirmation,” *Appl. Therm. Eng.*, vol. 20, pp. 1149–1159, 2000.

[46] M. Schneider, M. Romer, M. Tschudin, and H. Bolio, “Sustainable cement production—present and future,” *Cem. Concr. Res.*, vol. 41, no. 7, pp. 642–650, Jul. 2011.

[47] W. P. Bahnfleth and E. B. Peyer, “Variable primary flow chilled water systems: potential benefits and application issues,” Pennsylvania State University, Pennsylvania, 2004.

[48] BPMA, “Variable speed driven pumps: Best practice guide,” British Pump Manufacturers’ Association, Birmingham, 2004.

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

[50] BPMA, “Variable speed driven pumps: Best practise guide,” British Pump Manufactures’ Association, Birmingham, 2004.

[51] C. A. Rawlins, “Mine cooling and insulation of chilled water transport pipes,” *J. South African Inst. Min. Metall.*, vol. 107, no. 10, pp. 681–688.

[52] ASHRAE, *Handbook on equipment*. Atlanta: American Society of Heating, Refrigeration and Air conditioning Engineers, 1997.

[53] A. Whillier and J. Van der Walt, “Grafity-fed water systems in mines,” *J. South African Inst. Min. Metall.*, pp. 187–192, 1977.

[54] R. Hemp, W. Holding, and R. M. Stroh, *Environmental Engineering in South African Mines*. Cape Town, South Africa: Cape & Transvaal Printers, 1982.

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

[56] F. W. Stoecker and J. W. Jones, *Refrigeration and air conditioning*, 2nd ed. McGraw-

Field Cod

Hill, 1983.

[57] A. M. Holman, “Benefits of improved performance monitoring of mine cooling systems,” M.Eng. dissertation, Dept. Mech. Eng., NWU, Pretoria, 2013.

[58] D. Van Greunen, “Energy efficiency through variable speed drive control on a cascading mine cooling system,” M.Eng. dissertation, Dept. Mech. Eng., NWU, Pretoria, 2013.

[59] Carrier Corporation, *Operation and application of variable frequency drive (VFD) technology*. New York: Carrier Coperation Syracuse, 2005.

[60] F. W. Yu and K. T. Chan, “Improved energy performance of air cooled centrifugal chillers with variable chilled water flow,” *Energy Convers. Manag.*, vol. 49, pp. 1595–1611, 2008.

[61] R. Saidur, S. Mekhilef, A. Safari, and H. A. Mohammed, “Applications of variable speed drive (VSD) in electrical motors energy savings,” *Renew. Sustain. Energy Rev.*, no. 16, pp. 543–550, 2012.

[62] R. Saidur, “A review on electrical motors energy use and energy savings,” *Renew. Sustain. Energy Rev.*, no. 14, pp. 877–898, 2010.

[63] T. Q. Qureshi and S. A. Tassou, “Variable-speed capacity control in refrigeration systems,” *Appl. Therm. Energy*, vol. 16, no. 2, pp. 103–113, 1996.

[64] E. A. Abdelaziz, R. Saidur, and S. Mekhilef, “A review on energy saving strategies in industrial sector,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 150–168.

[65] E. Ozdemir, “Energy conservation opportunities with a variable speed controller in a boiler house,” *Appl. Therm. Eng.*, vol. 24, no. 7, pp. 981–993.

[66] H. Crowther and J. Furlong, “Optimising Chillers and Towers,” *AHRAE J.*, vol. 46, no. 7, pp. 34–40, 2004.

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

[68] J. du Plessis, M. Butterworth, and R. Mcintyre, “Ventilation and cooling strategy for a deep mechanised mine - South Deep in South Africa,” Bluhm Burton Engineering, 41 Sloane Street, Bryanston, Johannesburg, 2012.

[69] F. W. Yu and K. T. Chan, “Assessment of operating performances of chiller systems using cluster analysis,” *Int. J. Therm. Sci.*, vol. 53, pp. 148–155, 2012.

Field Cod

[70] J. Navarro-Esbrí, D. Ginestar, J. M. Belman, V. Miliàn, and G. Verdù, “Application of a lumped model for predicting energy performance of a variable-speed vapour compression system,” *Appl. Therm. Eng.*, vol. 30, no. 4, pp. 286–294, 2010.

[71] Eskom, “Eskom tariffs and charges booklet 2013/2014.” .

[72] J. Calitz, “Research and implementation of a load reduction system for a mine refrigeration system,” M.Eng. dissertation, Dept. Mech. Eng., NWU, 2006.

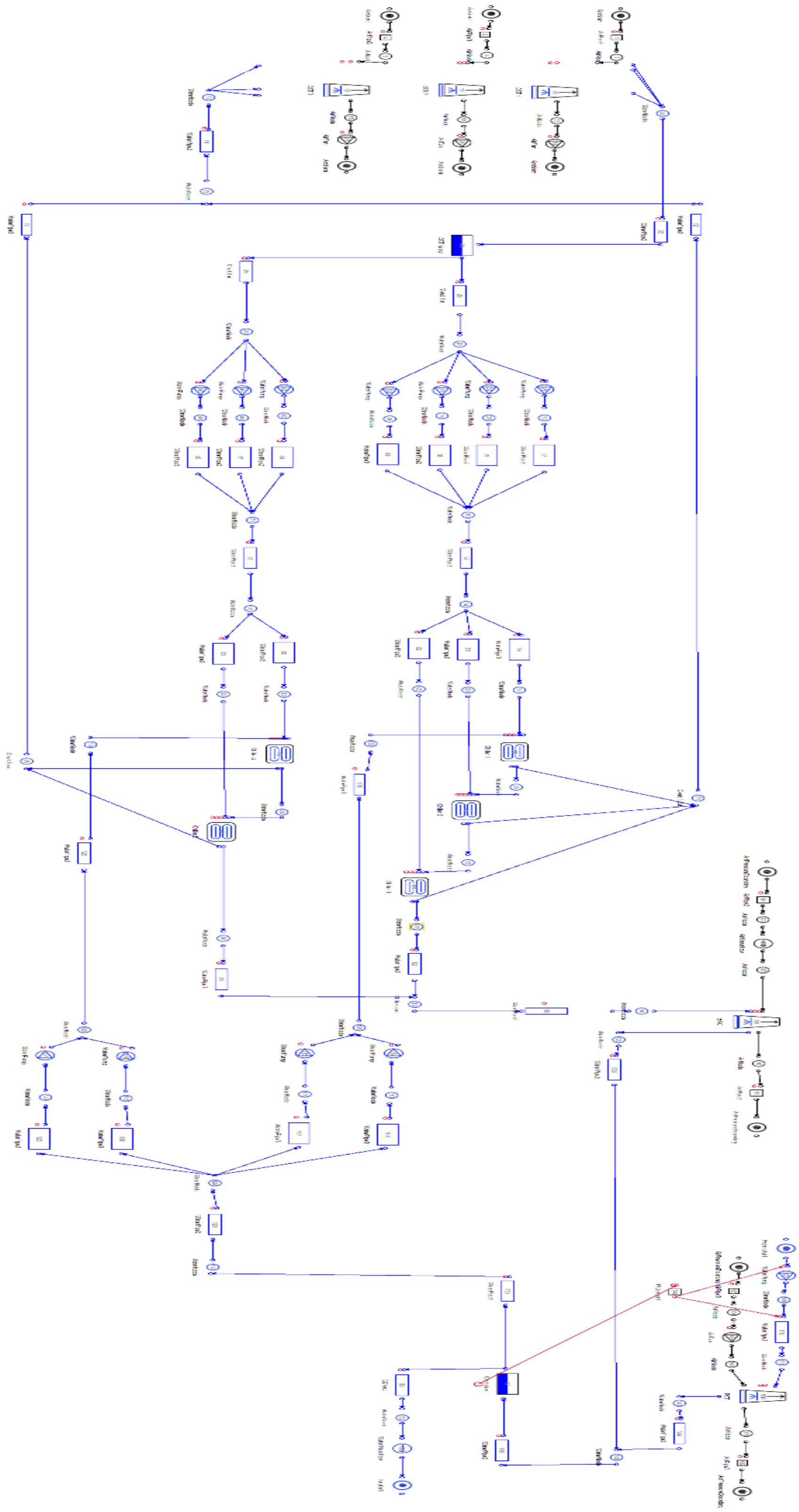
[73] R. Els, “Potential for load shifting in Ventilation and Cooling systems.” M.Eng. dissertation, Dept. Mech. Eng., NWU, Pretoria, 2000.

[74] S. van Jaarsveld, “A control system for the efficient operation of bulk air coolers on a mine.” M.Eng. dissertation, Dept. Comp. & Elec. Eng., NWU, Pretoria, 2014.

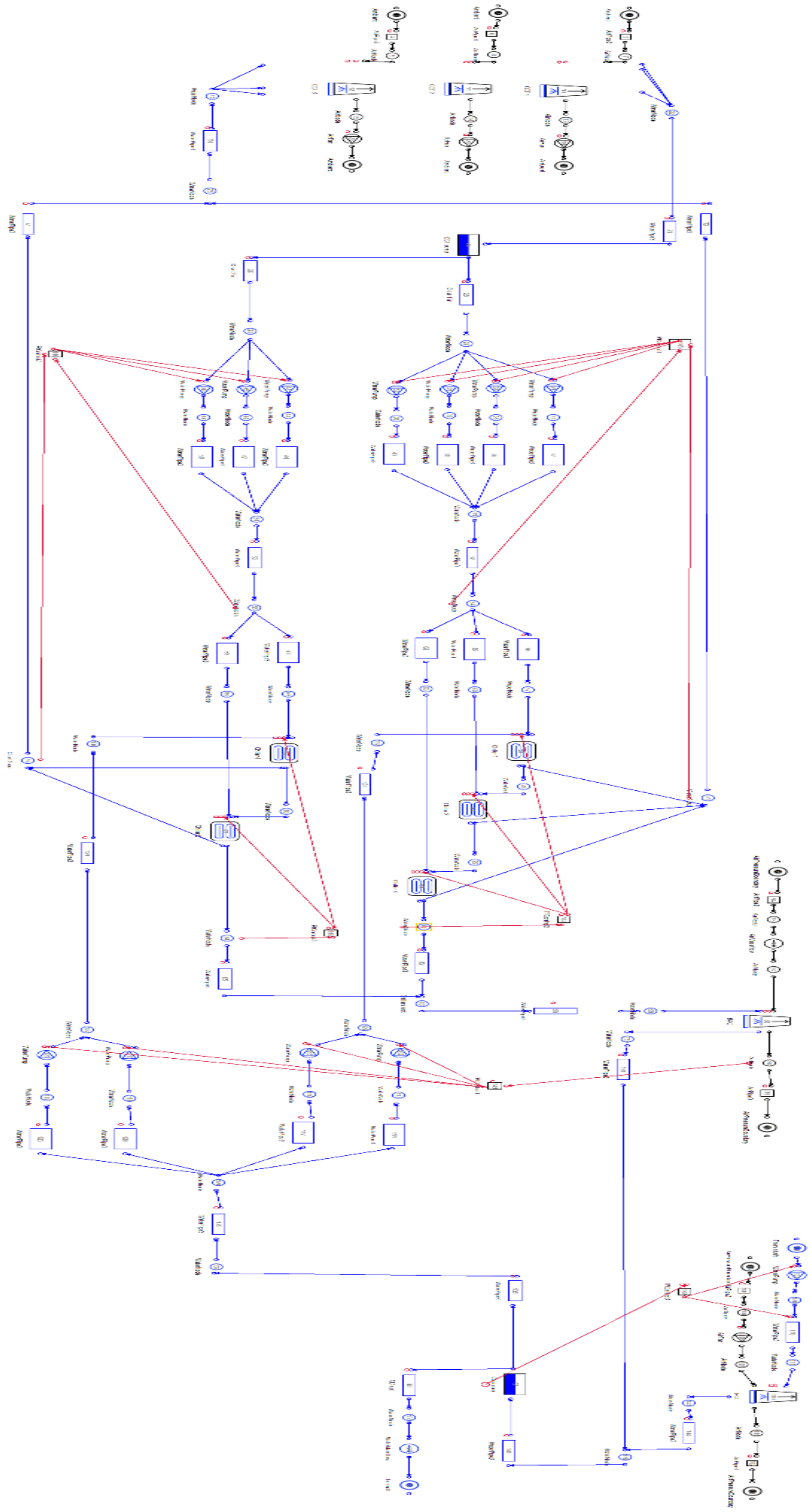
[75] J. van der Bijl, “A novel approach to sustainable DSM in deep mine refrigeration systems,” Ph.D. thesis, Dept. Mech. Eng., NWU, 2007.

7. APPENDICES

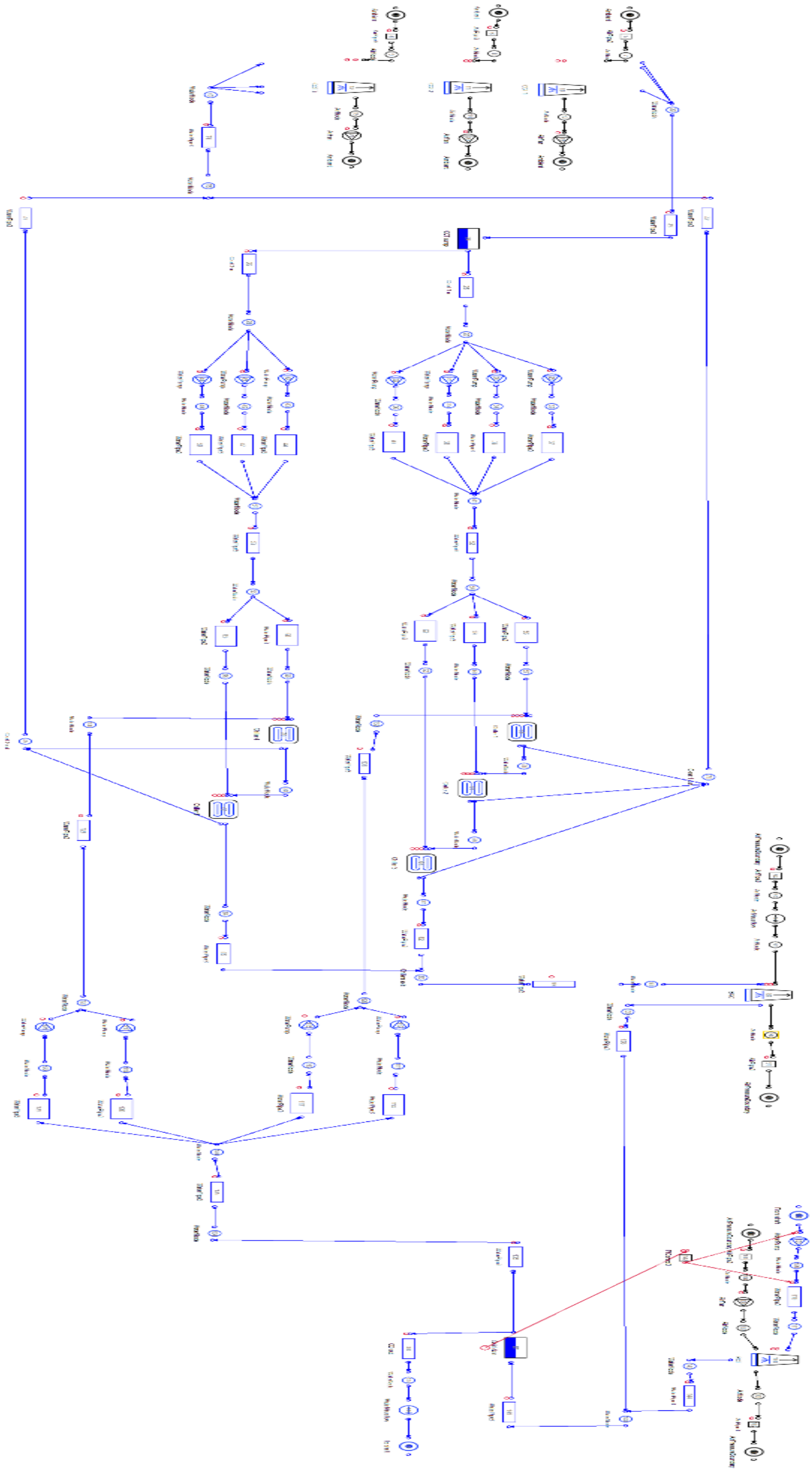
APPENDIX A: BASELINE CONTROL SIMULATION LAYOUT



APPENDIX B: ENERGY EFFICIENCY CONTROL SIMULATION LAYOUT



APPENDIX C: LOAD SHIFT CONTROL SIMULATION LAYOUT



APPENDIX D: COMBINED CONTROL SIMULATION LAYOUT