An integrated energy efficiency strategy for deep mine ventilation and refrigeration

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Thesis submitted for the degree *Doctor Philosophiae* in Mechanical Engineering at the Potchefstroom Campus of the North-West University

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May 2014

Abstract

Title: An integrated energy efficiency strategy for deep mine ventilation and refrigeration

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Degree: Philosophiae Doctor in Mechanical Engineering

Keywords: Strategy, sequence, combination, energy efficiency, load management, ventilation, refrigeration, surface BAC.

South Africa's electricity supply is under pressure. Mining is one of South Africa's largest electricity consumers with electricity-intensive services such as compressed air, cooling, ventilation, etc. More than 40% of mine electricity consumption is used for cooling and ventilation. There is a need to reduce the operational cost on a mine as electricity prices are set to increase at least 2% above South Africa's inflation target.

The mine-cooling and ventilation system was investigated for energy cost-saving. No clear energy and cost-saving strategy for the entire mine-cooling and ventilation system was found. Projects are implemented ad hoc and scattered throughout the system. A strategy is needed to help realise the total saving available on the entire mine-cooling and ventilation system.

An implementation strategy for load-management and energy-saving projects on a mine-cooling and ventilation system was developed. A peak clip project on the surface BAC was developed and added to the strategy. The resultant strategy attains all savings throughout the entire mine-cooling and ventilation system.

A peak clip project on the surface BAC of a typical mine results in an annual saving of R1.4 million. Implementing this new project on other mines could save R11 million annually. Implementing the sequenced combination of cooperative projects on a typical mine results in a saving of R30 million. That is a saving of 38% on the ventilation and cooling cost and 16% on the total mine electricity bill.

Opsomming

Titel: Energiedoeltreffende mynventilasie- en -verkoelingstelsels

Outeur: Mnr AJ Schutte

Studieleier: Prof M Kleingeld

Graad: Doktorsgraad in Meganiese Ingenieurswese

Sleutelwoorde: Strategie, volgorde, kombinasie, energiedoeltreffendheid, lasbeheer, ventilasie, verkoeling, grootmaat oppervlaklugverkoelingseenhede.

Suid-Afrika se elektrisiteitsvoorsiener is onder druk om in die land se behoeftes te voorsien. Mynbou bly steeds een van Suid-Afrika se grootste elektrisiteitsverbruikers, met elektrisiteit wat vir druklug, verkoeling, ventilasie en ander dienste gebruik word. Verkoeling en ventilasie gebruik meer as 40% van die myn se totale elektrisiteit. Met die prys van elektrisiteit wat ten minste 2% bo Suid Afrika se inflasiekoers gaan styg, word kostebesparing vereis.

Die mynverkoeling- en -ventilasiestelsel is vir kostebesparing ondersoek. Daar is bevind dat daar nie ’n riglyn is vir die implementering van projekte nie. Die lasbeheer- en kragbesparingsprojekte op die mynverkoeling- en -ventilasiestelsel word onbepland en verspreid gedoen. ’n Strategie word benodig om die totale besparing oor die hele stelsel te bewerkstellig.

’n Strategie is ontwikkel vir die implementering van lasbeheer en energie-besparingsprojekte op ’n myn se verkoeling- en -ventilasiestelsel. ’n Pieksnyprojek is ook vir die grootmaat oppervlaklugverkoelingseenhede (GLE) ontwikkel en by die strategie gevoeg. Die resultaat is dat die totale besparing op die hele stelsel behaal word.

’n Pieksny op die oppervlak GLE van ’n tipiese myn sal ’n jaarlikse besparing van R1.4 miljoen te weeg bring. As dit op al die ander myne in Suid-Afrika gedoen word, sal die besparing R11 miljoen beloop. Deur die ontwikkelde implementeringstrategie te volg, kan ’n tipiese myn tot R30 miljoen jaarliks bespaar. Dit is ’n 38% besparing op die jaarlikse ventilasie- en verkoelingskoste en 16% op die totale jaarlikse koste.

Acknowledgements

This dissertation represents my own research. Various others also contributed through discussions, cooperation, etc. As far as possible, recognition was given to all sources of information.

I apologise if the necessary recognition was not given. If anyone is of the opinion that I did not acknowledge their input, please contact me to make the necessary corrections.

I would like to use this opportunity to thank TEMM International for funding this research and express my gratitude to Prof EH Mathews, Prof M Kleingeld and the late Mr DH Velleman for giving me the opportunity to complete this study under their guidance and support.

I would like to thank colleagues at HVAC International and TEMM International for their contributions throughout the course of this study.

I thank my family and friends for their ongoing love and support throughout my life.

Finally, I thank God for His grace.

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Nomenclature

Anon	Anonymous
Ashrae	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAC	Bulk air cooler
BBE	Blhum Burton Energy / Blhum Burton Engineering
COMRO	Chamber of Mines Research Organisation
COP	Coefficient of performance
CSIR	Council for Scientific and Industrial Research
CWC	Chilled water car
DB	Dry-bulb
DSM	Demand-side management
EEP	Energy-efficiency project
EHS	Environmental health and safety
EMS	Energy management system
HPE	Hydro-power equipment
HVAC	Heating ventilation and air conditioning
IDM	Integrated demand management
IPP	Independent power producer
LMP	Load-management project
MM	Man and materials
MVSSA	Mine Ventilation Society of South Africa
MYPD 3	Third multi-year price determination
M&V	Measurement and verification
NERSA	National Energy Regulator of South Africa
PAI	Project appeal indication
PCLF	Planned capability loss factor
PLC	Programmable logic controller
RAW	Return air way
REMS	Real-time energy management system
RH	Relative humidity
SCADA	Supervisory control and data acquisition
TDH	Temperature-dependent heat

TIH	Temperature-independent heat
TOU	Time-of-use
UCLF	Unplanned capability loss factor
VRT	Virgin rock temperature
VSD	Variable speed drive
VUMA	Ventilation of underground mine atmospheres
WB	Wet-bulb

Cp	Specific heat capacity of the substance (kJ/kg.K)
Δd	Elevation change (m)
E	Energy per unit distance of elevation change (1 kJ/(102 m.kg))
q	Theoretical heat of auto-compression (kW)
Q	Airflow in shaft (m^3/s)
ρ	Air density (kg/m^3)
q	Quantity of energy or heat (kW)
m	Mass flow of the substance (kg/s)
ΔT	Temperature rise of the substance (K)
α	Thermal diffusivity of rock (m^2/h)
k	Thermal conductivity of rock (W/(m.K))
ρ	Rock density (kg/m^3)
F_o	Fourier number (dimensionless)
L	Length of section (m)
P	Perimeter of section (m)
r	Radius of circular section (m)
t_a	Air dry-bulb temperature (°C)
t_{vr}	Virgin rock temperature (°C)
ε	Function of Fourier number for instantaneous rate(dimensionless)
θ	Average of section (h)
Q	Energy absorbed by BAC (kW)
S	Enthalpy (kJ/kg)
X_{H2O}	Rate of water removal (kg/s)
W	Humidity ratio (kg/kg)
P	Power (kW)

q	Flow capacity (l/s or kg/s)
ρ	Density of fluid (kg/m^3)
g	Gravity (9.81 m/s^2)
h	Differential head (m)
T_{out}	Water temperature out (K)
T_{in}	Water temperature in (K)
V	Volts (V)
I	Amps (A)
pf	Power factor
$\dot{m}$	Mass flow (kg/s)
T_{in}	Temperature in (K)
T_{out}	Temperature out (K)
P_{ref}	Refrigeration motor power (kW)
P_{aux}	Auxiliary equipment power (kW)
Q	Thermal energy (kW)
P_{ref}	Motor power (kW)
$C_{pcondensate}$	Specific heat required to condensate water (kJ/kg)
T	Temperature (^oC)
S	Sigma heat
η	Efficiency

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1. Introduction

The present electricity supply situation in South Africa is summarised and the electricity usage of a deep-level mine is discussed. The chapter concludes with the purpose of this study, together with its contributions.

1.1. Electricity restrictions in South African mining

Energy conservation and awareness have become a fundamental issue of the 21st century. The time of abundant energy being readily available is over [1] [2]. Worldwide, non-renewable energy sources are becoming depleted. Rising population numbers in developing countries, growing economies and rising living standards increase the global demand for energy, particularly electrical energy [3] [4] [5].

South Africa is a developing country with a growing economy and expanding population. It is the government's agenda to improve the living standard of South Africans. As a result, the electricity demand is continually increasing [6]. The demand for electricity around 35.2 GW is approaching the installed generation capacity of 41.9 GW. Eskom's planned capability loss factor (PCLF) was 9.1% and its unplanned capability loss factor (UCLF) was 12.1% [7].

Summing the PCLF and UCLF (21.2%) indicates that Eskom had an available capacity of 8.9 GW below the installed capacity at 33.0 GW (78.8%). With the Medupi power station adding 4.3 GW to the grid, Eskom will be able to recover a little more than half of the capacity lost to planned and unplanned maintenance [7].

From the above it can be seen that there is more than the recommended reserve margin of 15% in terms of capacity. However, Eskom's capability is narrowly matching the demand. The South African reserve is insufficient to buffer a sudden increase in demand or a major unplanned stoppage. As a result, Eskom may again introduce unplanned national power shedding [8] [9].

Building new electricity generation plants takes an estimated 10 years and additional capital funding above the construction cost is needed to service debt [10]. One clear and obvious solution for providing sustainable, reliable and affordable electricity is to manage and control the demand for electricity [9]. Changes from load-management and electricity-saving initiatives are quick to implement. There is no interest paid to service debt, and capital saving is reinvested into further energy-saving initiatives.

Controlling the demand will ensure that the least amount of electricity is used for an application. This improved utilisation will reduce the load on the grid and create spare capacity. Spare capacity means that new extensions can be added to the grid and the available electricity can be distributed as needed to improve South Africans' lives.

The capital funding needed by Eskom to fund new power stations was granted by the National Energy Regulator of South Africa (NERSA). This capital will be acquired from electricity increases. As a result of these implemented and planned electricity tariff increases, consumers will be forced to utilise electricity more wisely.

In 2008, the price of electricity increased by 23% and in 2009 by another 52%. This was a combined increase of 87% within two years. Figure 1-1 shows the increase in the cost of electricity and what the increase would have been with inflation. With the third multi-year price determination (MYPD 3), against the consumer's will, NERSA approved an 8% increase in electricity prices [11].

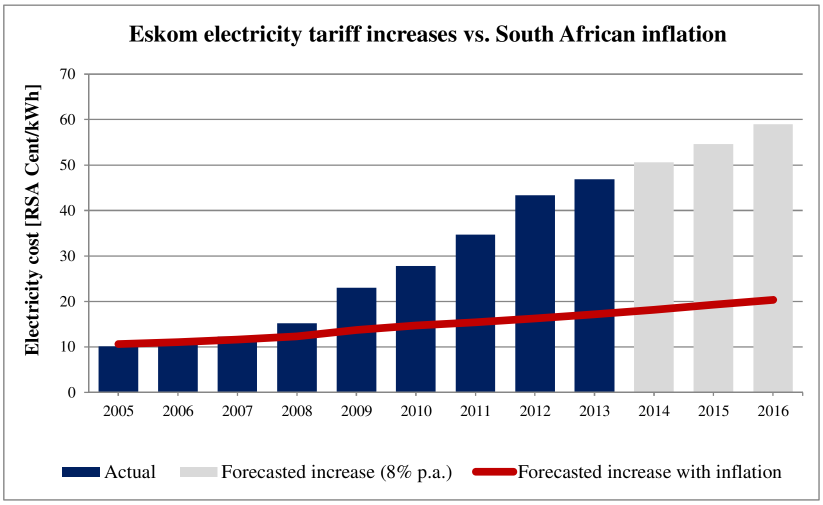


Figure 1-1: South African electricity price increase [11] [12] [13]

Table 1-1 indicates the electricity consumption of Sibanye Gold, South Africa's largest gold producer. The proposed 8% increase will add R430 million to its operating costs. Given that the gold price is R453 000 per kilogram, the group would need to mine an additional ton of gold to cover the increase [14].

Table 1-1: Annual financial implications on a gold mining group [15]

Sibanye Gold	
Electricity usage	437 MW
Percentage of Eskom sales	1.8%
Electricity bill	R2 100 million
Eskom increase	R430 million
Expected electricity bill	R2 530 million

South Africa's largest electricity provider has launched an integrated demand management (IDM) subdivision to promote and manage the consumption of electricity projects, namely Eskom-IDM. Its focus is on energy efficiency, load management and negotiating demand-response participation. The objective of IDM is to effectively manage the demand [7].

1.2. Mining as energy consumers

Various resources are mined in South Africa. Mining and exporting these resources is one of the largest commercial industries in South Africa. Mining is energy intensive and bought 14.6% of Eskom's electricity for 2012, as shown in Figure 1-2 [16]. In South Africa, the gold mines are the single greatest users of electricity across all mining sectors. The amount of electricity used for gold mining is almost as much as the electricity used by all the other mining sectors combined.

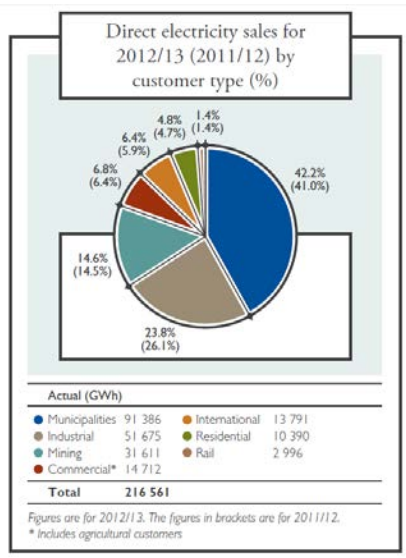


Figure 1-2: Eskom electricity sales [8]

Gold has been an important driver of the South African economy. The country supplies 12% of the global gold output and the mining sector creates work for around 417 000 people a year. Various additional work opportunities are created by secondary service companies, which are sustained through service contracts with the gold mines [17].

From the previous section it can be seen that gold mining is severely influenced by the recent Eskom tariff increases. To address energy consumption in South African mines, a breakdown of and an in-depth look at the electricity consumption of a typical deep-level mine are needed. South Africa is a world leader in the mining industry.

Mining can be split up into production and services. The focus of production is mining the gold reef. The focus of services is to ensure that the auxiliary systems needed and used by production are available. The auxiliary systems are compressed air, hoisting, pumping ventilation and cooling, as shown in Figure 1-3.

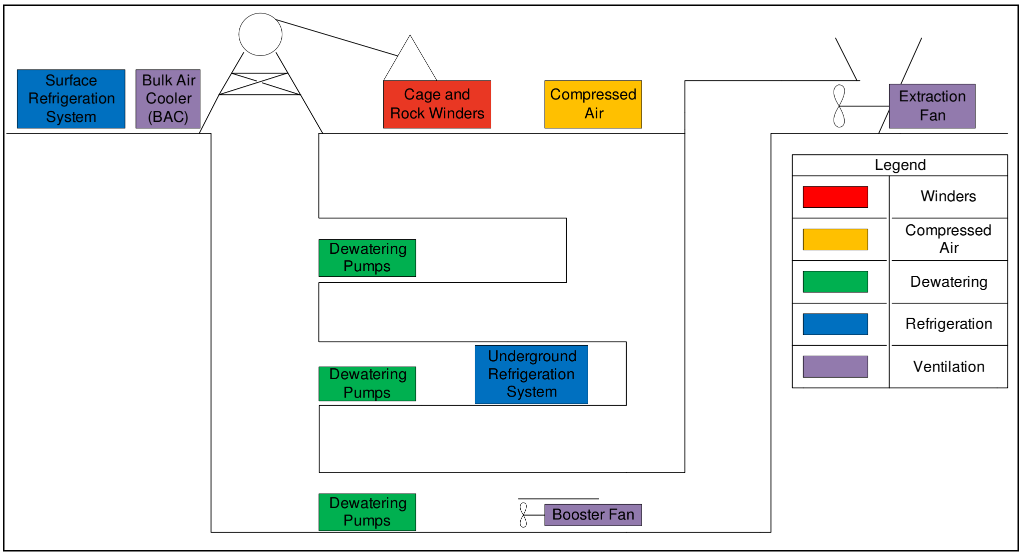


Figure 1-3: Mine production auxiliary systems

These auxiliary systems use 61% of the mine's electricity, as shown in Figure 1-4. Compressed air is generated on the surface and is used extensively throughout the mine for drilling, cleaning, ventilation, loading and actuation. Pneumatics is widely used in the mining environment due to its safety and versatility. The winders hoist men, materials, ore and waste.

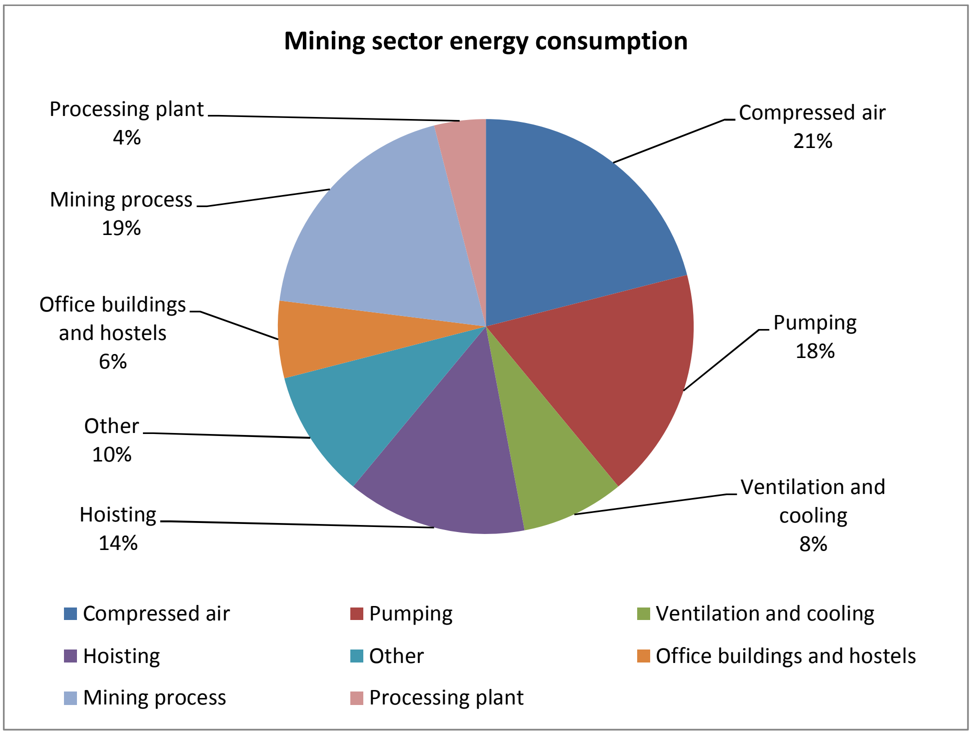


Figure 1-4: Breakdown of energy consumption in the mining sector [18]

Cooling and ventilation are needed, because one of the major day-to-day challenges a South African deep-level gold mine faces is high underground temperatures. Virgin rock temperature (VRT) increases as the mining depth increases and reaches temperatures of up to 70 ^{o}C [19].

This creates uncomfortable to dangerous working conditions for both humans and machines. Therefore, deep-level gold mines' ventilation and cooling systems require unique cooling methods.

If cost, reliability and safety are considered, the best ventilation method is surface extraction fans that ventilate the mine by extracting the used air and toxic gases. These fans create a vacuum in the mine, which sucks in fresh air from the surface. The surface extraction fans are assisted by the bulk air coolers (BACs) and booster fans underground.

Considering cost, reliability and safety, the best cooling technique has been shown to be large industrial refrigeration machines. The refrigeration system produces chilled water as a working fluid, which is used in the BACs and in mining sections underground.

The ventilation system BACs cool and dehumidify ventilation air. Chilled water sent underground is used for drilling, cleaning, cooling and dust suppression. The dewatering system of a mine consists of a pumping station on several levels. The complete water-reticulation system consists of the refrigeration plants, underground water supply and the mine dewatering systems, as shown in Figure 1-5.

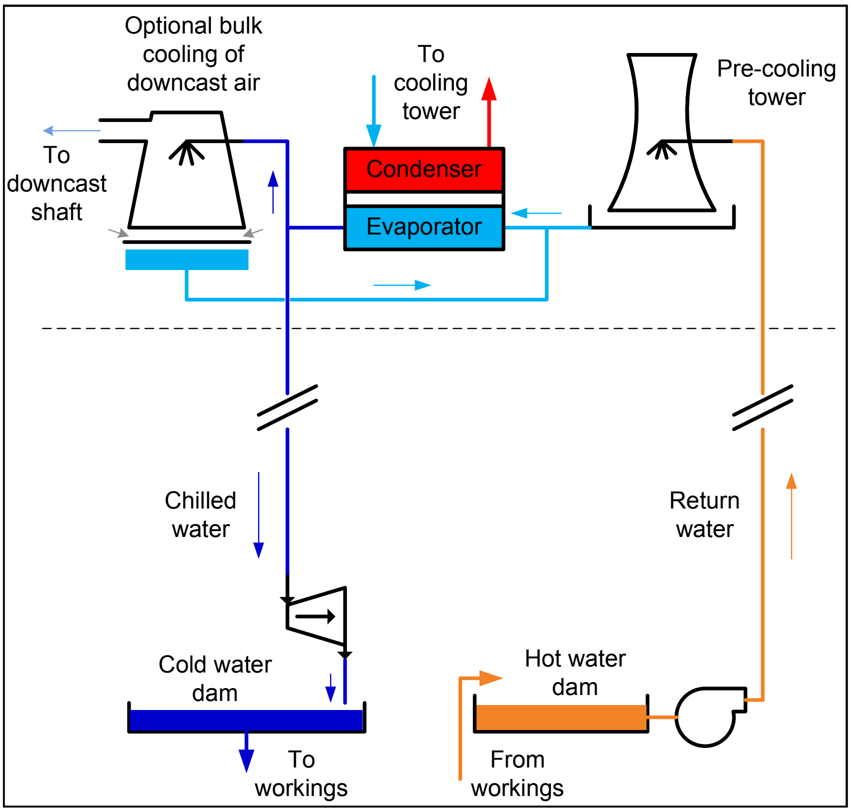


Figure 1-5: Water reticulation system

The mine water cycle is in a closed loop to lessen the environmental effects of the mining process. The blasted ore is cooled by heat conduction to cold water and evaporative cooling. The mine ventilation air is cooled and dehumidified by a BAC, which, as stated in the previous section, receives cold water from the refrigeration system.

It is clear that saving electricity in the mining industry can make a significant contribution to stabilising the national power grid supply.

1.3. Previous research

1.3.1. Background information

Formal research on mine cooling and ventilation started in South Africa in 1901. The Mine Ventilation Society of South Africa (MVSSA) was established in 1944 and the Chamber of Mines Research Organisation (COMRO) was established in 1964.

The principles for providing a healthy and safe thermal environment in a cost-effective manner were established by AWR Barenbrug in 1948 to increase productivity [21]. A filter to remove noxious gases found in blasting fumes from ventilation air was also developed in this period [22].

Research into ventilation and cooling issues was carried out by the Environmental Engineering Laboratory, initially under Whillier, and then in the late 1970s to early 1990s by Sheer and Bluhm [19]. In 1976, it was established that the underground working environment was heaven at 28 ^{o}C wet-bulb (WB) and hell at 33 ^{o}C WB.

Whillier, then the Director of the Environmental Engineering Laboratory of COMRO, coined the phrase "There is a 5 ^{o}C difference between heaven and hell underground". This phrase is still used in ventilation circles today [23] [24].

To combat high temperatures underground, refrigeration had been introduced since 1930. During this period, the refrigeration produced cold water to cool down the ventilation air. Effective and practical ways of cooling mine air continued to be developed. There was extensive research and development of direct and indirect water-to-air heat transfer equipment, such as cooling coils and spray chambers [25].

However, there is a limit to the cooling that can be applied to the air, and in 1976, Whillier proposed chilling the water used for dust suppression and drilling as additional cooling [23] [26].

The distribution of large quantities of water underground led to research into energy-recovery devices, such as turbines and hydro-lift devices, today known as three-chamber pipe feeders.

The use of ice was also examined due to its high latent heat, which leads to smaller mass flow rates or return water being pumped to the surface. Various methods for conveying ice from the surface to underground melting dams were examined [27].

In 1992, COMRO was taken over by the Council for Scientific and Industrial Research (CSIR). The collaborative three-year DEEPMINE research programme that started in 1998 involved mine owners, labour and government (the CSIR), universities, expert individuals and mine-owner specialists. The objective of DEEPMINE was to develop expertise and technology to mine gold safely and profitably at ultra-depths (3 to 5 km) [28] [29] [30].

Research included both an investigation to understand the engineering challenges and the development of new technologies. The cooling and ventilation of such deep mines formed part of the engineering challenges. From this research, mines have installed underground refrigeration systems. These systems have allowed mining in South Africa to exceed a depth of 3 000 m.

The success of DEEPMINE led to another collaborative research programme, FUTUREMINE. FUTUREMINE focused on improving productivity and reducing mining costs with a subsection focusing on ventilation, cooling and refrigeration.

FUTUREMINE's research was directed to areas related to the recirculation of air, cyclical use of ventilation and cooling systems, air-scrubbing technology, optimisation of chilled water reticulation (the use of ice), minimising heat losses in underground dams, tunnel insulation, obtaining direct cooling at the workface, improving underground refrigeration systems through dry-air cooling, and water heat-rejection systems.

Safety issues that were researched included the provision of ventilation and refrigeration in emergency situations, such as fan and refrigeration plant stoppages as a result of power failure, a number of software simulation programs to predict ventilation and heat flow transients, as well as software to monitor real-time underground environmental conditions [31].

COALTECH 2020 strongly focused on productivity, with little work done on ventilation issues. PLATMINE's refrigeration, cooling and ventilation research has been limited and mainly determined the application of gold mine research, specifically DEEPMINE and FUTUREMINE, to platinum mines.

The current need is research on load management and energy-saving. South African energy-cost escalations and the shortage in electricity-generating capacity are encouraging major electricity consumers in South Africa to re-evaluate their power use. The focus for the re-evaluation is on main fans and refrigeration systems.

Very little collaborative research and development work in mine refrigeration, cooling and ventilation is currently being conducted in South Africa. Most of the work being done addresses mine-specific problems. Yet, South Africa's research in the fields of refrigeration, cooling and ventilation in deep, hot mines remains world renowned [19].

1.3.2. Mine energy-saving

Mines are implementing self-funded and Eskom IDM-funded energy-efficiency projects (EEPs) and load-management projects (LMPs). LMPs save costs by making use of Eskom's cheaper time-of-use (TOU) tariffs. These projects do not impact on the total electricity consumption. EEPs aim to reduce the electrical energy consumed without affecting service delivery. These projects reduce the amount of energy wasted to provide said service delivery [32] [33].

Examples of these design-side management (DSM) projects are lighting, motor efficiency, heat pumps, compressed air, clear-water pumping, refrigeration and ventilation projects. Each project is researched and implemented with the results calculated according to measurement and verification (M&V) guidelines.

These projects are implemented ad hoc as funding is available. They reach their targets, but often not their full potential. There is a need to better evaluate projects and structure the implementation of DSM projects to unearth their full potential.

Energy-saving projects can be categorised as leading and lagging control. A leading project looks at system variables in conjunction with a simulation model to stop, start and control equipment predictively. Lagging projects respond to current system variables.

An example of a leading control system is one where the dewatering pumps are used to prepare the dewatering system dams for an evening load shift. An example of a lagging control system is offloading and stopping a compressor when a set point is reached.

1.3.3. Mine compressed air energy-saving

Compressed air on South African mines is another large electricity consumer with a reputation of wastage. This allows significant potential for electrical and financial savings.

A typical mine compressed-air system consists of multiple compressors at various locations, surface connection networks, underground distribution systems, thousands of users and leaks.

Energy-saving strategies, such as compressor control, surface distribution control, underground distribution control, replacing pneumatic applications and fixing air leaks were implemented ad hoc on mines.

Marais [34] designed an implementation procedure to sequence and integrate the above compressed-air energy-saving strategies. The developed sequence is shown in Figure 1-6.

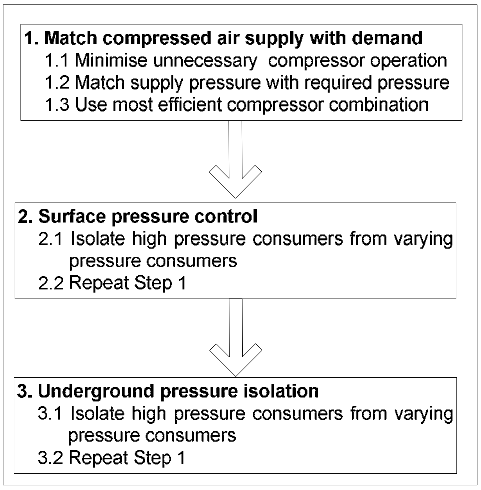


Figure 1-6: Compressed air sequenced implementation procedure [34]

Firstly, the compressor houses were upgraded with programmable logic controllers (PLCs), actuated blow-off valves, guide vain controls, blow-off controls, compressor selections, etc. This allowed the system pressure to be matched with the system pressure required at the given time of use [35].

Secondly, control and monitoring equipment are installed on the surface distribution network. This allows high-pressure and low-pressure sections, such as gold plants, shafts and backfill operations, to be isolated from each other. This changes the compressed air demand and again the compressed generation will need to be optimised to supply the required compressed air.

Thirdly, underground pressure isolation valves are installed to separate high-pressure consumers, such as loading boxes, from low-pressure consumers, such as refuge bays. Again, the generation control will need to be updated to accommodate the changes made to the compressed air system.

Following this procedure realises each strategy's full potential and ensures overall maximum savings. An electrical power saving of 109 MW was achieved through the implementation of the sequenced integrated approach in the compressed air systems of 22 mines [34].

A similar project-sequencing strategy should be followed in mine-cooling and ventilation systems.

1.3.4. Pumping

As stated in section 1.3.1, in 1976, Whillier proposed chilling the water used for dust suppression and drilling. This additional cooling in the work sections must have significantly increased the amount of water used underground. The mine's clear water-pumping system ensures that the used mine's chilled service water and any additional fissure water are pumped to the top of the mine to be re-used.

The efficiency of new and reconditioned pumps is high. The efficiency of a pump deteriorates during use. Inefficient pumps are either replaced or reconditioned. Energy can be saved through the replacement of inefficient pumps, but all the pumps deteriorate and a pumping system has a fairly average efficiency at any given time.

Pumping systems comprise three main components: the dam, pumps and columns. Pumping systems are ideal for load-management projects due to spare pumping, water storage and column capacity. A pumping project entails the automation of pumps and includes, but is not limited to, upgrades in instrumentation, actuated valves and PLCs to monitor the pumps.

Instrumentation upgrades usually include, but are not limited to, bearing temperature probes, vibration sensors, flow switches and pressure sensors. Dam-level sensors and network infrastructure are equally important to monitor and control the system from a central point on the surface.

A real-time energy management system (REMS) for pumping has been proven to be the best system to use with the abovementioned infrastructure and to realise energy cost-saving. This is done by scheduling the pumping at the least expensive time of day.

With the small amount of main components, the above projects are seen as a low-cost, fast and effective option when compared to turbines, three-pipe and ice projects. HVAC International has completed the pumping projects for nearly the entire South African mining industry. The remaining pumping projects were done by Blhum Burton Energy (BBE) or the mines themselves, with the help of system integrators, such as Powertech IST Otokon.

These systems had varying degrees of success. It seems evident that a REMS, added to the supervisory control and data acquisition (SCADA) system, along with proper monitoring and reporting, produces increased and sustainable savings [36].

1.3.5. Refrigeration

As with pumping projects, mine-refrigeration systems are also ideal for implementing load-management projects. Pumping load-management projects are mainly concerned with balancing mass flow of the water entering and leaving the pumping level.

Refrigeration load-shift projects are concerned with balancing the system's thermal energy. This is done by balancing the mass flow, as well as ensuring that the water is sufficiently chilled to deliver the required cooling (service) to the mine production sections. Mine water is chilled outside the Eskom peak period and stored. It is then used later by mine production during the Eskom peak period.

Previous studies conducted by Schutte and Calitz, have found that energy cost-saving potential can be achieved by applying low-cost load-management methods, such as back-passing of cold water and refrigeration machine vane control. Their projects were successfully implemented on surface refrigeration systems with no technical modifications [37] [38].

Van der Bijl developed a method to determine the amount of load-shifting that was possible on mine-surface refrigeration systems [39].

Implementing a load-management project on a mine-refrigeration system upgrades the PLCs, machine instrumentation, such as vibration probes, and field instrumentation, such as dam-level sensors.

The refrigeration machine's vain control is upgraded for better outlet temperature control. Pipework and a back-passing valve system for better inlet temperature control are also installed. The plant is automated with the stopping and starting of evaporator and condenser pumps happening with the refrigeration machines.

The overall plant control is better, allowing for the most efficient machines for the refrigeration system to operate efficiently. Research has been conducted with repeatedly proven results on the efficiency improvement of refrigeration machines through proper maintenance, and cleaning the tubes for better heat exchange.

1.3.6. Ice

Literature on ice used in mining is either about being an alternative to underground refrigeration systems, reducing the amount of water circulated or thermal ice storage. Hard ice or plate ice, and slurry ice are the two options available for mine cooling.

Whichever one is being made, an ice-water mixture is always used. The specific heat (C_p) of ice at 2.04 kJ/kg.K is not an advantage above the specific heat of water at 4.18 kJ/kg.K. Ice below 0 ^{o}C blocks pipes, as it freezes to the inside pipe wall. Thus ice below freezing point is rarely used [40] [41].

The advantage of this ice-water mixture is the latent heat or energy it absorbs to change the water from a solid to a liquid (to melt the ice) at 333.7 kJ/kg.K. In addition, most of the energy used for ice production is used to convert the water from a liquid to a solid state, known as ice [42].

Ice vs. underground refrigeration machines

As a mine deepens, the surface refrigeration systems become inadequate to cool the working levels. The chilled service water from the surface refrigeration plant picks up too much heat on its way to the working sections. The cooling from the chilled surface service water in the working areas becomes inefficient and ineffective.

Similarly, the chilled ventilation air from the surface also becomes inefficient and ineffective. Thus, the scope is to expand the mine-refrigeration capacity. The mine can consider two options at this point. One is to install an underground refrigeration system. The other is to install a surface ice plant as shown in Figure 1-7.

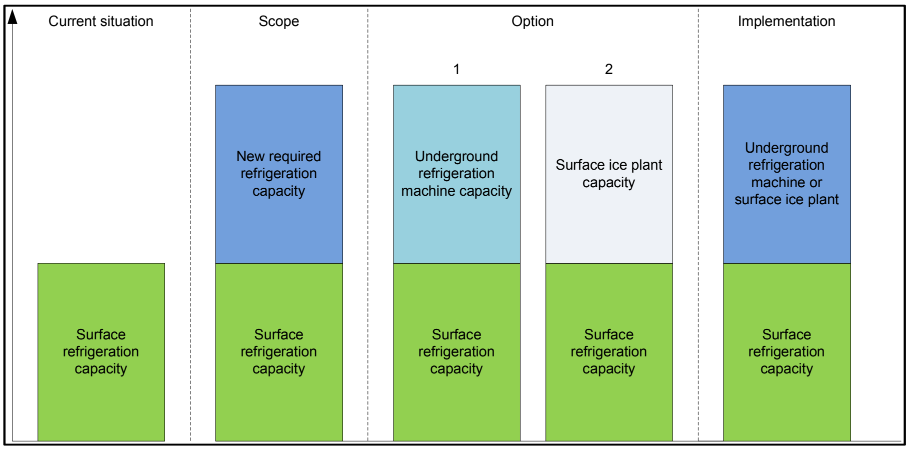


Figure 1-7: Mine expanding and cooling capacity

The coefficient of performance (COP) for an ice-producing machine is around 3, with a more accurate system COP assumption of 1.4. This is if one considers all other electrical energy usage, such as conveyer belts, and other auxiliary equipment, such as pumps, fans and ice scrapers. A refrigeration machine's COP is around 6, with a system COP of 3.5, including the pumps, fans and other auxiliary equipment.

Using ice instead of an underground refrigeration system for cooling deep-level gold mines remains debatable. Both systems have pros and cons, and the mine will need to evaluate which cons they are willing to work with to have the pros.

Most of the current research is being done by ice machine manufactures and installers. There seems to be a rather pro-ice theme in the way the research and tests are being conducted. The main advantage of surface ice plants is that refrigeration machines operating underground require more maintenance due to the harsh environment with the dust, heat and humidity. It is also difficult for major spare parts to reach the underground plants. Thus, surface ice is considered with the added motivation that it reduces the amount of water being pumped.

Ice reducing the amount of pumping

Sending down ice instead of water has also been researched and simulated. The main assumption here is that the amount of cooling is kept the same. This is illustrated in Figure 1-8. Keeping the amount of cooling the same can significantly reduce the amount of water that is circulated, considering that the energy that can be absorbed by ice is 333.7 kJ/kg.K.

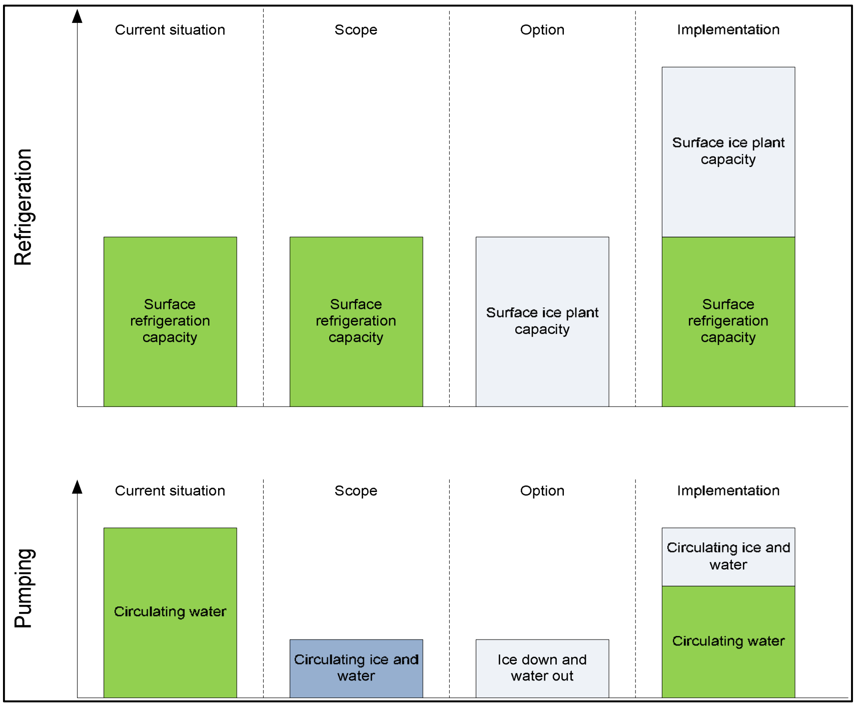


Figure 1-8: Mine reducing water circulation

However, there is no documented case study where the ice installed on a South African mine has reduced the amount of pumping. This is due to Parkinson's Law applied to mine ventilation and cooling. The mine ventilation and cooling requirement will increase or decrease to match the mine's installed ventilation and cooling capacity [43].

This is shown in the implementation of Figure 1-8, where the surface cooling has nearly doubled and the amount of water and ice circulated remains the same. This shows that this option, in its implementation and execution, is exactly the same as implementing ice instead of an underground refrigeration system to expand the mine's cooling capacity.

Thus, the energy-saving from circulating ice is improbable and will only be possible if a mine decommissions its surface refrigeration system and replaces it with an ice system. It should be noted that ice cannot drive a turbine or be used in other energy-recovering equipment, such as three-pipe systems. Again, the results of recent studies seem to reflect a rather pro-ice incentive.

Thermal ice storage

These load-management projects melt ice during the Eskom peak period when the ice and refrigeration machines are switching off. They make ice during Eskom's off-peak period.

Ice machines are installed when there is not enough spare cool capacity at a mine or when enough storage capacity dams have not been built. Storing energy, such as ice, requires a smaller volume compared to water. A new ice-making machine and storage system adds to the maintenance of a mine-refrigeration system.

Adding additional cooling capacity to the refrigeration system and applying Parkinson's Law to mine cooling and ventilation will not realise cost-savings.

Where there is adequate spare cooling and storage capacity, an existing machine will be converted into an ice machine and infrastructure will be added to the existing chill dam. Making ice is less efficient, and converting a plant will mean that the cooling capacity is reduced. The added infrastructure in the chill dam will also reduce the storage capacity. Again, following Parkinson's Law, the mine-cooling demand will be reduced to meet the installed cooling capacity.

These systems require a control system to engage and disengage the load management. These projects only partially upgrade the refrigeration plant's PLCs, back-pass controls, guide-vain controls and other field instrumentation. Most of the project capital is spent on either building or changing the machine and storage dam.

A mine-cooling system encounters a cyclical thermal load. The installed thermal cooling capacity of a refrigeration system is designed to cater for and match the maximum heat load of the system. The maximum heat load is encountered during the hottest and most humid part of the day, with the mine production consuming the maximum water [44].

The installed thermal cooling capacity can be reduced below the maximum required heat load. This is done by using thermal ice storage in conjunction with the cyclical heat load of mine ventilation and cooling systems [45] [46] [47].

1.3.7. Energy-recovery systems

Mining at great depth and using chilled service water have great potential energy that can be recovered. Energy recovery is done through the utilisation of either turbines or three-pipe systems.

Turbines

Turbines recover energy from the water sent down and reduce the amount of electricity needed to pump the water to the surface. A disadvantage is that turbines are not 100% efficient and pumps are still required to pump the deficit water to the surface where it is chilled.

Another disadvantage is that the energy recovered by the turbine cannot be stored, meaning that when no pumping or electricity is required, the turbine will be bypassed. It is not always possible to match the mine water demand with electricity and pumping demand.

The precision engineering required to design, manufacture and assemble or build a turbine is a drawback. This specialist work is not readily available in South Africa and is not cheap when imported. This results in a few new installations and a decline in existing installations. Due to the generation effect of turbines, there is also a concern whether it should be funded by Eskom's IDM programme or through the Independent Power Producer (IPP) programme.

There is a new trend in the mining industry to install a pump that can also function as a reaction turbine. These are less efficient than the traditional Pelton wheel turbines. They are, however, made in a similar manner to the normal or standard mine dewatering pump. The skills required to maintain and refurbish dewatering pumps are still prevalent in South Africa.

Three-pipe systems

Three-pipe systems use the U-tube effect and small pumps to overcome the additional head and friction losses to pump the water to the surface to be chilled.

Warm water mixes with chilled water in the pipe chambers. The systems are calibrated so that chilled water is pumped to the surface, rather than allowing warm water to be recirculated underground. This is at a loss of overall system efficiency as water reaching the surface is cooler than usual. The pre-cooling tower with essentially free cooling sees less of a cooling load, and the refrigeration machines need to process the recirculating water.

The utilisation of a three-pipe system is low. The efficiency is also not 100% and the mine requires pumps to pump the excess water when the three-pipe system is not available.

Building the primary three-pipe system and back-up pumps is a costly capital expenditure. The energy-saving from such a system seems to be worth investing in, especially when the pumping system capital expenditure has already been paid off.

The installation time of these projects is extensive. This increases the installation price and the eventual payback period. In South Africa, BBE, in collaboration with Hydro-power Equipment (HPE) and the mines, is installing three-pipe chambers.

1.3.8. Water system optimisation

Chilled mine service water is used for drilling, cleaning, dust suppression and cooling underground. Mines are focused on production, and the underground working environment is one of the harsher places on earth. This causes significant wear and tear, and damage to water-supply pipes and water-using equipment.

The water usage is a low priority. There is a constant supply of water to the working section, irrespective of the time of day or kind of activity occurring. It may be possible to teach miners to save water and energy, with the resultant cost-savings, in much the same way as Eskom's televised alert systems, but it is difficult to enforce. Creating a nice chilled working environment for oneself outweighs the advantage of cost-saving to the mining company.

Similar to compressed air projects, a simple solution is water system optimisation. This is done by installing pressure and flow control valves to control the water distribution. When there is no mining activity on a level, these valves reduce the pressure.

The water valves are also not closed completely. Closing the valve completely will mean that the pipes will drain out. Opening the valve will then result in severe water hammering. Chilled water cars (CWCs) also prevent the valves from closing.

This water system optimisation monitors mining resources and usage by mine production. An advantage of this monitoring is the detection of leakages, burst pipes and general wastage during production.

1.3.9. Cooling auxiliaries optimisation

Electrical energy-intensive mine-cooling and ventilation systems from the 1980s and 1990s lend themselves to improved energy efficiency because of the cyclical operation of mining and the diurnal changes in surface temperatures.

From section 1.3.5., it is evident that implementing a load-management project on a mine-refrigeration system upgrades and improves the entire system. Recently, there has also been proven research on variable flow control on mine-refrigeration systems, resulting in increased efficiency in the overall system.

The flow is controlled by installing variable speed drives (VSDs) on the evaporator, condenser and transfer pumps. These systems are known as the cooling auxiliaries system.

This control system focuses on controlling the flow with the least amount of back-passing and recirculation of water. The variable flow increases the pre-cooling and condenser cooling tower's COP. The system also increases the overall system's COP.

The system reduces the over-cooling of the BACs on the ventilation air sent underground. The result is an energy-saving project culminating in 1.8 MW on a 10 MW installed system [44]. These projects have been made possible by the control, monitoring and logging of data from load-management projects as described in section 1.3.5.

The FUTUREMINE study for the mines found that a power saving of 12% for a surface refrigeration plant, and a further 18% of underground and 3% of surface refrigeration capacity could be realised. The study concluded that the application of a cyclical operation of air-cooling systems in existing operations would be marginal when the savings are offset against the cost of introducing the equipment and control systems necessary to operate these strategies [31].

Using Eskom's IDM-funding increases the margin between savings and the implementation cost for the mine, making load-management and energy-saving projects possible.

1.3.10. Ventilation fans

Ventilation fans focus on either the booster fans or the main fans. The main fan either improves the control of the system or replaces the steel blades with carbon fibre blades. It is feasible that fitting carbon fibre blades should be combined with improved control, but improved control may not entail the replacement of blades.

Booster fans

Kukard [48] has investigated energy-saving on mine booster fans or auxiliary fans. He investigated more efficient motors and more efficient fans. His findings are that improving both the efficiency of the fan and the motor could lead to a saving of 11 kW on 45 kW fans. That is a saving of 24% [48].

Energy-saving will most likely not occur in centrifugal fans and pump systems, because the performance characteristics of the fan or pump are governed by affinity laws. In those cases, it is critical to optimise the load of the system to gain the benefit of the higher efficiency of energy-efficient motors [49].

From the above, it is clear that more efficient motors and fans result in better service delivery. The better service delivery is also achieved at a higher energy usage and at a higher cost. Substantial savings will be possible if the number of fans can be reduced significantly.

Main fan control

Opportunities exist to reduce the power absorbed by the main fan by reducing fan speed, pre-rotating the inlet air stream or damping the fan outlet. The pre-rotation of inlet air via radial vane controllers has proved to be a most practical and cost-effective option, especially when retrofitting existing main fans [50].

Five main fan stations of a mine are distributed over 20 km and have a baseline capacity of 20 MW. Main fan control was installed by BBE on 13 main fans and a saving of 5 MW was achieved. This translates into a 25% reduction [51].

Kukard [48] investigated the use of VSDs on main fans for control. His findings were that 561 kW and 660 kW could be saved on 2.25 MW and 3.5 MW respectively. That is an average saving of 25% and 19% [48]. The average for both studies is 23.5%.

Main fan carbon blades

Bluhm Burton Engineering and Bluhm Burton Energy [52] have also conducted research on the use of composite materials to construct the fans. Reducing the weight will reduce the inertia of the blade, and less energy will then be required to turn the blades, without affecting the amount of air flowing. 1 MW was saved on an installed and operating capacity of 9.45 MW and renders an 11% saving [52].

These composite blades are, however, not as resilient to being hit by blunt objects as their steel counterparts. More effective main fan savings have been achieved where the mines have switched off one of their three main fans.

Running on two fans still provides the needed ventilation. It seems difficult to simulate and predict what the effects of switching off a main fan will be and the simulated results may not be accurate; therefore, it is physically tested and implemented by the mine itself [a]. Mine ventilation system projects have included stopping the main mine ventilation fans during the Eskom evening peak. Research is also being done on installing VSDs on these fans and cutting back during the Eskom evening peak period.

1.3.11. Closed-loop underground BAC

Booysen et al. [32] have tested the possibility of doing a peak clip on an underground closed-loop bulk air-cooling system. Their research showed a 3 MW peak clip saving on an installed refrigeration capacity of 3 MW [32].

They do not appear to have done a simulation of what the effect will be on the system. Again, the simulation may not be feasible for determining energy-saving and the simulation may not be accurate. Therefore, it is physically tested with the help of the mine services and ventilation department.

The findings were that the reliability of the closed-loop refrigeration and bulk air-cooling system had a bigger effect on the underground working conditions than switching off for the Eskom evening peak.

[a] Riaan Meyer, Engineering Manager, Kopanang Gold Mine, AngloGold Ashanti, rimeyer@anglogoldashanti.com, 018 478 9994, February 2013.

Implementing a DSM project increases the monitoring and reporting on the system's performance and assists with fault finding. This improves the system reliability and results in a better underground working environment.

1.3.12. Interaction of systems

Vosloo [53] has investigated the interaction of systems. He investigated the effect of reducing the use of service water underground on mine-pumping and refrigeration systems. The amount of water used, pumped and chilled is the same. He also determined that the total amount of water in a mine needs to be monitored [53].

If there is too much water being circulated, pumping becomes a problem. Supplying chilled water becomes a problem if there is too little water in circulation. As a result, fissure water is wasted and expensive potable water is added to the system. This research showed that a cost-saving of 2c/kWh could be achieved on the 14c/kWh the mines were paying; that is a saving of 14% [53].

1.3.13. Other research efforts

Other refrigeration research efforts investigated the potential combination of solar energy and refrigeration, the comparison between hard ice and vacuum ice, and the status of water vapour refrigeration technology and equipment. In addition, recent work has again examined the effect of wet-bulb (WB) temperature on accidents and productivity in platinum mines [19] [54].

1.3.14. Other sectors' ventilation and cooling energy efficiency

Industrial and commercial ventilation and cooling systems focus on office blocks, shopping centres and cold storage warehouses. The ventilation and cooling energy strategies for these large buildings are focused on matching supply and demand.

Areas are only ventilated and cooled when there are people present, or as needed. The server rooms are continually cooled, while working areas are only cooled during work hours. Architectural design allows for systems that open windows at the top and bottom of buildings during the evening to ensure natural ventilation and cooling through the night.

Most industrial ventilation and cooling systems have a recycle rate. Only a percentage of fresh air is added to the ventilation system. Bluhm et al. are researching this practice for mining and underground ventilation [19].

Home ventilation and cooling systems focus on system efficiency, design efficiency and using heat-recovery systems. These installations are small and the control volume is preferably well insulated. There is also a focus on cooling and ventilation on demand. Combining systems with motion detectors reduces wastage.

1.3.15. In summary

The sections above covered research on mine energy-saving and the sequencing of compressed air projects, and showed what is currently being done on the following mine systems:

- Pumping
- Refrigeration
- Ice
- Energy recovery
- Water system optimisation
- Cooling auxiliaries optimisation
- Ventilation fans
- Underground closed-loop BACs

Research done on the interaction of these systems was also discussed, along with other research and what is currently being done in other sectors.

Master's dissertations and PhD theses relating to this thesis' focus area are listed in Table 1-2. The table indicates where the research has focused and the research is classified according to investigation, simulation, implementation or new hardware design.

The table then indicates how the thesis relates to either cooling or ventilation and its given subsection. It is then indicated whether the research was a specific DSM project or if it was aimed at improving process efficiency.

Articles and other research relating to this thesis' focus area are listed in Table 1-3. The table indicates what the focus of the research has been. Again the articles are classified according to investigation, simulation, implementation or new hardware design.

The table indicates whether the articles relate to cooling or ventilation and their given subsections. It is then indicated whether the research was aimed at improving process efficiency or if it was focused on a specific DSM project. It should be noted that all the anonymous authors are grouped under Anon.

Table 1-2: A summary of relevant dissertations and theses

Master's and PhD studies																						
							Cooling							Ventilation				DSM				
									Refrigeration					Bulk air cooling		Fans						
No.	Author	Citations	Investigation	Simulation	Implementation	New hardware	Pumping and water distribution	Energy recovery	Surface	Under-ground	Thermal ice storage	Ice	Mobile cooling unit	Surface	Under-ground	Under-ground booster	Main	Load management	Peak clipping	Energy efficiency	Process efficiency	Risk and appeal
1	Arndt, D	[55]		X					X												X	
2	Botha, A	[56]			X		X													X	X	
3	Bouwer, W	[57]		X																	X	
4	Bluhm, SJ	[25]	X			X								X							X	
5	Calitz, J	[37]	X		X				X									X				
6	Den Boef, M	[58][59]	X	X						X			X					X				
7	Els, R	[60][61]	X	X					X	X							X	X				
8	Fourie, A	[62]			X		X		X									X				
9	Greyling, J	[24]		X		X							X								X	
10	Janse van Vuuren, A	[63]			X		X	X													X	
11	Jonker, AS	[64]	X			X						X									X	
12	Kukard, WC	[48]	X													X	X			X		
13	Schutte, AJ	[38]		X	X				X									X				
14	Stanton, DJ	[65]	X			X				X			X								X	
15	Strydom-Bouwer, EL	[66]		X	X					X								X				
16	Swart, C	[67]	X	X						X							X				X	
17	Van Antwerpen, HJ	[68]	X					X														
18	Van der Bijl, J	[39]		X	X				X	X								X				
19	Van Eldik, M	[69]	X			X							X							X	X	
20	Vosloo, J	[53]	X	X			X		X									X		X	X	
21	Webber-Youngman, RCW	[70]	X				X		X								X					

Table 1-3: A summary of relevant articles

Mine ventilation and cooling articles (top 23 authors)																						
No.	Author	Citations	Investigation	Simulation	Implementation	New hardware	Cooling							Ventilation				DSM			Process efficiency	Risk and appeal
							Pumping and water distribution	Energy recovery	Refrigeration		Thermal ice storage	Ice	Mobile cooling unit	Bulk air cooling		Fans		Load management	Peak clipping	Energy efficiency		
									Surface	Underground				Surface	Underground	Underground booster	Main and recirculation					
1	Anon	[71][72][73] [74][75][76]				X			X	X				X							X	
2	Bluhm, SJ*	[19][28][77] [78][79][80]		X		X		X	X	X	X	X	X	X	X	X	X	X		X	X	
3	Ramsden, R	[81][82][83] [84][85]	X	X		X			X	X		X		X	X	X	X			X	X	
4	Hemp, R	[86][87][88]	X		X	X						X				X					X	
5	Barenburg, AWT	[21][89][90]	X	X					X					X			X				X	
6	Du Plessis, GE	[91][92][93]	X	X	X				X											X	X	
7	Marx, WM	[94][45]	X	X	X	X	X		X		X			X		X	X			X	X	
8	Sheer, TJ	[95][96]	X		X							X									X	
9	Burton, RC	[97][98]	X													X	X				X	
10	Chadwick, JR	[99][100]				X						X				X	X				X	
11	Eschenburg, HMW	[101][102]			X							X									X	
12	Funnell, RC	[29][30]	X				X						X								X	
13	Lambrechts, J de V	[103][104]	X		X				X						X		X				X	
14	Rawlins CA	[105][106]	X				X														X	
15	Smith, O	[107][108]	X		X		X		X					X	X		X				X	

No.	Author	Citations	Investigation	Simulation	Implementation	New hardware	Cooling						Ventilation					DSM			Process efficiency	Risk and appeal
							Pumping and water distribution	Energy recovery	Refrigeration		Thermal ice storage	Ice	Mobile cooling unit	Bulk air cooling		Fans		Load management	Peak clipping	Energy efficiency		
									Surface	Underground				Surface	Underground	Underground booster	Main and recirculation					
16	Starfield, AM	[109][110]	X										X								X	
17	van Antwerpen, HJ	[111][112]	X	X		X	X	X					X								X	
18	van der Walt, J	[26] [113]				X	X		X												X	
19	Von Glehn, FH	[114][115]		X	X								X			X					X	
20	Webber-Youngman, RCW	[116][117]	X	X	X		X		X					X			X				X	
21	Whillier, A	[23] [118]	X		X		X		X				X	X			X				X	
22	Wilson, RW	[46] [47]	X			X			X		X			X						X	X	
23	Booysen, W	[32]			X					X					X				X			

1.3.16. Conclusion

Most of the research carried out in mine refrigeration, cooling and ventilation over the past 100 years is applied in practice today. Mining in South Africa is taking place at VRTs of up to 70 °C. Simulation software and equipment, methods and systems borne out of research (especially DEEPMINE) are used and implemented daily.

One of the deep gold mines has 120 MW of refrigeration installed, including 100 kg/s of ice being sent down the mine and about 1 300 ℓ/s of chilled water circulated through the mining sections. An additional challenge is the shortage of electricity, forcing designs to be optimal from an energy-efficiency point of view [19].

It is also evident that research is spreading to other parts of the world as refrigeration is becoming necessary in mines in Central and North Africa, North and South America, Australasia and The East. Research in mine cooling and ventilation is not being carried out with the same intensity as in the past [19].

It is evident that each project is considered on its own and the merit for such a project consideration is primarily the cost-savings and payback. It is evident in, for example the ice projects, that the supplier uses IDM-funding to implement a new technology and get a foothold. After implementation it becomes evident that they are the only people capable of maintaining the system and the mine or customers become dependent on their service at any cost to keep the new equipment operational.

There is a need to evaluate projects according to risk. There is also a need to evaluate projects in terms of their “appeal” and collaboration with other projects. There is a need to structure, sequence and combine projects to achieve the best overall result for a mine. Lastly, there is a gap in the research on load management and peak clipping on surface BACs.

1.4. Research objectives

The main objectives of this research can be summarised as follows:

- Investigate the electricity usage of mine-cooling and ventilation systems.
- Investigate the effect of load-management and energy-saving projects.
- Investigate and assess in detail the interaction and collaboration between load-management and energy-saving projects.
- Investigate the interaction, collaboration and appeal of load-management and energy-saving projects.
- Develop a method to analyse the risk of each project.
- Develop a method to analyse the appeal of a project.
- State the optimal sequenced combination of strategies to implement load-management and energy-saving projects.
- Investigate the possibility of stopping surface BACs and refrigeration systems for the Eskom evening peak.

<u>Chapter 1 – Introduction</u>

This dissertation commences with familiarising the reader with the existing electricity situation in South Africa and provides an overview of the prevailing electricity restrictions in South African mining.

This section gives an introduction to mine energy usage and mine-cooling and ventilation systems. It covers previous research on the subject and states the research objectives and contributions of this study. It concludes with an outline of the thesis.

<u>Chapter 2 – Mine ventilation and refrigeration overview</u>

This chapter contains an in-depth look at the mine-cooling and ventilation system. It covers the ventilation and cooling process and goes into more detail on individual systems.

Chapter 3 – Mine cooling and refrigeration projects

This chapter covers the cost-saving, risk and appeal of a project. Cost-saving is calculated using Eskom's TOU pricing and each project's power profile. A risk evaluation matrix is developed and used to analyse the risk relating to projects. Another matrix is also developed and used to attain the project's project appeal indication (PAI).

The projects are combined by their interaction and possible interference and obstructions with one another. The final combination is then sequenced using the risk, PAI and cost-saving, as well as project implementation requirements.

Chapter 4 – Surface bulk air cooling and refrigeration

As stated in the previous section of this thesis, surface BACs have not been investigated for DSM projects. In this chapter, the surface BACs are investigated for a possible peak clip energy-saving project.

There is not sufficient theory to calculate the effect of stopping the BAC for two hours. The current theories do not include the capacitive effect of shaft infrastructure cooling ventilation air. A mine ventilation system was measured and empirical equations were derived.

These equations were used to determine the relation between stopping and starting the BAC and the temperature and relative humidity (RH) on underground levels for hour intervals. The equations are verified to be within 10% accuracy and deemed accurate enough to be used to determine the possibility of a peak clipping project.

The equations are used to model the effect on temperature and humidity relating to mining levels and the stopping and starting of the BAC. The proposed project is then implemented. In conclusion, it is stated what the effect of these projects would be for the entire mining community and South Africa.

Chapter 5 – Optimised implementation of mine-cooling and refrigeration energy-saving strategies

The surface BAC project is also analysed according to risk, PAI and cost-savings. It is added to the winning combination and sequenced correctly for a total integrated energy-efficiency strategy for mine ventilation and refrigeration systems.

Chapter 6 - Conclusion

In the conclusion, the results and outcome of this study are discussed. The aim of this study is achieved and the contribution stated. Further research is also recommended.

1.5. Contributions of this study

The contributions of this study are summarised as follows:

i. **Developing and practically illustrating, in a number of mine-cooling instances, a risk evaluation matrix for ventilation and cooling load management, as well as energy-saving strategies**
   - Previous research only focused on the cost-saving to justify a project.
   - Projects do not live up to their cost-saving promise and do not realise their full potential.
   - Other factors, such as risk, should also be considered for a more realistic evaluation of the total effect of a project.
   - A new risk matrix for energy-saving projects on mine refrigeration and ventilation was developed and practically illustrated in a number of mine-cooling instances.
   - Focus areas are service delivery, production, environmental health and safety (EHS) and overhead costs.

ii. **Developing a project "appeal indicator" to evaluate projects**
   - A project can now be evaluated considering risk together with cost-saving (see contribution i.).

- This is, however, still not enough, as there are additional appealing and less appealing effects resulting from doing an installation. New equipment or a new process is appealing, but the long implementation time, additional maintenance problems and initially hidden overhead costs are not appealing.
- For this reason, the projects are evaluated according to the amount of new equipment that forms part of the project, upgrading existing equipment or processes, the expansion of the mine information network, the ability for the project to log and display crucial mining system parameters, a short project implementation time, little downtime required for implementation and the interaction of such a project on other systems.

iii. Illustrating very effectively the effect of interaction between mine-cooling and ventilation energy-saving and load-management projects

- Most studies focus on single types of savings projects.
- The possible interaction between projects or systems is seldom considered.
- There is a need for an effective overview of the effects of available savings projects and their interaction.
- This thesis objectively and effectively evaluates and compares different projects with regard to cost-savings, risk and appeal, as well as the influence on other projects and systems.

iv. Showing different approaches to sequence these projects by using annual savings, risk or project appeal indicators

- As stated above, most studies focus on single types of savings projects.
- A problem arises when all the types of savings projects are considered.
- It was found that the main approaches to sequencing these projects are annual saving, risk or project appeal indicators.
- This thesis shows each approach and the resultant sequence.
- The differences in the above sequences show a need to consider all these approaches to determine an optimal sequence.

v. Establishing the best combination and sequence for implementing mine-cooling and ventilation energy-saving and load-management projects

- Various load-management and energy-saving projects for mine-cooling and ventilation systems have been implemented.
- The necessity of an integrated approach has been discussed. Three approaches to sequence these projects are shown.
- The problem is that energy strategies interact with and influence each other and build on shared infrastructure. The advantages of infrastructure upgrades are not optimised without considering both the interaction and sequential implementation of projects.
- This study will take into account the interaction between projects. Energy-efficiency projects are aided by load-management infrastructure. The savings from load-management projects also help to fund energy-efficiency projects.

vi. Proving that surface bulk air coolers can be stopped during the Eskom evening peak without adversely affecting underground conditions

- Surface BACs are one of the first cooling and ventilation systems to be installed to dehumidify and cool ventilation air as a mine activity goes deeper and ambient air is no longer sufficiently dry and cool for cooling and ventilation.
- The problem is that mines with one or more subshafts operate at a depth where underground BACs are required and the effect of the surface BAC on temperature and humidity is negligible.
- Peak clipping energy and energy cost-saving projects on surface BACs and refrigeration machines were established and proven to be viable.
- South Africa’s deep-level mines will benefit from the energy and energy cost-saving of implementing surface BAC peak clipping projects.

vii. Establishing that energy management systems should be part of all load-management and energy-saving projects

- Implemented projects are either hardware or energy management systems (EMSs), focusing on a specific application.
- A problem arises when overall management is required and these independent hardware and EMSs need to be integrated.
- It was found that EMSs could easily fit into an overall management system, while additional funding is needed to integrate standalone hardware.
- Each subsection should be individually controlled and managed. Overall system-integrating efforts will illuminate interactions, for example, reducing the ventilation and causing an increase in chilled water consumption in the working areas.
- An overall management system will be able to find the breakeven point between reducing ventilation and reducing mines' chilled water consumption. The optimal solution can then be implemented on the individual systems.

Table 1-4 summarises this study's contributions and focus area. It proposes that the sequence of implementing projects be from A1 to D2. It looks at the peak clip of surface BACs and refrigeration machines. All of this adds to the engineering field of energy-saving on mine ventilation cooling systems.

Table 1-4: Summary of this study's contributions

This study																				
					Cooling							Ventilation				DSM				
							Refrigeration					Bulk air cooling		Fans						
Contribution	Investigation	Simulation	Implementation	Integration	Pumping and water distribution	Energy recovery	Surface	Under-ground	Thermal ice storage	Ice	Mobile cooling unit	Surface	Under-ground	Under-ground booster	Main	Load management	Peak clipping	Energy efficiency	Process efficiency	Risk and appeal
i, ii	X				1,3	5	2,4	6	-	-	-	6	7	8	9,10	A	C	B	D	X
iii,iv,vi				X	X	X	X	X	-	-	X	X	X	X	X				X	
v	X	X	X				X					X					X			
Summary	X	X	X	X	X	X	X	X	O	O	X	X	X	O	X		X	X	X	X

1.6. References

[1] Electricity Consumers Resource Council (ELCON). *The economic impacts of the August 2003 blackout.* Washington, D.C., February 2004.

[2] United States Energy Information Administration. *International energy outlook.* Washington D.C., May 2007. [Online]. Available at: <http://www.eia.doe.gov/oiaf/ieo/index.html.> [Accessed on 3 August 2007].

[3] Weizmann Science Canada. Weizmann News. *Initiative for research in sustainable and alternative energy* 12:2. Toronto, Canada, 2006.

[4] Ashok, S., Banerjee, R. Load management applications for the industrial sector. *Applied Energy* 66:105-111. Elsevier, June 2000.

[5] Aumela, P. *Economic and financial data for South Africa*. South African Reserve Bank, Johannesburg, South Africa, October 2008.

[6] Surtees, R.M. *Electricity demand growth in South Africa and the role of demand side management*. Eskom, Johannesburg, South Africa. [Online]. Available at: <http://www.cput.ac.za/due07SOURCEWeb/SurteesSurtees.html> [Accessed on 10 August 2008].

[7] Eskom. *2013 annual report.* Eskom, Johannesburg, South Africa. [Online]. Available at: <http://www.eskom.co.za/live/index.php> [Accessed on 20 August 2013].

[8] Eskom. *2011 annual report*. Eskom, Johannesburg, South Africa. [Online]. Available at: <http://www.eskom.co.za/live/index.php> [Accessed on 23 June 2012].

[9] Republic of South Africa. *National response to South Africa's electricity shortage*. South African Government, Johannesburg, South Africa, January 2008.

[10] Vosloo, J.C. "Control of an underground rock winder system to reduce electricity cost on RSA gold mines", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[11] Swanepoel, J.A. Modelling for integrated energy optimisation in cement production. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. August 2013.

[12] Eskom, 2012. *Tariffs and charges*. Eskom, Johannesburg, South Africa. [Online]. Available at: <http://www.eskom.co.za/c/article/145/tariffs/> [Accessed on 23 June 2012].

[13] Statistics South Africa. *Consumer Price Index (CPI)*. Statistics South Africa, Johannesburg, South Africa, 2005.

[14] Sibanye Gold. *Operational history*. Sibanye Gold, Johannesburg, South Africa, June 2013.

[15] Turner, P. "The negative impact of Eskom's MYPD3 proposal". Nersa Gauteng public hearings. Sibanye Gold, Johannesburg, South Africa, 31 January 2013.

[16] Energy Research Institute. *Preliminary energy outlook for South Africa*. Johannesburg, South Africa, November 2004.

[17] Neser, H. "Energy savings through the automatic control of underground compressed air demand", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2008.

[18] Le Roux, H. Energy consumption reduction challenge. *Mining Weekly* 11(43):30, November 2005.

[19] Bluhm, S.J., Marx, W.M., Ramsden, R., Von Glehn, F.H. History of research in mine refrigeration, cooling and ventilation in South Africa. *Extracting the science: A century of mining research*. J Brune (Ed.). Society for Mining, Metallurgy, and Exploration, Inc. (SME), 2010.

[20] McPherson, M.J. *Refrigeration plant and mine air conditioning, subsurface ventilation and environmental engineering*:651-738. Springer Netherlands London: Chapman and Hall, 1993.

[21] Barenbrug, A.W.T. Economy in mine ventilation. *Bulletin of the Mine Ventilation Society of South Africa* 1, March 1948.

[22] Rabson, S.R. Investigation into the elimination of nitrous fumes. *Journal of the Mine Ventilation Society of South Africa* 50, 1955.

[23] Whillier, A. Machine water, the forgotten factor in mine cooling. *Journal of the Mine Ventilation Society of South Africa* 29, June 1976.

[24] Greyling, J. "Techno-economic application of modular air cooling units for deep level mining at Mponeng", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2008.

[25] Bluhm, S.J. "Thermal performance of direct-contact water air heat exchangers", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, University of the Witwatersrand, November 1990.

[26] Van der Walt, J., Whillier, A. Considerations in the design of integrated systems for distribution refrigeration in deep mines. *Journal of the South African Institute of Mining and Metallurgy* 79, December 1978.

[27] Sheer, T.J., Del Castillo, D., Csatary, C.J.L. Unconventional systems for removing heat from mines. *Proceedings of the Frigair '86 Conference.* ASHRAE SAIRAC, Pretoria, 1986.

[28] Bluhm, S.J., et al. Generation and distribution of refrigeration for ultra-deep mining: New challenges and insights. *Proceedings of the Frigair 2000, Gallagher Estate*. South African Institute of Refrigeration and Air-conditioning (SAIRAC), Johannesburg, 2000.

[29] Funnel, R.C., Bluhm S.J., Kempson, W.J., Sheer, T.J., Joughin, N.C. Examination of cooling effects in stopes using cold hydropower water. *Proceedings of the Frigair 2000*. South African Institute of Refrigeration and Air-conditioning (SAIRAC), Johannesburg, 2000.

[30] Funnel, R.C., Bluhm S.J., Sheer, T.J. Optimisation of cooling resources in deep stopes. *Proceedings of the 7th International Mine Ventilation Congres.,* EMAG. Krakow, 2001.

[31] Biffi, M., Du Plessis, J., Marx, W.M. The FutureMine Collaborative Research Initiative: Making Research Work. *Proceedings of the 8th International Mine Ventilation Congress.* ADS Gillies (Ed.). Brisbane QLD, The Australasian Institute of Mining and Metallurgy, Carlton, 2005. Reprinted and also available in the *Journal of the Mine Ventilation Society of South Africa* 59(4), 2006.

[32] Booysen, W., Van Rensburg, J.F. Load management on closed loop underground fridge plants and the effects on working conditions. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. CPUT, South Africa, August 2013.

[33] Pelzer, R., Mathews, E.H., Schutte, A.J. Energy efficiency by new control and optimisation of fridge plant systems. *Proceedings of the 7th International Conference on the Industrial and Commercial Use of Energy.* CPUT, South Africa, August 2010.

[34] Marais, J.H. "An integrated approach to optimise energy consumption of mine compressed air systems", thesis submitted in partial fulfilment of the requirements for the degree PhD in Mechanical Engineering, North-West University, November 2012.

[35] Booysen, W., Du Plessis, J.N., Van Rensburg, J.F. Development of an energy management solution for mine compressor systems. *Proceedings of the 7th International Conference on the Industrial and Commercial Use of Energy*. CPUT, South Africa, August 2010.

[36] Vosloo, J., Liebenberg, L., Velleman, D. Case study: Energy savings for a deep-mine water reticulation system. *Applied Energy* 92:328-335, 2012.

[37] Calitz, J. "Research and implementation of a load reduction system for a mine refrigeration system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[38] Schutte, A.J. "Demand-side energy management of a cascade mine surface refrigeration system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2007.

[39] Van der Bijl, J. "Sustainable DSM on deep mine refrigeration systems – a novel approach", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2007.

[40] Holman, J.P. *Heat transfer*, 9th edition. McGraw-Hill, 2002.

[41] Sonntag, R.E., Borgnakke, C., Van Wylen, G.J. *Fundamentals of thermodynamics*, 6th edition. John Wiley and Sons, 2003.

[42] Weast, R.C., Astle, M.J. *CRC Handbook of Chemistry and Physics*, 62nd edition. CRC Press Inc., 1981.

[43] Parkinson, C.N. *Parkinson's Law and other studies in administration* 24. Boston, Houghton Mifflin, 1957.

[44] Schutte, A.J., Maré, P., Kleingeld, M. Improved utilisation and energy performance of a mine cooling system through control of auxiliary systems. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. CPUT, South Africa, August 2013.

[45] Marx, W.M., Von Glehn, F.H., Wilson, R.W. Design of energy efficient mine ventilation and cooling systems. *Proceedings of the 11th U.S./North American Mine Ventilation Symposium, 5-7 June 2006*. Pennsylvania, USA, Taylor and Francis, 2006.

[46] Wilson, R.W., Bluhm, S.J., Funnel, R.C., Smith, H. Surface bulk air cooler concepts producing ultra-cold air and utilising thermal storage. *Proceedings of Managing the Basics*. The Mine Ventilation Society of South Africa, Pretoria, 2003.

[47] Wilson, R.W., Bluhm, S.J., Von Glehn, F.H. Thermal storage and cyclical control of mine cooling systems. *Journal of the Mine Ventilation Society of South Africa* 58(4), October/December 2005.

[48] Kukard, W.C. "Research on reducing cost of underground ventilation networks in South African mines", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[49] Dalgleish, A.Z., Grobler, L.J. Performance assessment of the national energy efficiency motor retrofit programme. *Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy*: 159-167. Cape Town, 16-17 August 2011.

[50] Pooe, T., Marx. W.M., Du Plessis, J., Janse van Rensburg, J., Van den Berg, L. Main fan energy management – actual savings achieved. *Proceedings of the 9th International Mine Ventilation Congress*. New Delhi, 2009.

[51] Gold Fields. *Golden age: News and views for the Gold Fields Global Community*:11. Johannesburg, February 2011.

[52] Fourie, J.W. Power savings by impeller replacements for main fan stations in the South African gold mining industry. *Proceedings of the 9th Conference on the Industrial and Commercial Use of Energy*: 1-6. Stellenbosch, 15-16 August 2012.

[53] Vosloo, J. "A new minimum cost model for water reticulation systems on deep mines", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2008.

[54] Marx, W.M. *Identification of optimum underground working temperatures*. Anglo Platinum, 2009.

[55] Arndt, D. "Further extension verification and application of integrated building HVAC systems and control simulation", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, University of Pretoria, November 2000.

[56] Botha, A. "Optimising the demand of a mine water reticulation system to reduce electricity consumption", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2010.

[57] Bouwer, W. "Designing a dynamic thermal and energy system simulation scheme for cross industry applications," thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2004.

[58] Den Boef, M. "Integrated thermal simulation of underground mobile cooling systems", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2001.

[59] Den Boef, M. "Assessment of the national DSM potential in mine underground services", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2003.

[60] Els, R. "Potential for load shifting in ventilation and cooling systems", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, University of Pretoria, November 2000.

[61] Els, R. "Energy evaluation and load shifting feasibility in South African mines", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2002.

[62] Fourie, A. "Optimising control of a combined mine pumping and refrigeration system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2008.

[63] Janse van Vuuren, A. "Optimising the savings potential of a new three-pipe system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2009.

[64] Jonker, A.S. "An investigation into the life-cycle cost of a vacuum-ice cooling system for deep mines", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, University of Pretoria, November 1997.

[65] Stanton, D.J. "Development and testing of an underground remote refrigeration plant", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2003.

[66] Strydom-Bouwer, E.L. "DSM opportunities in underground refrigeration systems", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2008.

[67] Swart, C. "Optimising the operation of underground mine refrigeration plants and ventilation fans for minimum electricity cost", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2003.

[68] Van Antwerpen, H.J, "An investigation into the viability of using turbines for simultaneous secondary pressure regulation and energy recovery in mine cooling water systems," dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2002.

[69] Van Eldik, M. "An investigation into the DSM and energy efficiency potential of a modular underground air cooling unit applied in the South African mining industry", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2006.

[70] Webber-Youngman, R.C.W. "An integrated approach towards the optimisation of ventilation, air cooling and pumping requirements for hot mines," thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2005.

[71] Anon. The refrigeration systems on Western Deep Levels Ltd. *Journal of the Mine Ventilation Society of South Africa:*7-18. MINTECH, January 1974.

[72] Anon. How to cool deep mines and save 28.5 million dollars a year. *Mining Equipment International* 2(4):22. New York, GeoArchive, 1978.

[73] Anon. New water spray cooler. *United States Bureau of Mines Technical Note*:1. Washington D.C., NTIS, February 1982.

[74] Anon. Multistage water spray coolers. *United States Bureau of Mines Technical Note*:1. Washington D.C., NTIS, February 1985.

[75] Anon. Thermal energy recovery system for deep mines. *United States Bureau of Mines Technical Note*:1. Washington D.C., NTIS, February 1986.

[76] Anon. Air-conditioning in the world's deepest coal mine – Germany. *Coal and Safety (Japan)* 4: 40-42. Energy SciTec, March 1994.

[77] Bluhm, S.J., Whillier, A. Design of spray chambers for bulk cooling of the air in mines. *Journal of the South African Institute of Mining and Metallurgy* 79(1):1-9, 1987.

[78] Bluhm, S.J., Wilson, R.B. *Heat loads and optimized cooling requirements for mining at extreme depths on the Witwatersrand*. Frigair '96, Johannesburg, March 1996.

[79] Bluhm, S.J., Biffi, M., Wilson, R.B. Optimized cooling system for mining at extreme depths. *CIM Bulletin* 93(10036):146-150, 2000.

[80] Bluhm, S.J., Marx, W.M., Von Glehn, F.H., Biffi, M. Vuma mine ventilation software. *Journal of the Mine Ventilation Society of South Africa* 54(3):65-72, 2001.

[81] Ramsdem, R., Bluhm, S.J., Sheer, T.J., Burton, R.C. Research into the control of the underground thermal environment in South African gold mines. *Proceedings of the Mine Safety and Health Congress*. Chamber of Mines of South Africa, Johannesburg, 1987.

[82] Ramsdem, R., De Carvalho, J. Water system for distributing cooling in deep South African gold mines. *4th International Mine Ventilation Congress*. Brisbane, Australia, July, 1988.

[83] Ramsdem, R. Mine cooling towards the 21st century. *Journal of the Mine Ventilation Society of South Africa* 43(9):162-168, September, 1990.

[84] Ramsdem, R., Lloyd, F. Investigation into the use of slurry ice at Western Deep Levels. *5th International Mine Ventilation Congress*. Johannesburg, October, 1992.

[85] Ramsdem, R., Finlayson, R.M., Butterworth, M.D. "Practical experience with the pneumatic conveying of slurry ice at Western Deep Levels", paper presented at the Mmemech 94 Conference, Johannesburg, September 1994.

[86] Hemp, R. Sources of heat in mines. In: *Environmental Engineering in South African Mines*, J. Burrows, (Eds.). The Mine Ventilation Society of South Africa, 1982.

[87] Hemp, R. Air temperature increases in airways. *Journal of the Mine Ventilation Society of South Africa* 38(1-2), 1985.

[88] Hemp, R. Air temperature increases in airways – further work. *Journal of the Mine Ventilation Society of South Africa* 40(1):1-11, 1987.

[89] Barenburg, A.W.T. Notes on the "effective temperature" scale. *Papers and discussions, 1942-1945*: 603 et seq. Association of Mine Managers of South Africa, The Chamber of Mines of South Africa.

[90] Barenburg, A.W.T. The battle of the BTUs. *Journal of the Mine Ventilation Society of South Africa* 20, 1967.

[91] Du Plessis, G.E., Liebenberg, L., Mathews, E.H. Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system. *Applied Energy*, 2012.

[92] Du Plessis, G.E., Liebenberg, L., Mathews, E.H., Du Plessis, J. N. A versatile energy management system for large integrated cooling systems. *Energy Conversion and Management* 66:312-325, 2013.

[93] Du Plessis, G.E., Liebenberg, L., Mathews, E.H. The use of variable speed drives for cost-effective energy savings in South African mine cooling systems. *Applied Energy* 111: 16-27, 2013.

[94] Marx, W.M. Providing an acceptable working environment in ultra-deep mines. *Journal of the Mine Ventilation Society of South Africa* 51(2):57-60, 1998.

[95] Sheer, T.J. Investigation into the use of ice for cooling mines. *Proceedings of the Frigair '83 Conference*. ASHRE SAIRAC, Pretoria, 1983.

[96] Sheer, T.J., Ramsden, R., Butterworth, M.D. Ice as coolant for deep mines. *Proceedings of the 7th International Mine Ventilation Congress:* 354-361. Krakow, June, Poland, EMAG, 2001.

[97] Burton, R.C., Plenderleith, W., Steward, J.M., Pretorius, B., Holdings, W. Recirculation of ventilation and cooling of deep gold mines. *Proceedings of the 3rd International Mine Ventilation Congress*. Herrogate, England, The Institution of Mining Engineers, 1984.

[98] Burton, R.C., Kielblock, A.J., Sheer, T.J., Bluhm, S.J. *Future implication of controlling the thermal environment in deep gold mines* 1:163-178. Chamber of Mines Research Organization (COMRO), 1986.

[99] Chadwick, J.R. Ice cooling for deep mines. *World Mining* 36(2):38-39. Ei Compendex, February 1983.

[100] Chadwick, J.R. Ice cooling and recirculation. *International Mining* 2(6):27-29. MINTECH, June 1986.

[101] Eschenburg, H.M.W., Hemp, R., Roux, E.L.K. "The use of ice for underground cooling at Harmony Gold Mine", paper presented at the Gold 100 Conference, Johannesburg, September 1986.

[102] Eschenburg, H.M.W., Middleton, J.V.G., Hemp, R. 1000 ton per day ice plant for underground cooling at Harmony Gold Mine. *International Journal of Refrigeration* 9(6):357-361, November 1986.

[103] Lambrecht, J. de V. The estimation of ventilation air temperatures in deep mines. *Journal of the Chemical and Metallurgical Society of South Africa* 50, 1950.

[104] Lambrecht, J. de V. Optimization of ventilation and refrigeration in deep mines. *Proceedings of the 8th Commonwealth Mining and Metallurgical Congress*, *Australia and New Zeeland.* Australasian Institute of Mining and Metallurgy (AESIS), (6):1525-1533, 1967.

[105] Rawlins, C.A., Phillips, H.R. Mine cooling strategies and insulation of chilled water pipes. *Proceedings of the 7th International Mine Ventilation Congress:*371-379. Krakow, June, Poland, EMAG, 2001.

[106] Rawlins, C.A., Phillips, H.R. Reduction of mine heat loads. *Proceedings of the 7th International Mine Ventilation Congress:* 380-389. Krakow, June, Poland, EMAG, 2001.

[107] Smith, O. Effects of a cooler underground environment on safety labour and labour productivity. *Proceedings of the 3rd International Mine Ventilation Congress*. Herrogate, England, The Institution of Mining Engineers, 1984.

[108] Smith, O., Bluhm. S.J. "Load audits and simulation to develop DSM potential in the mining sector", Report for the Department of Minerals and Energy Affairs. Report no. ED9206:16-17, August, 1996.

[109] Starfield, A.M. "A theoretical study of heat flow in rock surrounding underground excavations", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, University of the Witwatersrand, November 1965.

[110] Starfield, A.M. A study of heat transfer and moisture pick-up in mine airways. *South African Institute of Mining and Metallurgy* 68(5):211-234, 1967.

[111] Van Antwerpen, H.J., Greyvenstein, G.P. Use of turbines for simultaneous pressure regulation and recovery in secondary cooling water systems in deep mines. *Energy Conservation and Management* 46:563-575, 2005.

[112] Van Antwerpen, H.J., Greyling, J. Energy audit of mine refrigeration water system by means of simulation. *Proceedings of the 9th Industrial and Commercial Use of Energy Conference*: 87-92. Stellenbosch, August 2012.

[113] Van der Walt, J., De Kock, E.M. Developments in the engineering of refrigeration installations for cooling mines. *International Journal of Refrigeration* 7(1):27-40, January 1984.

[114] Von Glehn, F.H., Wernick, B.J., Chorosz, G., Bluhm, S.J. ENVIRON A computer program for the simulation of cooling and ventilation systems on South African gold mines. *Proceedings of the 12th International Symposium on the Application of Computers and Mathematics.* In: *Mineral Industries 1*. SAIMM, Johannesburg, 1987.

[115] Von Glehn, F.H., Bluhm, S.J. Practical aspects of ventilation of high-speed developing tunnels in hot working environments. *Tunnelling and Underground Space Technology* 15(4):471-475, 2000.

[116] Webber-Youngman, R.C.W., Franz, R.M., Butterworth, M.D., Marx, W.M. Fundamentals of planning for deep mine ventilation and cooling systems. *Journal of the Mine Ventilation Society of South Africa* 59(1):13-17, 2006.

[117] Webber-Youngman, R.C.W. An integrated approach towards the optimisation of ventilation, air cooling and pumping requirements for hot mines. *Australasian Institute of Mining and Metallurgy Publication Series*: 75-64, 2005.

[118] Whillier, A. Present-day trends on cooling practices on South African gold mines. *Proceedings of the 12th CMMI Congress*. Johannesburg, South Africa, 1982:697-702.

2. Mine ventilation and refrigeration overview

This chapter explains mine-cooling and ventilation systems and explores the actual requirements and constraints of these systems.

2.1. Prelude

Chapter 1 clearly described the need for load-management and energy-saving projects on mines. This chapter covers deep-level mining, refrigeration, ventilation and cooling. The purpose of this chapter is to provide an understanding of deep-level mining and mine-refrigeration systems.

2.2. Deep-level mining and refrigeration

South Africa is world renowned for the depth of its mines. The best way to mine the buried riches at great depth is to sink a shaft down and from the shaft tunnel to the ore. For the depth of South African mines, this process is repeated several times and it is common to have up to two subshafts on a mine.

The length of a single shaft is limited by the weight of the steel cable supporting the cage and skip. Specially tapered cable is used in some mines to extend the shaft and do away with one of the subshafts. A mine has several service levels for the dewatering system. Thus, the total head needed to pump water to the surface is broken into more manageable pumping sections.

The heat stress in a mine is the qualitative assessment of the work environment based on temperature, air velocity, humidity and radiant energy. The physiological response to heat stress is called heat strain. The WB temperature at which the ventilation air is no longer sufficient and is required to be cooled again or exhausted, is known as the reject temperature. This is based on the relationship between the heat stress and strain.

The rejection temperature ranges between 25.5 ^{o}C and 29 ^{o}C WB. At a depth of 2 500 to 3 000 m, the ventilation air in the shaft has risen to the reject temperature. This is due to auto-compression and shaft heat loads. At this depth, ventilation air from the surface air must either be exhausted or cooled again. Thus, any mining below these levels is solely reliant on underground cooled ventilation air [1].

The heat loads on a mine-cooling and ventilation system are adiabatic compression, electromechanical equipment, ground water, wall rock heat flow, heat from broken rock and other sources.

These heat loads are summed to calculate the entire mine heat load. First, temperature-independent heat (TIH) sources are calculated, because their results influence temperature-dependent heat (TDH) sources.

The theoretical heat load imposed on ventilation air by adiabatic compression is given in Equation 1, which is a simplified form of the general energy equation:

$$q = Q\rho E\Delta d \qquad \text{(Eq.1) [1]}$$

Where:

q	=	theoretical heat of auto-compression (kW)
Q	=	airflow in shaft (m^3/s)
ρ	=	air density (kg/m^3)
E	=	energy added per unit distance of elevation change (1kJ/(102m.kg))
Δd	=	elevation change (m)

The adiabatic compression process is not truly adiabatic and auto-compression is a more appropriate term. The actual temperature increase for air descending down a shaft does not match the theoretical adiabatic temperature increases for the following reasons:

- The rock and shaft lining thermal inertia, which absorbs and releases heat at different times of the day, correlating to seasonal and daily surface temperature fluctuations.
- The individual depth to ground rock temperature gradient.
- The increase in moisture content from evaporation, which suppresses the DB temperature rise.

The WB temperature lapse rate averages about 1.4 K WB per 300 m. It is much less sensitive to evaporation or condensation than the DB temperature. It does, however, vary, depending on the entering temperature, humidity ratio and pressure drop in the shaft [1].

Electromechanical equipment, such as electric motors and diesel engines, transfers heat to the air. The loss component of substations, electric input devices, such as lights, and all energy used on a horizontal plane appears as heat added to the air. Fans raise the air temperature by an average of 0.25 K per kPa and pressures up to 2.5 kPa are common.

Ground water or fissure water has the largest variance on mine heat loads. It ranges from zero to overwhelming values. The water enters the mine at near VRTs and continues to release heat until it reaches the surface. The amount of heat it releases can be calculated using Equation 2.

$$q = mCp\Delta T \qquad \text{(Eq.2) [2]}$$

Where:

q	=	quantity of energy or heat (kW)
m	=	mass flow of the substance (kg/s)
C_p	=	specific heat capacity of the substance (kJ/kg.K)
ΔT	=	temperature rise of the substance (K)

The evaporation of water from the wall rock surfaces lowers the surface temperature of the rock, which increases the rock's temperature gradient. This depresses the DB temperature of the air and allows more heat to flow from the rock. Most of this extra heat is expended in evaporation. The latent heat required to turn water into vapour is 2 257 kJ/kg.K.

Wall rock is the main heat source in most deep mines; the earth's core has been estimated at 5 700 ^{o}C and heat flows from the core to the surface at an average of 0.007 W/m^2.

There is a geothermal gradient as the rock gets warmer as the mine deepens. Depending on the thermal conductivity of the rock, the gradient varies from 1 to 7 K per 100 m of depth. Wall rock heat flow is in an unsteady state. It decays with time, because of the insulating effect of cooled rock near the rock and air boundary.

The Goch Patterson equations [3]:

$$\alpha = k/\rho c \qquad \text{(Eq.3)}$$

$$Fo = \frac{\alpha\theta}{r^2} \qquad \text{(Eq.4)}$$

$$\epsilon = \{1.017 + 0.7288\log_{10}(Fo) + 0.1459[\log_{10}(Fo)]^2 - 0.01572[\log_{10}(Fo)]^3 - 0.004525[\log_{10}(Fo)]^4 + 0.001073[\log_{10}(Fo)]^5\}^{-1} \qquad \text{(Eq.5)}$$

$$Heat\ flux\ \left({}^{W}/{}_{m^2}\right) = \frac{k(tvr - ta)(\varepsilon)}{r} \qquad \text{(Eq.6)}$$

$$Total\ heat\ flow\ (W) = (Heat\ flux)(L)(P) \qquad \text{(Eq.7)}$$

Where:

α	=	thermal diffusivity of rock (m^2/h)
k	=	thermal conductivity of rock (W/(m.K))
ρ	=	rock density (kg/m^3)
Fo	=	Fourier number (dimensionless)
L	=	length of section (m)
P	=	perimeter of section (m)
r	=	radius of circular section (m)
t_a	=	air DB temperature (^oC)
t_{vr}	=	VRT (^oC)
ε	=	function of Fourier number for instantaneous rate (dimensionless)[4]
θ	=	average of section (h)

What is lacking in the Goch Patterson equations is that they do not have a convection heat transfer coefficient at the rock and air boundary. This results in the heat transfer in a dry drift being overestimated by 8 to 15%. They do not have a wetness factor either. Though it may not be visible, all drifts have some wetness. Water on the perimeter draws more heat from the wall rock and, in this regard, the result underestimates the heat transfer.

From measured results and commercial software with 20 to 60% of the perimeter wetted, the overestimate nearly equals the underestimate. It is also recommended to keep the length below 60 m when using the Goch Patterson equations.

Freshly blasted broken rock can release substantial amounts of heat in a confined area. The rock's initial temperature will be the VRT and the final temperature reached when it is hoisted to surface. The heat load from broken rock can be calculated using the aforementioned variables with Equation 2.

Other sources of heat, such as the oxidation of timber and sulphide minerals, can be locally significant. Heat from blasting can also be appreciable at 4 200 kJ/kg and is usually swept away between shifts. It is not tallied in heat load projections. Body metabolism is only a concern in refuge chambers and rarely tallied in heat load projections.

Ventilation engineers can write their own software using the above equations, or use commercially available software to determine heat loads. These programs will then account for convective heat transfer, wetness, elevation changes and TIH sources. Taking into account that all variables through hand calculations can be tedious, the program input must be very carefully derived or the output will be of no use and misleading.

As stated in the previous section, there are methods for reducing the amount of service water circulated underground, fans used and the use of energy-recovery devices.

The above calculation and requirements have led to several developments, such as cooling the ventilation air on the surface, the use of large industrial refrigeration machines for producing water close to 0 °C, and the installation of ice-making machines on the surface and large refrigeration machines underground [5].

The cooling load of a shallow mine is entirely absorbed by ventilating ambient air through the mine and the use of service water.

As the mining depth increases, the service water may be cooled on the surface by the vertical forced-draught cooling tower.

Further increases in depth require a surface refrigeration system to cool the ventilation air. Mines developing and operating ever deeper into the earth's crust require the ventilation air and service water to be cooled by the surface refrigeration system [6].

The refrigeration machine uses working fluids such as R134A, ammonia and R22 and R21 to produce chilled water. The ventilation system uses the chilled water as working fluid to cool down the air, and mining uses air and water as working fluid to cool down the underground working sections [7].

Research has been conducted on using compressed, cooled and dehumidified air as a cooling agent, but no such system has been implemented. Compressed air intended for drilling is used for localised cooling at sections where the ventilation system is lacking [7].

Underground refrigeration systems or surface ice plants are required for South African gold mining depths. At these depths, the use of turbines are also the order of the day and three-pipe energy-recovery systems are also in operation at various mines.

2.3. Mining ventilation and cooling processes

The mine thermal heat load is absorbed by environmental cooling and refrigeration cooling, as shown in Figure 2-1. Mines use negative pressure ventilated by the main extraction fans shown in Figure 2-2.

These fans remove all the used air from the mine through the return air way (RAW) shaft. Fresh ambient air is sucked in through the man and materials (MM) shaft. BACs are used to cool and, more importantly, dehumidify the fresh ambient air. The BAC also acts as a solid particles filter system.

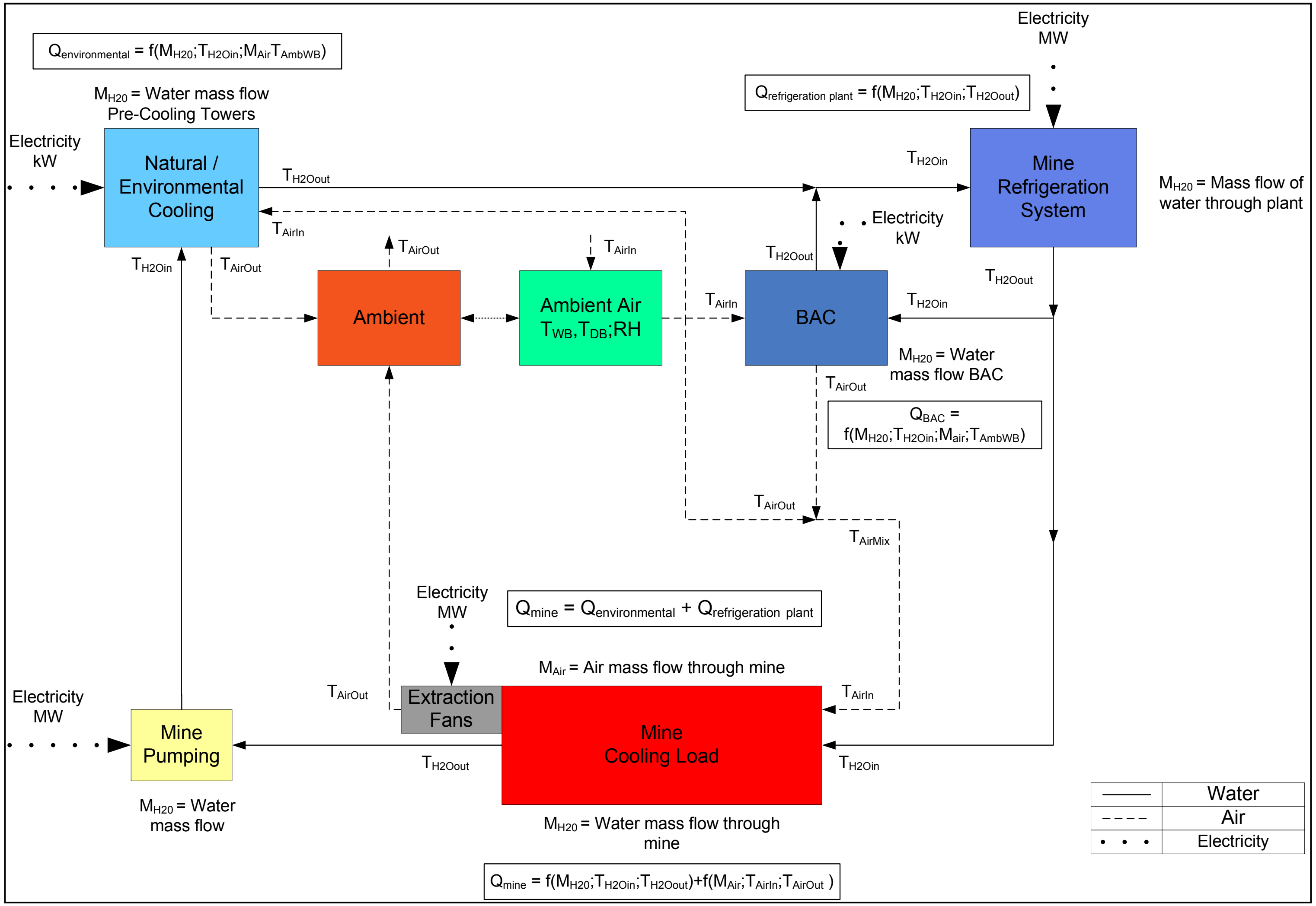


Figure 2-1: Mine ventilation and cooling [8]

Figure 2-2: Main mine extraction fans

The virgin rock is a heat source and ambient air is both a heat source and a heat sink. The energy from the virgin rock is transferred to mine service water and ventilation air. The BAC absorbs energy from the ambient air before it mixes the ambient air and uses it as ventilation air. Environmental cooling of the mine service water by the pre-cooling towers allows energy to be transferred to the ambient air.

The evaporator absorbs energy from the BAC and mine service water. This energy is transferred to the condenser in the refrigeration system and the condenser dissipates the energy into the ambient heat sink. The flow of energy is shown in Figure 2-3.

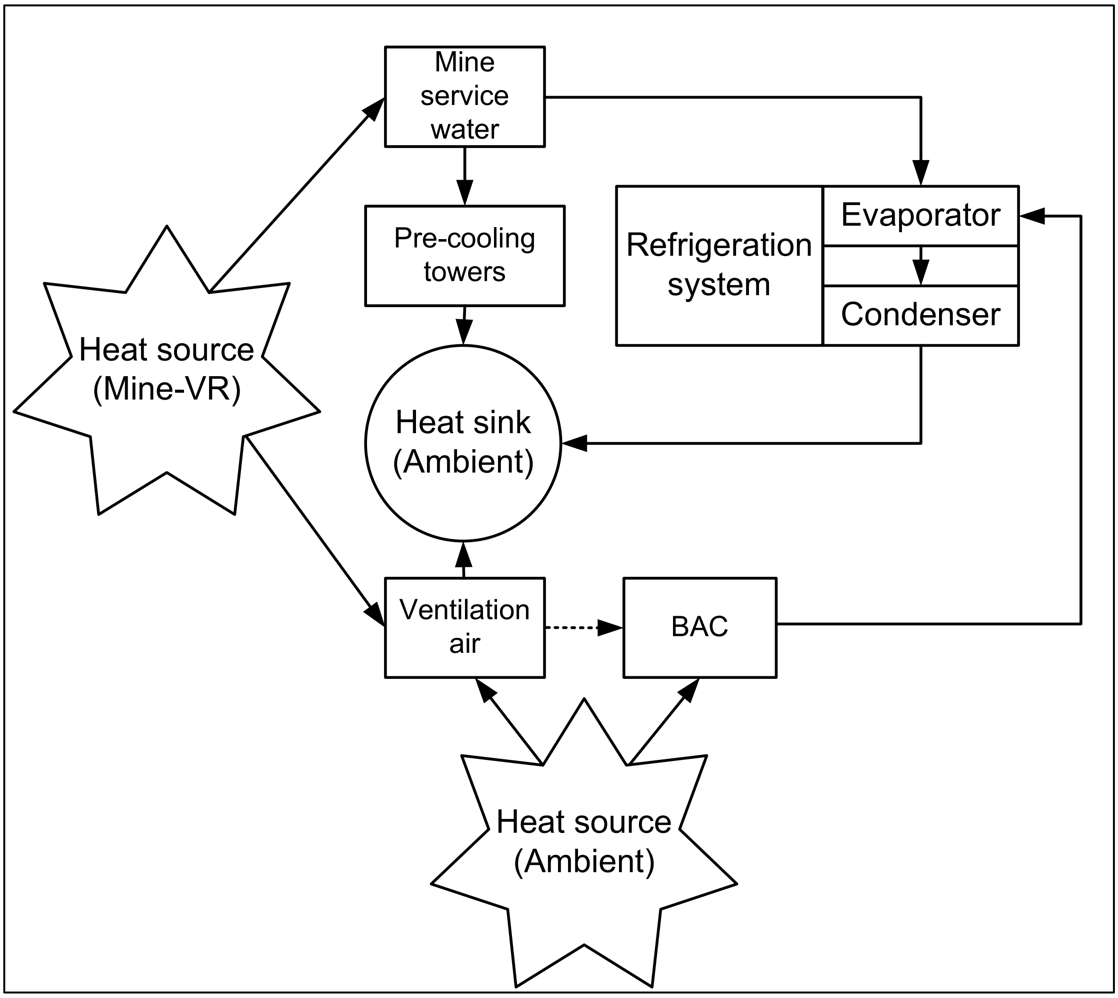


Figure 2-3: Mine cooling energy flow

The fans of the BAC blow the dehumidified cold air into the MM shaft a few metres under the surface, ensuring that the majority of the ventilation air going down the MM shaft is from the BAC, as shown in Figure 2-4. The BAC fans do not push the air through the mine. Cold air can be felt blowing out of the top of the MM shaft in the case where the main extraction fans are stopped and the BAC is operational.

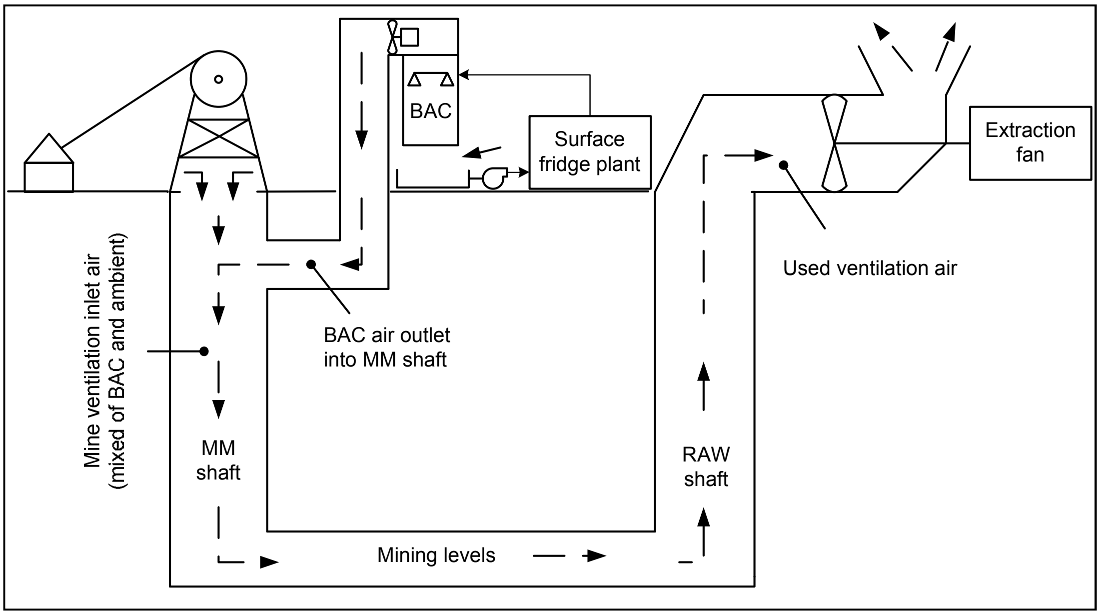


Figure 2-4: BAC blowing chilled air into the MM shaft

The mine may also have booster fans (shown in Figure 2-5) installed at various levels throughout the mine to aid with the ventilation of certain areas. The main fans, BAC and booster fans are referred to as the mine ventilation system.

Figure 2-5: Mine booster fan

The ventilation and cooling infrastructure that a mine needs to operate at depth is shown in Table 2-1 and Figure 2-6.

Table 2-1: Mine cooling requirement vs. depth [9]

Depth description	Ventilation			Service water			
	Forced ventilation	Surface cooled ventilation	Underground cooled ventilation	No cooling	Pre-cooling	Surface cooled	Underground cooled
Shallow	X			X			
Deep	-	X		-	X		
Medium depth	-	X		-	X	X	
Great depth	-	X	X	-	X	X	
Ultra deep	-	X	X	-	X	X	X

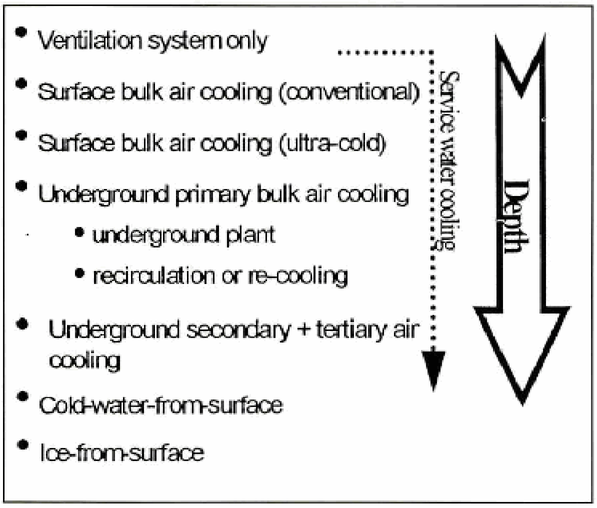


Figure 2-6: Phases of introducing mine cooling [10]

The refrigeration system, either on the surface or underground with its distribution network, is referred to as the mine-cooling system. As shown in Table 2-1, service water used for drilling and cleaning is also chilled.

The service-water temperature increases at a rate of 1 °C per 250 m due to auto-compression and heat exchange with the surroundings. It should be noted that the increase in water temperature because of heat exchange with the surroundings cools the air in the travel way. Heat is absorbed from the walls to the air, from the air to the pipe and from the pipe to the water.

The amount of heat absorbed by the water is less than the air when it reaches the working areas (stopes) and results in service water cooling down the working area.

The water is collected at the lowest level of the mine, filtered and then pumped back to the surface. Energy-recovery devices, such as turbines, are used where the water is sent down the shaft to reduce the pressure of the system.

All these components make up the mine water-reticulation system. The mine water-reticulation system is a semi-closed circuit. The system loses water due to evaporation and fissure water enters the system. Excess water is treated before it is discharged on the surface, and potable water or water from boreholes or rivers is added as needed. The cost of water treatment and acquiring water is high. This ensures that the mine operates as close as possible to a closed-loop system.

Figure 2-7 illustrates the mine water-reticulation system. The water in the system is also constantly filtered and treated due to the dissolving salts and minerals, as well as suspended solid particles.

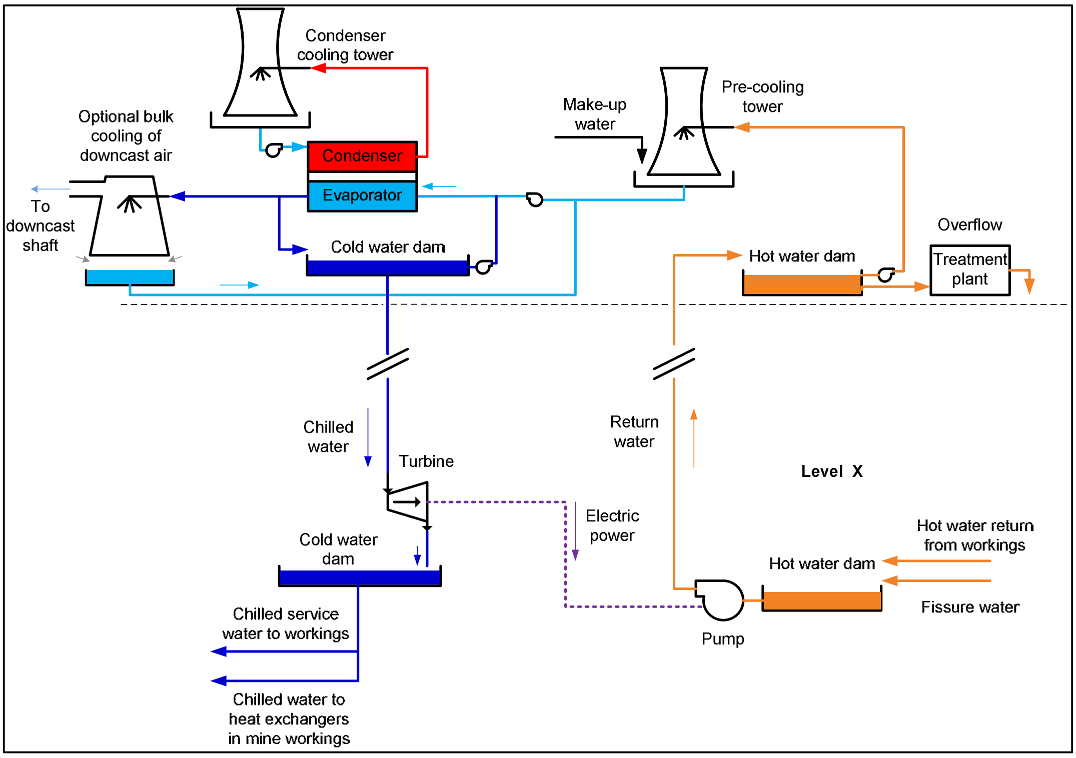


Figure 2-7: Water reticulation system [11]

The power consumption of the surface refrigeration system depends on the atmospheric conditions and will change with the changing seasons. The contribution of the refrigeration system to the total power consumption of the mine may be reduced from 25 to 13% when the seasons change from summer to winter.

The mine-refrigeration system consists of storage dams, pipes, valves, pumps and industrial-sized refrigeration machines, also known as chiller machines and fridge plants. These direct contact heat exchangers, shell and tube heat exchangers, and compressors operate on a Carnot-cycle of compression, heat exchange, decompression and heat absorption. There are also ammonia machines, as well as a few ice machines.

Refrigeration machines are constructed to handle a variation in thermal loads. The parallel setup shown in Figure 2-8a is used for applications where the temperature difference is fairly constant and the flow varies. The series setup shown in Figure 2-8b is for applications where the flow remains constant and the temperature varies. The series parallel setup shown in Figure 2-8c is used where both the flow and temperature vary [5].

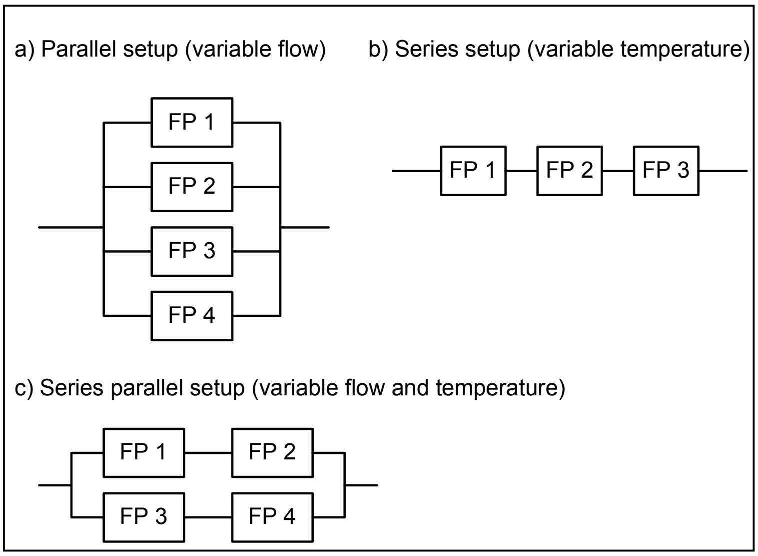


Figure 2-8: Refrigeration machine configurations

Surface cooling systems of deep-level mines provide chilled water between 3 and 5 °C [12]. A typical South African mine-surface cooling system is displayed in Figure 2-9.

The water flow path through the cooling system in Figure 2-9 can be explained as follows: Water is pumped from underground at a temperature of 24 to 28 °C [12] into the hot water dam. From the hot water dam, the water is pre-cooled to between 19 and 21 °C via pre-cooling towers and stored as pre-cooled water in the pre-cooling dam.

In the pre-cooling dam, the water mixes with BAC return water and overflowing chilled water from the chill dam when its capacity is surpassed. The water temperature in the pre-cooling dam is approximately 9 to 12 °C [13].

From the pre-cooling dam, water is pumped through fridge plants, where it is further cooled to 3 °C, and then into the chilled water dam. From there it is used by the BAC system and sent underground as mine service water.

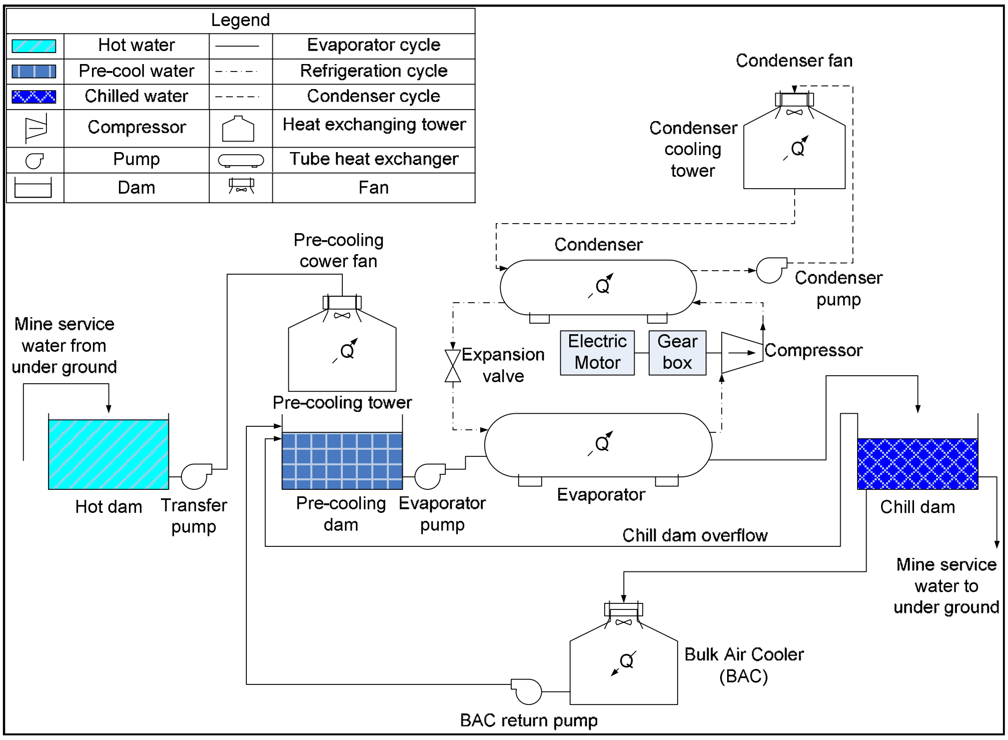


Figure 2-9: Mine-surface cooling system [14]

With this overview of mine cooling and ventilation, the following section will look more closely into the mine ventilation and cooling subsections.

2.4. Ventilation and cooling subsections

This section will start with the mine ventilation subsections and continue with the mine cooling subsections. The mine ventilation consists of BACs, booster fans and main or extraction fans.

Surface BACs and the main fans are found on the surface with underground BACs and booster fans installed underground. The BACs operate in conjunction with the mine-refrigeration and water-supply system. The fans can operate as standalone units and do not require other sections or systems.

The fans used by a BAC can also be seen as booster fans as they assist with the movement of air into and through the mine. The BAC can be a vertical forced-draught air-cooling tower or a horizontal forced-draught air-cooling tower.

A surface BAC cools and dehumidifies ambient air used for ventilation cooling. The following equation is used for the BAC:

$$Q = \dot{m}_{air}(S_{out} - S_{in}) \qquad \text{(Eq.8) [15]}$$

Where:

Q = energy absorbed by BAC (kW)

$\dot{m}_{air}$ = mass flow of air (kg/s)

S_{out} = out of the BAC (kJ/kg)

S_{in} = into the BAC (kJ/kg)

Dehumidification's rate of water removal is given by the following equation:

$$X_{H2O} = \dot{m}_{air}(W_1 - W_2) \qquad \text{(Eq.9) [2]}$$

X_{H2O} = rate of water removal (kg/s)

$\dot{m}_{air}$ = mass flow of air (kg/s)

W_1 = humidity ratio (kg/kg)

W_2 = humidity ratio (kg/kg)

During the winter months, the surface BAC pictured in Figure 2-10 is not required, because the ambient air is sufficiently cold and dry for ventilation cooling. The extra refrigeration capacity then allows for maintenance on the refrigeration system.

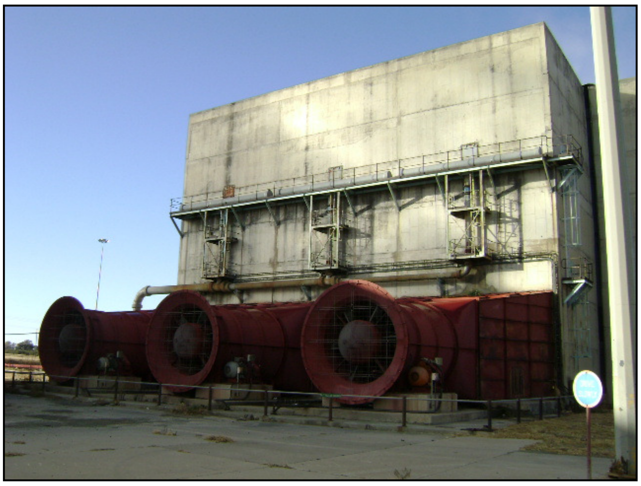


Figure 2-10: Bulk air cooler

The BAC system can be in a closed loop with the refrigeration machine. The water is pumped through both the refrigeration machine and the BAC, as shown in Figure 2-11a. Water can also be pumped from the chill dam to the BAC and back to the pre-cooling dam as shown in Figure 2-11b.

In some instances, the water is gravity-fed to the BAC from the chill dam and pumped back to the pre-cooling dam. The flow through the BAC is then controlled using a valve as shown in Figure 2-11c. There are also instances where the BAC is built on top of the pre-cooling dam and water is pumped into the BAC and falls into the pre-cooling dam as shown in Figure 2-11d.

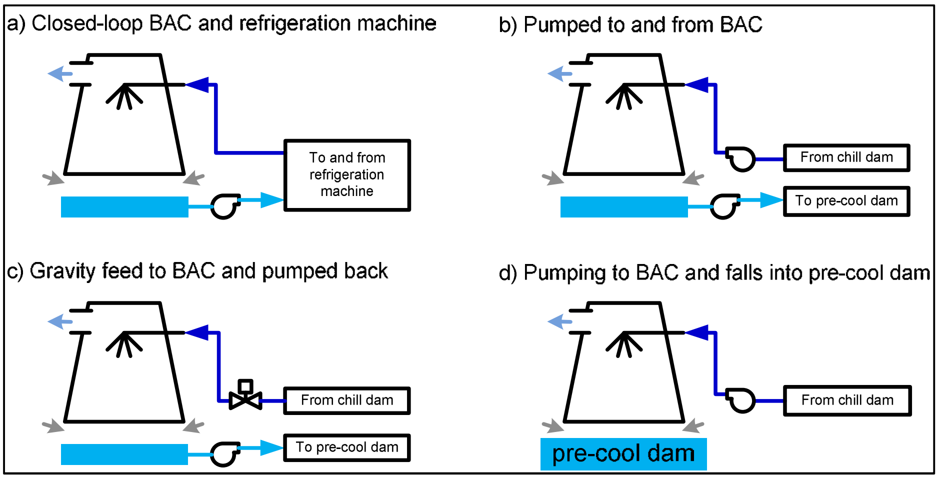


Figure 2-11: BAC configurations

Underground bulk air coolers:

- can be in a closed loop with the refrigeration machines;
- can use the chilled water from one of the cascade chill dams and return the water to a cascade hot dam; or
- can use the chill water from one of the cascade chill dams; the BAC outlet water can still be used in the mining section.

Underground BACs do the same as surface BACs in cooling and dehumidifying the air. They act as a dust filter and absorb the water condensate from the dehumidification process. In mechanised mining, this secondary cooling is done by fitting an air conditioning unit to cool down the cab of the machine. Ventilation in these systems is critical to remove fumes [16].

As mining development goes beyond the initial planning with subshafts and further decline shafts, the ventilation needs to be boosted. This is done with underground booster fans, as shown in Figure 2-5. These fans help the airflow along to the new sections, bypassing the old mining sections.

Ventilation air is also conducted to work areas through ducting. Inline booster fans, shown in Figure 2-12, are installed with the ducting. They force fresh air into the new development sections or working areas, displacing used air.

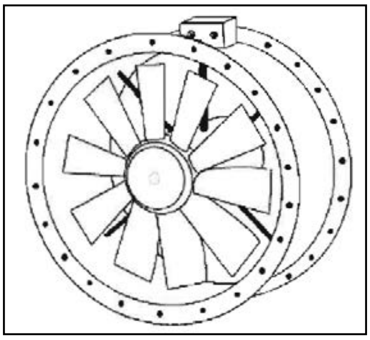


Figure 2-12: Inline booster fan [17]

The main mine fans on the surface, as described in the previous section and pictured at the start of this chapter, usually consist of three to four 2 MW fans. These fans extract air from the mine at a rate of 0.05 to 0.09 m^3/s [1][17].

Mine service water from surface refrigeration machines is sent underground into a series of cascading dams. The water is stored in these dams and then gravity-fed through pipes, as depicted in Figure 2-13, into the mine working areas.

Figure 2-13: Isolated chilled water pipe and hot water dam

The network supplying the working areas starts from the shaft and then goes into the levels at the stations. The water follows the haulage way along the strike from the station and splits off into the footwall cross-cuts as shown in Figure 2-14. From there it is used by mining production in the stopes. The used water flows back to the shaft in the return drain.

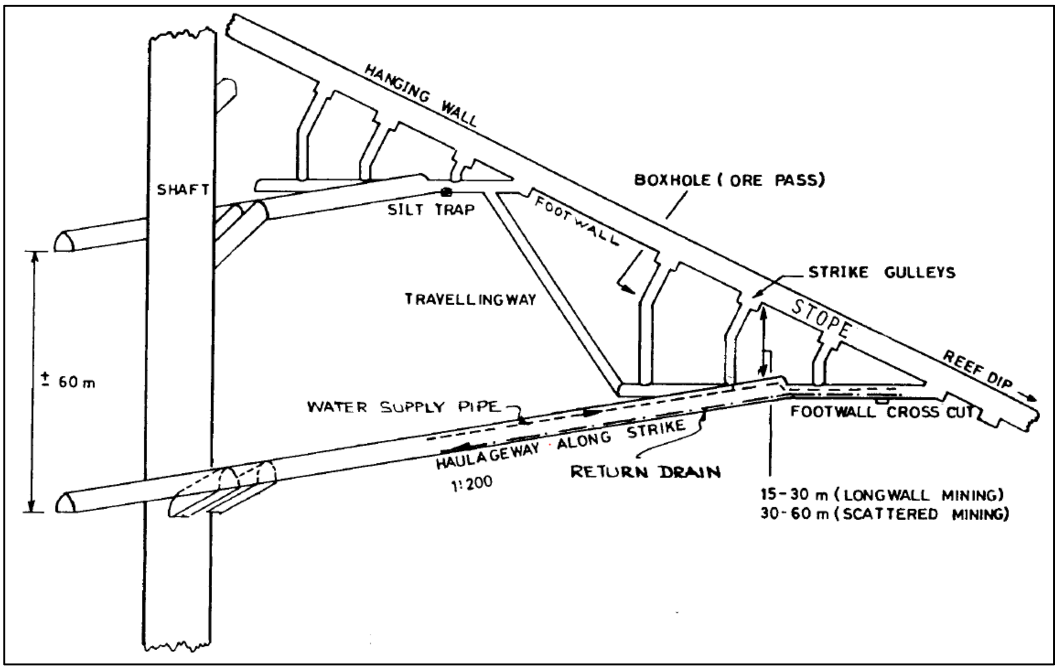


Figure 2-14: Mining operations layout [18]

At the shaft, the water flows down to the next level in the drain system and accumulates at the bottom of the shaft. The water and mud are split from each other through the settlers as shown in Figure 2-15.

Figure 2-15: Mine settler separating production water and mud [19]

The gold-rich mud is pumped by a mud pump, shown in Figure 2-16, into a mud press, shown in Figure 2-17. The mud is sent with the ore to the surface gold plant. The clear water is pumped to the surface through a series of cascading dams and pump stations.

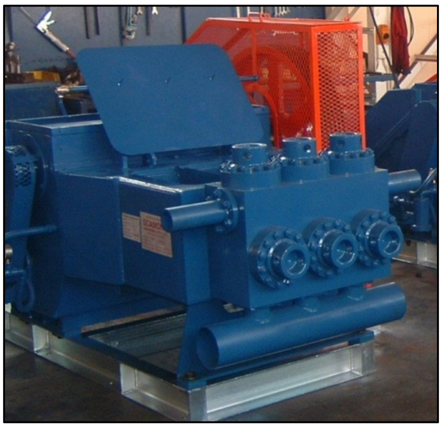


Figure 2-16: Mud pump

Figure 2-17: Mud press

Multistage high-pressure pumps are used to pump the water between cascading dams to the surface. There are multiple pumps per pumping station, and two columns between pumping stations and the following dam for redundancy. It is critical to pump the water out of the mine and prevent the lowest level from flooding.

These pumps have eight stages, as shown in Figure 2-18. Typical flow is 250 ℓ/s per pump with the typical distance between levels being 2 500 ft or 762 m.

The greatest head is typically between the first mining level and the surface due to the depths at which South African mines operate.

Figure 2-18: Mine dewatering pumps

The theoretical equation used for pumping and turbines is shown below:

$P_h = q\rho gh$ (Eq.10)[20]

Where:

P_h = power (kW)

q = flow capacity (l/s or kg/s)

ρ = density of fluid (kg/m^3)

g = gravity (9.81 m/s^2)

h = differential head (m)

Leading pumping companies like Sulzer are marketing new technologies where a pump can be used as a turbine as well. The main energy-recovery devices used in South African mines to reduce mine-pumping costs are turbines and three-pipe systems.

There are various types of turbines. As stated in the previous paragraph, companies like Sulzer are promoting technologies where dewatering pumps are used as turbines.

The Pelton wheel is, however, currently the most popular application of these technologies in South Africa's deep mines, and is shown in Figure 2-19.

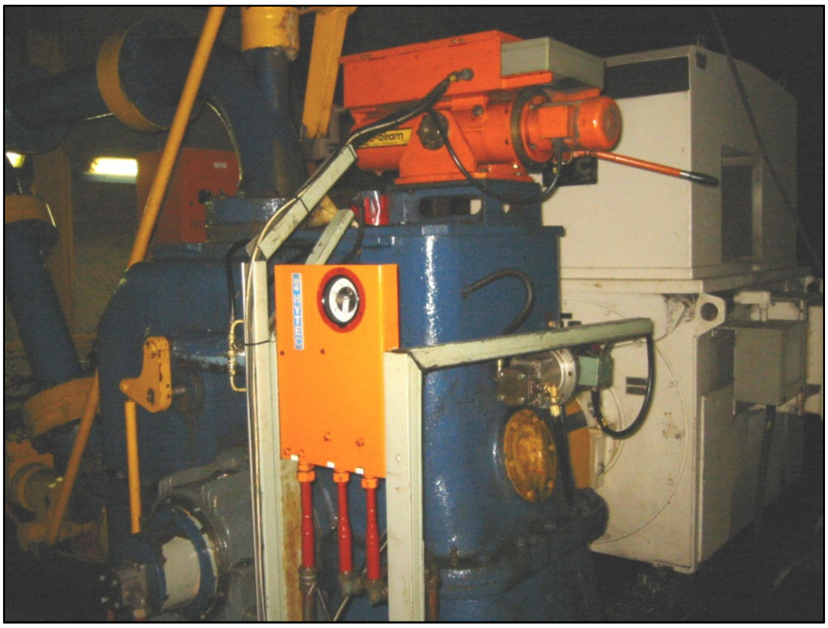


Figure 2-19: Pelton wheel turbine

The turbines used have two nozzles and one bucket. The critical parts of the turbine are the needle valve or spear and bucket. These components are specifically manufactured and hardened to survive the high operating pressure.

Dirty water is the turbines' main enemy. Particles cut away the needle valve and buckets until the turbine fails. These components are manufactured overseas due to the manufacturing and hardening involved. They are expensive and not readily available in South Africa. Most mines struggle with water quality, especially mines where the production has surpassed the settler operating capacity [21].

Some mines also use dissipating valves in conjunction with the turbines to provide the needed flow to mine production areas. These dissipating valves are usually on a common manifold with the turbine. Opening a dissipating valve when a turbine is in operation reduces the supply pressure to the turbine. This reduces the pressure differential across the turbine, resulting in the turbine running below capacity.

Turbines running at lower capacity, as described above, and the low utilisation of turbines, due to critical spare equipment supply problems in South Africa, result in a low rate of energy recovery compared to the available or possible energy- and cost-savings.

A new and popular alternative is the three-pipe system, also known as the Three UPSs, shown in Figure 2-20. Three pipes work on the U-tube principle and use chilled water going underground to push the warm water out from underground.

The resultant head difference and friction losses in the pipes are overcome with small pumps compared to dewatering pumps. The system is calibrated to allow a small amount of chilled water to be circulated back to surface.

Figure 2-20: Three-pipe system [22]

Surface refrigeration plants are a major operational cost for the mine and consist of a pre-cooling tower, refrigeration machines, dams and auxiliary equipment. The refrigeration machines consist of the evaporator and condenser circuits shown in Figure 2-21 [22].

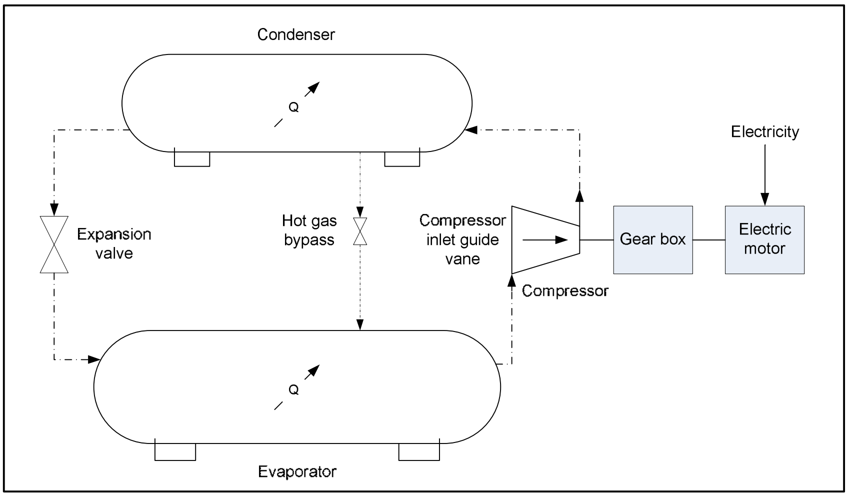


Figure 2-21: Refrigeration machine

The compressor inlet guide-vane controls the amount of cooling done with a feedback loop, using the difference between the outlet water set point and the actual temperature. The hot gas bypass is used to give the evaporator an artificial load and prevents the system from freezing the water. A mine-refrigeration machine is shown in Figure 2-22.

Figure 2-22: Mine-refrigeration machine

The refrigeration machine equation for the heat absorbed by the evaporator is given below:

$$Q_{evap} = \dot{m}_{water} C_{pwater} (T_{out} - T_{in})$$ (Eq.11) [14]

Where:

Q_{evap}	=	energy absorbed by evaporator (kW)
$\dot{m}_{water}$	=	mass flow of water (kg/s)
C_{pwater}	=	specific heat of water (kJ/kg.K)
T_{out}	=	water temperature out (K)
T_{in}	=	water temperature in (K)

The equation used for three-phase power is given below:

$$P_{ref} = \sqrt{3} V I pf$$ (Eq.12) [14]

Where:

Pref	=	motor power (kW)
V	=	volts (V)
I	=	amps (A)
pf	=	power factor

The equation used for the heat absorbed by the condenser to be dissipated to the atmosphere is given below:

$$Q_{cond} = \dot{m} C_{pwater} (T_{out} - T_{in})$$ (Eq.13)[14]

Where:

Q_{cond}	=	energy absorbed by condenser (kW)
$\dot{m}_{water}$	=	mass flow of water (kg/s)
C_{pwater}	=	specific heat of water (kJ/kg.K)
T_{out}	=	water temperature out (K)
T_{in}	=	water temperature in (K)

The COP for a machine indicates how much thermal cooling is done for each unit of electricity put into the refrigeration machine compressor:

$$COP_{machine} = \frac{Q_{evap}}{P_{ref}}$$ (Eq14)[14]

Where:

$COP_{machine}$	=	coefficient of performance
Q_{evap}	=	energy absorbed by evaporator (kW)
P_{ref}	=	motor power (kW)

The COP for the plant indicates how much thermal cooling is done for all the electricity put into the plant:

$$COP_{plant} = \frac{Q_{evap}}{P_{ref}+P_{aux}}$$ (Eq.15) [14]

Where:

COP_{plant}	=	coefficient of performance
Q_{evap}	=	energy absorbed by evaporator (kW)
P_{ref}	=	motor power (kW)
P_{aux}	=	power of auxiliary fans, pumps, etc.

The efficiency of a refrigeration machine is given below:

$$\eta_{machine} = \frac{Q_{evap}+P_{ref}}{Q_{cond}}$$ (Eq.16) [2]

Where:

$\eta_{machine}$	=	machine efficiency
Q_{evap}	=	energy absorbed by evaporator (kW)
P_{ref}	=	motor power (kW)
Q_{cond}	=	energy absorbed by the condenser (kW)

There is no actuated or dynamic flow control on the condenser water-pumping system. Again, the required flow for maximum thermal load is given with a pressure build-up between the pump and the flow restriction.

2.5. Conclusion

Deep-level mining in South Africa requires ventilation and cooling due to the high VRT encountered at their working depth. This cooling is done with air, water and ice. From this chapter, it can be seen that deep-level mining ventilation and cooling is a vastly complex system.

The mine-ventilation subsection consists of booster fans and main extraction fans. The cooling subsection consists of the water-reticulation system and refrigeration system. The water-reticulation system consists of pumps, turbines and other energy-recovery devices, such as three pipes.

The mine-cooling load is absorbed by the mine-refrigeration system and ambient air. The cooling load on the refrigeration system is from ambient air and mine service water.

The refrigeration system consists of pre-cooling towers, BACs, and evaporator and condenser circuits. The BACs cool and dehumidify a large portion of the air used for ventilation. The pre-cooling towers cool down mine service water with ambient air before it enters the evaporator circuit.

The evaporator circuit absorbs the heat from the service water turning it into chilled water before it is sent underground and used in the BAC. The condenser absorbs all the heat from the refrigeration machine and cools the water with ambient air.

The mine-refrigeration system has, as input, electricity, which results in a change in temperature for a given flow. There will be an energy-saving by reducing the needed temperature change by either decreasing the inlet temperature, or increasing the outlet temperature set point. There will also be an energy-saving if the water flow through the refrigeration system is reduced.

2.6. References

[1] ASHRAE. HVAC applications. *ASHRAE Handbook* 29.1–29.13, 2011.

[2] Stoecker, F.W., Jones, J.W. *Refrigeration and air conditioning*, 2nd edition, 1983.

[3] Gosh, D.C., Patterson, H.S. The heat flow into tunnels. *Journal of the Chemical, Metallurgical and Mining Society of South Africa* 41, 1940.

[4] Whillier, T. Sources of heat in mines. In: *Environmental engineering in South African mines*, H. Burrouws, S. Holding (Eds.). Mine Ventilation Society of South Africa, 1982.

[5] Van der Walt, J., De Kock, E.M. Developments in the engineering of refrigeration installations for cooling mines. *International Journal of Refrigeration* 7(1): 27-40, January 1984.

[6] Man-chao, H.E. Application of HEMS cooling technology in deep mine heat hazard control. *Mining Science and Technology* 19, 2009.

[7] Del Castillo, D. Air cycle refrigeration system for cooling mines. *International Journal of Refrigeration* 11(2): 87-91, March 1988.

[8] Schutte, A.J., Strydom-Bouwer, E.L., Kleingeld, M., Van Rensburg, J.F. Energy efficient demand-side management opportunities in underground refrigeration systems. *Proceedings of the 6th International Conference on the Industrial and Commercial Use of Energy.* CPUT, Cape Town, South Africa, August 2009.

[9] Mackay, L., Bluhm, S., Van Rensburg, J. "Refrigeration and cooling concepts for ultra-deep platinum mining", paper presented at the 4th International Platinum Conference, Platinum in transition 'Boom or Bust'. The Southern African Institute of Mining and Metallurgy, 2010.

[10] Bluhm, S.J., Von Glehn, F.H., Smit, H. Important basics of mine ventilation and cooling planning. *Journal of the Mine Ventilation Society of South Africa* 75(1), 2004.

[11] McPherson, M.J. Refrigeration plant and mine air conditioning. *Subsurface ventilation and environmental engineering:* 651-738. Springer Netherlands London: Chapman and Hall, 1993.

[12] Van der Walt, J., Whillier, A. Considerations in the design of integrated systems for distributing refrigeration in deep mines. *Journal of the South African Institute of Mining and Metallurgy*, December 1978.

[13] Van der Bijl, J. "Sustainable DSM on deep mine refrigeration systems – a novel approach", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2007.

[14] Schutte, A.J. "Demand-side management of a cascade mine surface refrigeration system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2007.

[15] Sonntag, R.E., Borgnakke, C., Van Wylen, G.J. *Fundamentals of thermodynamics*, 6th edition. John Wiley and Sons, 2003.

[16] Brake, D.J. Design of the world's largest bulk air cooler for the enterprise mine in northern Australia. *Mine Ventilation: Proceedings of the North American/Ninth US Mine Ventilation Symposium, Kingston, Canada, 8-12 June 2002*. Taylor & Francis, 2002 (also available in *Mine Ventilation:* 381-387. De Souza (Ed.). Swets & Zeitlinger, Lisse.

[17] Kukard, W.C. "Research on reducing cost of underground ventilation networks in South African mines", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[18] Stephenson, D. Distribution of water in deep gold mines in South Africa. *International Journal of Mine Water* (2):21-30, Granada, Spain, 1983.

[19] Vosloo, J. "A new minimum cost model for water reticulation systems on deep mines", thesis submitted in partial fulfilment of the requirements for the degree PhD in Engineering, North-West University, November 2008.

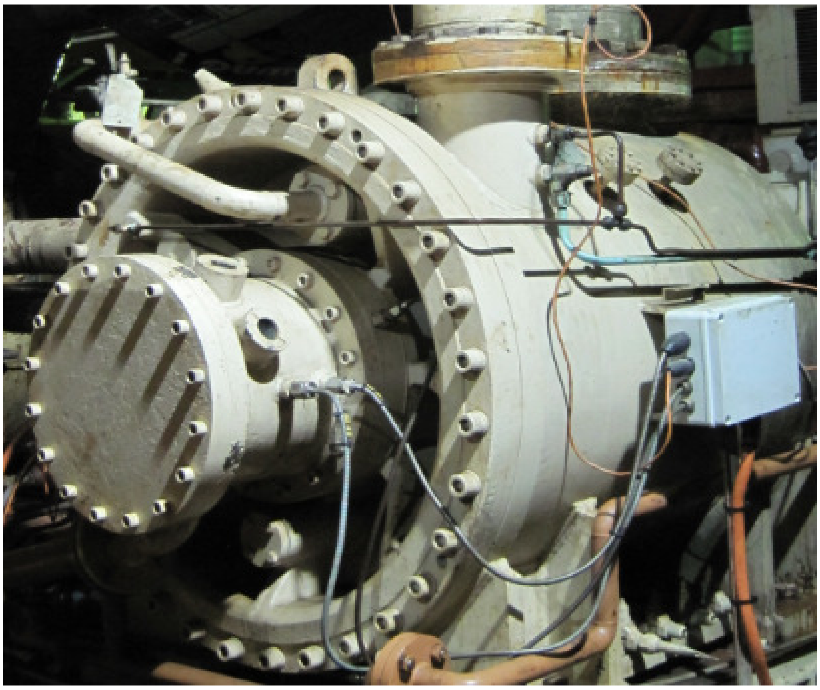
[20] Pope, J. E. *Rules of thumb for mechanical engineers*. Gulf Publishing Company, 1997.

[21] Schutte, A.J., Pelzer, R., Mathews, E.H. Improving cooling system efficiency with pre-cooling. *Electricity & Control*: 56-60, March 2013.

[22] Le Roux, D. Energy recovery from incoming high pressure cold water in deep level mines. *Proceedings of the 9th International Conference on the Industrial and Commercial Use of Energ*. CPUT, Stellenbosch, South Africa, August 2012.

[23] Van Antwerpen, H.J., Greyvenstein, G.P. Use of turbines for simultaneous pressure regulation and recovery in secondary cooling water systems in deep mines. *Energy Conversion and Management* 46: 563–575, 2005.

3. Mine-cooling and refrigeration projects



The best combination and sequence of energy-saving projects are developed after their evaluation according to cost-saving, risk and PAI.

3.1. Prelude

Chapter 2 of this thesis described mine ventilation and cooling with subsections and auxiliaries. Chapter 1 indicated that a sequencing strategy is necessary for the implementation of compressed air energy-saving projects. Chapter 2 indicated that the installation of mine-cooling and ventilation systems also has to take place according to a specific sequence.

This chapter develops the implementation sequence for the best combination of energy-saving projects on mine-cooling and ventilation systems.

The sequence is based on project risk, project appeal and magnitude of savings. Each project has its own reported saving relevant to the specific focus area. In this chapter, these savings are related to the entire mine-cooling and ventilation system. This is done using each system's contribution to the entire mine-cooling and ventilation annual cost.

Risk is a function of severity and likelihood. The chosen unit for severity and likelihood is a production shift. Mining operations work on three eight-hour shifts. The three shifts are the drilling, blasting and cleaning shift, and correlate to the morning, afternoon and evening shifts. A production shift constitutes all three of the aforementioned shifts.

The severity of the impact of a project can have the following impacts on the mine: a month's lost production, a week's lost production, a production shift, a level of production, a section of a level production and no impact. These impacts correlate to the catastrophic, major, moderate, minor, insignificant and not applicable descriptions of severity. They are also numbered level 5 to level 0.

The likelihood that a project will have an impact is categorised according to the following occurrences: once on all production levels during a production shift, once on a production level during a production shift, once a week, once a month, once a year and never. These then correlate to level 5 to level 0, and are named frequent, frequent to moderate, moderate, moderate to seldom, seldom and never.

The severity level is then multiplied by the likelihood level to determine the risk. The following four areas have been identified to evaluate a project: service delivery, production, and environmental health and safety.

The health and safety of miners is extremely important to the labour-intensive mining sector in South Africa, given the country's socio-economic situation and history. It is also important that the same level of service be continuously supplied. The aim of the load-management and energy-saving project is to improve the efficiency of production.

These areas are not all equally important and each risk area is multiplied by a weight. EHS is the most important area of consideration, followed by production. Both service delivery and overhead cost are said to be equally important, as shown in the risk evaluation sheet in Figure 3-1.

Hazard identification and risk assessment

Project:		Section:	

Magnitude and severity - Lost production shifts	Likelihood - shift interval between
The severity relates to the resultant lost amount of production shifts due to identified risk	*The likelihood is described as the amount of shifts between occurrence of identified risk event*
Level 5 - Catastrophic (A month's lost production shifts)	Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Major (A week's lost production shifts)	Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (A production shift)	Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 -Minor (A level of a production shift - not recoverable)	Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Insignificant (A section of a production shift - recoverable)	Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Not possible	Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 -Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery				**0**	1	0
Production				**0**	2	0
Environmental health and safety				**0**	3	0
Overhead cost				**0**	1	0

Evaluation of project	
Weighed risk indicator	0.00
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	0%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-1: Risk evaluation matrix

The PAI is evaluated according to the matrix shown in Figure 3-2. The aspects considered to determine the PAI are new equipment, the upgrading of existing equipment, extending the mine's monitoring and networking capacity, displaying and logging mine system variables, short implementation time, little downtime and interaction with other systems.

Project appeal indicator (PAI)

Project:

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment		1	
Upgrading existing equipment		7	
Monitoring and networking the mine		8	
Displaying and logging mine system variables		9	
Short implementation time		8	
Little down time required for implementation		8	
Interaction with other systems		7	

Evaluation of project	
Sum of weighed aspect scores	
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	0%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-2: PAI matrix

Each aspect has a separate desirability. Displaying and logging a system variable is seen as the most desirable function needed for sustainable load management and energy cost-saving. It is followed by expanding the mine network and monitoring capability. The aforementioned is followed by a short implementation time and little downtime of equipment.

A point out of 10 is given to indicate how sufficiently the project addresses each of these aspects. This point is then multiplied by the desirability weight and the results are added together. The appeal indicator is then expressed as a percentage of the maximum possible appeal.

The following section shows each section of the cooling and ventilation system's contribution to the annual electricity cost of the mine ventilation and cooling system.

3.2. Mine cooling and refrigeration system cost

3.2.1. Introduction

Chapter 1 established the following cooling and ventilation load-management and energy-saving strategies:

- Pumping control
- Fridge plant control
- Thermal ice storage
- Ice circulation
- Energy recovery
- Water system optimisation
- Cooling auxiliaries
- Auxiliary fans
- Main fan control
- Main fan carbon blades
- Closed-loop underground bulk air cooling

Chapter 2 discussed mining operations and the systems on which the above project are implemented. These projects were all implemented in their specific focus area and on different mines. This makes it difficult to know their effect on the overall system.

A simplified mine model needs to be developed to determine each project's effectiveness in the entire system. This enables different projects to be compared with each other. The model consists of the following subsections, as shown in Figure 3-3:

- Pumping
- Surface service-water refrigeration
- Underground service-water refrigeration
- Surface air refrigeration
- Underground air refrigeration
- Ventilation fans (booster and main or extraction fan)

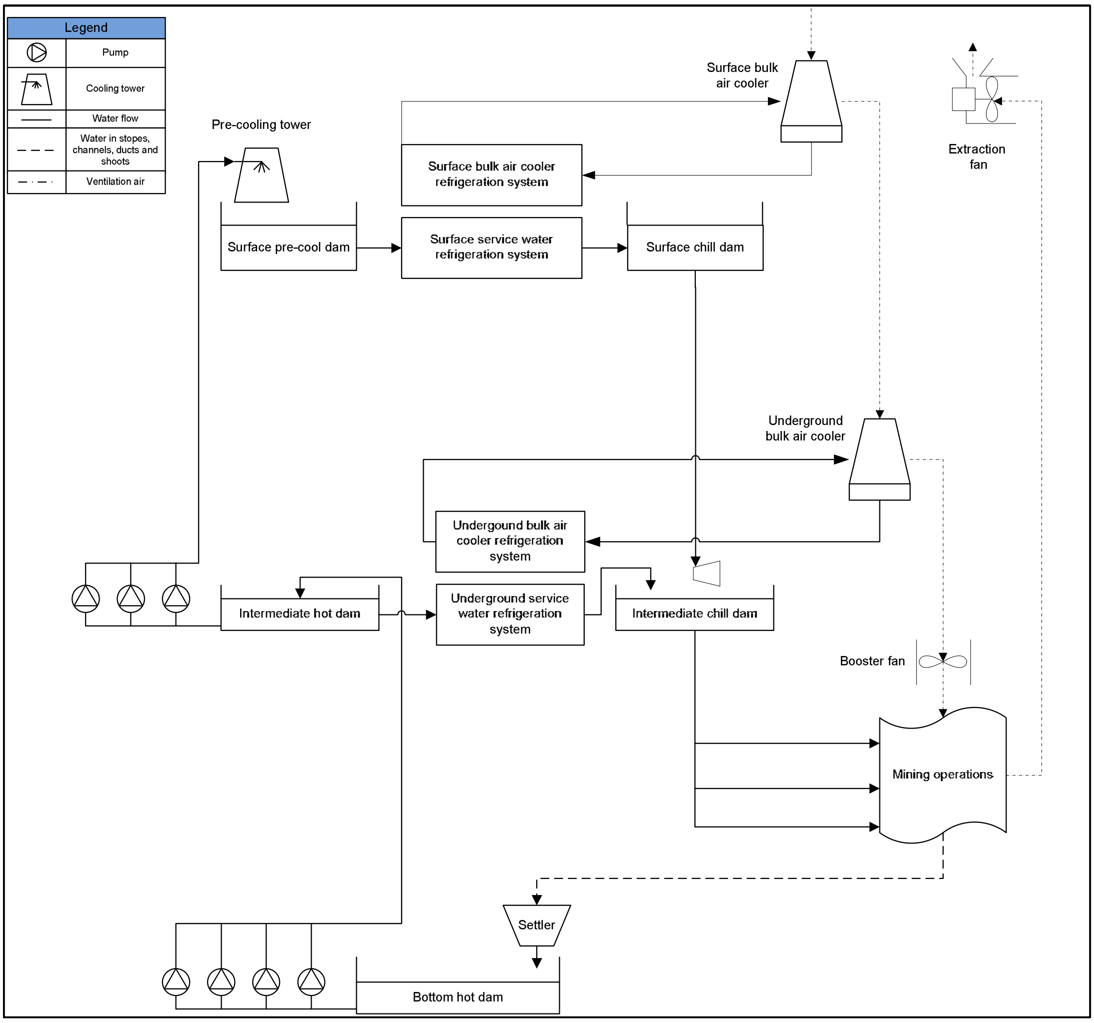


Figure 3-3: Simplified mine model

The power usage of each subsection of the model will be developed in the following sections. An accurate model is needed to ensure that the results obtained are credible and can be used to compare the different projects.

3.2.2. Pumping

As stated in Chapter 2, a mine-pumping system can have several levels and a range of pumps on each level. To simplify the model, only two pumping stations are simulated. The first pumping station pumps water from the bottom hot dam at the settlers to the intermediate hot dam. The second station pumps water from the intermediate dam to the surface.

Each system has a head of 1 800 m and thus the mine is 3 600 m deep. This correlates to a typical deep-level mine in South Africa. The mining operation uses an average of 240 ℓ/s, which comes to 21 Mℓ/day. For the model, 100 ℓ/s is circulated underground and 140 ℓ/s is pumped to the surface as shown in Figure 3-4.

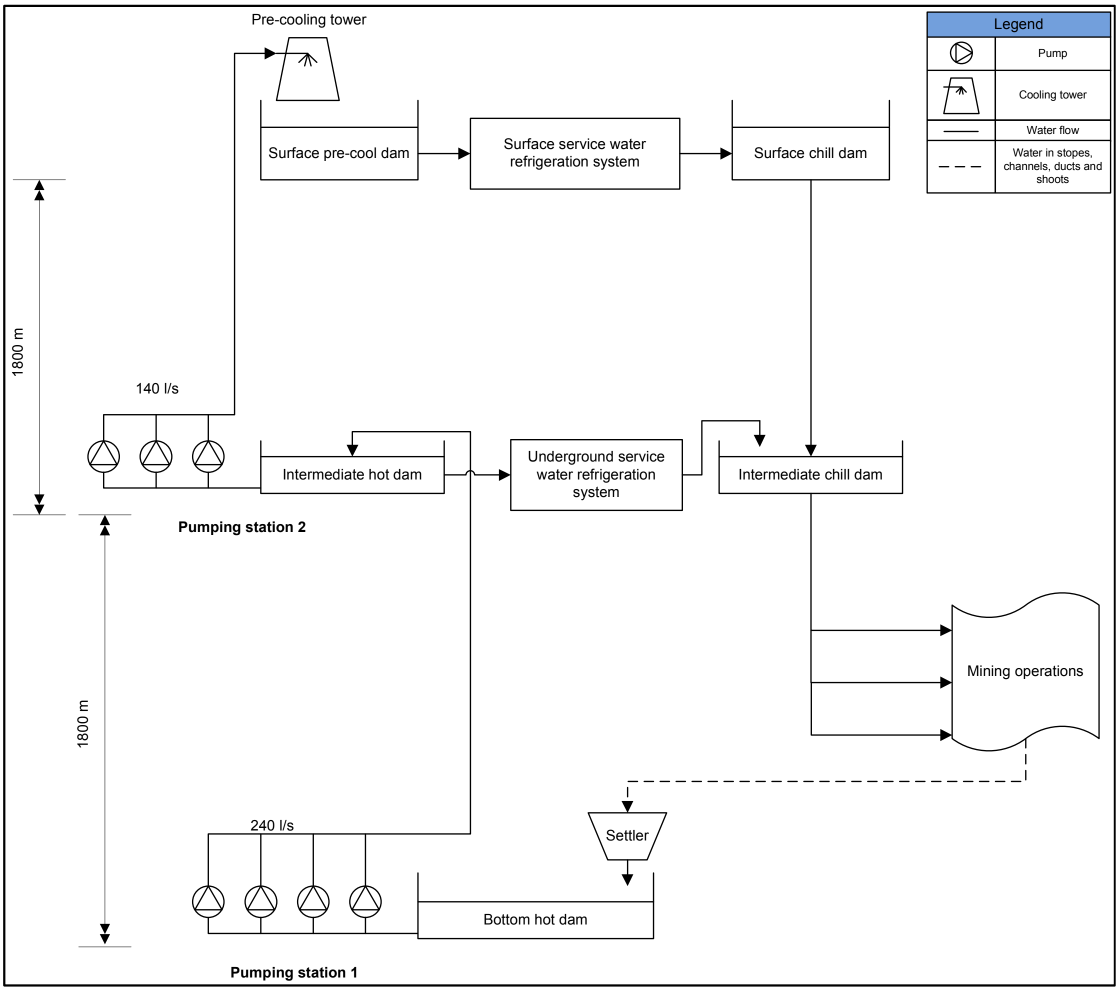


Figure 3-4: Mine pumping simulation

Using Equation 10, the power is calculated as illustrated in Table 3-1. The efficiency used accounts for the pump efficiency, pipe friction, the efficiency between the pump and electric motor and the electric motor's own efficiency. The total power for the mine-pumping section is then 7.5 MW.

Table 3-1: Mine-pumping simulation values

Pumping station 1		
Head	1 800	m
Flow	0.24	m^3/s
Efficiency	88	%
Power	4 763	kW
Pumping station 2		
Head	1 800	m
Flow	0.14	m^3/s
Efficiency	88	%
Power	2 778	kW
Total pumping kW	7 542	kW
Constants		
P	998.21	kg/m^3
G	9.72	m/s^2
Total depth	3 600	m

Load-management and energy-efficiency projects focus mainly on working weekdays. Mines operate during the week and every second Saturday. Mines do not operate on the remaining Saturdays, Sundays and public holidays. This thesis will focus on the power usage on working weekdays.

3.2.3. Service water refrigeration

From Chapter 2, it is evident that the refrigeration is either done on the surface or underground. The surface and underground refrigeration systems have been split into two systems each. One part of the system caters for the BAC thermal load and the other for the service-water thermal load.

The surface refrigeration system for service water cools 140 ℓ/s from 26 °C to 3 °C. This is done by the pre-cooling towers and the refrigeration machines. The COP used for the surface refrigeration plant incorporates the pre-cooling towers, refrigeration machines and all auxiliary equipment.

The temperature of the water sent underground increases from adiabatic compression at 2.34 ^{o}C/1 000 m and enters the intermediate chill dam at 7.21 ^{o}C [1].

The underground refrigeration system cools 100 ℓ/s from 26 ^{o}C to 3 ^{o}C. Again, an underground refrigeration plant COP is used, which incorporates the refrigeration machine, as well as all the auxiliary equipment. The underground refrigeration machine's chilled water mixes with the chilled water from the surface in the intermediate chill dam. The temperature of the water going to the working sections is 5.29 ^{o}C.

The above correlates to a typical deep-level mine in South Africa. Using Equation 2, the service-water refrigeration power is calculated at 2.4 MW on the surface and 2.0 MW underground. The total service-water refrigeration is 4.4 MW, as shown in Table 3-2.

Table 3-2: Mine service-water refrigeration

Surface		
Inlet temperature	26	^{o}C
Outlet temperature	3	^{o}C
Flow	0.14	m^3/s
Thermal kW	13 464	kW
COP	5.58	
Power	2 413	kW
Underground		
Inlet temperature	26	^{o}C
Outlet temperature	5	^{o}C
Flow	0.1	m^3/s
Thermal kW	8 781	kW
COP	4.5	
Power	1 951	kW
Total service-water refrigeration power	4 364	kW
Constants		
C_{pwater}	4 181	J/(kg.K)

3.2.4. Bulk air-cooling refrigeration

The ventilation air is cooled by the BAC on the surface and underground. These systems can be integrated with the service-water refrigeration for redundancy on a mine. For the purpose of this study and to simplify the model, the bulk air cooling is evaluated separately from the service-water refrigeration.

Klerksdorp is a well-known mining town in South Africa. The town's weather data was obtained from the South African Weather Service for 2010, 2011 and 2012. A summary of the DB temperature and relative humidity (RH) is shown in Figure 3-5.

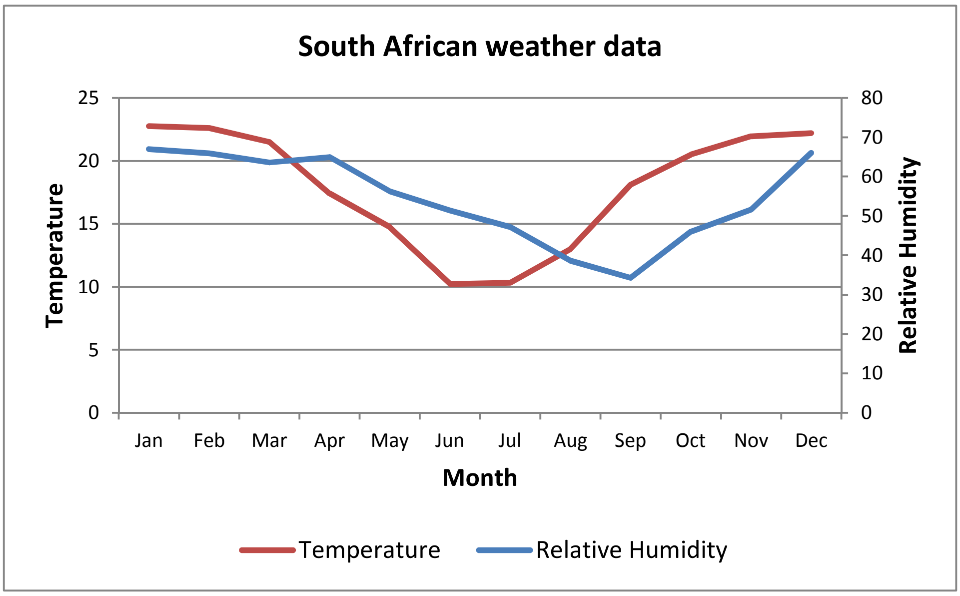


Figure 3-5: South African weather data

The surface BACs are switched off during the winter months (June, July and August). The average winter DB temperature and RH is 11.20 ^{o}C and 45.75%. Using the Ashrae psychrometric chart no. 6 for elevation, 1 500 m gives an enthalpy of 24 kJ/kg.

The average summer DB temperature and humidity is 20.20 ^{o}C and 57.30%. Using the above psychrometric chart, that gives an enthalpy of 46 kJ/kg. The surface BAC cools the air down to 5 ^{o}C; at this temperature it is beneath dew point and the RH is 100%. The enthalpy of the air leaving the BAC is 28 kJ/kg.

The BAC inlet air humidity ration is 10.2 $g_{moisture}/kg_{dry\ air}$ and the outlet air humidity ration is 6.5 $g_{moisture}/kg_{dry\ air}$. Using Equation 9, the rate of water removal is calculated at 1.85 kg/s. The latent heat required to condensate water at the dewatering rate is calculated using Equation 17:

$$Q_{condensate} = X_{H2O}Cp_{condensate} \qquad \text{(Eq.17) [2]}$$

Where

$Q_{condensate}$ = latent heat / thermal energy (kW)

X_{H2O} = rate of water removal (kg/s)

$Cp_{condensate}$ = specific heat required to condensate water (kJ/kg)

The specific heat required in Equation 17 to condensate water can be calculated using Equation 18.

$$Cp_{condensate} = (2500.8 - 2.36T + 0.0016T2 - 0.00006T3) \qquad \text{(Eq18) [2]}$$

Where

$Cp_{condensate}$ = specific heat required to condensate water (kJ/kg)

T = dry-bulb temperature (^{o}C)

Using Equation 18 with the air at 5 ^{o}C, gives a specific heat constant of 2 489 kJ/kg. The latent thermal energy required with a water removal rate of 1.85 kg/s and using Equation 17 is calculated at 4 605 kW. As shown in Table 3-3, this is added to the thermal energy of 12 500 kW that is needed to chill the air. The net result is that 4 073 kW of electrical power is needed for the surface bulk air-cooling refrigeration system.

Table 3-3: Mine air-refrigeration surface

Fans		
Mass flow	500	kg/s
Pressure	0.5	kPa
Efficiency	48	%
BAC fan power	521	kW
Air cooling		
Enthalpy in	46	kJ/kg
Enthalpy out	21	kJ/kg
Mass flow	500	kg/s
Thermal kW	12 500	kW
Condensate		
Inlet humidity ratio	10.2	g/kg
Outlet humidity ratio	6.5	g/kg
Condensate rate	1.85	kg/s
$Cp_{condensate}$	2 489	kJ/kg
Thermal kW	4 605	kW
Water		
Inlet temperature	3	^{o}C
Outlet temperature	14	^{o}C
Flow	0.38	m^3/s
Thermal kW	17105	kW
COP	4.2	
Power	4 073	kW
Constants		
C_{pwater}	4 181.30	J/(kg.K)

There is an average of 1.4 ^{o}C or K per 300 m increase in WB temperature as the ventilation air goes down the shaft. Leaving the surface BAC at 5 ^{o}C WB, the air inlet at the underground BAC will be 13.4 ^{o}C WB.

From the psychrometric chart, this gives an enthalpy of 43 kJ/kg. Assuming the RH has gone up to 50%, one will get a DB temperature of 20.4 ^{o}C and a humidity ratio of 10.2 $g_{moisture}/kg_{dry\ air}$.

This air needs to be chilled by the underground BAC. Using the same equation as for the surface refrigeration system, the underground calculation is shown in Table 3-4.

Table 3-4: Mine air refrigeration underground

Fans		
Mass flow	500	kg/s
Pressure	0.5	kPa
Efficiency	48	%
Underground BAC fan power	521	kW
Air		
Enthalpy in	43	kJ/kg
Enthalpy out	21	kJ/kg
Mass flow	500	kg/s
Thermal kW	11 000	kW
Condensate		
Inlet humidity ratio	10.2	g/kg
Outlet humidity ratio	6.5	g/kg
Condensate rate	1.25	kg/s
$Cp_{condensate}$	2 489	kJ/kg
Thermal kW	3 111	kW
Water		
Inlet temperature	3	^{o}C
Outlet temperature	14	^{o}C
Flow	0.31	m^3/s
Thermal kW	14 111	kW
COP	5	
Power	2 822	kW
Constants		
C_{pwater}	4181.30	J/(kg.K)

The power required for the refrigeration of air on surface refrigeration is 4.0 MW and underground it is 2.8 MW. The surface air-refrigeration system is stopped for the three winter months.

In total, the refrigeration of air will contribute 6.8 MW in summer and only 2.8 MW in winter to the mine ventilation and cooling power. The weighted average contribution of the air refrigeration is 5.8 MW.

3.2.5. Fans

The ventilation is achieved by using fans. A 15 m-diameter shaft results in a cross-section area of 176 m^2. At 2.4 m/s, the mine will be ventilated by 422 m^3/s of air. With the density of air taken as 1.18 kg/m^3, the mine is then ventilated by 500 kg/s of air. Looking at the previous section, it will be noted that all this air is cooled by the two BACs.

Mine ventilation fans		
Main fans		
Air		
Mass flow	500	kg/s
Pressure	2.5	kPa
Efficiency	48	%
Power	2 604	kW
Booster fans		
Air		
Mass flow	300	kg/s
Pressure	2.5	kPa
Efficiency	48	%
Power	1 563	kW
Total ventilation fan power	4 167	kW
Constants		
P	1.18	kg/m^3

An assumption was made that 3/5 of the ventilation air is boosted into sections and along the way from the MM shaft to the return air way. Having a pressure of 2.5 kPa across the ventilation fans results in the total power requirement being 4.2 MW for fans. The ventilation operates constantly throughout summer and winter on both operational days and non-operational days.

Fans add temperature to the air at 0.25 °C/kPa (K/kPa). At 2.5 kPa, a fan would increase the temperature of the air by 0.625 °C (K). From the BACs, it can be seen that their main function is to remove humidity. The fans add temperature, but no moisture to the air.

The temperature increase from the fans is not included in the simplified model of the mine. However, it remains advisable to install fans on the intake of cooling cars and BACs and not on the intake to the working sections.

3.2.6. Conclusion

In conclusion, the power usage of the mine-cooling and ventilation system can be seen in Table 3-5 and in Figure 3-6.

Table 3-5: Mine power usage for weekdays

Cooling and ventilation weekdays		
Pumping	7 542	kW
Refrigeration	10 241	kW
Fans	4 167	kW
Total	**21 949**	**kW**

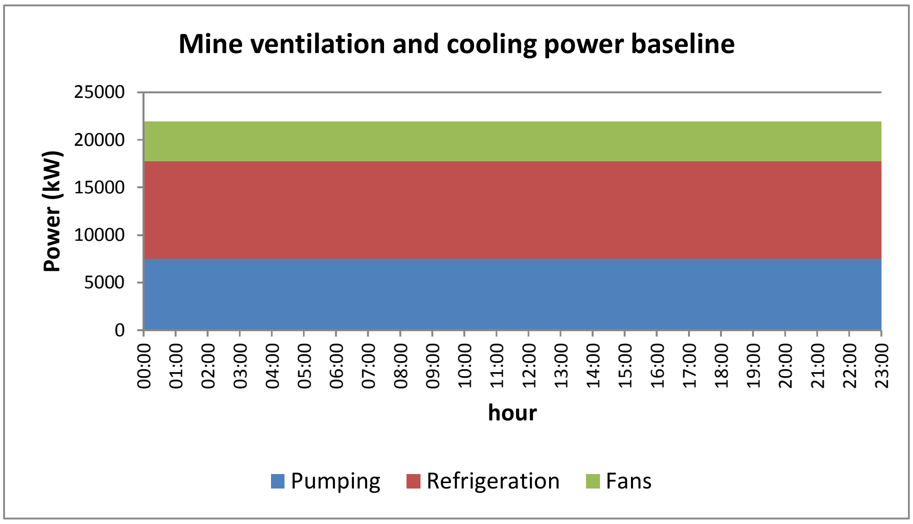


Figure 3-6: Mine ventilation and cooling power baseline

There are 365 days in a year and the mines do not operate on Sundays, public holidays and every second Saturday. South Africa has 13 public holidays. As stated earlier, the load-management and energy-saving projects focus on weekdays. The amount of weekdays is calculated as shown in Table 3-6.

Table 3-6: Winter and summer workdays and off-days

Days of the year	
Total days a year	365
Saturdays and Sundays	104
Public holidays	13
Effective workdays	**248**

The electricity price for summer, winter and the weighted average during a typical day is shown in Table 3-7. The weighted average cost excludes administrative and service charges, distribution network charges, reactive and environmental charges and transmission network charges.

Table 3-7: Weighted weekday average price of electricity in South Africa

Electricity price in South Africa			
	Weekday		
Time	Summer	Winter	Weighted average
00:00	32.70	37.76	33.97
01:00	32.70	37.76	33.97
02:00	32.70	37.76	33.97
03:00	32.70	37.76	33.97
04:00	32.70	37.76	33.97
05:00	32.70	37.76	33.97
06:00	51.53	69.53	56.03
07:00	74.88	229.52	113.54
08:00	74.88	229.52	113.54
09:00	74.88	229.52	113.54
10:00	51.53	69.53	56.03
11:00	51.53	69.53	56.03
12:00	51.53	69.53	56.03
13:00	51.53	69.53	56.03
14:00	51.53	69.53	56.03
15:00	51.53	69.53	56.03
16:00	51.53	69.53	56.03

Electricity price in South Africa			
Time	Weekday		
	Summer	Winter	Weighted average
17:00	51.53	69.53	56.03
18:00	74.88	229.52	113.54
19:00	74.88	229.52	113.54
20:00	51.53	69.53	56.03
21:00	51.53	69.53	56.03
22:00	32.70	37.76	33.97
23:00	32.70	37.76	33.97
Average	50.12	92.27	60.66
Weight	9	3	
Colours	Peak	Standard	Off-peak

The above charges and the profile in Figure 3-6 give the weekday cost baseline shown in Figure 3-7.

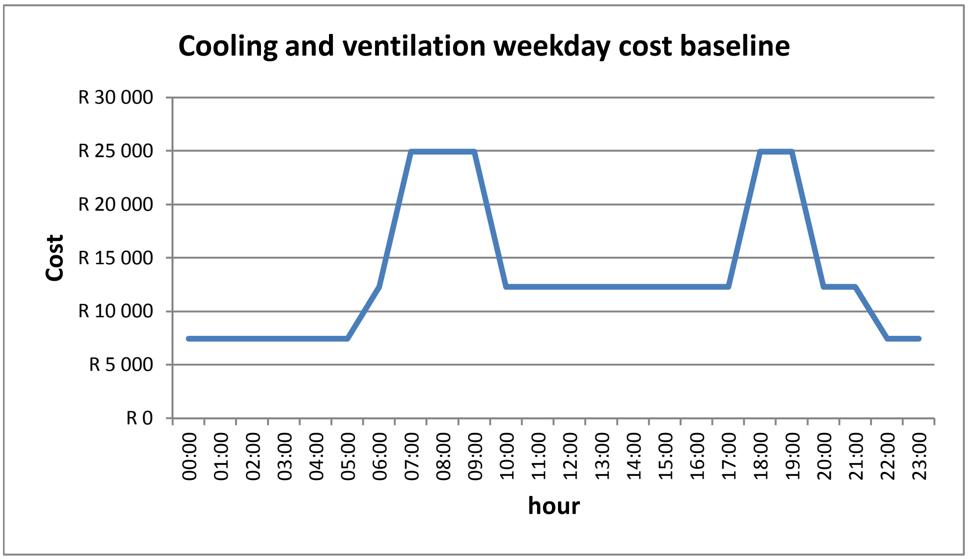


Figure 3-7: Weekday cost baseline

The annual ventilation and cooling system electricity cost calculation is shown in Table 3-8.

Table 3-8: Mine ventilation and cooling annual weekday electricity cost

Annual weekday electricity cost		
Total hourly power	21 949	kW
Hours per day	24	h
Weighted average power cost	0.61	R/kWh
Number of weekdays	248	days
Annual cost	R79	million

If the ventilation and cooling constitute 41% of the mine power consumption, it puts the annual mine electricity bill for weekdays at R193 million.

The model mine ventilation and cooling system power profiles are shown in Figure 3-6. This profile, with an annual cost of R79 million, will now be used to determine the effect of load-management and energy-saving projects in the following sections. This is done in conjunction with the risk evaluation and determining the PAI of a project.

3.3. Load-management strategies

3.3.1. Introduction

As stated in Chapter 1, electricity cost is one of the major input costs for a mine. Eskom has different generation methods, such as coal, nuclear, hydro and gas turbine. Each of these has an implied generation cost. Eskom runs the low-cost coal-burning, nuclear and hydro units as base load.

Eskom then runs the gas turbines as the demand increases and exceeds the base load capacity. The generation cost is reflected in the summer and winter tariffs and there are different tariff structures for weekdays, Saturdays and Sundays. Lastly, there is a TOU tariff structure over a 24-hour period, as shown in Table 3-9.

Table 3-9: Eskom tariff structure

Time	Summer 2013 (ZARc/kWh)			Winter 2013 (ZARc/kWh)		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
00:00	32.70	32.70	32.70	37.76	37.76	37.76
01:00	32.70	32.70	32.70	37.76	37.76	37.76
02:00	32.70	32.70	32.70	37.76	37.76	37.76
03:00	32.70	32.70	32.70	37.76	37.76	37.76
04:00	32.70	32.70	32.70	37.76	37.76	37.76
05:00	32.70	32.70	32.70	37.76	37.76	37.76
06:00	51.53	32.70	32.70	69.53	37.76	37.76
07:00	74.88	51.53	32.70	229.52	69.53	37.76
08:00	74.88	51.53	32.70	229.52	69.53	37.76
09:00	74.88	51.53	32.70	229.52	69.53	37.76
10:00	51.53	51.53	32.70	69.53	69.53	37.76
11:00	51.53	51.53	32.70	69.53	69.53	37.76
12:00	51.53	32.70	32.70	69.53	37.76	37.76
13:00	51.53	32.70	32.70	69.53	37.76	37.76
14:00	51.53	32.70	32.70	69.53	37.76	37.76
15:00	51.53	32.70	32.70	69.53	37.76	37.76
16:00	51.53	32.70	32.70	69.53	37.76	37.76
17:00	51.53	32.70	32.70	69.53	37.76	37.76
18:00	74.88	51.53	32.70	229.52	69.53	37.76
19:00	74.88	51.53	32.70	229.52	69.53	37.76
20:00	51.53	32.70	32.70	69.53	37.76	37.76
21:00	51.53	32.70	32.70	69.53	37.76	37.76
22:00	32.70	32.70	32.70	37.76	37.76	37.76
23:00	32.70	32.70	32.70	37.76	37.76	37.76
Colours	Summer			Winter		
	Peak	Standard	Off-peak	Peak	Standard	Off-peak

Load-management strategies focus on the TOU of electricity. The cheapest tariff for energy use is the off-peak tariff in the summer at 32.70 c/kWh. The most expensive tariff for energy use is during the Eskom peak hours on a winter's weekday at 229.52 c/kWh. The highest tariff is six times more expensive than the cheapest tariff.

There must be a form of capacitance in the operation to manage the load according to the electricity cost. Dams in a pumping setup are an excellent example of capacitance. The equipment doing the work must also be operating below installed capacity.

Another example of this is pumps with an installed capacity of 500 ℓ/s operating in a mine that, on a typical day, pumps 240 ℓ/s. The dams at the bottom fill up during the most expensive TOU and water is pumped during the least expensive TOU.

Pumping energy cost-saving will be discussed in more detail in the following section and is followed by fridge plant projects and thermal storage. These projects are categorised as load management because they essentially remain energy neutral.

3.3.2. Pumping

Mines use water for drilling, dust suppression, cleaning and cooling in the working area, as described earlier in this thesis. The water is supplied from the intermediate chill dam and used in the working sections. The water from the working sections flows down return channels to the shaft. At the shafts, it falls down chutes to the bottom where it is collected.

The collected water is full of mud. The water and mud are separated in the settlers and mud is processed as described in the previous chapter. The clear water is then pumped to the mine-refrigeration system on the surface or underground at a level above mine operations, as shown in Figure 3-4.

As stated, the mine operates on a three-shift cycle. During the morning shift, holes are drilled and filled with explosives. The afternoon shift is also referred to as the blasting shift. The mine is cleared of mining production personnel for the blasting shift. The evening shift is used to clear the area of the blasted ore by moving it into the ore passes. It can be concluded that chilled water is not used during the blasting shift.

The mine's chill dam should be filled with sufficient water to be used during a shift. There is a time delay from when the water is used and when the water is again caught in the settlers. Other factors are local cooling cars, many water leaks and poor discipline by mine personnel not closing taps and not unplugging equipment in working sections. This contributes to, and in some cases causes, a near constant flow of service water.

The control on the dam levels should leave sufficient capacity to give mine personnel time to attend to the problems without flooding the mine. The installed pumping capacity with redundant standby pumps that allow for maintenance exceeds the utilised pumping capacity.

The load-management control system takes the abovementioned risks and opportunities into account. Maximum dam level set points are chosen lower than the actual maximum capacity of the dam. Minimum dam level set points are chosen higher to minimise the risk of sucking the mud accumulating at the bottom of the dam into the pumps.

Pumping efficiency is also optimised by distributing the load between two columns and two pumps. The scheduling of the pumps is done in such a way as to minimise the risk and is also integrated with the mine maintenance schedule. The ventilation and cooling power profile is shown in Figure 3-8.

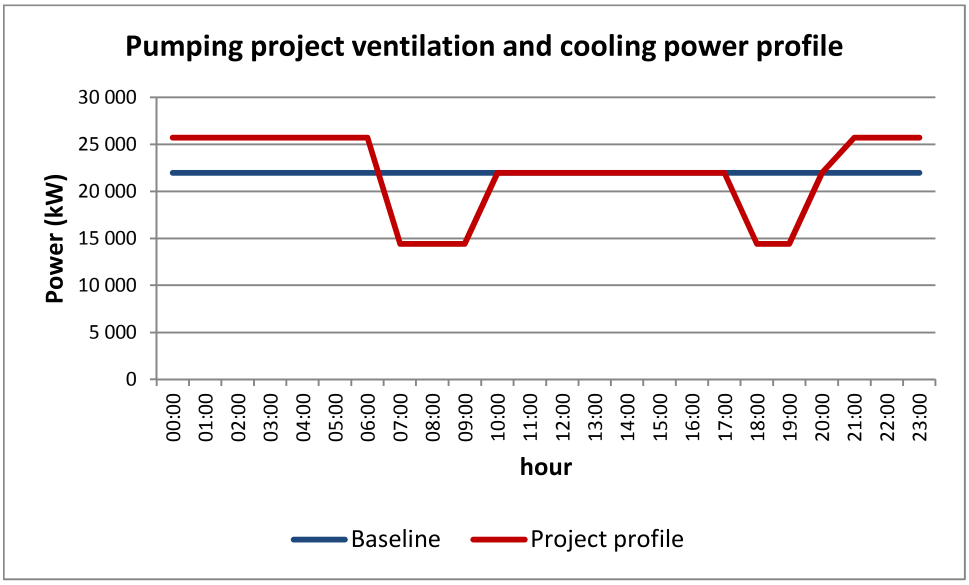


Figure 3-8: Pumping project ventilation and cooling power profile

The cost profile is shown in Figure 3-9 and an annual cost-saving of 9% at R6 million is achieved.

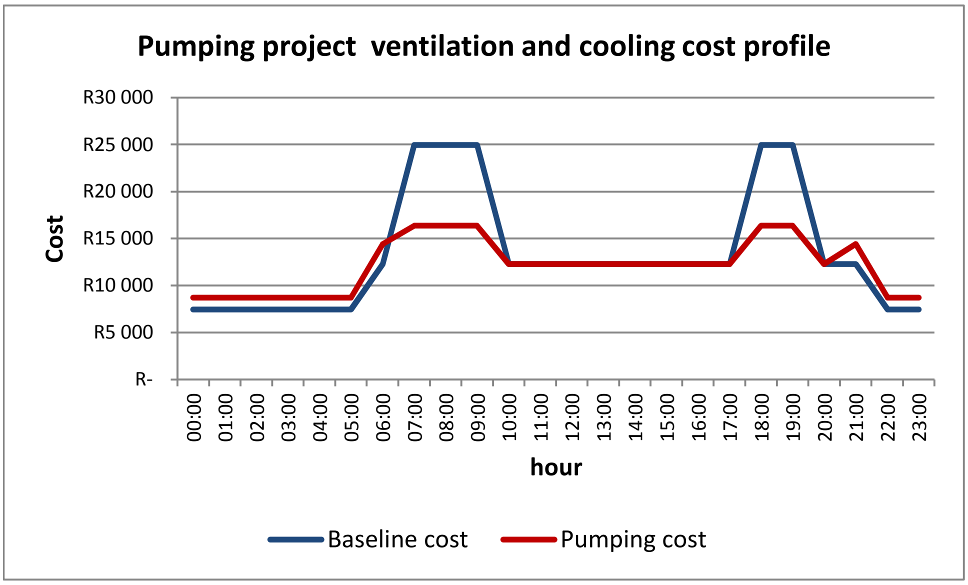


Figure 3-9: Pumping project ventilation and cooling cost profile

These projects have been investigated, simulated and implemented. They are tried, tested and proven energy cost-saving strategies for a mine-cooling and ventilation system. The evaluation procedure as described at the start of this chapter was applied to the pumping load-management project and the result is shown in Figure 3-10.

From the risk analysis, it can be seen that the project scores 1.14 out of a maximum possible score of 25. This means that the project seldom has a significant effect on the mine operation. Dividing the score by the maximum possible score indicates where the project lies on a 0 to 100% ruler. It can be seen that pumping is a minimum risk project at 5%.

Hazard identification and risk assessment

Project:	Pumping	**Section:**	Clear water pumping

Magnitude and severity - Lost production shifts
The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between
The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 -Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project does not interfere with service delivery	1	1	1	1	1
Production	Project does not interfere with production	1	1	1	2	2
Environmental health and safety	Project does not affect the environment or the health and safety of employees	1	1	1	3	3
Overhead cost	Project reduces maintenance cost through preventative maintenance	1	2	2	1	2

Evaluation of project	
Weighed risk indicator	1.14
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	5%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	Pumping
	0	

Figure 3-10: Pumping risk evaluation

Another element that should be considered when choosing a load-management or energy-efficiency project is whether the project will upgrade and enhance existing infrastructure, reduce maintenance or add additional systems that will increase maintenance.

The cost-saving is realised using a REMS with the required infrastructure upgrades to allow the control and monitoring of the pumps and dam levels. The implementation time for these projects is 12 months. The PAI is calculated in Figure 3-11. Implementing a pumping project correctly will enhance the existing infrastructure, setting a good foundation for other projects.

Project appeal indicator (PAI)

Project: Pumping

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	1	1	**1**
Upgrading existing equipment	8	7	**56**
Monitoring and networking the mine	8	8	**64**
Displaying and logging mine system variables	8	9	**72**
Short implementation time	7	8	**56**
Little down time required for implementation	7	8	**56**
Interaction with other systems	6	7	**42**

Evaluation of project	
Sum of weighed aspect scores	347
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	50%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	Pumping
	40	
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-11: Pumping PAI

An added benefit of this project is the monitoring of total water volume in the system. It reduces the amount of water that needs to be treated before it is rejected. It also limits the amount of potable water added to the system.

Monitoring the system allows bottlenecks in the system to be mitigated and also aids in pump maintenance through load scheduling and performance monitoring. Having the network installed with trending data makes fault-finding quick and easy, and helps with the overall maintenance of the system, as well as needed repairs.

3.3.3. Fridge plant

The service-water refrigeration system chills the water used to cool the working areas. These systems can be situated on the surface or underground. These systems usually have a lead-lag configuration to adapt to varying temperatures and flow as shown in Figure 3-12.

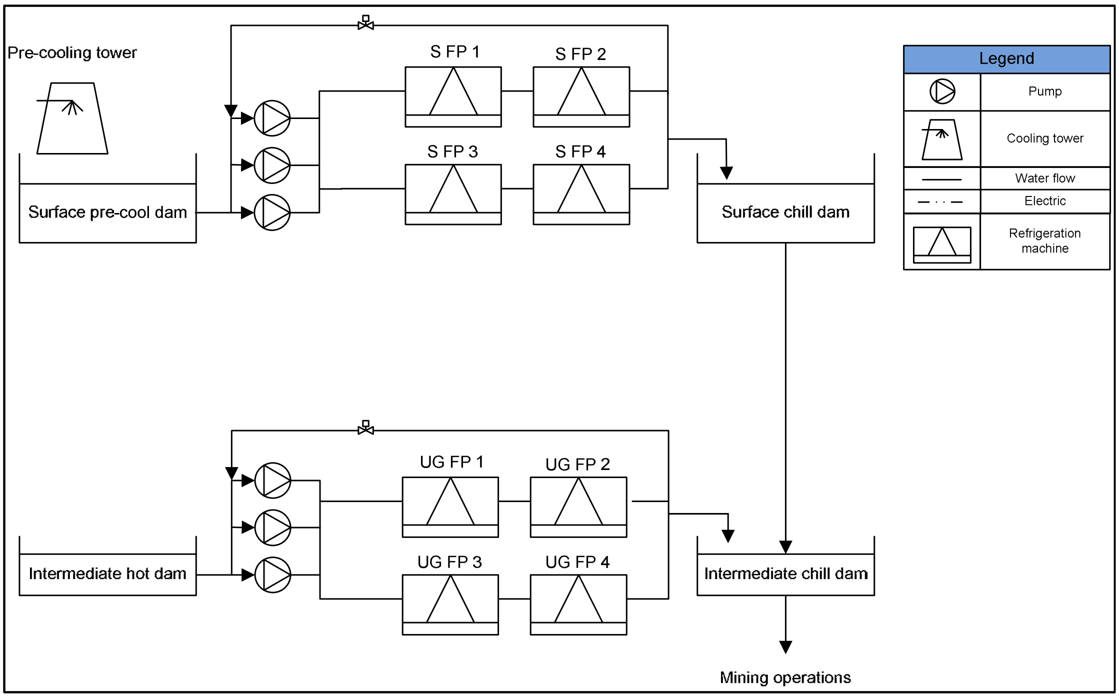


Figure 3-12: Mine refrigeration system

Similar to the pumping described above, the refrigeration system has a certain cooling capacity and thermal storage. The cooling load can by shifted to realise a minimum energy cost by utilising the cooling capacity and thermal storage correctly. Figure 3-13 shows the power profile of the mine-cooling and ventilation system after a fridge plant project was implemented on both the surface and underground service-water refrigeration system.

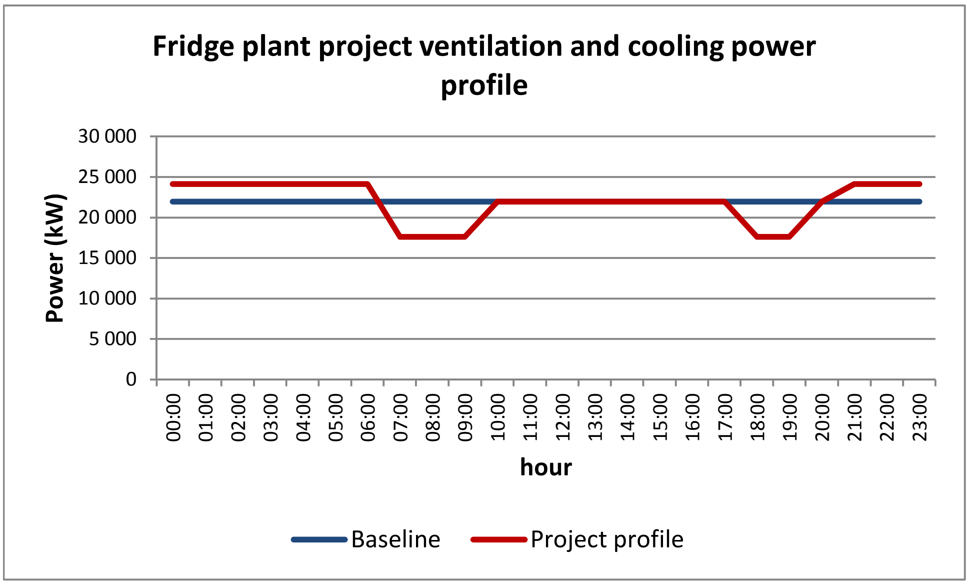


Figure 3-13: Fridge plant project ventilation and cooling power profile

The resultant change on the mine-cooling and ventilation cost is shown in Figure 3-14. The annual saving of the project will be R4 million. It realises a 5% saving on the total annual mine-cooling and ventilation electricity bill.

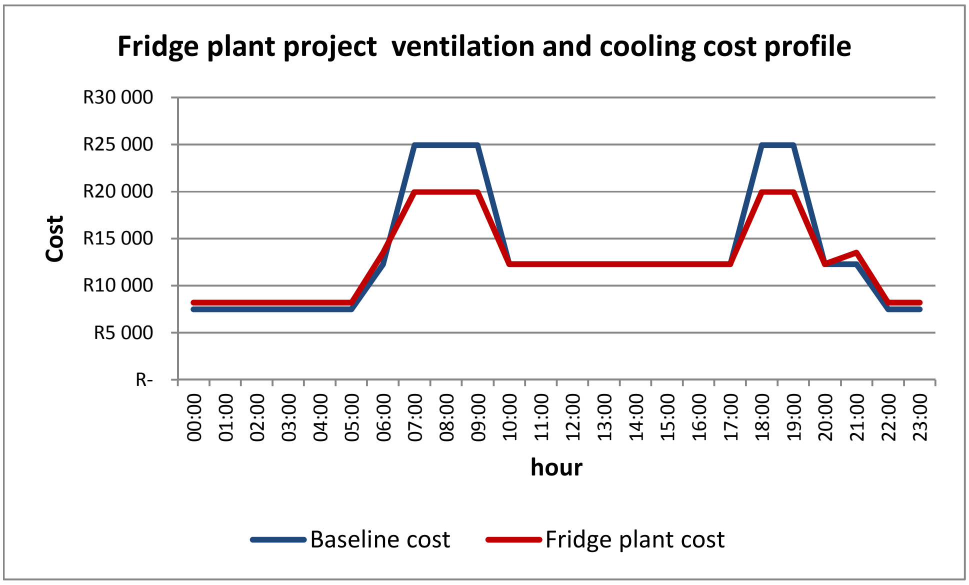


Figure 3-14: Fridge plant project ventilation and cooling cost profile

Several such systems have been investigated, simulated and implemented. Figure 3-15 shows the risk analysis for fridge plant projects.

There is no risk involved in these projects when the dams and refrigeration machines are used within their safe limits.

Hazard identification and risk assessment

Project:	Fridge plant	**Section:**	Refrigeration

Magnitude and severity - Lost production shifts
The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between
The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 -Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		**Evaluation of risk**			**Weight**	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project may delivery warmer water for a period during the day if not set-up correctly	2	2	4	1	4
Production	Project does not interfere with production	1	1	1	2	2
Environmental health and safety	Project does not affect the environment or the health and safety of employees	1	2	2	3	6
Overhead cost	Project may cause additional wear on components such as seals leading to their replacement	2	3	6	1	6

Evaluation of project	
Weighed risk indicator	2.57
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	10%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	Fridge plant
	5	
	0	

Figure 3-15: Refrigeration risk evaluation

These projects may have an energy-efficiency component to them, due to most of the cooling happening during the cooler evening when the plant has the best efficiency. These effects are not significant and are not taken into account as a load-management project is evaluated as being energy neutral.

The saving is realised by using a REMS with the required infrastructure upgrades to allow the control and monitoring of the plant. The estimated implementation time for these projects is 12 months.

Project appeal indicator (PAI)

Project: **Fridge Plant**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	1	1	**1**
Upgrading existing equipment	7	7	**49**
Monitoring and networking the mine	6	8	**48**
Displaying and logging mine system variables	8	9	**72**
Short implementation time	7	8	**56**
Little down time required for implementation	4	8	**32**
Interaction with other systems	3	7	**21**

Evaluation of project	
Sum of weighed aspect scores	279
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	40%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	Fridge Plant
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-16: Refrigeration PAI

An added benefit of this project is the monitoring of the service-water cooling system. Monitoring the system allows bottlenecks in the system to be mitigated and also aids in system maintenance through the load scheduling and performance monitoring of equipment.

Having the network installed with trending data makes fault-finding quick and easy, and helps with the overall maintenance of the system, as well as needed repairs. Upgrading the control of the system also gives a more constant and reliable outlet temperature. The machine's improved control reduces the amount of trips.

3.3.4. Thermal ice storage

Similar to the fridge plant projects described in the previous section, thermal ice storage also uses cooling capacity and thermal storage to reduce the cost of cooling and chilling the service water.

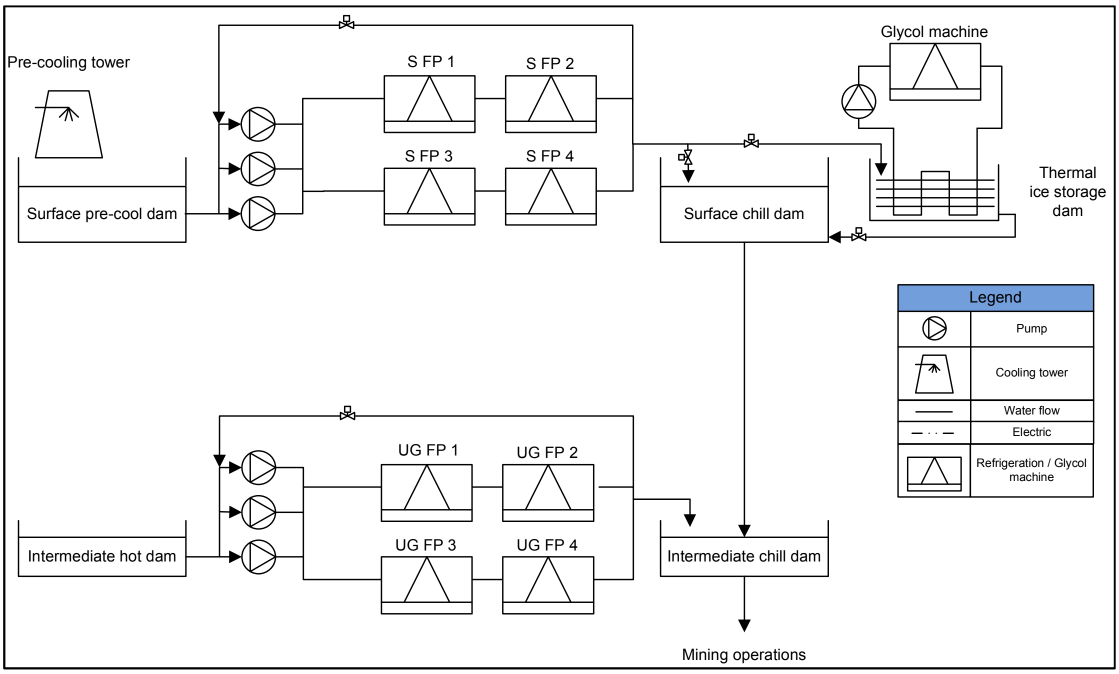


Figure 3-17: Thermal ice storage

Additional cooling capacity and thermal storage for the plant need to be built on these projects. Using ice reduces the civil cost as a small dam is built for extra capacity.

To increase cooling, a glycol plant is either added or an existing machine is retrofitted to produce sub-zero temperatures for the glycol system. The glycol is circulated in a closed-loop pipe system through the small dam. Mine service water is then iced around the pipe to achieve thermal storage.

Building an additional plant adds capacity and electricity consumption. Retrofitting an existing plant reduces its efficiency and uses more electricity to achieve sub-zero temperatures. Both these options add to the power and energy consumption of the system.

There is also no evidence that such a project has been done on underground service-water refrigeration systems. The ventilation and cooling power profile of a thermal ice-storage project on the surface service-water refrigeration system is shown in Figure 3-18.

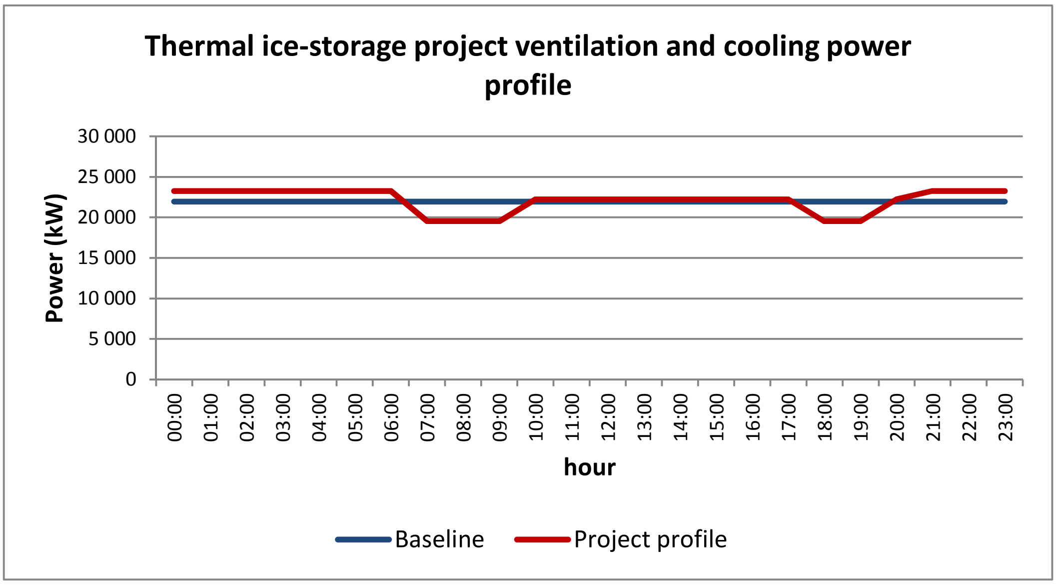


Figure 3-18: Thermal ice-storage project ventilation and cooling power profile

With the added power, the thermal ice-storage system achieves a R2 million annual saving. This is a 2% saving on the annual mine-cooling and ventilation electricity bill. The mine-cooling and ventilation power usage profile is shown in Figure 3-19.

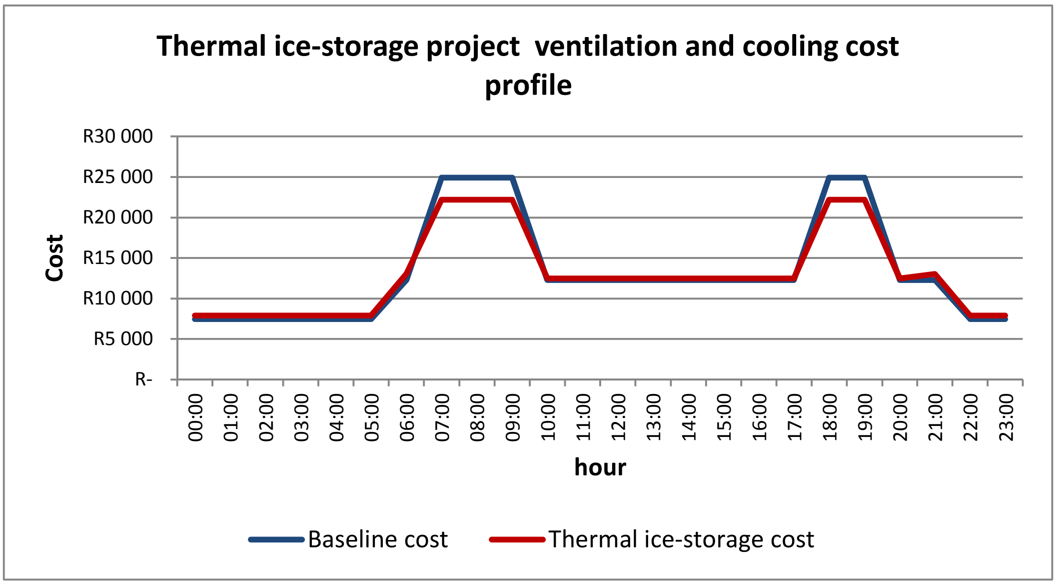


Figure 3-19: Thermal ice-storage project ventilation and cooling cost profile

Applying Parkinson's Law to mine ventilation and cooling, the mine-cooling load will increase and use the full surface service-water cooling capacity. This happens when one disregards the load-management project and uses the thermal ice-storage system as an after-cooler for the refrigeration system.

The service water at the same flow rate of 140 ℓ/s is then chilled from 3 ^{o}C to 0.5 ^{o}C before it is sent underground. Supplying colder water increases the energy usage of the system. This increased power usage and the added inefficacy of making ice increases the annual cost of the mine-cooling and ventilation system.

For this study, however, the project is evaluated as it is intended and several such systems have been investigated, simulated and implemented on the surface refrigeration. The risk analysis for thermal ice-storage projects is shown in Figure 3-20.

The build-up of ice due to uneven melting and uneven freezing produces service and production risks. There is a risk to the environment with the construction of dams and adding new chemicals to the refrigeration system. The added infrastructure adds to the overhead cost of the mine.

Hazard identification and risk assessment

Project:	Thermal ice storage	**Section:**	Refrigeration

Magnitude and severity - Lost production shifts
The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 - Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between
The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		**Evaluation of risk**			**Weight**	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project can interfere with service delivery due to uneven melting and freezing	2	5	**10**	1	10
Production	Project can interfere with production due to decreased service delivery	2	5	**10**	2	20
Environmental health and safety	Project requires a dam to be build with new pipe work which has an affect the environment. Additional chemical exposure to employees	4	3	**12**	3	36
Overhead cost	Project adds overhead expense for glycol and added maintenance	3	4	**12**	1	12

Evaluation of project	
Weighed risk indicator	11.14
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	45%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	Thermal ice storage
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-20: Thermal ice-storage risk evaluation

These savings are realised using additional hardware infrastructure. These projects do not come with a REMS.

Due to the cost of converting an existing machine and building additional storage, very little is spent on upgrading the other refrigeration machines. Very little is also spent on upgrading the overall infrastructure of the surface refrigeration system. There is thus no improvement in the control and monitoring of the plant. The estimated implementation time for these projects is 36 months. The PAI for such projects is shown in Figure 3-21.

Project appeal indicator (PAI)

Project: **Thermal ice storage**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	8	1	**8**
Upgrading existing equipment	1	7	**7**
Monitoring and networking the mine	2	8	**16**
Displaying and logging mine system variables	4	9	**36**
Short implementation time	3	8	**24**
Little down time required for implementation	4	8	**32**
Interaction with other systems	2	5	**10**

Evaluation of project	
Sum of weighed aspect scores	133
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	19%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	
	20	
Undesirable project	10	Thermal ice storage
	0	

Figure 3-21: Thermal ice-storage PAI

3.3.5. Conclusion

Energy cost-saving projects focus on reducing the operational cost of the mine-cooling and ventilation system according to Eskom's TOU tariffs.

The pumping projects utilise the mine-water storage and pumping capacity to realise the most cost-effective pumping schedule. Fridge plant projects use the installed cooling capacity and thermal storage to realise the most cost-effective cooling schedule.

Both these systems are combined with a REMS and the overall upgrading of the plant infrastructure for monitoring and control from a central point. The risks with the above two projects are low and a big advantage is the remote stop and start of the pumps and refrigeration machines. These projects can be installed and completed within 12 months.

Thermal ice-storage cost-saving is offset with added electricity consumption. There is more risk with such a project and little other infrastructure is added for the control and monitoring of the mine systems.

These projects take up to three years. Significant time and costs are allocated to the design, planning, fabrication, manufacture and construction of these projects. In the following section, the cost-saving, risk and PAI of energy-saving strategies are examined.

3.4. Energy-efficiency initiatives

3.4.1. Introduction

The previous sections' load-management projects still use the same amount of or more energy after completion. The energy is just used at the most cost-effective time. Energy-efficiency projects aim to reduce the amount of power required or the amount of time the power is required. Electricity and energy generated or harnessed and used in the cooling and ventilation system is also considered an energy-efficiency project.

There is an initial impression on mines that their systems operate efficiently. They assume that, with a reduction in power, comes a reduction in service delivery. They are also blinded by the mentality that the system has operated in its current state for the past 20+ years. They believe that any change to the system will negatively affect the system.

Mine personnel are more accepting of load-management projects as they require the operation to run the same way, just at different times of the day. Engineers and energy managers are usually commissioned to first investigate load-management projects and then energy-efficiency projects. After load-management investigation and projects, a suspicion arises that the mines' plants and systems are not as efficient as initially assumed.

The simulation model built for load-management projects is a good starting point for energy-efficiency project investigations. If a load-management system has been implemented, the simulation can also be improved using the logged data of an EMS.

The load-management implementation time of between 12 and 36 months also allows sufficient time to build a relationship with mine personnel and, with their help, optimise the system simulation model. Their suspicions about where the energy system operates inefficiently can then be investigated.

The simulation results and captured data can then be evaluated and the results used to motivate funding for these energy-efficiency projects. The results should ensure that the project will not reduce service delivery or negatively affect the system's operation.

Equipment upgrades for either load-management or energy-efficiency projects on a subsection of the ventilation and cooling system are beneficial. It is even more beneficial when upgrades are done on shared infrastructure of a load-management and energy-efficiency project.

Installing an EMS to achieve load management then allows for faster, easier and more accurate energy-efficient project investigations that are less risky and leave less to chance. The reporting and long-term maintenance on such a system also makes it easier to identify energy wastage.

In the following section, the mine ventilation and cooling energy-saving strategies are discussed and analysed. This is done according to the same criteria as the load-management strategies from the previous section. Energy recovery is the first energy-saving project, because it harnesses already available potential energy.

3.4.2. Energy recovery

The problem with energy-recovery devices comes with the reporting of the saving. The assumption is that the saving is proportional to the amount of electricity generated, as shown in Equation 19.

Energy cost-saving = Energy generated x Cost of energy (Eq. 19)

At 140 ℓ/s, the power generated by the energy-recovery system is 1 712 kW. Increasing the flow to 200 ℓ/s increases the power generated to 2 445 kW. Using Equation 19 will show that the cost-saving for 140 ℓ/s is R24 916 per day. The saving for 200 ℓ/s equates to R35 595 per day.

This is an increase of R10 678 per day. Based on these reported savings, the mine wrongly increases the flow from 140 ℓ/s to 200 ℓ/s. The correct reported saving is given by Equation 20.

Energy cost-saving = (Baseline power – Power after project) x Cost of energy (Eq.20)

The baseline should be measured at the start of the project. For the example, the baseline of 2 778 kW is measured at 140 ℓ/s and equates to a cost of R40 447 per day. At 140 ℓ/s, the profile after implementation is 1 067 kW, which equates to R15 532 per day. The saving is then R24 916 per day, which is the same as using Equation 19.

Increasing the flow to 200 ℓ/s will result in the profile increasing from 1 067 kW to 1 524 kW and the cost increasing from R15 532 per day to R22 188 per day. The saving, using Equation 20, is then R18 259 per day and not R35 595 per day as reported using Equation 19.

The above does not even take into account the additional 60 ℓ/s that will have to be processed by the mine-surface service-water refrigeration system. It is thus crucial that an EMS is installed with an energy-recovery project to report the correct saving.

An EMS on the surface and underground refrigeration system will report the cooling load profile and can report a saving or increase due to the energy-recovery project. An EMS on the pumping system can determine the baseline power and measure the implemented project profile to determine the saving. An EMS on the turbine will ensure it is optimally utilised and report the power generated.

To effortlessly integrate all these EMSs, it is important that they are compatible with each other and with a central program. They should be able to work together while maintaining focus on their separate systems. Standardisation is the process of developing and implementing technical standards that achieve the aforementioned goals.

It can thus be concluded that a mine should standardise on compatible EMSs that integrate effortlessly. Products from the same company are built on the same platform and with the same core principles, and are known to be compatible and to effortlessly integrate with one another and with new programs from that company.

Turbines

South African gold and platinum mines operate at great depth, with which comes great potential energy. Energy-recovery devices convert this potential energy into working energy.

Turbines are the first energy-recovery device that can be used for energy-saving projects. As discussed in Chapter 2, they are either coupled directly to a pump, or they generate energy that can be used for pumping. A layout is shown in Figure 3-22.

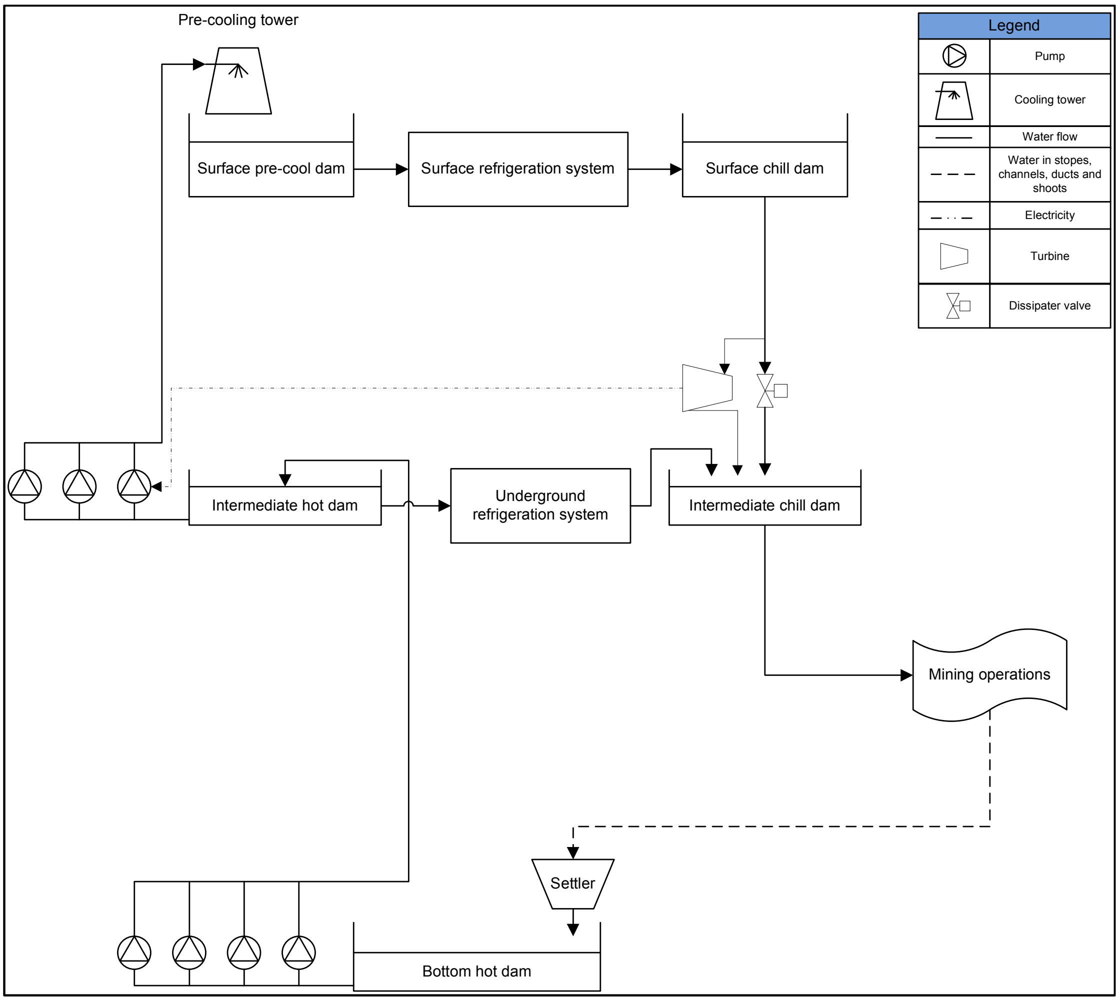


Figure 3-22: Mine turbine layout

Turbines are efficient. Due to the extreme forces exerted on them and the poor quality of mining service water, they break often and have a low utility rate.

Special parts and labour are required to maintain a turbine. These parts and labour in most cases need to be imported due to South Africa not possessing the required design and manufacturing skills and infrastructure.

If the maintenance and consumable parts are not manufactured correctly, it could cause a catastrophic failure of the turbine. The energy generated by a turbine can be calculated by using Equation 10. The potential energy is multiplied with the efficiency and utilisation factors as shown in Table 3-10.

Table 3-10: Mine turbine power

Head	1 800	M
Flow	0.14	m^3/s
Efficiency	95	%
Utilisation	70	%
Power	1 626	kW
Constants		
ρ	998.21	kg/m^3
g	9.72	m/s^2

For the simulation, the power generated by the installed turbine will be used directly for pumping. Thus, a saving of 1.6 MW is achieved on the pumping system. The mine-cooling and ventilation power profile for a turbine project is shown in Figure 3-23.

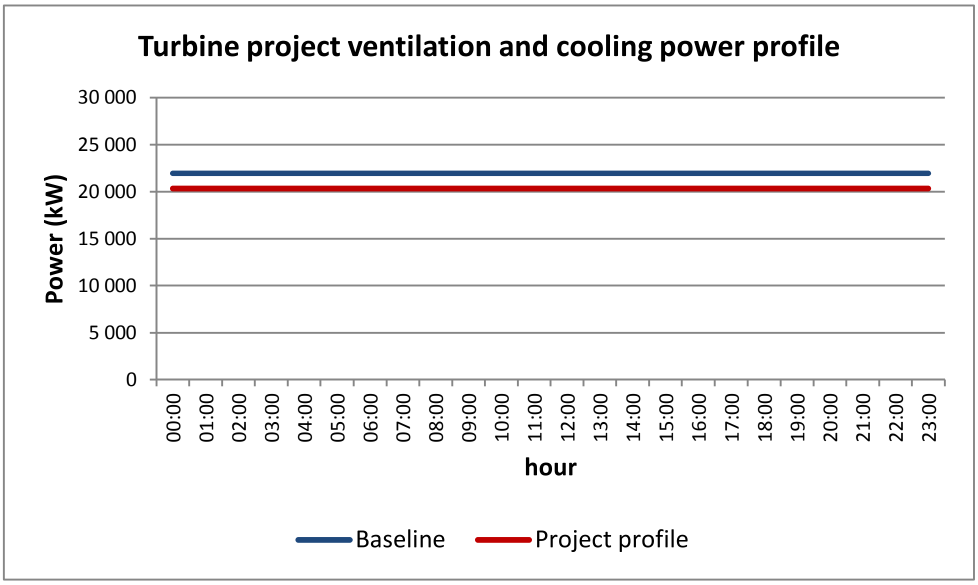


Figure 3-23: Turbine project ventilation and cooling power profile

The ventilation and cooling cost profile for a turbine project is shown in Figure 3-24. An annual saving of R6 million is achieved and is 7% of the mine ventilation and cooling annual electricity bill.

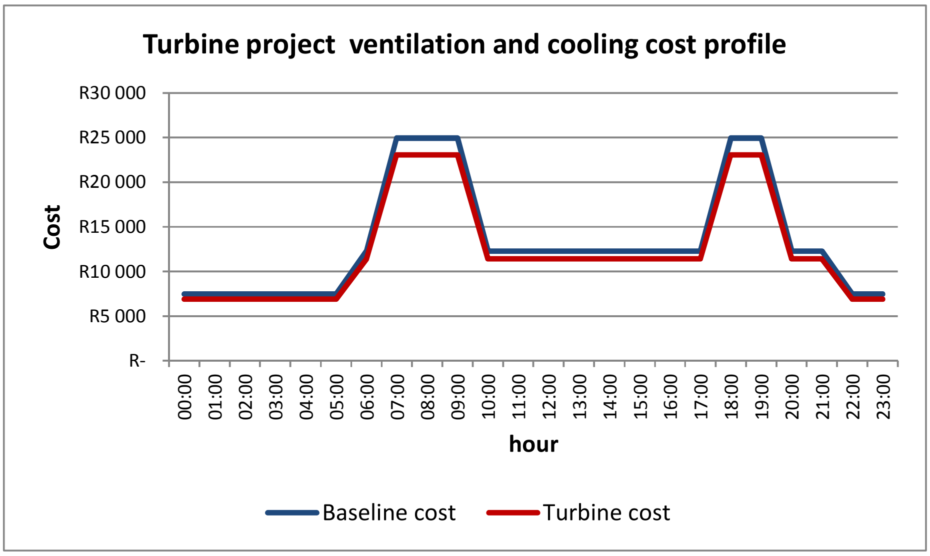


Figure 3-24: Turbine project ventilation and cooling cost profile

The turbines project is evaluated in the same way as the load-management projects of the previous section and the result is shown in Figure 3-25. With a bypass valve being mandatory, there is no risk to service delivery or production. The pumping system can operate independently from the turbines and the mine will not flood.

The high speed at which the Pelton wheel turns, poses a danger to employee health and safety. The replacement cost of nozzles and Pelton wheels, added to the additional maintenance required, increases the overhead cost for the mine. An overall score of 17% makes it an appealing low-risk project.

Using other turbine technologies, such as the impact turbine, could further reduce the risk. This comes at a loss of efficiency. These new systems should increase the utilisation of the system. The increase in utilisation should outweigh the loss in efficiency. Overall, the evaluation of the Pelton wheel is sufficient for turbine-type energy-recovery devices.

A drawback of these projects is that load management cannot be utilised according to Eskom's TOU. The energy generated by the turbine cannot be stored. The turbine is bypassed, reducing its utilisation if the mine production requires service water and there is no need for pumping.

Hazard identification and risk assessment

Project: Turbines — **Section:** Water distribution

Magnitude and severity - Lost production shifts
The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between occurrences
The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	With a bypass valve being mandatory there is little risk to service delivery	1	3	3	1	3
Production	Project does not interfere with production	1	1	1	2	2
Environmental health and safety	High speed of peloton wheel adds to the dangers and risk exposure of employees	3	1	3	3	9
Overhead cost	Project adds overhead expense. The high pressure degrades the peloton wheel and nozzle. replacing them is added maintenance	4	4	16	1	16

Evaluation of project	
Weighed risk indicator	4.29
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	17%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	Turbines
	10	
	5	
	0	

Figure 3-25: Turbine risk evaluation

With a turbine project, the majority of the project cost will go towards hardware and installation. Infrastructure to distribute the power generated to where the power is used will also need to be installed. Existing systems and equipment will not be upgraded. The mine network and monitoring is expanded by adding the turbines to the SCADA system.

Again, no EMS is supplied to control the turbine and ensure that it is optimally used by simulation and considering water demand and dam levels. An EMS also prevents bottlenecks and eliminates unutilised standing time.

The implementation of such a project exceeds 12 months, with the majority of parts being manufactured overseas. The PAI for a turbine project is shown in Figure 3-26.

Project appeal indicator (PAI)

Project: **Energy recovery turbines**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency (S)	Desirability (D)	Score (SxD)
New equipment	7	1	**7**
Upgrading existing equipment	3	7	**21**
Monitoring and networking the mine	6	8	**48**
Displaying and logging mine system variables	6	9	**54**
Short implementation time	2	8	**16**
Little down time required for implementation	4	8	**32**
Interaction with other systems	2	5	**10**

Evaluation of project	
Sum of weighed aspect scores	188
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	27%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	Energy recovery turbines
	20	
Undesirable project	10	
	0	

Figure 3-26: Turbine PAI

Three-pipe systems

Other energy-recovery devices are three-pipe systems. The U-tube pumping system described in Chapter 2 is illustrated in Figure 3-27. Again, the poor quality of the mine water results in a low utility rate of this application as the special valves fail. The system is not 100% efficient and additional pumping is required to ensure that the mine does not flood.

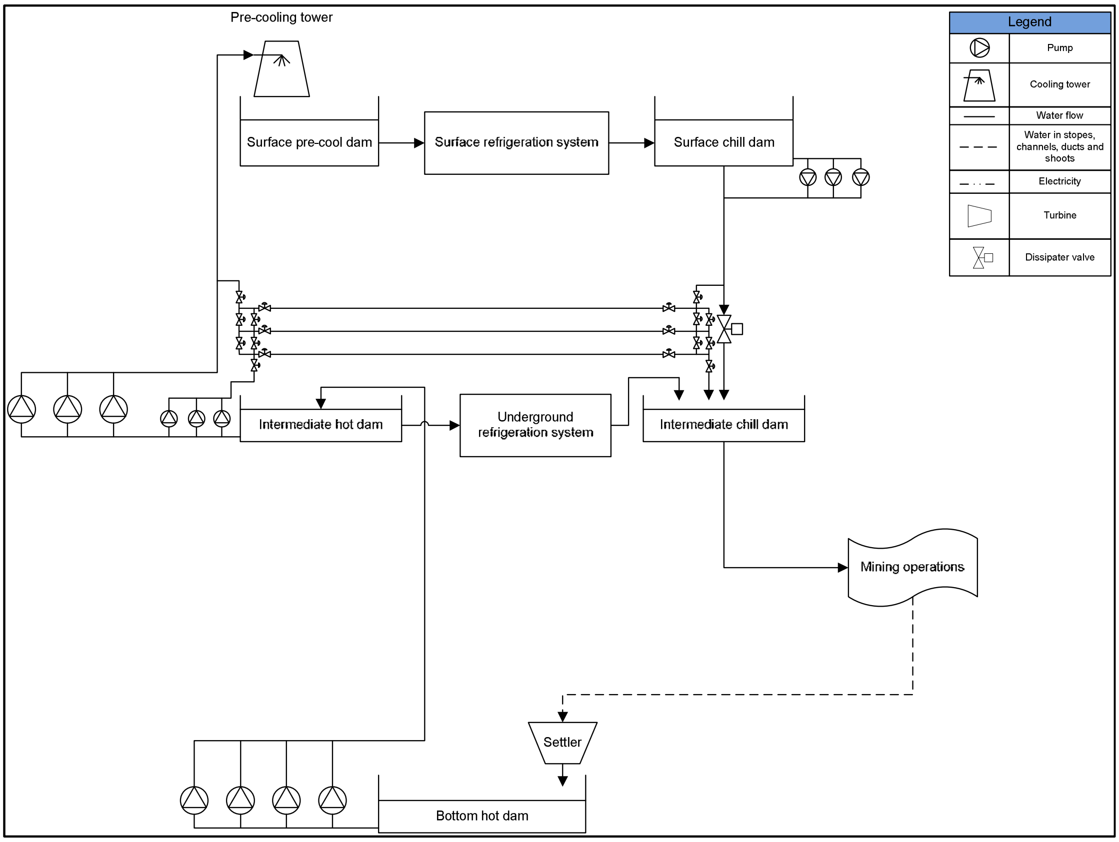


Figure 3-27: Three-pipe layout

The energy used for this project can be calculated as the energy used by the pumps to pump the leftover water to the surface, as well as the auxiliary pumps, which overcome a much smaller head. The pipe friction component is added to the head of the auxiliary pumps in metres. The power used by a three-pipe system is calculated by using Equation 10.

Table 3-11: Three-pipe power calculations

Underground three-pipe auxiliary pumps		
Head	50	m
Flow	0.12	m^3/s
Efficiency	88	%
Power	68	kW
Surface three-pipe auxiliary pumps		
Head	100	m
Flow	0.12	m^3/s
Efficiency	88	%
Power	136	kW
Mine pumps		
Head	1 800	m
Flow	0.02	m^3/s
Efficiency	88	%
Power	333	kW
Total pumping	537	kW
Constants		
P	998.21	kg/m^3
G	9.72	m/s^2

The second-stage pumping power of 2 778 kW is replaced by a three-pipe system that will use 537 kW. The system has a utilisation factor of 60%, which will result in a saving of 1 345 kW, as shown in Figure 3-28.

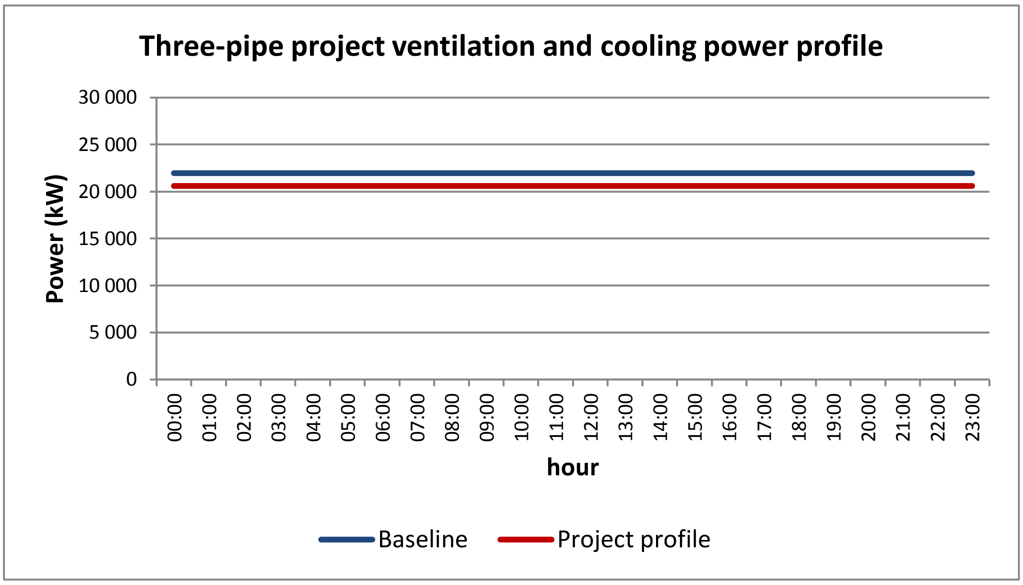


Figure 3-28: Three-pipe project ventilation and cooling power profile

The three-pipe project realises a 6% annual cost-saving of R5 million on the mine ventilation and cooling annual electricity bill. The three-pipe project ventilation and cooling cost profile is shown in Figure 3-29.

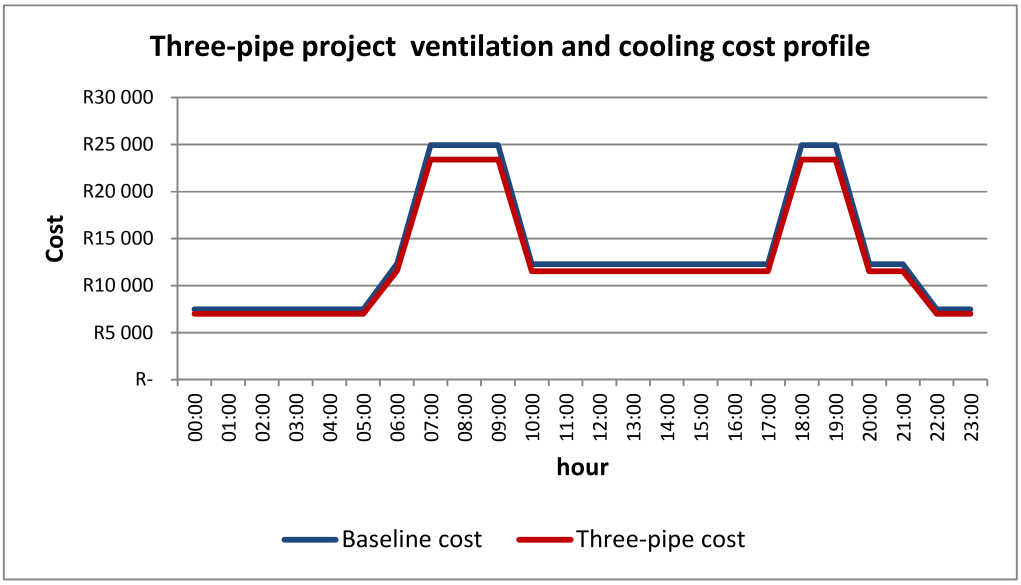


Figure 3-29: Three-pipe project ventilation and cooling cost profile

These systems are maintenance intensive and a risk to mine service delivery. Pumps and dissipater valves are needed to operate the mine when these systems are not available.

This lowers the risk on mine production, health and safety. Again, the risk relating to the three-pipe energy-saving initiative was analysed and the results are shown in Figure 3-30

Project appeal indicator (PAI)

Project: **Energy recovery three-pipe**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency (S)	Desirability (D)	Score (SxD)
New equipment	7	1	**7**
Upgrading existing equipment	1	7	**7**
Monitoring and networking the mine	6	8	**48**
Displaying and logging mine system variables	6	9	**54**
Short implementation time	3	8	**24**
Little down time required for implementation	3	8	**24**
Interaction with other systems	4	5	**20**

Evaluation of project	
Sum of weighed aspect scores	184
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	26%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	Energy recovery three-pipe
	20	
Undesirable project	10	
	0	

Figure 3-30: Three-pipe risk evaluation

With a three-pipe project, as with a turbine project, the majority of the project cost will go towards hardware and installation. The infrastructure required to join the two columns also needs to be installed. Space needs to be created as these systems are the same size as a pumping chamber. Existing systems and equipment, such as the pumps and their control, will not be upgraded.

The mine network and monitoring are expanded by adding the three-pipe system to the SCADA system. Again, no EMS is supplied to control the turbine and ensure that it is optimally used, preventing bottlenecks and eliminating unutilised standing time. The implementation of such a project exceeds 12 months. The PAI for a three-pipe project is shown in Figure 3-31.

Project appeal indicator (PAI)

Project: **Energy recovery Three-pipe**

Sufficiency point out of 10	**Desirability point out of 10**
The sufficiency point indicates how well a project contributes to an aspect out of 10.	*The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.*

Aspects	**Sufficiency (S)**	**Desirability (D)**	**Score (SxD)**
New equipment	7	1	**7**
Upgrading existing equipment	1	7	**7**
Monitoring and networking the mine	6	8	**48**
Displaying and logging mine system variables	6	9	**54**
Short implementation time	3	8	**24**
Little down time required for implementation	3	8	**24**
Interaction with other systems	4	5	**20**

Evaluation of project	
Sum of weighed aspect scores	184
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	26%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	Energy recovery Three-pipe
	20	
Undesirable project	10	
	0	

Figure 3-31: Three-pipe PAI

With a PAI of 26%, a three-pipe project is acceptable. The following projects are energy-saving projects that focus on reducing inefficiencies and the amount of working fluid or service water being circulated through the mine.

3.4.3. Ice

Mines utilise ice as an energy-saving strategy to reduce the amount of water circulated and to save on pumping energy. Ice is produced as either hard ice or as ice slurry. Both are difficult to transport to where it is used and needed. This problem has largely been solved with the development and use of pipe conveyer belts as shown in Figure 3-32.

Ice is actually an alternative for underground refrigeration systems. The saving on pumping is only justified on mines deeper than 1.9 km. A problem is that a major part of the cooling with ice cools the underground chill dam and surrounding area, as it absorbs energy to melt the ice. From here, water is sent to the working area at close to 1 ^{o}C. It is not practical to get ice to the working area and use it at its full potential there.

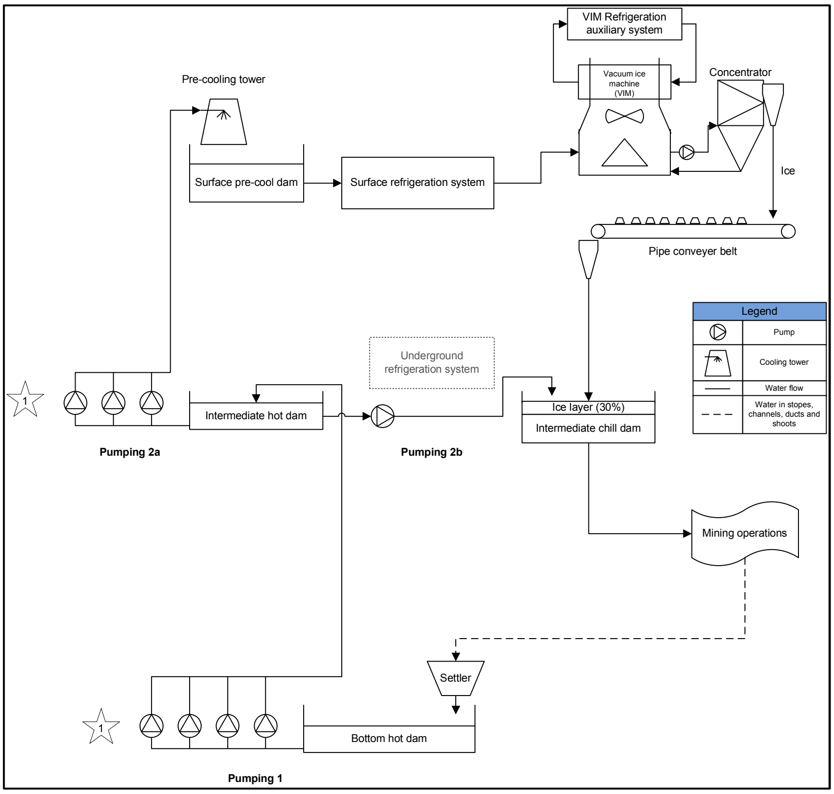


Figure 3-32: Ice layout

Sending water at 1 ^{o}C is better than the 5 ^{o}C achieved by the combination of surface and underground refrigeration systems. As stated in Chapter 1, with Parkinson's Law applied to mine ventilation and cooling, the mine-cooling demand will absorb this additional 4 ^{o}C of cooling. There will be no decrease in the net amount of water circulated, because the mine thermal load increases to match the cooling supplied.

The underground refrigeration system is bypassed in the simulation model in order to test the use of ice as an energy-efficiency project. As stated in Chapter 1, ice absorbs latent heat at 333.7 kJ/kg.K when melting.

Using this, as well as equations 10 and 11, it is calculated that 73 kg/s of ice slurry needs to be created on the surface to replace the underground refrigeration machines. The slurry is 70% ice and 30% water, which means that 50 kg/s of ice is produced.

Table 3-12: Ice project calculations

Pumping 1			**Surface refrigeration**		
Head	1 800	m	Inlet temperature	26	^{o}C
Flow	240	kg/s	Outlet temperature	3	^{o}C
Efficiency	88	%	Flow	73	kg/s
Power	4 763	kW	Thermal kW	7 048	kW
			COP	5.58	
			Power	1 263	kW
Pumping 2 a			**Ice machine**		
Head	1 800	m	Inlet temperature	3	^{o}C
Flow	73	kg/s	Outlet temperature	0	^{o}C
Efficiency	88	%	Slurry	70	%
Power	1 455	kW	Flow ice	51	kg/s
			Flow water	22	kg/s
			Thermal ice	17 120	kW
			Thermal water	919	kW
			Thermal kW	1 8040	kW
			COP	3.8	
			Power	4 747	kW

Pumping 2 b			Ice dam		
Head	29	m	Inlet temperature	26	°C
Flow	167	kg/s	Outlet temperature	1	°C
Efficiency	88	%	Flow water	167	kg/s
Power	53	kW	Thermal kW	17 426	kW
Total pumping	6 271	kW	Total cooling	6 010	kW
Constants			Constants		
ρ	998.21	kg/m^3	C_{pwater}	4181	J/(kg.K)
g	9.72	m/s^2	Cp_{ice}	333.7	kJ/(kg.K)

The total pumping and refrigeration electrical power usage for ice is 12 281 kW. As seen in Figure 3-33, it is slightly more than the model with the underground refrigeration system. The increase can be attributed to the water going into the working sections at 1 °C instead of 5 °C. This shows that, in reality, ice improves service delivery and cannot be counted as an energy-efficiency project.

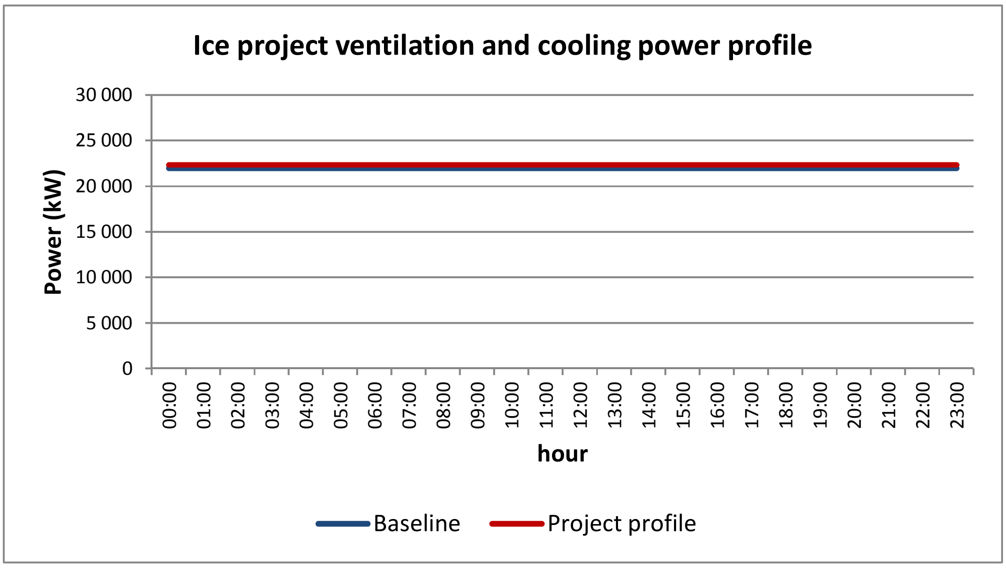


Figure 3-33: Ice project ventilation and cooling power profile

Figure 3-34 shows the increase in the ventilation and cooling cost profile. Delivering more cooling increases the cost of the mine ventilation and cooling system by R1 million per annum. This is an increase of 2%. The energy-recovery systems, such as three-pipe systems and turbines described in the previous section, cannot be utilised in conjunction with ice.

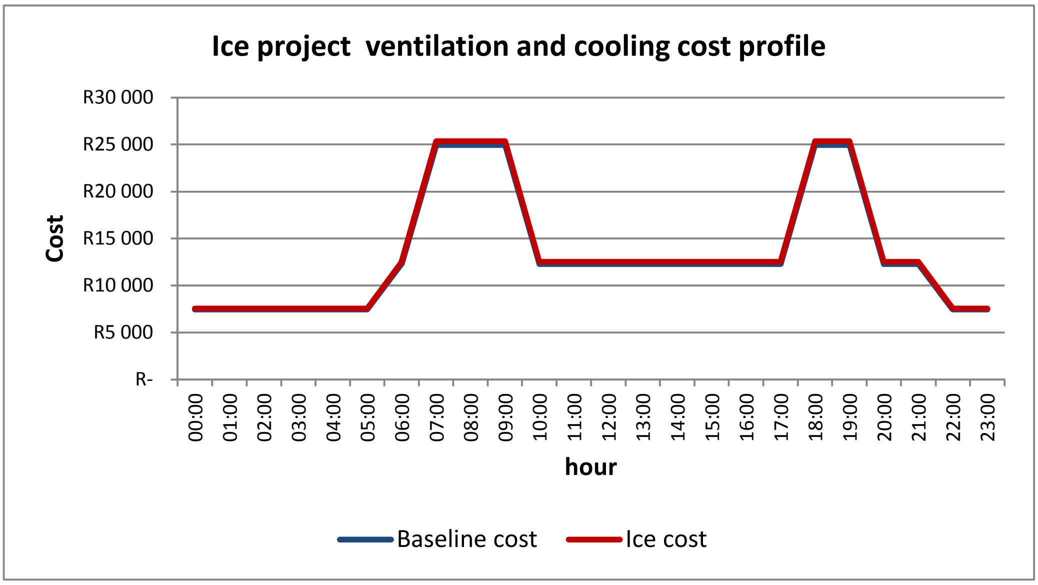


Figure 3-34: Ice project ventilation and cooling cost profile

Ice, as a new technology, has a risk to service delivery, as underground refrigeration systems cannot be installed as a backup. Not having a contingency system poses a risk to production and mine health and safety. The construction of these machines entails the expansion of the surface refrigeration system. Expanding the surface refrigeration system will entail the destruction of local fauna and flora. These risks are evaluated in Figure 3-35.

Hazard identification and risk assessment

Project:	Ice	**Section:**	Surface Refrigeration

Magnitude and severity - Lost production shifts
The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between occurrences
The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Using ice lowers the intermediate chill dam's temperature	1	1	1	1	1
Production	Ice has little effect on production	4	2	8	2	16
Environmental health and safety	These machines affect the fauna a and flora for their construction. Adding danger with moving equipment such as conveyer belts.	3	5	15	3	45
Overhead cost	Project adds overhead expense due to scale build-up on VIM extraction blade. The use of saline solution affects mine steel infrastructure and there is added maintenance on the ice machines and conveyer belt.	4	4	16	1	16

Evaluation of project	
Weighed risk indicator	11.14
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	45%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	Ice
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-35: Ice risk evaluation

These projects take longer than five years to implement. They add hardware infrastructure on the surface. The project does not upgrade existing equipment and, in the simulation, the underground refrigeration system was made redundant.

An ice project does not come with an EMS, and such a system will then have to be installed on the pumping, refrigeration and additional ice machines to monitor, log and report the saving. The PAI for an ice project is determined in Figure 3-36.

Project appeal indicator (PAI)

Project: **Ice**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency (S)	Desirability (D)	Score (SxD)
New equipment	8	1	**8**
Upgrading existing equipment	2	7	**14**
Monitoring and networking the mine	2	8	**16**
Displaying and logging mine system variables	2	9	**18**
Short implementation time	3	8	**24**
Little down time required for implementation	4	8	**32**
Interaction with other systems	2	5	**10**

Evaluation of project	
Sum of weighed aspect scores	122
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	17%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	
	20	
Undesirable project	10	Ice
	0	

Figure 3-36: Ice PAI

3.4.4. Water-supply optimisation

This energy-saving strategy works well after a pumping and refrigeration load-management project has been implemented. Using the simulation models needed for each project, as well as data from the pumping and refrigeration system, allows the water consumption to be monitored and analysed.

It was concluded in the pumping section that there is no-one in the working sections during the afternoon blasting shift. This means that no water is productively used during this time. Control valves are then installed on the mining levels.

The pressure supplied to a level also depends on its depth through auto-compression. Using the installed valves to regulate the pressure during the drilling and cleaning shift results in energy-saving. It may also cause an increase in production on pressure-starved upper levels.

It is possible to totally shut off the water flow to a level during the blasting shift. The pipes would, however, drain empty due to leaking pipes and open-ended cooling cars. Opening the valves under these circumstances would cause water hammer and damage the water distribution network. Therefore, the water pressure on a level is significantly throttled during the blasting period. This reduces the flow through leaks and results in an energy-saving.

Reducing the water has a positive effect on mine service delivery due to less pumps and refrigeration machines being used. Figure 3-37 shows the installation of an EMS used to control the installed level valves on the mine-cooling and ventilation model. Level-control valves reduce the flow from 240 ℓ/s to 180 ℓ/s for the eight-hour blasting shift. This reduces the water circulation to an average of 220 ℓ/s.

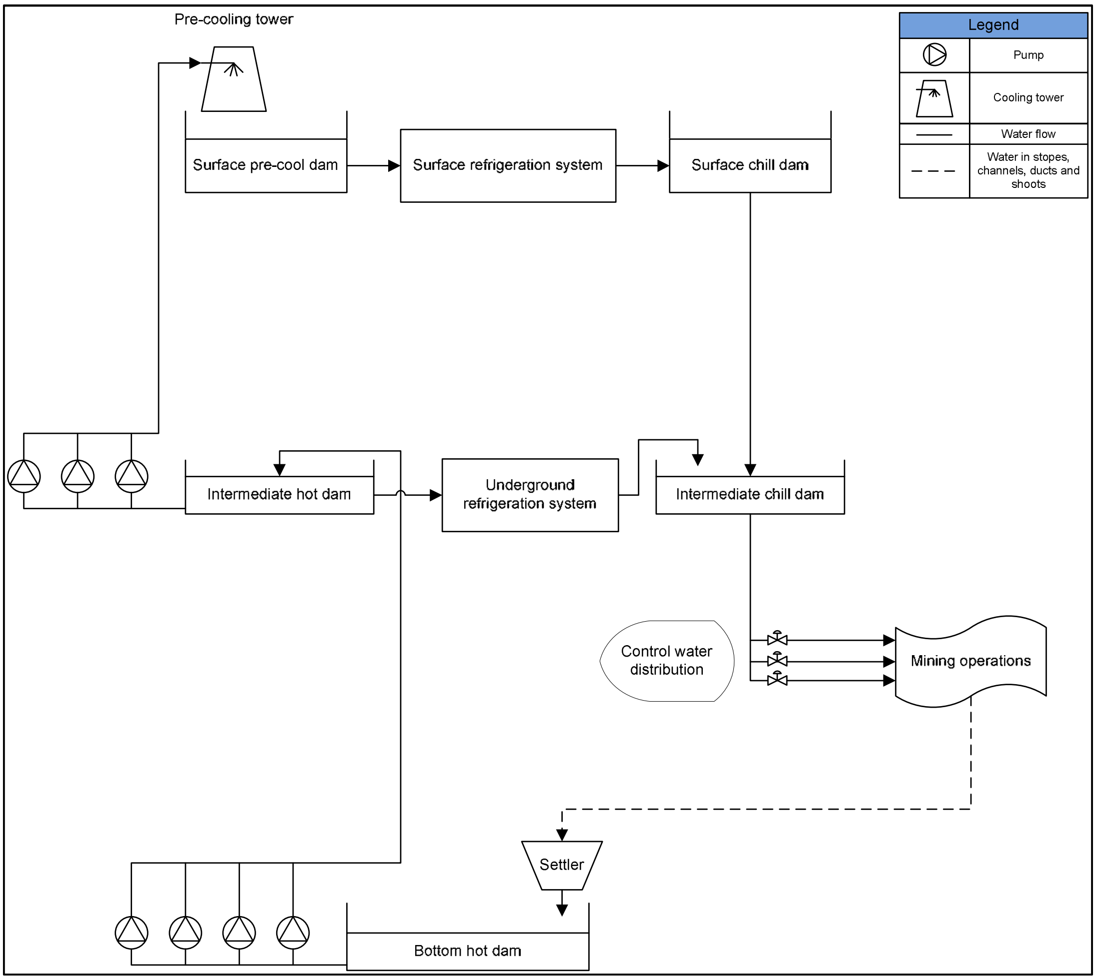


Figure 3-37: Optimal use of water distribution layout

This reduces the amount of water that needs to be pumped and chilled by an average of 20 ℓ/s. The result on the mine ventilation and cooling system's power profile is shown in Figure 3-38.

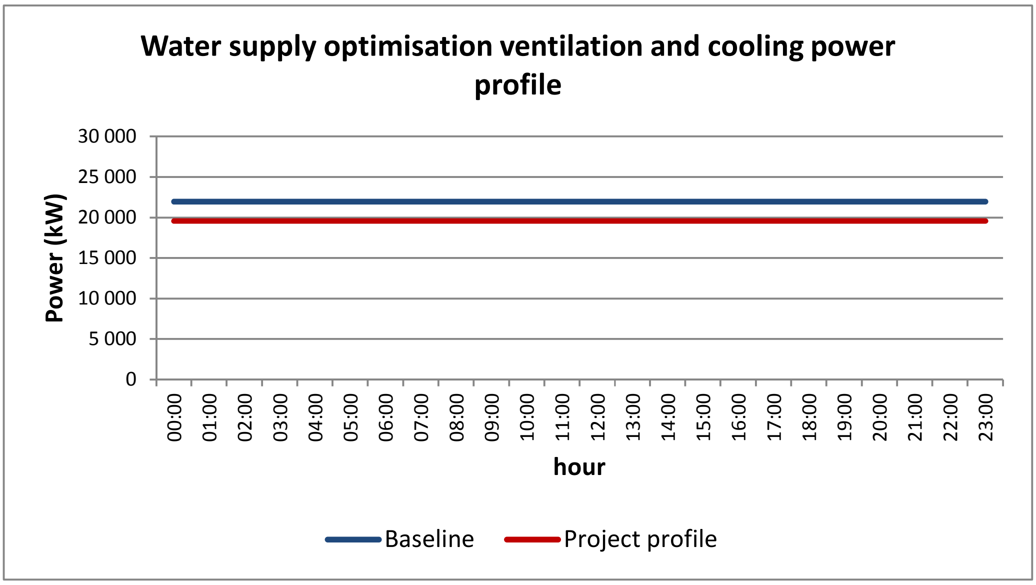


Figure 3-38: Water-supply optimisation project ventilation and cooling power profile

The annual electricity cost is reduced by R9 million. This is an 11% saving on the annual electricity cost of cooling and ventilation. Figure 3-39 shows how the reduction in water demand influences the cost profile.

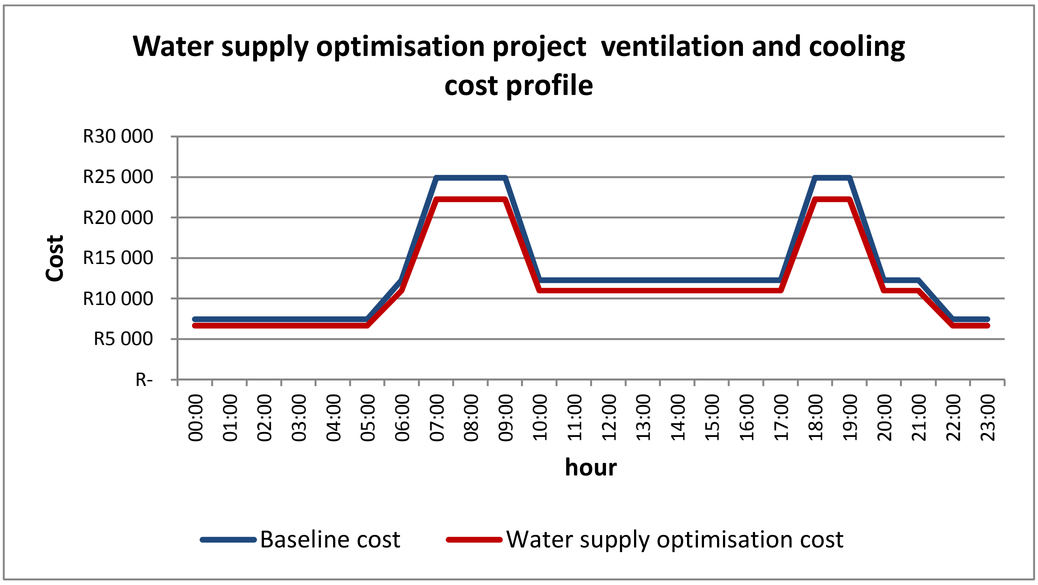


Figure 3-39: Water-supply optimisation project ventilation and cooling cost profile

This strategy has limited risk for mine service delivery. The strategy can affect production when a valve fails to open. There is minimal maintenance on these valves. The risk evaluation is shown in Figure 3-40.

Hazard identification and risk assessment

Project: Water supply optimisation

Section: Service water distribution

Magnitude and severity - Lost production shifts

The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between occurrences

The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	A valve failure will cause a level to be without water	4	1	4	1	4
Production	These valves distributes the pressure equally to all production sections	1	1	1	2	2
Environmental health and safety	These projects has no effect on the mine environmental health and safety	1	1	1	3	3
Overhead cost	The installed valves will require maintenance	3	2	6	1	6

Evaluation of project	
Weighed risk indicator	2.14
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	9%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	Water supply optimisation
	0	

Figure 3-40: Water-supply optimisation risk evaluation

These projects take a year to implement. They extend the mine network and monitor each production level's pressure and flow. Trending, monitoring and reporting this also reduces the amount of water wasted on a level.

If the work is planned and scheduled correctly, there is no downtime on the installation, as a level can be completed on an off-day.

Project appeal indicator (PAI)

Project: **Optimal use of water distribution**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency (S)	Desirability (D)	Score (SxD)
New equipment	6	1	**6**
Upgrading existing equipment	4	7	**28**
Monitoring and networking the mine	9	8	**72**
Displaying and logging mine system variables	9	9	**81**
Short implementation time	9	8	**72**
Little down time required for implementation	9	8	**72**
Interaction with other systems	7	5	**35**

Evaluation of project	
Sum of weighed aspect scores	366
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	52%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	Optimal use of water distribution
	40	
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-41: Optimal use of water PAI

3.4.5. Optimisation of cooling auxiliaries

From data logged by the fridge plant project, inefficiency was seen in the mine-surface refrigeration system. This is due to the over-design of the surface refrigeration system and its running on partial load for most of the year.

The pre-cooling towers, BACs and refrigeration machine evaporator and condenser circuits were targeted for energy-saving strategies. This resulted in the following energy-saving strategies being developed:

- Pre-cooling tower efficiency
- BAC water flow control
- Fridge plant evaporator flow control
- Fridge plant condenser flow control

The surface refrigeration system is optimised and control is implemented using VSDs as shown in Figure 3-42.

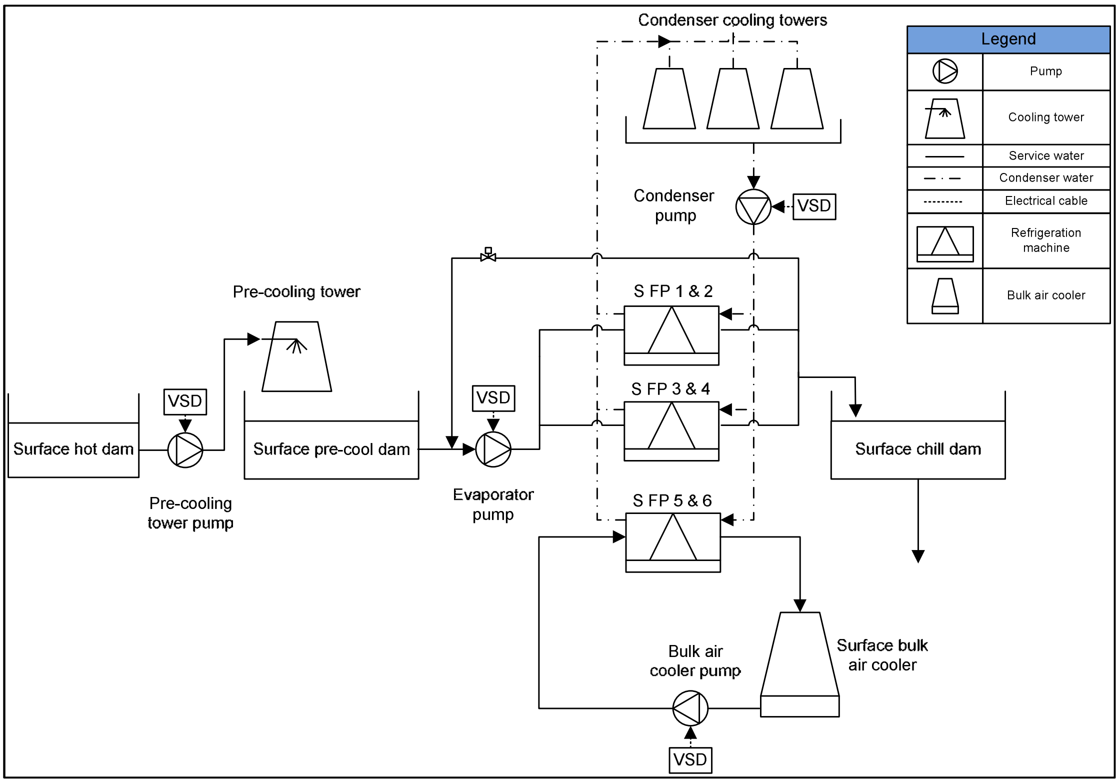


Figure 3-42: Optimisation of cooling auxiliaries system layout

These systems were designed to operate at full load capacity. Their design is full load capacity delta temperature at a constant flow. At partial load, the delta temperature over the components is reduced. The temperature reduction in the pre-cooling towers and evaporators is due to the recirculation of water.

The above is still acceptable, because each component still delivers its required service. Installing VSDs allows the system to operate at the full load delta temperatures over components by cutting back on the flow with the VSDs. As shown in Figure 3-43, there is a power-saving from the VSDs and there is also a saving due to increased plant performance with the increase of delta temperature over equipment such as the pre-cooling towers.

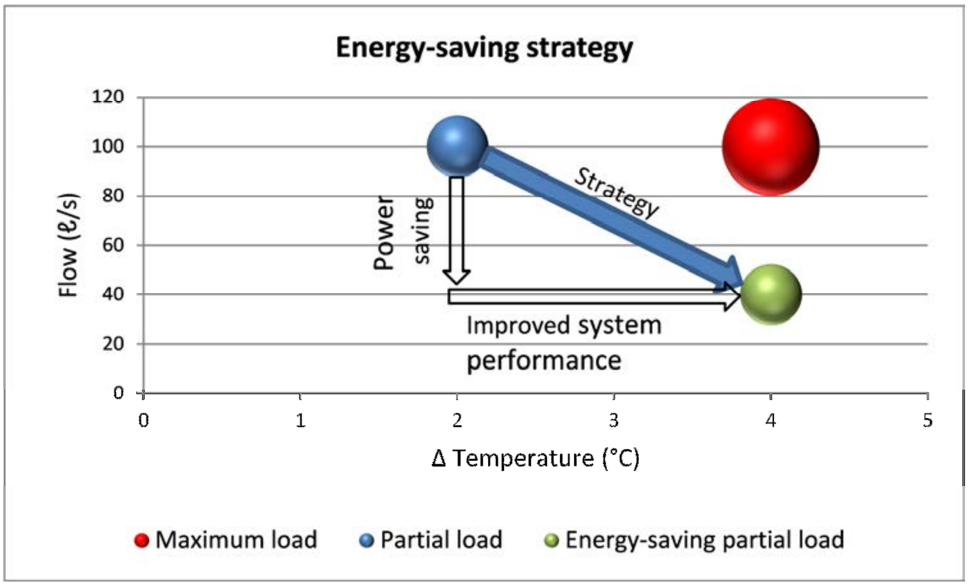


Figure 3-43: Cooling auxiliary energy-saving explained [3]

A 16% daily average power-saving of 1 457 kW was achieved on a baseline of 8 959 kW. The simulation result of a 16% saving on the surface service water and bulk air-cooling refrigeration systems is 1 350 kW. The power-saving on the entire mine-cooling and ventilation system is shown in Figure 3-44.

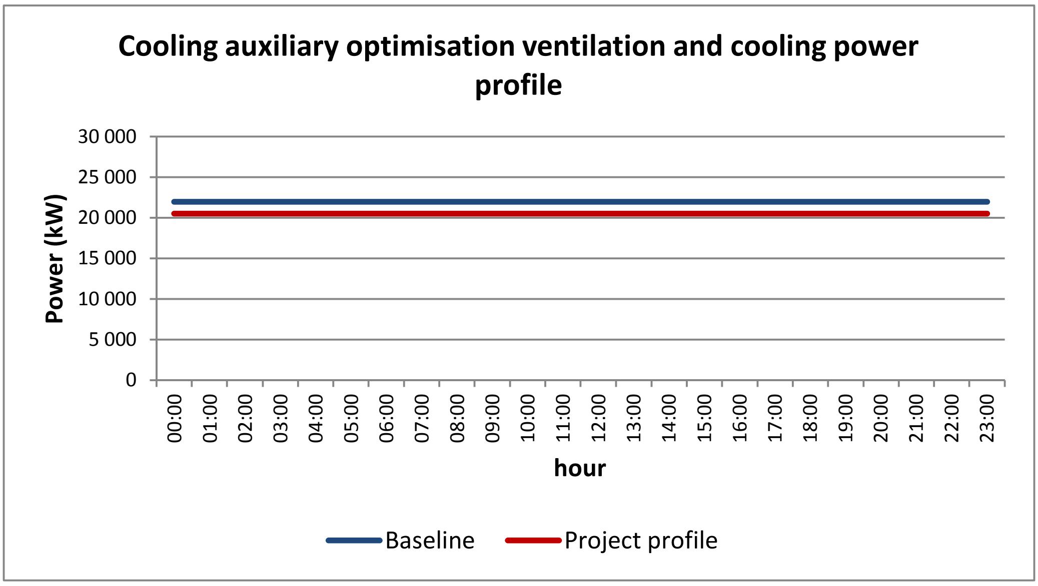


Figure 3-44: Cooling auxiliary optimisation project ventilation and cooling power profile

The cost profile of such a project is shown in Figure 3-45. The annual cost-saving is R5 million and equates to a 7% saving on the mine's annual electricity bill for ventilation and cooling.

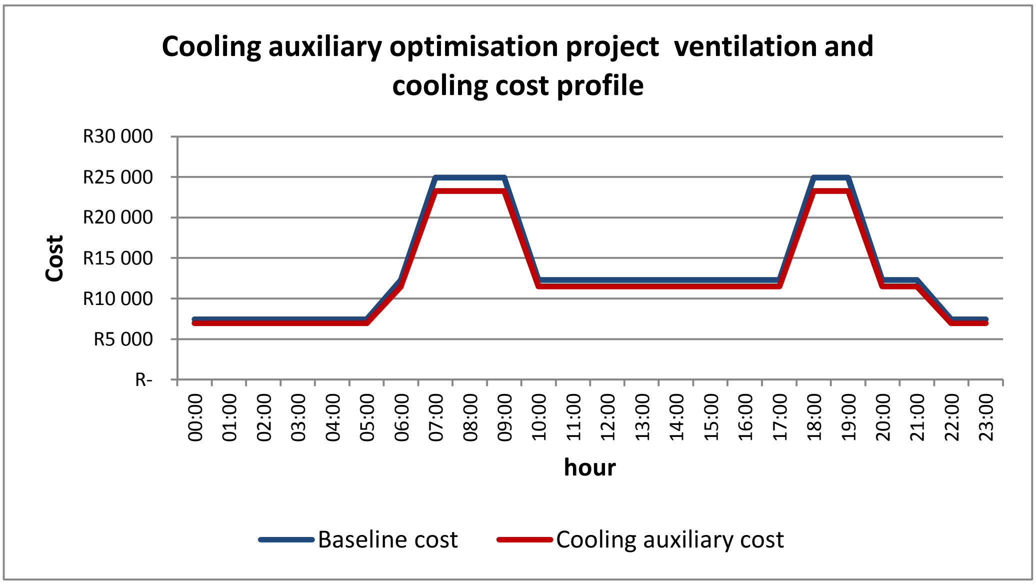


Figure 3-45: Cooling auxiliary optimisation project ventilation and cooling cost profile

The only infrastructures added to the system are VSDs and an EMS. The control philosophy of the system is also updated. Even more data is logged and trended than in the case of the fridge plant load-management project.

There is no risk on service delivery of production. There is no effect on environmental health and safety and VSDs require minimal maintenance. The risk analysis of a cooling auxiliaries project is shown in Figure 3-46.

Hazard identification and risk assessment

Project:	Cooling auxiliary optimisation	**Section:**	Surface refrigeration

Magnitude and severity - Lost production shifts	**Likelihood - shift interval between occurrences**
The severity relates to the resultant lost amount of production shifts due to identified risk	*The likelihood is described as the amount of shifts between occurrence of identified risk event*
Level 5 - Catastrophic (A month's lost production shifts)	Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Major (A week's lost production shifts)	Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (A production shift)	Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 -Minor (A level of a production shift - not recoverable)	Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Insignificant (A section of a production shift - recoverable)	Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Not possible	Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project and flow control does not effect service delivery	1	1	1	1	1
Production	Project doesn't effect production	1	1	1	2	2
Environmental health and safety	There is no affect on underground working environment from controlling the surface BAC	3	1	3	3	9
Overhead cost	VSDs don't have moving parts and require minimal maintenance such cleaning air filters	1	1	1	1	1

Evaluation of project	
Weighed risk indicator	1.86
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	7%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	Cooling auxiliary optimisation
	0	

Figure 3-46: Optimisation of cooling auxiliaries risk evaluation

This project adds new equipment and, although minimal maintenance on the VSDs is required, there is still a need to train mine personnel on how to use VSDs. VSDs also make the control of an electric motor safer due to all the motor parameters that they read. It is crucial for mine personnel to be able to do fault-finding and repair the electric motors. The PAI is determined in Figure 3-47.

Project appeal indicator (PAI)

Project: **Optimisation of cooling auxiliaries**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	7	1	**7**
Upgrading existing equipment	7	7	**49**
Monitoring and networking the mine	5	8	**40**
Displaying and logging mine system variables	8	9	**72**
Short implementation time	8	8	**64**
Little down time required for implementation	7	8	**56**
Interaction with other systems	6	5	**30**

Evaluation of project	
Sum of weighed aspect scores	318
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	45%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	Optimisation of cooling auxiliaries
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-47: Optimisation of cooling auxiliaries PAI

These projects are implemented within a year and require almost no downtime, as cables are installed during the week and terminated on Sundays and off-Saturdays. This project integrates well with the fridge plant project, as its focus is to limit waste and the load-management project's objective is time of use.

3.4.6. Fans

Energy-efficiency projects on the mine fans can be grouped into the following three sections:

- Booster fans
- Main fans' control
- Main fans' carbon replacement

This section continues to investigate the cost-saving, risk and appeal of these projects as energy-efficiency projects.

Booster fans

The booster fans shown in Figure 3-3 at the beginning of this chapter contribute 1 563 kW to the ventilation and cooling power profile. Using 45 kW fans means that an estimated 35 booster fans need to be installed underground.

From Kukard [9], it was calculated that an 11 kW or 24% saving was possible per fan. The resultant saving is 375 kW. Figure 3-48 shows the impact of such a project on the mine's ventilation and cooling power profile.

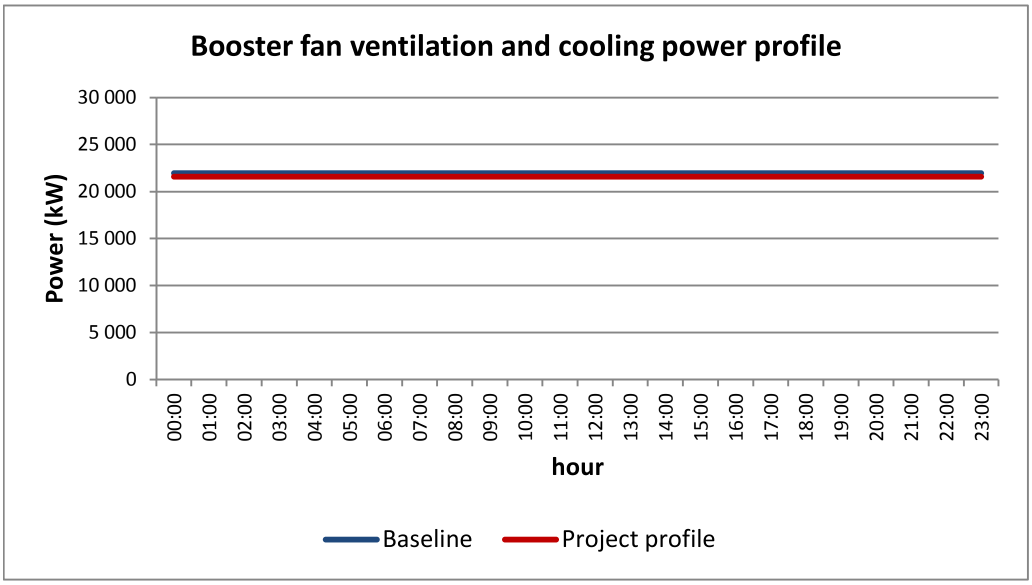


Figure 3-48: Booster fan project ventilation and cooling power profile

The cost-saving of 2% results in an annual capital saving of R1 million on the annual electricity bill of the entire mine's ventilation and cooling. The cost profile is shown in Figure 3-49.

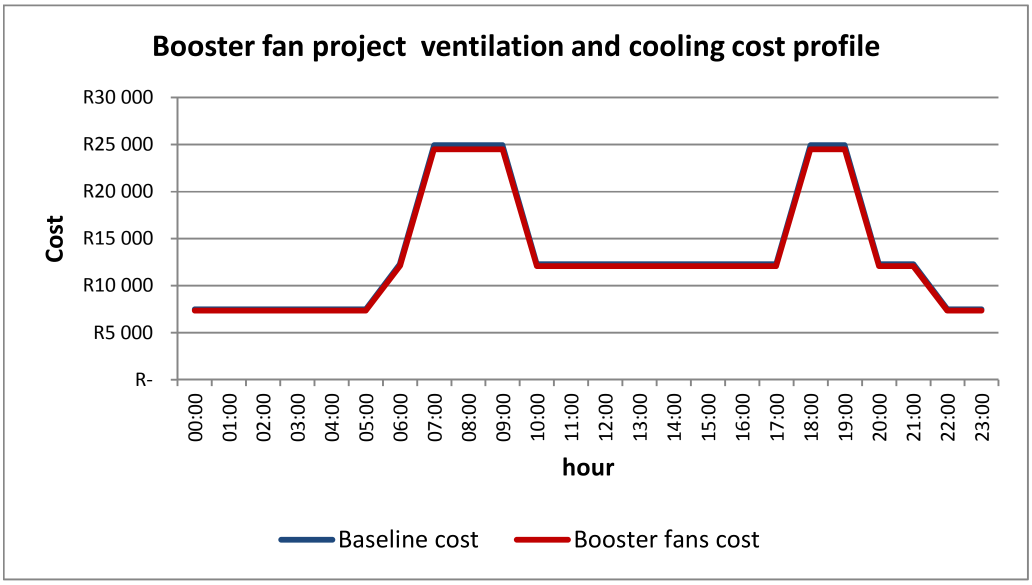


Figure 3-49: Booster fan project ventilation and cooling cost

The risk matrix that follows shows that a booster fan project will maintain service delivery, but it would be at a better efficiency. The mine production is unaffected.

To further reduce the power consumption, more efficient fans should be installed to replace larger inefficient fans. If the reduction in size does not correlate with the increase in efficiency, there may be service delivery problems, which will negatively affect the underground working environment.

Higher efficiency fans and motors will require added maintenance to sustain the saving. The added maintenance and replacement parts will add to the company's overhead cost as shown in the risk matrix in Figure 3-54.

Hazard identification and risk assessment

Project: Booster fans

Section: Underground ventilation

Magnitude and severity - Lost production shifts

The severity relates to the resultant amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between occurrences

The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project maintain service delivery at better efficiency	2	2	4	1	4
Production	Production will be unaffected if service delivery is maintained	2	2	4	2	8
Environmental health and safety	Not maintaining service delivery will negatively affect underground working environment	4	3	12	3	36
Overhead cost	Maintaining a fleet of high efficient fans and motors will require intense maintenance	4	4	16	1	16

Evaluation of project	
Weighed risk indicator	9.14
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	37%

Rating the resultant percentage risk indicator

No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	Booster fans
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-50: Booster fans risk evaluation

Replacing the fans means that all-new equipment will be installed. There is not much of an upgrade on other existing equipment. With such a project, it is impractical to network to each booster fan and show system variables on the mine's SCADA system.

As stated, most of the project capital will be spent on buying new and smaller fans. The implementation of such a project will be fairly easy and will require minimal downtime. There is little interaction between booster fans and other mine equipment, such as the pumps or refrigeration machines. The PAI is calculated in Figure 3-51.

Project appeal indicator (PAI)

Project: Booster fans

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	9	1	**9**
Upgrading existing equipment	1	7	**7**
Monitoring and networking the mine	1	8	**8**
Displaying and logging mine system variables	1	9	**9**
Short implementation time	2	8	**16**
Little down time required for implementation	7	8	**56**
Interaction with other systems	2	5	**10**

Evaluation of project	
Sum of weighed aspect scores	115
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	16%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	
	20	
Undesirable project	10	Booster fans
	0	

Figure 3-51: Booster fans PAI

It can be noted that investigating the mine's air ventilation and identifying inefficient areas, inefficient use and over-usage of booster fans could reduce the number of booster fans required and result in a more appealing and lower-risk project with better savings.

Main fan control

The main fans shown in Figure 3-3 at the beginning of this chapter contribute 2 604 kW to the ventilation and cooling power profile. From Chapter 1 it was found that a 23.5% saving could be achieved by controlling these fans. This results in a saving of 612 kW. This saving on the mine ventilation and cooling power profile is shown in Figure 3-52.

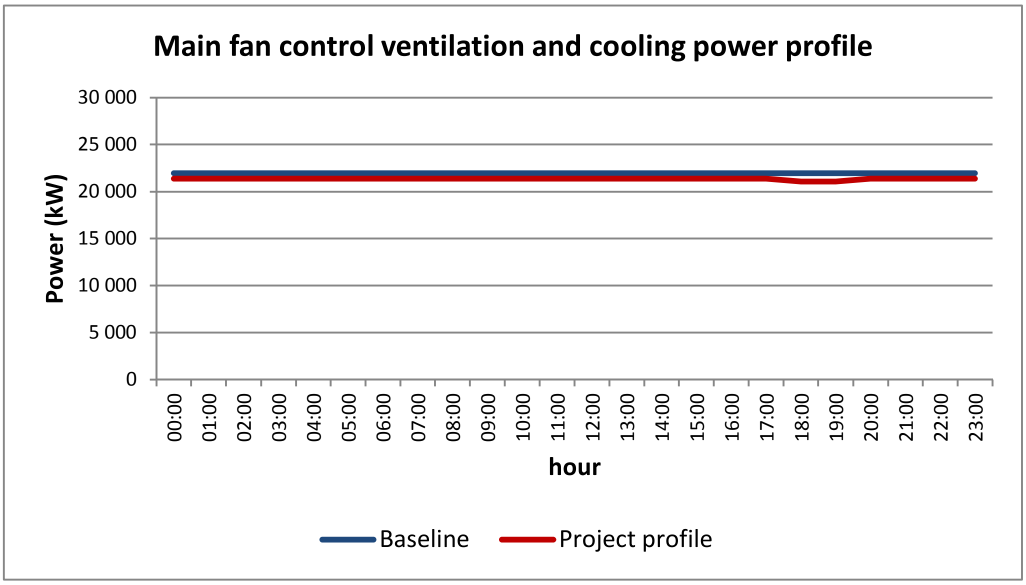


Figure 3-52: Main fan control project ventilation and cooling power profile

The annual cost-saving is R2 million and 3%. Figure 3-53 shows the cost profile for a main fan control project.

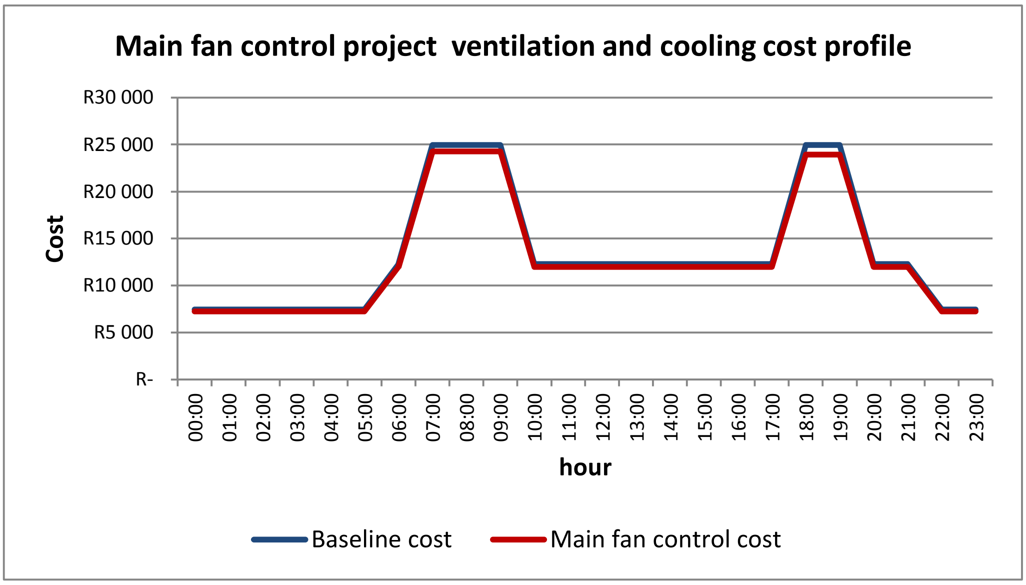


Figure 3-53: Main fan control project ventilation and cooling cost

The risk matrix in Figure 3-54 shows that doing main fan control can directly affect the service delivery of the system, reducing the amount of fresh air ventilated through the mine. Reducing the amount of ventilation air may cause an increase in working temperatures and will have an effect on production.

The reduction in ventilation air may also increase the build-up of toxic gases and negatively affect the working environment. An advantage of the control would be that the overall main fan system will be better monitored and preventative maintenance can be done.

Hazard identification and risk assessment

Project:	Main fans control	**Section:**	Surface ventilation

Magnitude and severity - Lost production shifts	Likelihood - shift interval between occurrences
The severity relates to the resultant lost amount of production shifts due to identified risk	*The likelihood is described as the amount of shifts between occurrence of identified risk event*
Level 5 - Catastrophic (A month's lost production shifts)	Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Major (A week's lost production shifts)	Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (A production shift)	Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 -Minor (A level of a production shift - not recoverable)	Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Insignificant (A section of a production shift - recoverable)	Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Not possible	Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project directly affects ventilation underground	3	3	9	1	9
Production	Changing the working environment will reduce production	3	3	9	2	18
Environmental health and safety	Reducing the ventilation will lead to build up of noxious gasses and increased temperatures	3	3	9	3	27
Overhead cost	The suction created on the blades may lead to more maintenance	2	2	4	1	4

Evaluation of project

Weighed risk indicator	8.29
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	33%

Rating the resultant percentage risk indicator

No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	Main fans control
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-54: Main fans control risk evaluation

Looking at the appeal of such a project, it can be seen that new equipment is supplied. The main fan system will be upgraded and the monitoring and networking to the main fans will need to be updated.

Being able to log and display more system variables over the new network on the SCADA is appealing. Retrofitting the main fan controls will have a relatively short implementation time, as the system only has a maximum of three fans. In addition, all the work is done on the surface.

Downtime of the fan is, however, required when the system is being implemented and commissioned. Where this project loses its appeal is with the interaction with other projects, because the main fans are a system on their own.

Project appeal indicator (PAI)

Project: **Main fan control**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	3	1	**3**
Upgrading existing equipment	7	7	**49**
Monitoring and networking the mine	4	8	**32**
Displaying and logging mine system variables	7	9	**63**
Short implementation time	4	8	**32**
Little down time required for implementation	4	8	**32**
Interaction with other systems	1	5	**5**

Evaluation of project	
Sum of weighed aspect scores	216
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	31%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	Main fan control
	20	
Undesirable project	10	
	0	

Figure 3-55: Main fans control PAI

Main fan carbon blades

From Chapter 1, it was found that an 11% saving could be achieved by replacing the main fan steel blades with new carbon blades. This results in a saving of 286 kW. The saving on the mine ventilation and cooling power profile is shown in Figure 3-56.

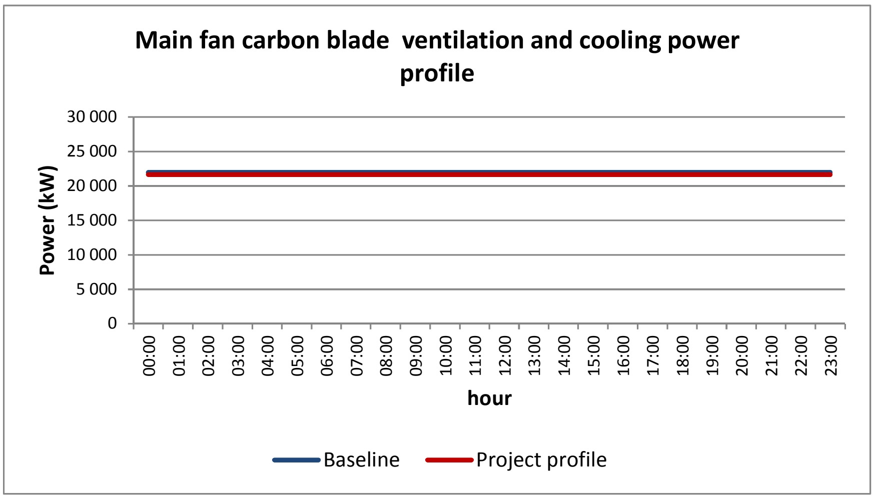


Figure 3-56: Main fan carbon blade project's ventilation and cooling power profile

An annual cost-saving of 1% at R1 million is achieved and the cost profile is shown in Figure 3-53.

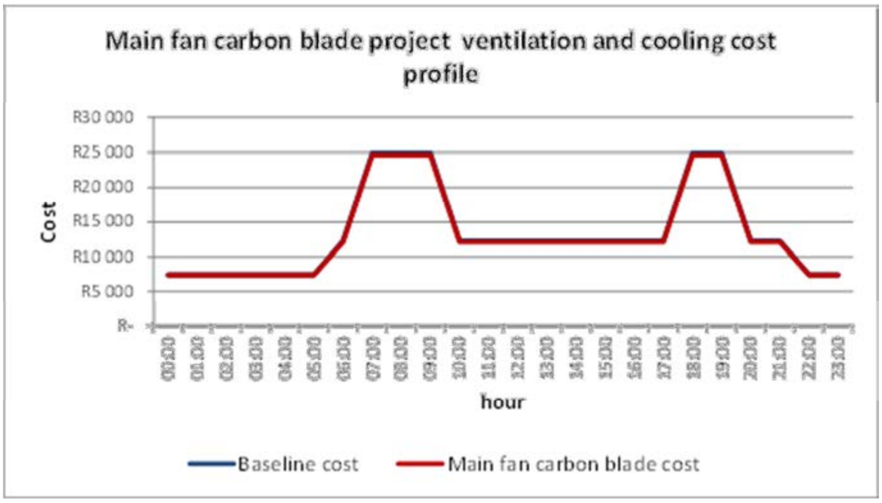


Figure 3-57: Main fan carbon blades project's ventilation and cooling cost

The risk matrix that follows shows that retrofitting the main fans' blades with carbon or composite blades may influence the mine ventilation if the design and fabrication is not done accurately.

This will again lead to the build-up of toxic gases, and the underground production will be affected as additional booster fans will need to be utilised to ventilate areas where the noxious gases build up before production can resume.

The situation described above could have a negative impact on the health and safety of the miners. Retrofitting the blades will require new maintenance procedures to be installed, as well as the need to source new equipment to maintain the new technology. Composite or carbon blades are not as resilient to strikes of debris as their steel counterparts and will need to be inspected regularly.

Hazard identification and risk assessment

Project:	Main fans carbon fibre blade	**Section:**	Surface ventilation

Magnitude and severity - Lost production shifts	**Likelihood - shift interval between occurrences**
The severity relates to the resultant lost amount of production shifts due to identified risk	*The likelihood is described as the amount of shifts between occurrence of identified risk event*
Level 5 - Catastrophic (A month's lost production shifts)	Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Major (A week's lost production shifts)	Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (A production shift)	Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 -Minor (A level of a production shift - not recoverable)	Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Insignificant (A section of a production shift - recoverable)	Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Not possible	Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		**Evaluation of risk**			**Weight**	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	Project may influence ventilation if design is not same as previous blade	3	3	**9**	1	9
Production	Influencing ventilation will influence production	4	3	**12**	2	24
Environmental health and safety	Reducing the ventilation will lead to build up of noxious gasses and increased temperatures	3	3	**9**	3	27
Overhead cost	Different composite blades will require different maintenance teams and schedule as well as spare parts	4	3	**12**	1	12

Evaluation of project	
Weighed risk indicator	10.29
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	41%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	Main fans carbon fibre blade
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	
	0	

Figure 3-58: Main fan carbon blades risk evaluation

On the PAI of the project, it can be seen that it scores high on the new equipment installation and upgrading of infrastructure. But this project does not enhance the mine's networking and monitoring capabilities, nor does it log and display system variables.

The design, construction and testing of a blade will delay the immediate implementation of the project. The positive aspect of such a project is that relatively little downtime is required to change the steel blade to a composite blade.

Replacing the blades on the main fan has little effect on the other systems, nor does it contribute to the enhancement of other systems on the mine.

Project appeal indicator (PAI)

Project: **Main fan carbon fibre blades**

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	9	1	**9**
Upgrading existing equipment	7	7	**49**
Monitoring and networking the mine	1	8	**8**
Displaying and logging mine system variables	1	9	**9**
Short implementation time	6	8	**48**
Little down time required for implementation	7	8	**56**
Interaction with other systems	1	5	**5**

Evaluation of project	
Sum of weighed aspect scores	184
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	26%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	
Acceptable	30	Main fan carbon fibre blades
	20	
Undesirable project	10	
	0	

Figure 3-59: Main fans carbon blades PAI

3.4.7. Closed-loop underground bulk air coolers

The closed-loop underground BAC consumes 2 822 kW of the mine ventilation and cooling power. From Booysen and Van Rensburg [4], the project states that the underground BAC is stopped during the evening peak period. This gives a saving of 2 822 kW during the evening peak and an average power saving of 235 kW. The power profile is shown in Figure 3-60. [4]

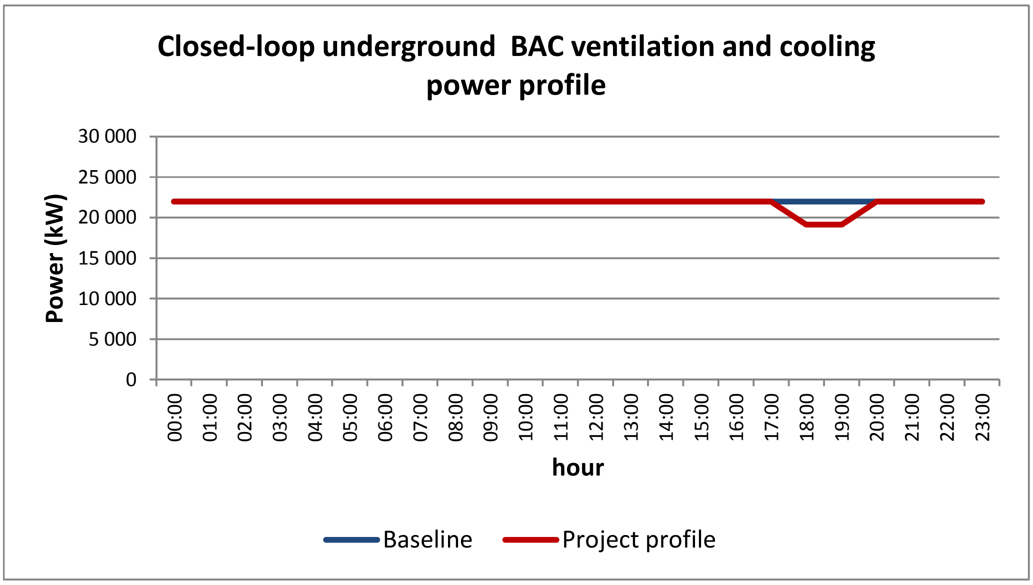


Figure 3-60: Closed-loop underground BAC project ventilation and cooling power profile

The cost-saving is R2 million and 2% of the total yearly electricity bill. The cost profile is shown in Figure 3-61.

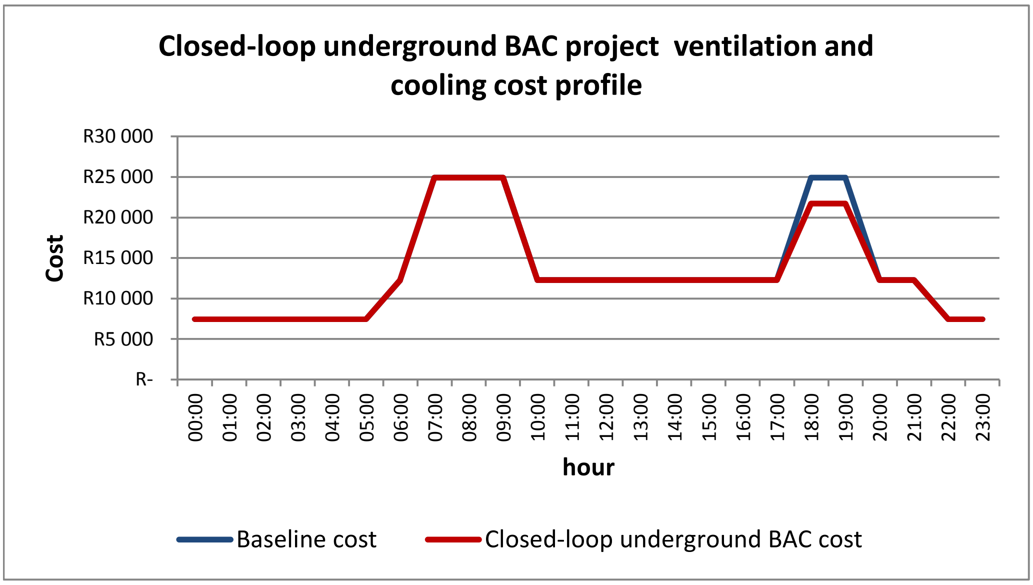


Figure 3-61: Closed-loop underground BAC project's ventilation and cooling cost

The underground closed-loop BAC is stopped during the blasting shift when there are no workers in the production areas. Ventilation during this period is essential to remove toxic fumes from the blast. The risk evaluation of the closed-loop underground BAC project is shown in Figure 3-62.

Because this project saving is realised during the blasting shift and during the evening Eskom peak period, there is no influence on production. From Booysen and Van Rensburg [4], it was found that prolonged stoppage due to unscheduled maintenance had a negative effect on the underground EHS. Monitoring the system allows for scheduled preventative maintenance and actually reduces the temperature underground.

As with the fridge plant project, there may be some additional wear on components being stopped and started once a day. Replacing these components adds to overhead and labour costs. There is still a debate on whether running equipment 24/7 reduces the amount of maintenance when compared to starting and stopping the equipment, but only operating it 22 hours a day.

Hazard identification and risk assessment

Project:	Closed-loop underground BAC	**Section:**	Underground cooling

Magnitude and severity - Lost production shifts	**Likelihood - shift interval between occurrences**
The severity relates to the resultant lost amount of production shifts due to identified risk	*The likelihood is described as the amount of shifts between occurrence of identified risk event*
Level 5 - Catastrophic (A month's lost production shifts)	Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Major (A week's lost production shifts)	Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (A production shift)	Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 -Minor (A level of a production shift - not recoverable)	Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Insignificant (A section of a production shift - recoverable)	Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Not possible	Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		**Evaluation of risk**			**Weight**	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	The BAC is stopped during the blasting period and doesn't affect service delivery	1	1	1	1	1
Production	The BAC is stopped during the blasting period and doesn't affect production	1	1	1	2	2
Environmental health and safety	It was shown that monitoring this system improved the environmental health and safety conditions underground	1	1	1	3	3
Overhead cost	As with the fridge plant project there may me additional wear on components	2	3	6	1	6

Evaluation of project	
Weighed risk indicator	1.71
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	7%

Rating the resultant percentage risk indicator		
No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	
	5	Closed-loop underground BAC
	0	

Figure 3-62: Closed-loop underground BAC risk evaluation

The PAI is calculated in Figure 3-63 for closed-loop underground bulk air cooling.

Project appeal indicator (PAI)	
Project:	Closed-loop underground BAC

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	1	1	1
Upgrading existing equipment	4	7	28
Monitoring and networking the mine	4	8	32
Displaying and logging mine system variables	9	9	81
Short implementation time	9	8	72
Little down time required for implementation	8	8	64
Interaction with other systems	2	5	10

Evaluation of project	
Sum of weighed aspect scores	288
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	41%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	
	40	Closed-loop underground BAC
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 3-63: Closed-loop underground BAC PAI

3.4.8. Conclusion

Energy-efficiency investigations and research are done on data obtained from load-management projects. Clients expect a decrease in service delivery when the amount of energy used is decreased. The simulation models and calculations done for load-management projects are verified during their implementation. With data logging and trending, these models can be revised and used to investigate energy-efficiency projects.

It has been shown that the best energy-efficiency project is water-supply optimisation. Energy-recovery projects are also rewarding, along with the optimisation of surface cooling auxiliaries. Ice projects cannot be seen as energy-efficiency projects. Ice is only an alternative to underground refrigeration. It was reasoned and found that the thermal load increased and that ice improved service delivery at an increased cost.

The sum of the fan projects and closed-loop underground bulk air-cooling project is equivalent to the average of the other projects' savings, excluding ice of course.

The build-up of heat and toxic gases is a major risk to the ventilation and needs to be considered when doing fan projects. Removing inefficiency, such as done by the cooling auxiliaries project, had the least risk. The water system optimisation and cooling auxiliaries optimisation projects had the best PAI.

In conclusion, the energy- and cost-savings from the energy-efficiency projects although reported high, seemed much lower when compared with each other on the entire mine-cooling and ventilation system. It seems that a combination of projects is required to really achieve a significant saving on the mine-cooling and ventilation system.

3.5. Sequencing and combinations of load-management and energy-efficiency projects

3.5.1. Introduction

The previous section discussed individual cost-saving and energy-saving projects. However, there is some interaction between such projects due to the fact that they are all part of mine ventilation and cooling. This section looks at the interactions to combine and sequence ventilation and cooling load-management and energy-efficiency projects.

Energy-saving projects have a higher risk factor on mine service delivery, overhead cost, production and EHS, as shown in Figure 3-64.

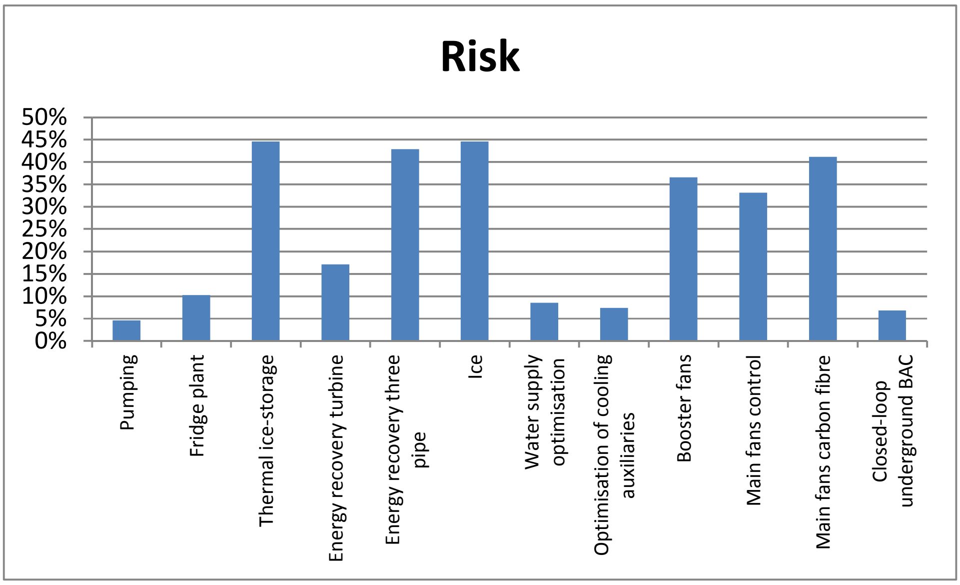


Figure 3-64: Project risk summary

The PAI for projects with EMSs is higher than for projects that focus solely on hardware to achieve load management of energy-saving. The evaluation of each project's PAI is shown in Figure 3-65.

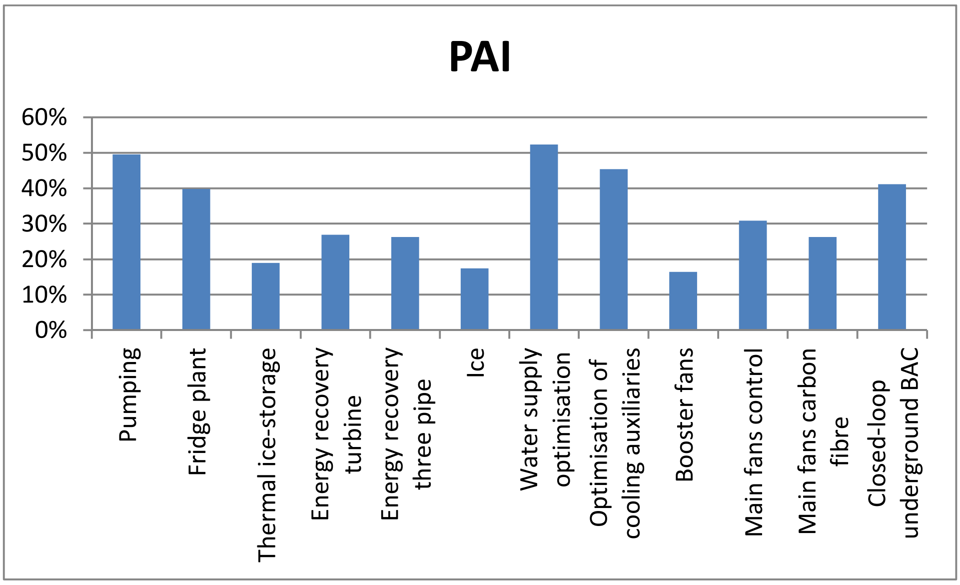


Figure 3-65: PAI summary

Projects that focus on load management and the reduction of water circulation have the biggest annual cost-saving. Projects that focus on reducing the amount of cooling and harnessing potential energy have the second-largest annual saving. Ice increased the cooling load and showed an increase in annual spending.

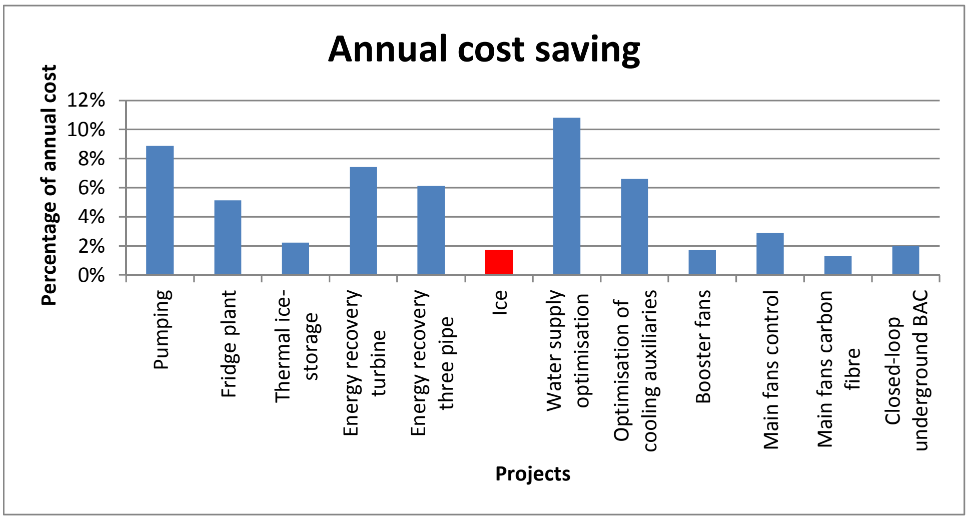


Figure 3-66: Annual cost-saving summary

The project risk plotted against the annual saving is shown in Figure 3-67. A justification line, where a 1% annual saving equates to a 6% project risk, is also plotted. The projects on the ventilation side, such as fans and thermal storage, ice and three-pipe systems are above this line.

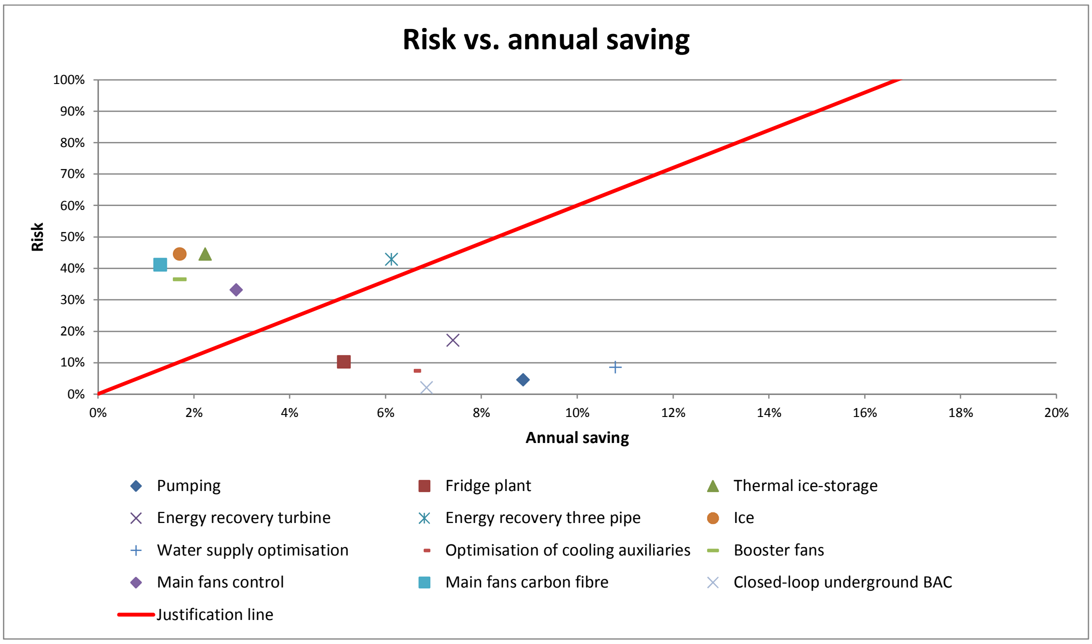


Figure 3-67: Risk vs. annual saving

Load-management and energy-efficiency projects with an EMS, along with turbines, are below the line. It can be concluded that EMSs reduce the risk of a project, while increasing the annual saving achieved.

3.5.2. Combining projects

If the results of all 12 projects are merely summed, the net saving of the implementation would be 53%. But these projects affect each other and some cannot be combined. This section looks at establishing the best combination of the 12 projects.

Ice is omitted from the combination as it has been shown that it adds energy and cost to the system and cannot be combined with energy-recovery projects. The two energy-recovery projects cannot be combined either. The turbine project is chosen, because it has a higher annual saving, a better PAI and lower risk than the three-pipe project.

The thermal ice-storage project cannot be combined with a fridge plant project. The fridge plant project has a higher annual saving, better PAI and also a lower risk when compared to the thermal ice-storage project. Thermal ice storage is not considered either, as there is a chance that the project infrastructure is used later as an after-cooler, as discussed earlier in this study.

The thermal ice storage is again omitted, because it will need to be decommissioned or changed back to a normal refrigeration machine if it is combined with an optimisation of cooling auxiliaries project.

A load-management project on the mine-pumping system will assist with the load management on the refrigeration system. This is due to the shared dam capacity of these projects. Optimal results will be achieved by monitoring their interaction.

Energy recovery is not 100% effective and pumping is still required for the deficit between water sent down and water pumped up. A pump and an energy-recovery device are very similar. Both are controlled according to their downstream and upstream dam levels, ensuring that the one is full and the other one is not emptied.

It was also shown that the pumping profile should be used to report on the saving in an energy-recovery project. For this reason, it is proposed that the pumping EMS incorporates the simulation, control, monitoring and reporting of an energy-recovery device, such as a turbine.

With impact turbines, the turbine doubles as a pump.

Energy-recovery devices also require near constant flow, which does not correlate with mine production of drilling, blasting and cleaning. Having a constant flow underground will influence the load shift on the refrigeration system, which, in return, will have an effect on the pumping load shifting. This can be solved if the pumping EMS oversees the use of the turbine and there is interoperability between the pumping EMS and fridge plant EMS.

The water-supply optimisation realises a cost-saving by reducing the amount of water that needs to be circulated between the pumped, refrigeration and mine operations. This, however, reduces the load that can be shifted on the pumping and refrigeration machines. It also reduces the amount of energy that can be recovered by energy-recovery systems.

The saving from the reduction of water being circulated outweighs the decreased load-management opportunities. Reducing the water opens up more capacity both in terms of storage, and pumping and cooling capacity. This increase in capacity will again benefit the load-management system, as it will ensure that the load management is done both sustainably and optimally.

Using the cooling auxiliaries optimally produces more cooling capacity and may increase the thermal storage potential, thus aiding in the load-shifting energy cost-saving of the fridge plant project.

The optimal use of cooling auxiliaries is aided by the infrastructure supplied with fridge plant projects, especially the logging of data and upgrading of monitoring infrastructure. As with the water-supply optimisation, the optimisation of cooling auxiliaries increases the storage capacity and cooling capacity of the surface plant, allowing for an optimal and more sustainable fridge plant load-management project.

A fan's main focus is on air quality underground. As described in Chapter 1, there have been a few studies on recirculating a portion of the mine ventilation with fresh air from the surface. Currently all the ventilation air is fresh air from the surface. Booster fans' focus is distributing the cooled and dehumidified air through the mine's working sections.

Again, keeping with the assumption that the mine-cooling load is constant, any reduction in ventilation air will require a reduction in the temperature and humidity of the air. Thus, a load-management and energy-saving project on mine fans may lead to an increased demand on a mine-refrigeration system. This reasoning is summarised in Table 3-13.

Table 3-13: Combination of energy cost-saving cooling and ventilation projects

Combination of projects	
Pumping	
Fridge plant	
Turbine	
Water-supply optimisation	
Optimisation of cooling auxiliaries	
Booster fan	
Main fan control	
Main fan carbon blade	
Closed-loop underground BAC	
Omitted projects	**Reason for omission**
Ice	Not an energy cost-saving project
Three pipe	Turbine
Thermal ice storage	Fridge plant and optimisation of cooling auxiliaries

The following section will look at the order in which the above projects should be implemented.

3.5.3. Sequencing the combination of projects

As stated throughout this study, there is a need for a structured approach to mine-cooling and ventilation load-management and energy-saving projects. The previous sections evaluated the projects and their interaction with each other and concluded with the best combination of projects for the mine-cooling and ventilation system.

Following the combination without a sequence will result in the simultaneous implementation of a pumping-fridge-plant-cooling-auxiliary-fan-turbine project. Such an all-in-one project is deemed to fail, because it has too many variables to consider and is not properly defined, designed and planned. The mine has limited resources and cannot install control valves on all mining levels while automating all the pumps on the pumping levels and installing VSDs on the surface refrigeration system.

It can thus be concluded that the projects should be installed one at a time, following a sequence. From a mine finance and costing view, the easiest way to structure the implementation of these projects is to start implementing the project with the greatest saving first and to continue downward to the project that realises the smallest saving as shown in Figure 3-68.

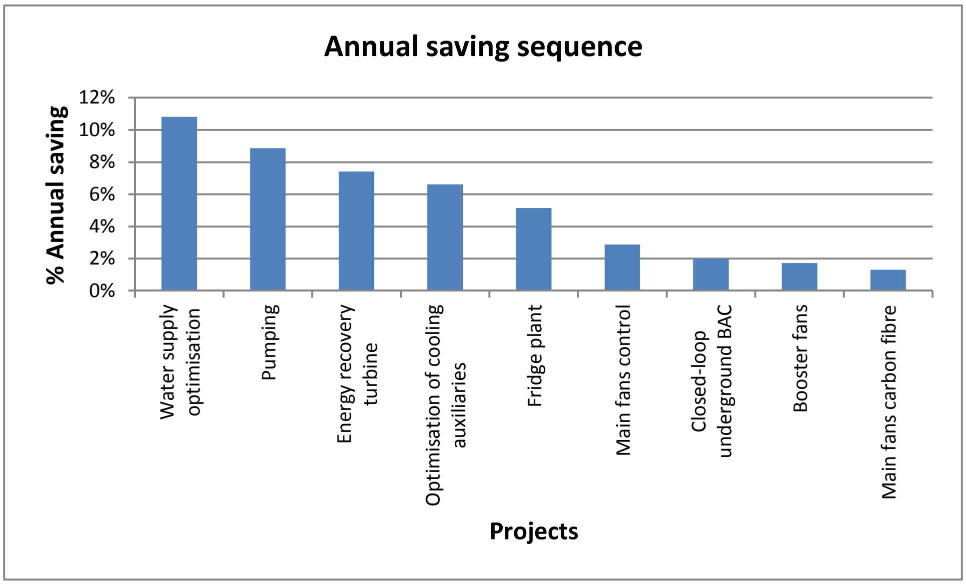


Figure 3-68: Project sequence according to annual cost-savings

From a mine operational and production view, looking at service delivery, production, EHS, as well as overhead cost, the easiest way to structure the implementation of these projects is to start with the most risk-averse project and to continue with the projects where risk needs to mitigated as shown in Figure 3-69.

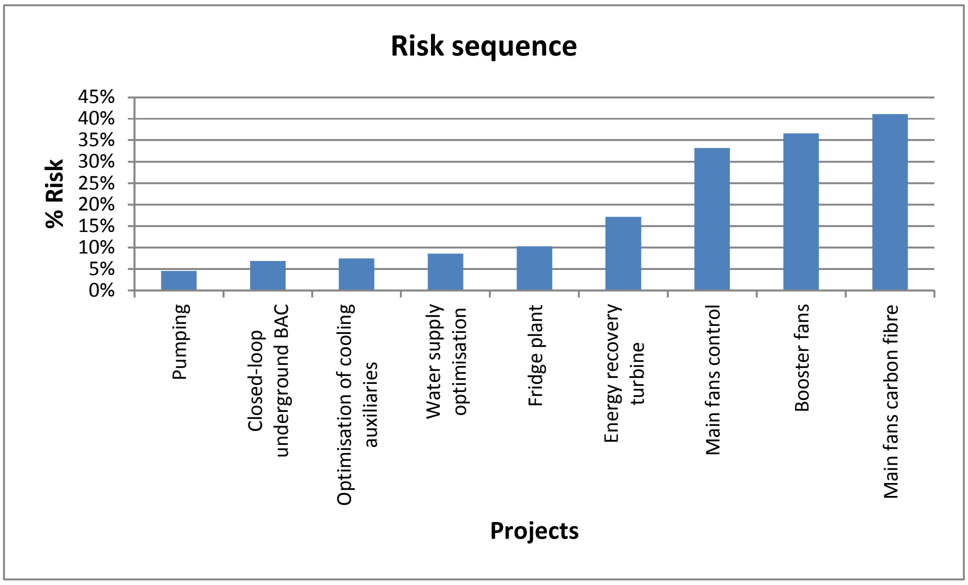


Figure 3-69: Project sequence according to annual cost-savings

From a mine service department and maintenance view, considering new equipment, upgrading existing equipment and the expansion of the mine networking and monitoring infrastructure, the sequence will be done according to the PAI as shown in Figure 3-70.

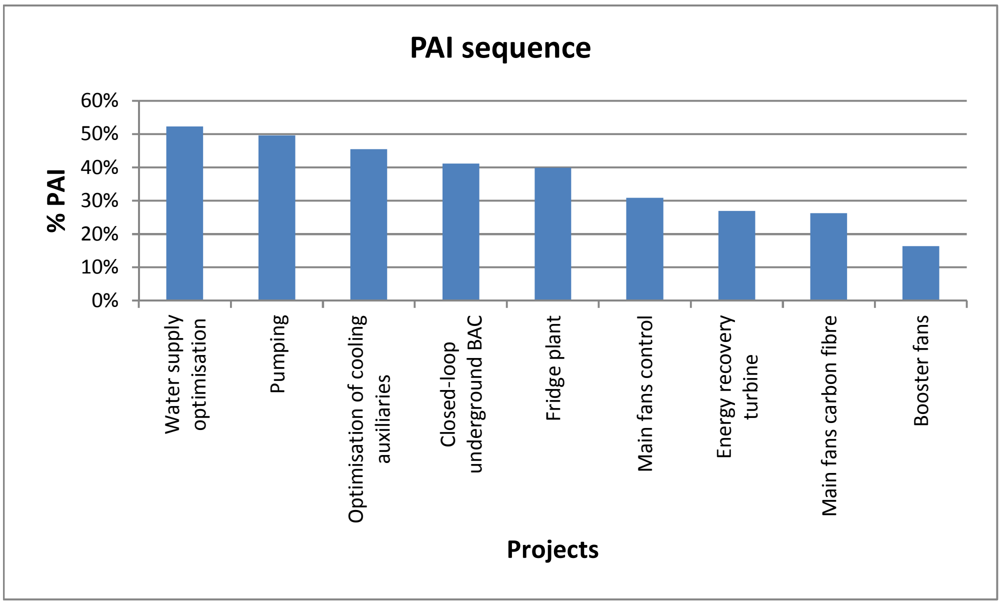


Figure 3-70: Project sequence according to PAI

Using three different views, three different sequences have been obtained. The interaction of projects, as well as the process followed to implement a project, will need to be evaluated, while considering annual saving, risk and appeal to determine the sequence of implementation.

It is important that the correct project is correctly designed and correctly implemented to ensure that the promised savings are achieved sustainably without hassles, problems and delays. To ensure the above, the steps in Table 3-14 should be followed:

Table 3-14: Project implementation steps

Step	Action	Example
1.	Identify system	Clear water pumping
2.	Identify main components	Dams, pumps and columns
3.	Determine boundary conditions	Water is received from settlers at the bottom of the hot dam and water is drawn from the surface hot dam by the surface refrigeration system.
4.	Determine interaction between components	Which pumps are linked to which columns and in which dams do these columns discharge?
5.	Simulation	Construct and use a mathematical model to simulate the clear water-pumping system. Focus on dam levels, flows and power usage.
6.	Verify simulation	The simulated flows and changes in dam levels should reflect actual flows and changes in dam levels.

7.	Design project	Make engineered changes to the simulation system to manage the load and realise energy-saving. Manipulate the flow and dam levels to achieve cost-saving without bursting any columns, flooding the mine or pumping the mining water down the flood channel on the surface.
8.	Present designed project and do tests	Present the simulated results of the engineered system changes and test if these changes are possible and deliver the desired effect.
9.	Implement project	Automate all the pumps on all the pumping levels and install the network so that everything can be monitored and controlled from the surface.
10.	Optimise control	There is a matter of discrepancy between reality, mathematics and simulation assumptions made. This step is where these discrepancies are mitigated, such as the first 10% of a dam filling up in an hour, and the next 10% in 30 minutes, where it was assumed that 10% equates to 45 minutes.
11.	Verify saving	If an accurate simulation model was designed using the correct equations and interaction of components, the predicted saving should match the measured savings at this point.
12.	Monitor and report savings and maintain project	With the savings verified, it is important to monitor and report to sustain the savings, as savings from such projects are renowned to deteriorate over time. Maintaining the project and project infrastructure also ensures a sustainable project.

Information, layouts and data are required for the above steps. System information entails installed capacity and the amount of equipment. Layouts show the capacity and equipment that relate. Data shows how the capacity and equipment are used to achieve the desired result or effect.

The fewer variables there are that need to be monitored and the less information that is needed, the easier the layouts are and the least amount of data is required for a project. Systems should be put in place to assist with information, layouts, data and the evaluation of data as the system's variables increase.

The water-supply optimisation project is first in the cost-saving and appeal sequence. This project, however, is done on the supply to the working sections on the mine working levels. The closer the service target for the load management and energy-savings is to mine production, the higher the perceived risk.

The water-supply optimisation project's focus is to control and reduce pressure and flow. This then results in a saving on pumping and refrigeration systems. This means that it indirectly realises a saving on systems over which it has no control. Therefore, this system cannot be the first to be implemented. It is recommended that projects related to the pumping and refrigeration system are implemented first.

The optimisation of the cooling auxiliaries project is appealing and relatively low risk, with the main focus being the installation of VSDs to control the flow through the system. To simulate the effect of changing the flow through each subsection of the surface refrigeration system requires a lot of information, system characteristics and data, as well as a detailed layout of the system. A fridge plant project with an EMS is the ideal tool to use to gather the data needed for an optimised cooling auxiliaries project.

The mine-pumping system has a high saving, low risk and high appeal. The system layouts, information and data on the pumps are easier to obtain than, for example, information on the water distribution on a level.

Pumping levels are also required to use log sheets to monitor the running hours of the pumps. It is noted when a pump is started and stopped. This information is not available for mining levels with regard to the pressure and amount of flow consumed.

As stated earlier, load-management projects are regarded as energy-efficiency projects as there is a perception that reducing the amount of energy will reduce the service delivery and production. Taking this and the previous three paragraphs into account, the sequence is started with the fridge plan or pump projects.

Between the two, it is easier to research and implement a pumping project, because the focus is only on dam levels. With a fridge plan project, both the dam level and the dam temperature need to be considered. Also, load management on the pumping system that supplies the refrigeration systems is the first step to doing load management on the refrigeration systems.

A pumping project ensures that there is a network down the shaft, all the way to the bottom. The project also installs network access points on all the pumping levels. Thus, the sequence starts with a pumping project, followed by a fridge plant project where the underground fridge plants can effortlessly be added to the network.

This is then followed with a water-supply optimisation project and a cooling auxiliaries project. The mining levels can also be controlled over the network installed by the pump project.

It is important to first reduce the entire flow through the surface refrigeration system before optimising the flow in the refrigeration system. Because the power usage of the pumping and refrigeration system is already being monitored and reported, the savings from the water-supply optimisation project can be effortlessly reported.

Reducing the amount of water circulated will ensure that the settler improves, improving the quality of the water.

Having control over the clear water pumping, service-water cooling and water usage at the mining levels will give enough data and information for the installation of an energy-recovery device, such as the chosen turbine project. Again, the monitoring and reporting on the pumping system allow for the correct saving to be reported in an energy-recovery project.

The pumping project made network access possible on the underground fridge plant level. The fridge plant project incorporates the underground service-water refrigeration system. This means that most of the infrastructure is already in place to effortlessly implement a closed-loop underground BAC project.

Again, data and information on air temperature from the closed-loop underground BAC project can be used for both the booster fan project and the main fan control project. The network installed with a pumping system can also be used as the base to control and monitor underground booster fans. With the data and information obtained from the main fan control project, a main fan carbon fibre blade project can be implemented.

The implementation sequence is thus shown in Table 3-15.

Table 3-15: Sequence for implementing the best combination

Sequence	Project
1	Pumping
2	Fridge plant
3	Water-supply optimisation
4	Optimisation of cooling auxiliaries
5	Energy-recovery turbine
6	Closed-loop underground BAC
7	Booster fans
8	Main fans
9	Main fan carbon blade

3.5.4. Results

The above sequenced combination of strategies was implemented on the simplified mine model created in section 3.2. The effect of the water-supply optimisation project on the pumping, refrigeration and turbine is also taken into account in the results for an accurate picture and not to overstate the possible saving. The baseline and sequenced combination power profile results are shown in Figure 3-71.

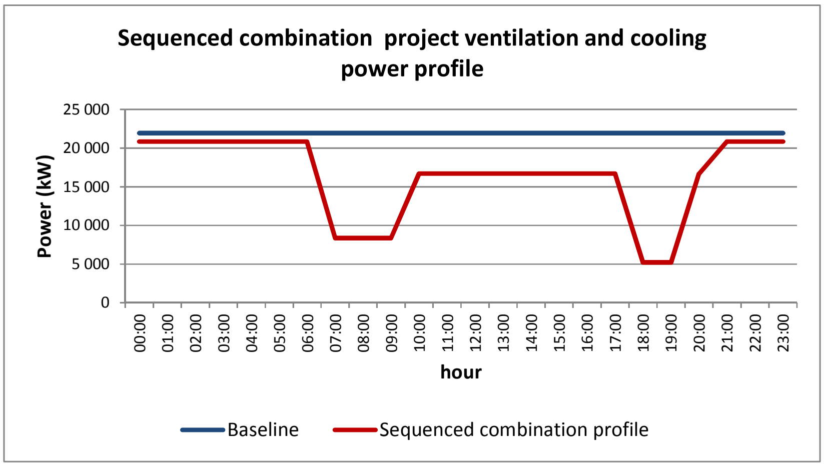


Figure 3-71: Sequenced combination power profile

The implementation of the sequenced combination of strategies resulted in an annual cost reduction of the mine ventilation and cooling of R29 million. That is a saving of 36% on the annual cost of the ventilation and cooling system, and 15% on the annual costs for the entire mine for weekdays. Figure 3-72 shows the change in the weekday cost profile.

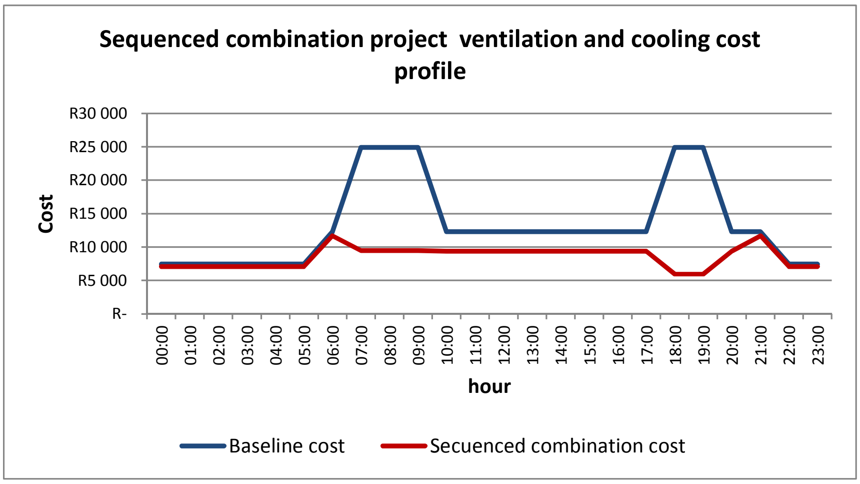


Figure 3-72: Sequenced combination cost profile

The sequenced combination can be verified according to the sequence of published literature, as shown in Table 3-16.

Table 3-16: Verification of sequenced combination

Sequence	Project	Publication	Citation
1	Pumping	2003	[5]
2	Fridge plant	2006	[6]
3	Water-supply optimisation	2011	[7]
4	Optimisation of cooling auxiliaries	2012	[3]
5	Energy-recovery turbine	2012[1]	[8]
6	Closed-loop underground BAC	2013	[4]
7	Booster fans	2006[2]	[9]
8	Main fans	2012	[10]
9	Main fan carbon blade	2013	[11]

1. This is a recent publication of an implemented energy-recovery system. Publications on turbines and their installations have been around since at least 1985 [12].
2. This publication tests the idea of a booster fan project. There is no publication on a successful installation that realised an energy-saving.

3.5.5. Conclusion

The results of the previous two sections' evaluations of load-management and energy-efficiency projects were evaluated in this section. The savings, risk and PAI were plotted for all projects.

The risk was also plotted against the saving. A line where a 1% annual saving equates to a 6% project risk is also plotted, dividing them into six above and six below the line. The six below the line were the pumping, fridge plant, water-supply optimisation, optimisation of cooling auxiliaries, turbine and closed-loop underground BAC projects.

Between similar and conflicting projects, the best one was selected and included in the combination. Ice was disregarded as it improves service delivery when chosen to replace underground refrigeration.

The derived combination will not achieve its potential without a sequence being added to it. The sequence was derived using the saving, risk and PAI from the previous section. Knowledge on the project implementation process was also used to establish the correct sequence and ensure that the cart is not put before the horse.

The sequenced combination was implemented on the simplified simulation model and achieved a saving of R29 million. Considering that a year is the average implementation time for each of the listed projects, it equates to a nine-year study to implement and verify the results. The sequenced combination is, however, verified using the sequence of publicised implementation results.

3.6. Conclusion

This chapter established a sequenced combination for energy-saving strategies on a mine ventilation and cooling system. The projects were divided into load-management and energy-efficiency projects. A simplified simulation was used to determine the power usage of a mine's cooling and ventilation system. The annual cost was calculated using the simulation model and Eskom's tariff structure.

The effect of each individual project on the power usage was simulated and the cost-saving calculated, using the model. A risk matrix was established to analyse the risk of a project with regard to service delivery, production, EHS, as well as overhead cost. The appeal of a project was indicated with the PAI.

The PAI was determined with regard to new equipment, upgrading existing equipment, expanding the mine network and monitoring, a short implementation time, little downtime required for implementation and the interaction with other projects.

It was determined that ice is not an energy-efficient option, as it increased service delivery. Ice is an option when underground refrigeration is required and it is compared to underground refrigeration machines where service delivery is important. The result of the each project's cost-saving, risk and PAI is shown in Table 3-17.

Table 3-17: Summary of risk, PAI and annual saving

Project	PAI	Risk	Annual cost-saving
Pumping	50%	5%	9%
Fridge plant	40%	10%	5%
Thermal ice storage	19%	45%	2%
Energy-recovery turbine	27%	17%	7%
Energy-recovery three pipe	26%	43%	6%
Ice	17%	45%	-2%
Water-supply optimisation	52%	9%	11%
Optimisation of cooling auxiliaries	45%	7%	7%
Booster fans	16%	37%	2%
Main fan control	31%	33%	3%
Main fan carbon fibre	26%	41%	1%
Closed-loop underground BAC	41%	7%	2%

Table 3-17 is plotted in Figure 3-73 with the PAI on the X-axis, the risk on the Y-axis and the size of the ball illustrating the project's annual cost-savings. The highest-risk projects are ice and thermal ice storage. From the graph, it can also be seen that higher risk projects do not result in higher savings.

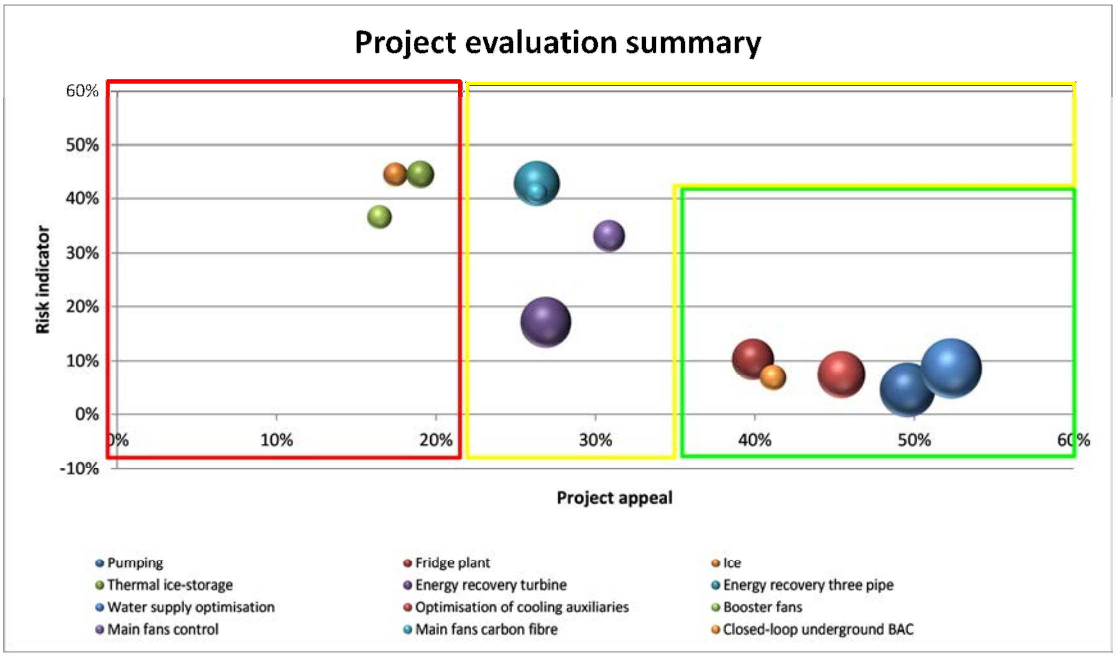


Figure 3-73: Project evaluation summary

The best combination of projects was determined by choosing the best option where there was conflict. The sequence was determined using the above criteria and project experience. The sequenced combination is shown in Table 3-18.

Table 3-18: Sequenced combination

Sequence	Project
1	Pumping
2	Fridge plant
3	Water-supply optimisation
4	Optimisation of cooling auxiliaries
5	Energy-recovery turbine
6	Closed-loop underground BAC
7	Booster fans
8	Main fans
9	Main fan carbon blade

The sequenced combination was implemented on the simplified simulation model and achieved a saving of R29 million.

The results from this section are summarised in Table 3-19 with regard to the contribution of this study.

Table 3-19: Contribution summary

This study																			
Contribution	Investigation	Simulation	Implementation	Integration	Cooling							Ventilation				DSM			Process efficiency
					Pumping and water distribution	Energy recovery	Refrigeration		Thermal ice storage	Ice	Mobile cooling unit	Bulk air cooling		Fans		Load shifting	Peak clipping	Energy efficiency	
							Surface	Underground				Surface	Underground	Underground booster	Main				
I	X	X			1,	C2		A3		D2	D1	B1,C3	B2		A4	A	B	C	D
Ii				X	X	X/ 0	X	X	O	O	X	X	X	X	X				X
Summary	X	X	X	X	X	X	X	X	O	O	X	X	X	X	X		X	X	X

In conclusion, load-management systems should be implemented first, followed by energy-efficiency projects. It was determined that EMSs help realise sustainable cost-savings and also aid in reporting the correct saving.

There should be standardised EMSs that integrate effortlessly.

It should be mentioned that this analysis did not include operational procedures aimed at good housekeeping, for example, fixing leaks, cleaning refrigeration machines to enhance the heat transfer, maintaining pumping systems to ensure that efficient pumps are being used, etc.

As electricity costs increase, so does the incentive to do more expensive and complicated projects. As a result, projects that in the past were deemed too risky are now being considered and implemented. Among these projects are load management on underground fridge plants with limited water storage capacity [4]. After evaluation, these perceived risky projects were found to be both low risk and appealing, though the saving was lower.

Figure 3-74 shows the system from the beginning of the chapter with the energy-saving project shown and numbered according to the sequence. A load-managing energy-efficiency project has not yet been implemented on the surface air-refrigeration system.

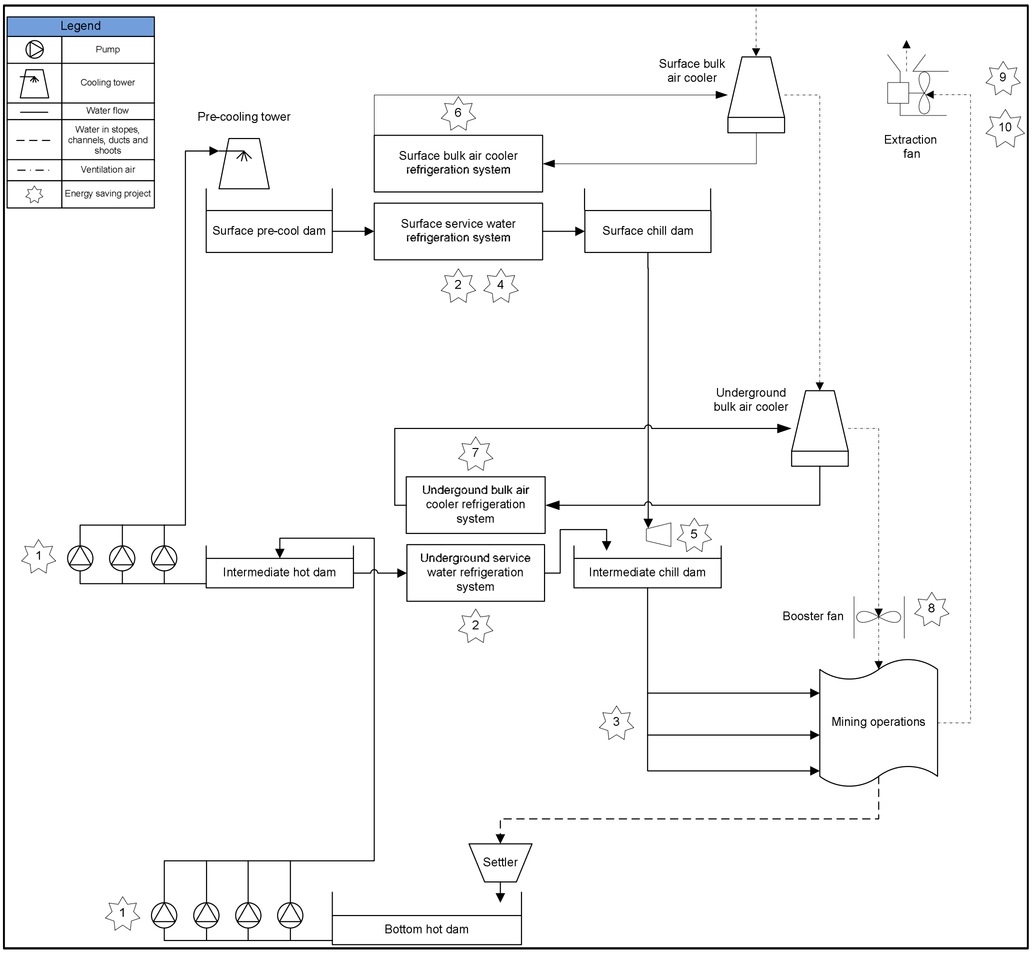


Figure 3-74: Summary layout of the system sequenced combination shown

The development of this new savings projects for the surface air-refrigeration system is the focus of the rest of this thesis. In Chapter 5, this new savings project is analysed in the same way as the existing projects. The new project is then added to the sequenced combination.

3.7. References

[1] Efrat, T., Rott, S. 27 MW industrial cooling applications based on the IDE's energy efficient vacuum icemaker. *IIR Proceedings Series Refrigeration Science and Technology*: 177-183. International Institute of Refrigeration, May 2010.

[2] ASHRAE. HVAC applications. *ASHRAE Handbook,* 29.1–29.13, 2011.

[3] Schutte, A.J., Maré, P., Kleingeld, M. Improved utilisation and energy performance of a mine cooling system through control of auxiliary systems. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. CPUT, Cape Town, South Africa, August 2013.

[4] Booysen, W., Van Rensburg, J.F. Load management on closed loop underground fridge plants and the effects on working conditions. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. CPUT, Cape Town, South Africa, August 2013.

[5] Swart. C. *Target electricity cost-saving report, with emphasis on clear water pump system*. HVAC International, July 2003.

[6] Calitz, J. "Research and implementation of a load reduction system for a mine refrigeration system", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[7] Botha, A. "Optimising the demand of a mine water reticulation system to reduce electricity consumption", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2010.

[8] Le Roux, D. Energy recovery from incoming high pressure cold water in deep level mines. *Proceedings of the 9th International Conference on the Industrial and Commercial Use of Energy*. CPUT, Stellenbosch, South Africa, August 2012.

[9] Kukard, W.C. "Research on reducing cost of underground ventilation networks in South African mines", dissertation submitted in partial fulfilment of the requirements for the degree Master's in Engineering, North-West University, November 2006.

[10] Pooe, T., Marx. W.M., Du Plessis, J., Janse van Rensburg, J., Van den Berg, L. Main fan energy management – actual savings achieved. *Proceedings of the 9th International Mine Ventilation Congress*. New Delhi, 2009.

[11] Fourie, J.W. Power savings by impeller replacements for main fan stations in the South African gold mining industry. *Proceedings of the 9th Conference on the Industrial and Commercial Use of Energy*: 1-6. Stellenbosch, 15-16 August 2012.

[12] Torbin, R., Cardenas, R., Thimons, E. First impulse turbine in the US mining industry. In*: Waterpower'85:* 183-191. ASCE.

4. Surface bulk air cooling and refrigeration

Surface bulk air coolers are investigated for energy-saving.

4.1. Prelude

The literature researched in Chapter 1 showed a gap in research done on a peak clip initiative on the surface BACs. The overview of mine-cooling systems in Chapter 2 discussed surface refrigeration systems and BACs, showing that a saving on the surface BAC will lead to a saving in electricity.

In Chapter 3, the surface BAC was the only system in the mine-refrigeration and cooling system that did not have a project focusing on it. There is also no project included in the current sequenced combination, although the optimisation of cooling auxiliaries project achieved energy efficiency by reducing the over-cooling done by the surface BAC. The outlet air temperature was increased from 5 ^{o}C to the mine ventilation design of 7 ^{o}C.

In this chapter, a peak clipping energy-saving projects will be investigated on the surface BAC. The electricity saving will be achieved on the refrigeration machine servicing the surface BAC. This project has largely not been pursued due to the effect it may have on the underground environment. Normal building applications of a heating ventilation and air conditioning (HVAC) system perform calculations in terms of enthalpy.

Unsaturated air enters a mining level and moves sufficiently slowly to allow for full saturation to occur over the long level airway with no heat additions from any source and free-standing water covering the floor. The air gains latent heat as the water evaporates. The WB temperature, DB temperature and water temperature all become equal because the sensible heat lost by the air is balanced by the latent heat gained.

The process is known as the adiabatic saturation process and there is no net addition or loss of heat for the air and water combined. Looking at the air alone, water mass has been transferred to it and that water mass already contained sensible heat before evaporation.

Taking psychrometric readings and calculating the enthalpy using equations show that the enthalpy of the air does not remain constant.

Omitting the sensible heat of liquid water that has evaporated resulted in a property value that remained truly constant throughout the adiabatic saturation process. This property is known as sigma heat, S.

Sigma heat features in the majority of analyses concerning subsurface climatic changes. For this study, however, the ventilation over a level is not analysed. The study looks at the temperature down the shaft and entering the level unsaturated. Enthalpy will be used to describe these states of energy and compare them. Mine working conditions underground at various temperatures are listed in Table 4-1.

Table 4-1: Wet-bulb temperature's effect on work

WB temperature range	Effect on work
$T_{wb} < 27\ ^oC$	Worker efficiency 100%
$27 < T_{wb} < 29\ ^oC$	Economic range for acclimatised workers
$29 < T_{wb} < 33\ ^oC$	Safety factor range corrective action required
$33\ ^oC < T_{wb}$	Only short-duration work with adequate breaks

From Table 4-1, the air entering a level can be expected to be below 27 ^{o}C WB. Table 4-1 also shows that a reject temperature of 29 ^{o}C WB is economical and acceptable. At the reject temperature, the air either needs to be extracted or re-cooled. The upper limit of DB air temperature is taken as 45 °C, as this is the point where a burning sensation is felt on the skin. An environment with a WB temperature above 37 °C is unable to support human life for any extended period of time.

Another reason a peak clipping project on the surface BAC was not pursued is because the BACs are switched off during the winter, which is Eskom's most expensive TOU. From Chapter 3, it is evident that the average winter DB temperature and RH is 11.20 ^{o}C and 45.75%. Using the Ashrae Psychrometric chart no. 6, for an elevation of 1 500 m, gives an enthalpy of 24 kJ/kg.

The average summer DB temperature and RH is 20.20 ^{o}C and 57.30%, giving an enthalpy of 46 kJ/kg and a WB temperature of 14.5 ^{o}C. The BAC outlet air temperature before an optimisation of cooling auxiliaries project was 5 ^{o}C WB.

The mine ventilation design is 7 ^{o}C. These temperatures are beneath dew-point temperature and the RH is 100%. The design enthalpy is 28 kJ/kg and the over-cooled air enthalpy is 21 kJ/kg leaving the BAC.

Studies have been conducted to utilise old working areas as thermal storage for ventilation. These areas and the steel infrastructure within these areas are cooled when spare capacity is available on the BAC. Then the thermal storage is utilised when the mine load exceeds the cooling done by the BAC [1].

4.2. Surface bulk air coolers

As stated in Chapter 2, surface BACs can be a vertical forced-draught contact heat exchanger or a horizontal forced-draught contact heat exchanger. The water spray also acts as a scrubber to clean ambient air of solid particles before it is sent underground.

In the summer, the daily temperatures range between 16 and 28 ^{o}C with the RH ranging from 85 to 38%. The daily summer temperature and RH are shown in Figure 4-1. The surface BACs cool and dehumidify summer ambient air as stated in the previous section for ventilation cooling.

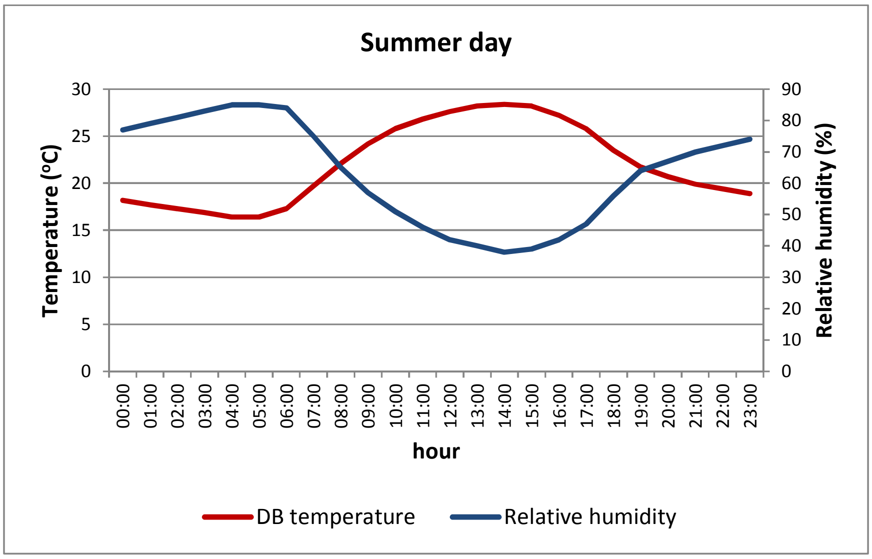


Figure 4-1: Summer day temperature and relative humidity

During the winter months, the surface BAC is not required because the ambient air is sufficiently cold and dry for ventilation cooling. Figure 4-2 shows the winter daily temperature and humidity profiles. In the winter, the daily temperatures range between 19 and 3 °C, with the RH ranging from 76 to 25%.

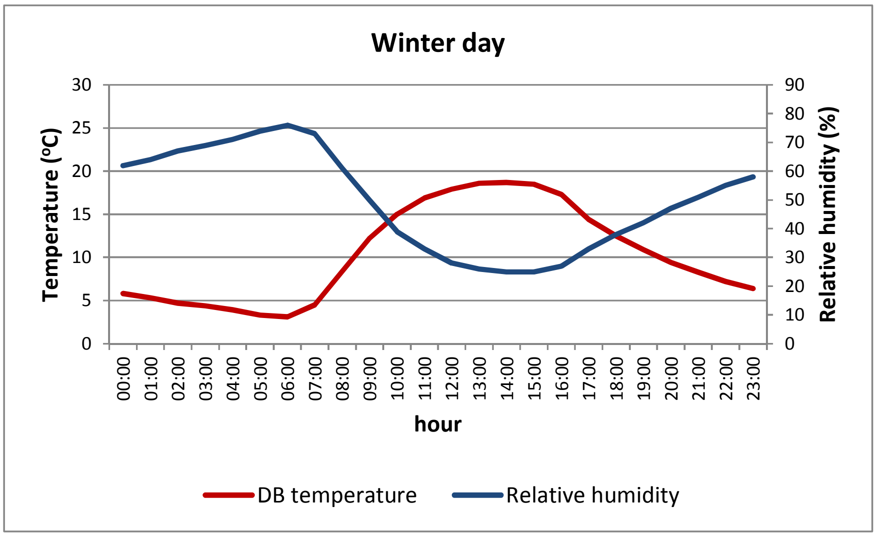


Figure 4-2: Winter day temperature and relative humidity

It seems possible to switch off the surface BAC during the summer, considering that the maximum dew-point temperature in the winter is warmer than the minimum dew-point temperature in the summer, and the maximum winter RH is higher than the minimum summer RH.

The BAC system can be in a closed loop with the refrigeration machine, as shown in Figure 4-3, or in an open loop with water pumped from the chill dam through the BAC as shown in Figure 4-4. With both setups, the refrigeration machines absorb the heat load the BAC absorbed from the ambient air. From the simulation used in Chapter 3, a closed-loop system is evaluated.

A saving on the surface closed-loop BAC implies that the same saving can be achieved on an open-loop system.

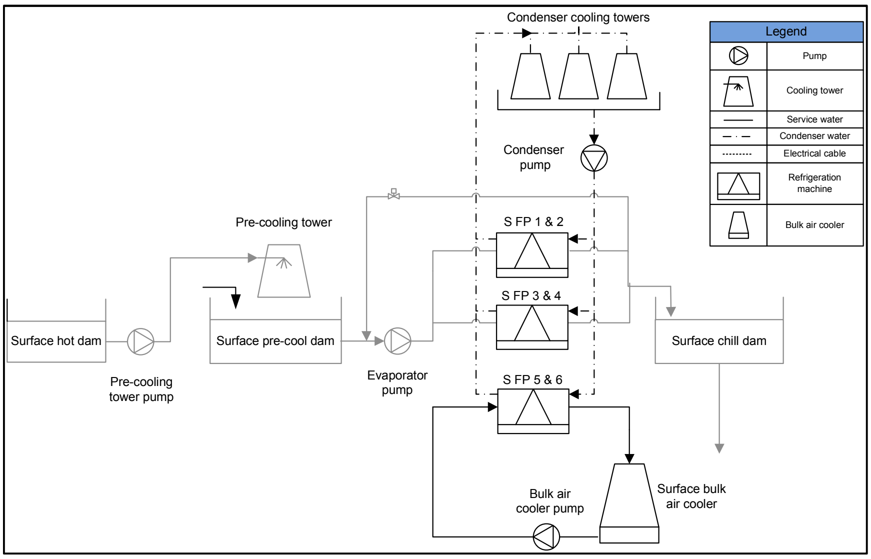


Figure 4-3: Closed-loop surface BAC

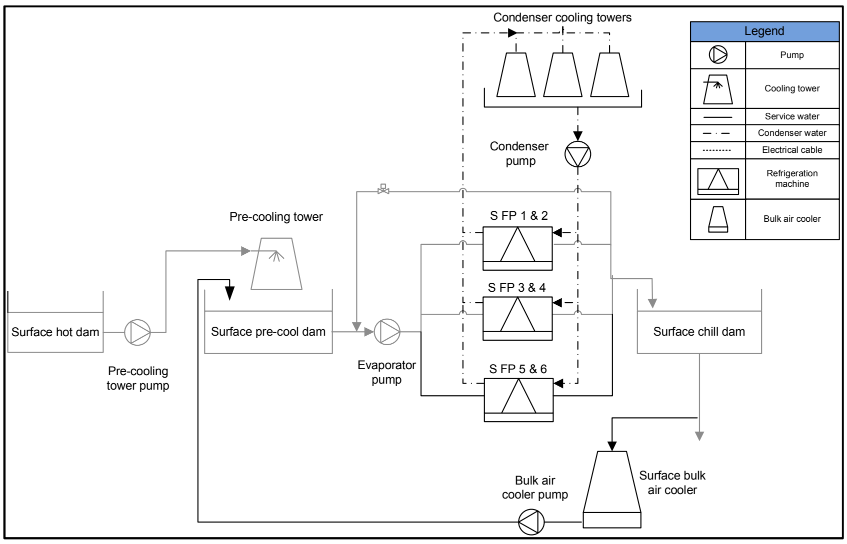


Figure 4-4: Open-loop surface BAC

From Chapter 2, it is known that closed-loop surface BACs are the second ventilation and cooling system installed as a mine develops, following the main fans required for ventilation.

For this reason, surface BACs are found on most South African gold and platinum mines. Also from Chapter 2, it is recommended that deep and ultra-deep mines install secondary and tertiary underground air coolers.

A mine shaft's diameter can vary between 5 m and 25 m, with a typical diameter of 15 m. A mine that is 3.6 km deep has a diameter-to-depth ratio of 1:240. The mining activity is up to 3 km from the shaft. Visualising the ventilation effort from the surface is the same as trying to cool down a cake in the oven at 60 to 70 ^{o}C, with air from the fridge at 5 to7 ^{o}C through 12 straws end to end, assuming that a straw has a diameter-to-length ratio of 1:38.

The average summer DB temperature and RH are 20.20 ^{o}C and 57.30% respectively. Using the above psychrometric chart gives an enthalpy of 46 kJ/kg. The surface BAC cools the air down to 5 ^{o}C.

This temperature is beneath dew-point temperature and the RH is 100%. The enthalpy of the air leaving the BAC is 21 kJ/kg. Cooling the air to 7 ^{o}C, which is also below dew-point temperature, results in a RH of 100% and an enthalpy of 26 kJ/kg.

The BAC inlet air humidity ratio is 10.2 $g_{moisture}/kg_{dry\ air}$ and the outlet air humidity ratio is 6.5 $g_{moisture}/kg_{dry\ air}$ at 5 ^{o}C and 7.5 $g_{moisture}/kg_{dry\ air}$ at 7 ^{o}C. Using Equation 9, the rate of water removal is calculated at 1.85 kg/s and 1.35 kg/s. The latent heat required to condensate water at the dewatering rate is calculated using Equation 17. The specific heat required in Equation 17 to condensate water was calculated using Equation 18.

The result is shown in Table 4-2 and a saving of 892 kW is achieved by the optimised cooling auxiliaries project. Doing a peak clip project before the cooling auxiliaries project can realise a saving of 4 073kW. After a cooling auxiliaries project, the saving will be 3 181 kW. The optimisation of the cooling auxiliaries project already reduces the cooling done by the BAC to the mine ventilation specification. Showing that a peak clipping project is possible on this system implies that a project is also possible on a system before the optimisation of a cooling auxiliaries project.

Table 4-2: Mine air-refrigeration surface

Outlet air 5 °C			**Outlet air 7 °C**		
Fans			*Fans*		
Mass flow	500	kg/s	Mass flow	500	kg/s
Pressure	0.5	kPa	Pressure	0.5	kPa
Efficiency	48	%	Efficiency	48	%
BAC fan power	521	kW	BAC fan power	521	kW
Air cooling			*Air cooling*		
Enthalpy in	46	kJ/kg	Enthalpy in	46	kJ/kg
Enthalpy out	21	kJ/kg	Enthalpy out	26	kJ/kg
Mass flow	500	kg/s	Mass flow	500	kg/s
Thermal kW	12 500	kW	Thermal kW	10 000	kW
Condensate			*Condensate*		
Inlet	10.2	°C	Inlet	10.2	°C
Outlet	6.5	°C	Outlet	7.5	°C
Condensate rate	1.85	kg/s	Condensate rate	1.35	kg/s
$Cp_{condensate}$	2 489	kJ/kg	$Cp_{condensate}$	2 489	kJ/kg
Thermal kW	4 605	kW	Thermal kW	3 360	kW
Water			*Water*		
Inlet temperature	3	°C	Inlet temperature	3	°C
Outlet temperature	14	°C	Outlet temperature	13	°C
Flow	0.38	m^3/s	Flow	0.34	m^3/s
Thermal kW	17 105	kW	Thermal kW	13 360	kW
COP	4.2		COP	4.2	
Power	4 073	kW	Power	3 181	kW
Constant					
C_{pwater}	4181	J/(kg.K)			

This section showed that a saving on the surface BAC system relates to a saving on the refrigeration machines. The effect of reducing the amount of cooling done by the surface refrigeration system on underground conditions is considered in the following section.

4.3. Peak clip initiative

The previous section showed that a peak clipping project on the surface BAC will realise a saving on the refrigeration machines. The effect of such a project should be evaluated on the underground working conditions of the mine.

There are software packages that simulate mine ventilation in detail, such as VUMA, illustrated in Figure 4-5. These systems usually use a grid of nodes solved in sequence to analyse and solve the system. To build, populate and compile such a simulation requires an entire mine ventilation department. This department builds the tunnels and measures all the parameters and characteristics of a specific mine.

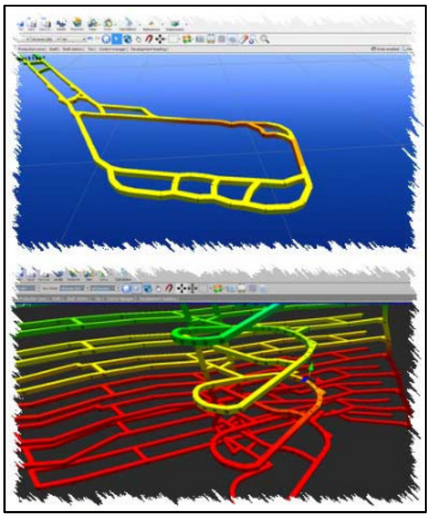


Figure 4-5: VUMA simulation package [2]

The air leaves the BAC on the surface and travels down the MM shaft. From the MM shaft, it enters each mining level and absorbs moisture and heat until it is discharged at 29 ^{o}C WB. To evaluate what effect a peak clip will have on the underground conditions, it is proposed that the effect on the inlet conditions of each level should be evaluated. This will be an accurate, measureable, simplified and effective analysis.

Air moving down the shaft is heated by auto-compression and sensible heat from the rock face. There is also an increase in the RH, as it absorbs moisture from the shaft. The moisture in the shaft can be due to fissure water or leaking water pipes. From literature, there are essentially four ways to determine the effect on the air moving down the shaft, as summarised in Table 4-3.

Table 4-3: Four downcast ventilation air analysis methods

No.	Method	Based on	Reference
1.	Temperature gradient	Empirical measurements	[3]
2.	WB gradient	Empirical measurements	[4]
3.	Goch Patterson	Heat exchange with the rock face	[5]
4.	Adiabatic compression	Adiabatic compression	[4]

The air temperature gradient of 9.76 ^{o}C per 1 000 m is used to justify on which level secondary air cooling should be done. With a BAC outlet temperature of 7 ^{o}C, the temperature at 1 800 m is 25 ^{o}C and at 3 600 m it is 42 ^{o}C.

It is assumed that the BAC outlet temperature will become the surface ambient temperature of 20 ^{o}C. The temperature underground at the inlet of mining levels will then be 38 ^{o}C at 1 800 m and 55 ^{o}C at 3 600 m, following the temperature gradient.

This equation justifies surface air cooling, as well as where the secondary cooling should be installed. Using Method 1 shows the significant effect of stopping the surface BAC with an increase of 12 ^{o}C.

A reject temperature of 29 ^{o}C WB equates to 32 ^{o}C DB and 80% RH. Using Method 1 on the extraction side will show that the outlet temperature at the surface main fans equates to -3.1 ^{o}C. This is below freezing and colder than the temperature supplied by the BAC.

The BAC outlet temperature will be 7 ^{o}C DB for 22 hours a day and 20 ^{o}C DB for the remaining two hours of the day. This equates to a daily average of 8.1 ^{o}C DB. Using this value as the input value for Method 1 gives a level temperature of 43.1 ^{o}C. Again, underground cooling is required.

It can then be concluded that Method 1 only applies to steady-state conditions when motivating for surface bulk air cooling and secondary bulk air cooling underground. It cannot be used to determine the effect of a peak clip project on the surface BAC during the Eskom evening peak period.

Method 2's WB temperature gradient is a 1.4 ^{o}C increase per 300 m. From the 7 ^{o}C BAC outlet, this gives a WB temperature of 15 ^{o}C at 1 800 m and 24 ^{o}C at 3 600 m. Taking the RH to be 50%, it gives a DB temperature of 31.5 ^{o}C. Again, a reject temperature of 29 ^{o}C WB equates to 32 ^{o}C DB and a RH of 80%. Using the same ratio, the extraction surface temperature is 12 ^{o}C.

Again, it is assumed that the BAC outlet temperature will become the surface ambient temperature of 14.6 ^{o}C WB. The WB temperature underground at the inlet of mining levels will then be 23.0 ^{o}C at 1 800 m and 31.4 ^{o}C at 3 600 m, following the WB temperature gradient. Taking the RH to be 50%, the DB temperature is then 31.5 ^{o}C. The above two scenarios are summarised in Figure 4-6.

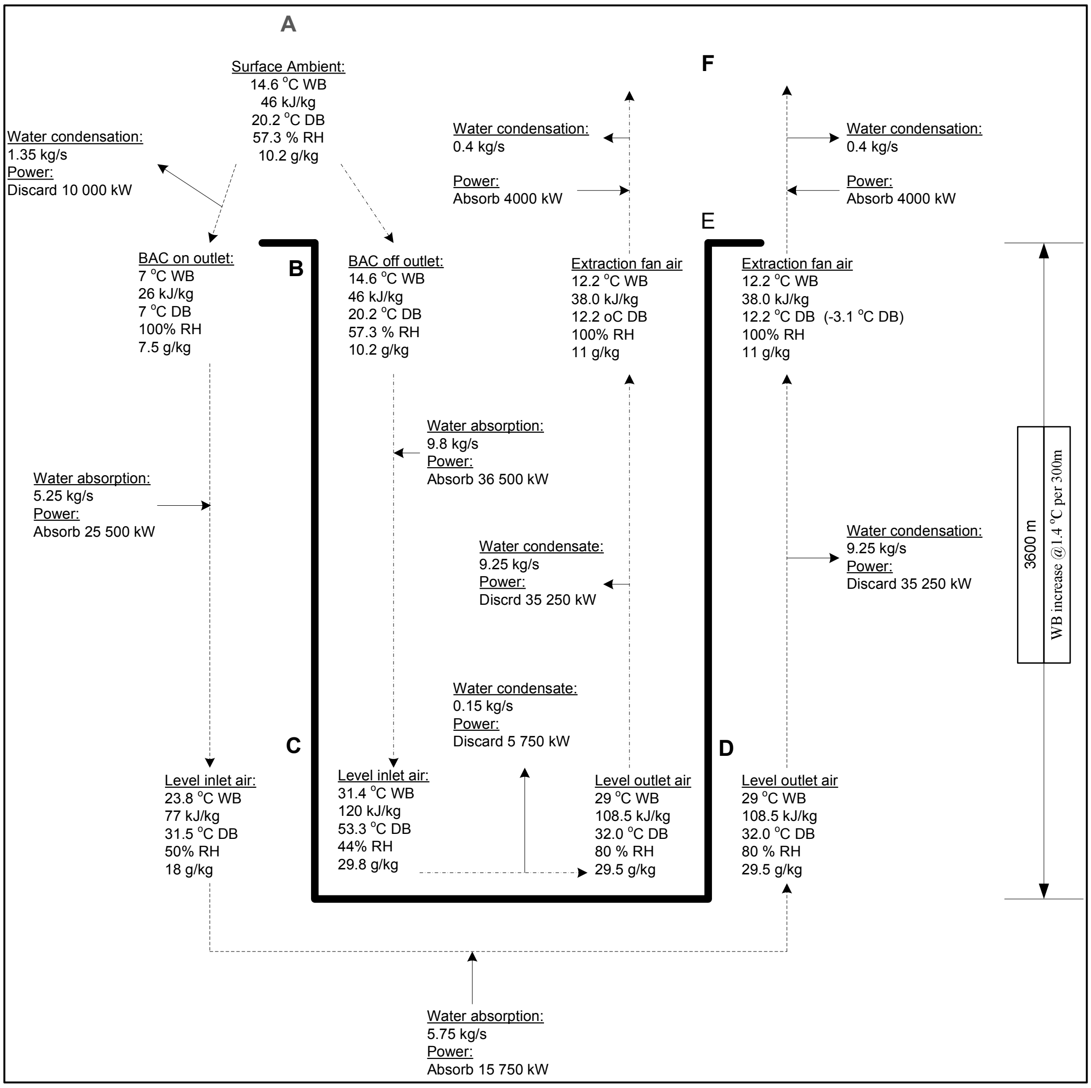


Figure 4-6: WB temperature gradient simulation

The inlet WB temperature on the level is 31 °C, which is higher than the reject temperature of 29 °C WB. This indicates that additional underground cooling needs to be done if there is no cooling on the surface.

The WB temperature lapse rate varies, however, depending on the entering temperature, humidity ratio and pressure drop in the shaft. It is still a steady-state solution and does not take into account that the shaft and working areas are cooled before and after the peak clip.

The BAC outlet temperature will be 7 ^{o}C WB for 22 hours a day and 14.6 ^{o}C WB for the remaining two hours of the day. This equates to a daily average of 7.63 ^{o}C WB. Using this value as the input value for Method 2 gives a level temperature of 24.4 ^{o}C.

The DB temperature is required in Equation 6 of the Goch Patterson equations. This is the variable that needs to be determined at the inlet of the levels with and without surface bulk air cooling to evaluate the energy-saving strategy.

$$\alpha = k/\rho c \qquad \text{(Eq.3)}$$

$$Fo = \frac{\alpha\theta}{r^2} \qquad \text{(Eq.4)}$$

$$\epsilon = \{1.017 + 0.7288\log_{10}(Fo) + 0.1459[\log_{10}(Fo)]^2 - 0.01572[\log_{10}(Fo)]^3 - 0.004525[\log_{10}(Fo)]^4 + 0.001073[\log_{10}(Fo)]^5\}^{-1} \qquad \text{(Eq.5)}$$

$$Heat\ flux\ \left({}^{W}/_{m^2}\right) = \frac{k(t_{vr} - t_a)(\varepsilon)}{r} \qquad \text{(Eq.6)}$$

$$Total\ heat\ flow\ (W) = (Heat\ flux)(L)(P) \qquad \text{(Eq.7)}$$

Where:

α	=	thermal diffusivity of rock (m^2/h)
k	=	thermal conductivity of rock (W/(m.K))
ρ	=	rock density (kg/m^3)
c	=	heat capacity (kJ/(kg.K)
Fo	=	Fourier number (dimensionless)
L	=	length of section (m)
P	=	perimeter of section (m)
r	=	radius of circular section (m)
t_a	=	air dry-bulb temperature (^{o}C)

t_{vr} = virgin rock temperature (°C)

ε = function of Fourier number for instantaneous rate (dimensionless)[4]

θ = average age of section, (h)

It is possible, though, to calculate the heat flow from the rocks using the values from the WB temperature gradient evaluation above. Taking a mine that has been open for 20 years, it will equate to 20*365*24=175 200 h. As stated, the diameter of the shaft is 15 m and the radius 7.5 m. As shown in Table 4-4, the average thermal diffusivity is taken as 0.0077 m^2/h.

Table 4-4: Thermal conductivity and diffusivity of rock types

Rock type	Thermal conductivity [W/mK]	Diffusivity (m^2/h)
Granite	1.92	0.012
Quartzite	5.50	0.008
Shale	2.39	0.003
Average	3.27	0.0077

A Fourier number of 24 is calculated with the instantaneous rate being 0.445, as shown in Table 4-5. The average rock temperature gradient in South Africa is 1.2 °C per 100 m and the rock at the surface is 23 °C. This gives a rock temperature at 3 600 m of 64 °C.

Table 4-5: Goch Patterson equations

Thermal diffusivity	0.0077	m^2/h
Age (20j)	17 5320	h
Radius	7.5	m
Fo	24	
E	0.445	
Thermal conductivity	3.27	
t_{vr}	64	°C
t_a	32	°C
Heat flux	6.21	W/m2
L	3 600	m
P	47	
Total heat flow	1 054	kW

Increasing the air DB temperature to 53 °C results in a total heat flow of 362 kW. It is recommended that the length be kept below 60 m when using the Goch Patterson equations. The theoretical heat load imposed on ventilation air by auto-compression is given in Equation 1, which is a simplified form of the general energy equation:

$$q = Q\rho E\Delta d \qquad \text{(Eq.1) [4]}$$

Where:

q = theoretical heat of auto-compression (kW)

Q = airflow in shaft (m^3/s)

ρ = air density (kg/m^3)

E = energy added per unit distance of elevation change (1kJ/(102m.kg))

Δd = elevation change (m)

The above equation is used and the results are shown in Table 4-6.

Table 4-6: Auto-compression energy

Airflow	424	m^3/s
Elevation	3 600	m
Mass flow	500	kg/s
Power	17 658	kW
Constants		
Air density	1.18	kg/m^3
E	0.0098	kJ/kg

The heat from the Goch Patterson analysis is added to the auto-compression heat in Table 4-7.

Table 4-7: Total theoretical heat load down the shaft

Auto-compression	17 658	kW
Goch Patterson	1 054	kW
Total	18 712	kW

The heat flow from a section that has been opened for 20 years is 6% of the total heat. About 94% of the heat load is created by auto-compression. Method 2 calculated the heat load down the shaft 36% higher, at 25 500 kW.

From the above, it can be taken that heat load and humidity absorbed by the surface BAC are again added to the air by auto-compression before the ventilation air enters the mining levels.

The four evaluation methods from literature cannot be used to determine if switching to a mine-surface BAC for two hours a day will have a significant effect on the underground environment. For this reason, an empirical approach was followed to analyse the effect on the underground cooling system, using loggers shown in Figure 4-7.

Figure 4-7: Data loggers used for empirical measurements

A mine system extensively controlled by EMSs was selected. Initial investigation was done after a fridge plant project and before an optimisation of cooling auxiliaries project.

The loggers were installed on the surface to measure the ambient and the BAC outlet air. They were installed on 38-level and 75-level to measure the air conditions entering these levels. Figure 4-8 shows a layout of the mine. The loggers were installed and the mine operated as usual. No test was done during this period.

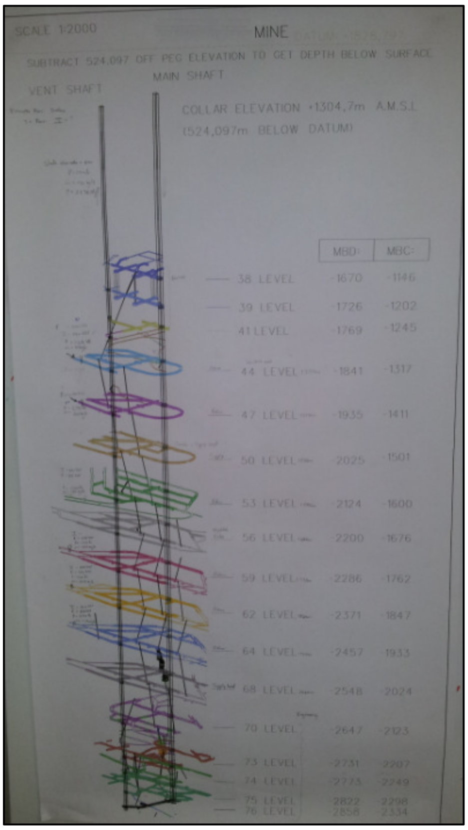


Figure 4-8: Layout of mine showing 38-level and 75-level

The data was logged with two-minute intervals and processed into hourly average values. From the data, it was evident that the BAC was not always operational, because all the data was measured at the same time and air travelling down the shaft from the surface at 20 m/s would reach 75-level in about two minutes.

The data was divided into BAC on and BAC off data sets. The surface ambient air variables are not controlled. The air conditions on the levels were plotted against surface ambient conditions as shown in the figures below.

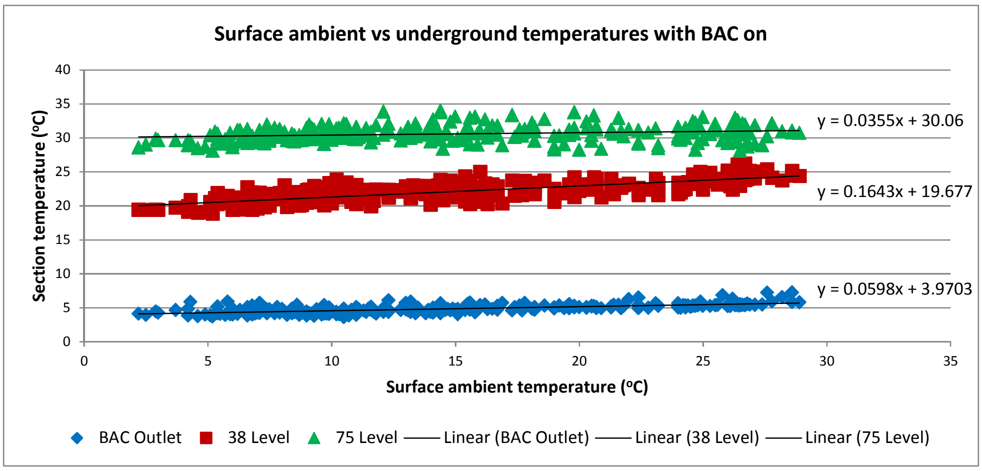


Figure 4-9: Surface ambient vs. underground temperatures with BAC on

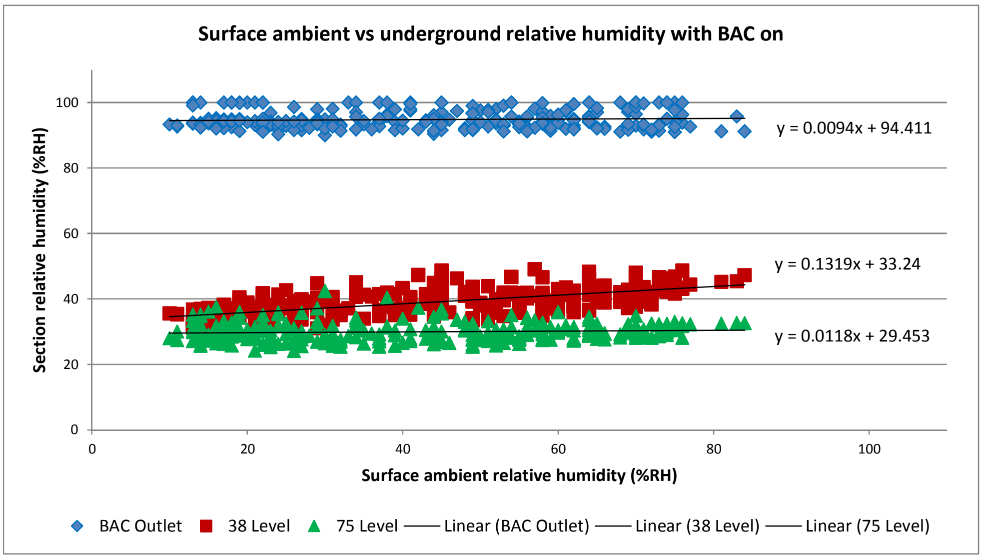


Figure 4-10: Surface ambient vs. underground relative humidity with BAC on

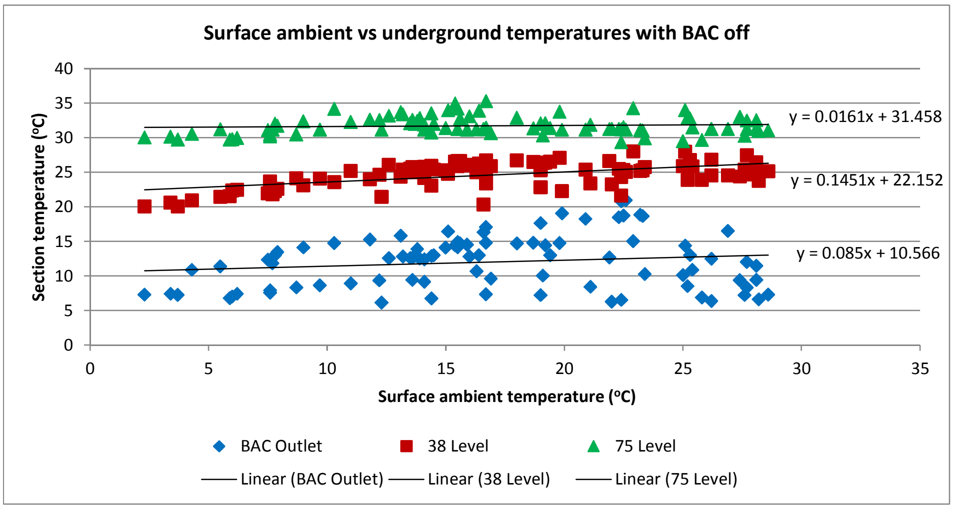


Figure 4-11: Surface ambient vs. underground temperatures with BAC off

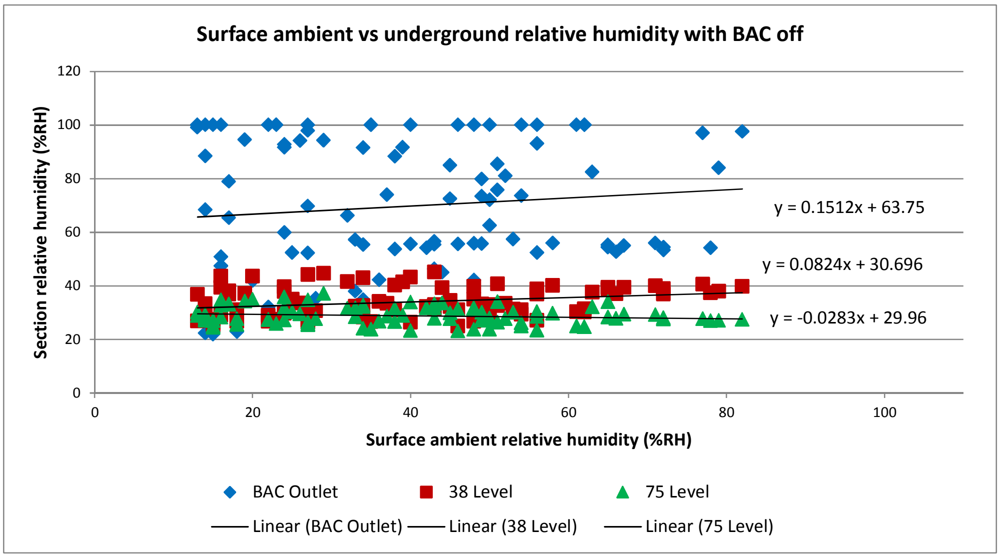


Figure 4-12: Surface ambient vs. underground relative humidity with BAC off

The trend line function in Excel was used to derive the line equations that indicate what the hourly BAC outlet temperature, 38-level temperature and 75-level temperature would be at the specified surface ambient temperature for the BAC running and not running.

The simulation from these equations is plotted against a day that the BAC was on for 24 hours. Figure 4-13 shows the temperature calculated from the surface ambient air and the temperatures measured on the levels and at the BAC outlet. The results show that these equations are accurate.

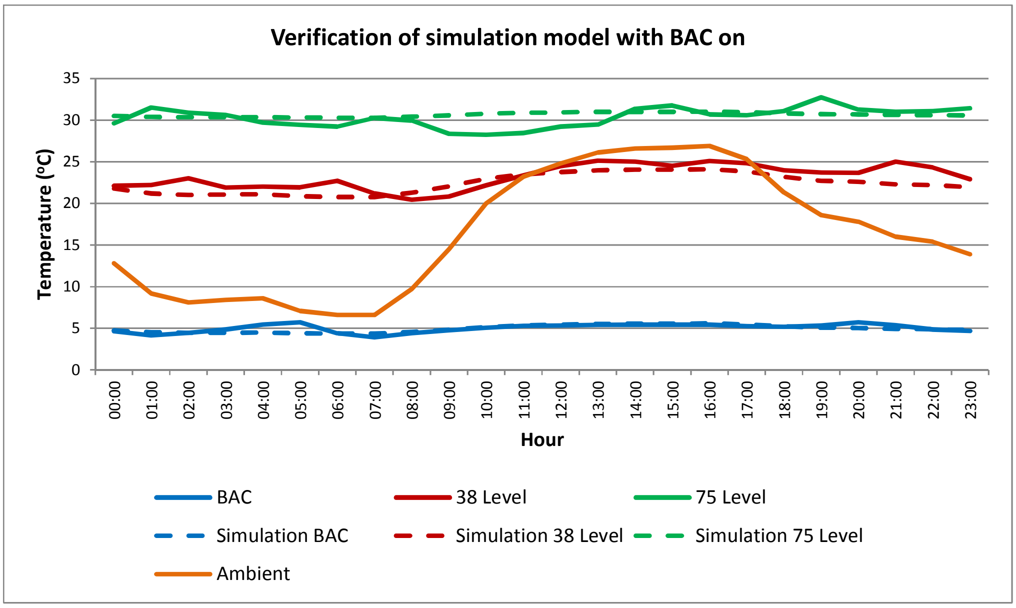


Figure 4-13: Verification of simulation model with BAC on

Figure 4-14 shows the percentage difference between the simulated and measured values. The simulation is within 10% and will be used to calculate the underground conditions when the BAC is operational.

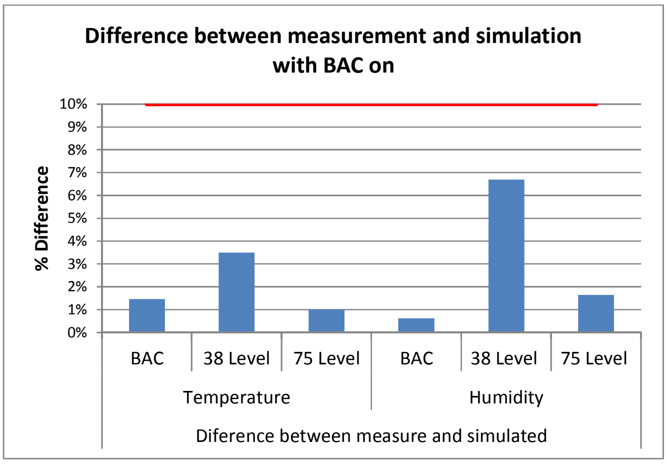


Figure 4-14: Percentage error or simulation with BAC on

The simulation from these equations is plotted against a day that the BAC was off for 24 hours. Figure 4-15 shows the temperature calculated from the surface ambient air and the temperatures measured on the levels and at the BAC outlet. The results show that these equations are accurate.

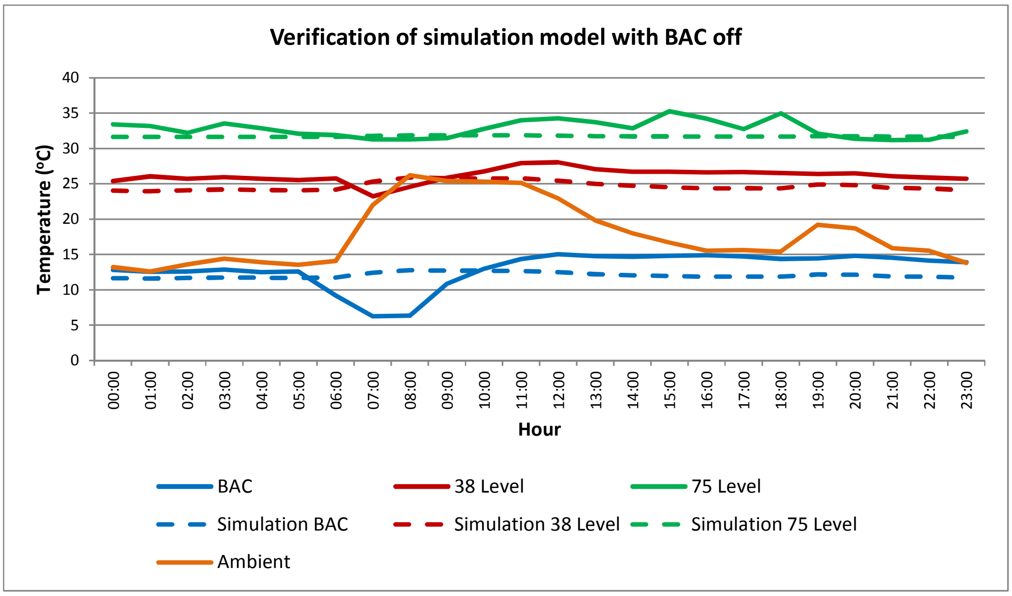


Figure 4-15: Verification of simulation with BAC off

Figure 4-16 shows the percentage difference between the simulated and measured values. The simulation is within 10% and will be used to evaluate the effect of switching off the BAC for the Eskom evening peak.

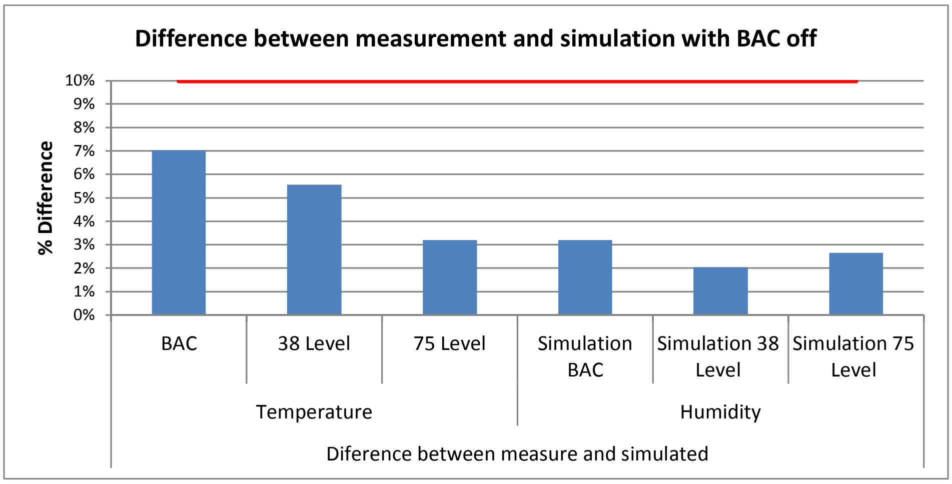


Figure 4-16: Percentage error of simulation verification with BAC off

The expected effect of switching off the surface BAC for the Eskom evening peak can be seen in Figure 4-17. There is an increase in the BAC outlet temperature for the two hours, but it does not quite reach the ambient air temperature as the air is still cooled by the cold infrastructure in the BAC.

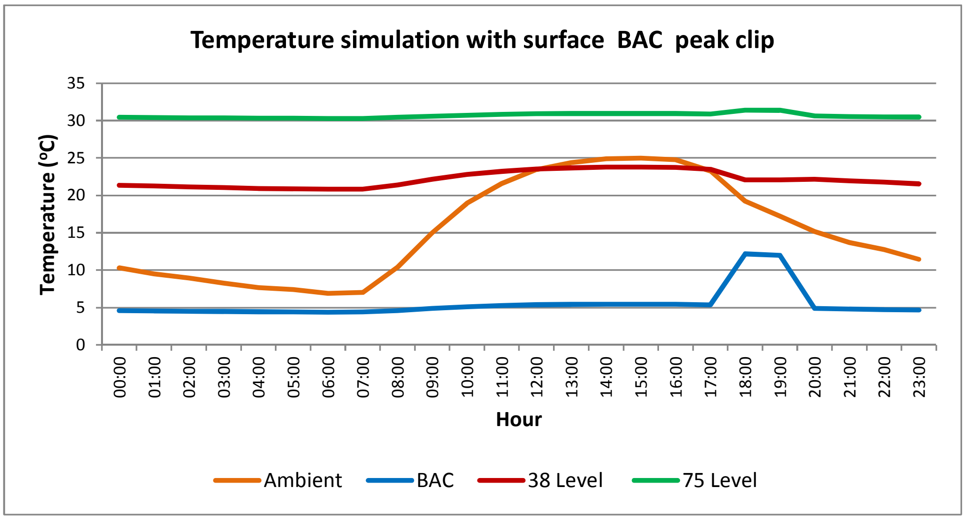


Figure 4-17: Mine A surface BAC peak clip effect on underground temperatures

The temperature of 75-level increased, but remained within the limit. Figure 4-18 shows the simulation against the average profile for the entire period. It is evident that an evening peak clip project on the surface BAC would not have a significant effect on the overall average temperatures experienced underground.

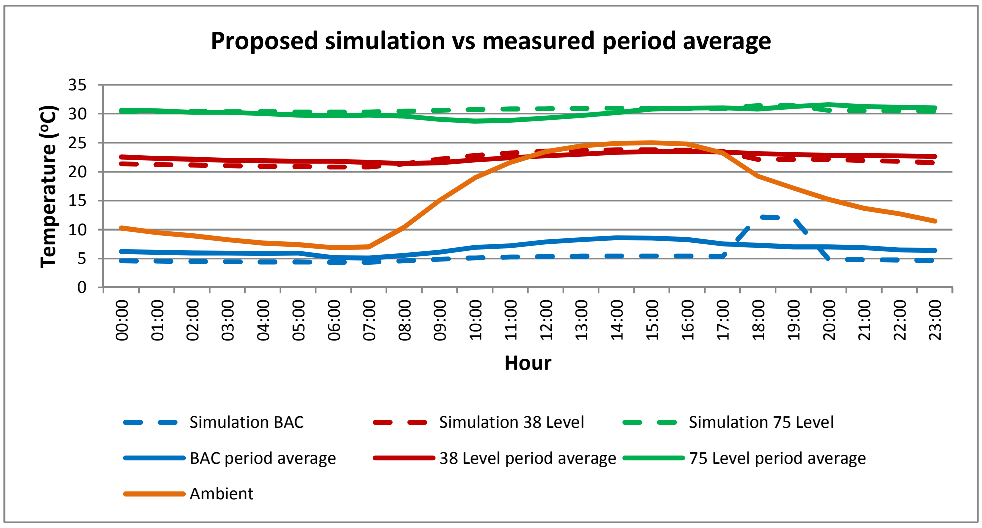


Figure 4-18: Proposed simulation vs. measured period average

The top line in Figure 4-19 is the temperature increase with the depth of the virgin rock. The bottom line is the temperature increase with the depth of the air from the BAC. The second line from the top is the expected temperature increase of the ambient air when the BAC is switched off, while the second line from the bottom is what seems to be actually happening when the BAC is switched off for an hour.

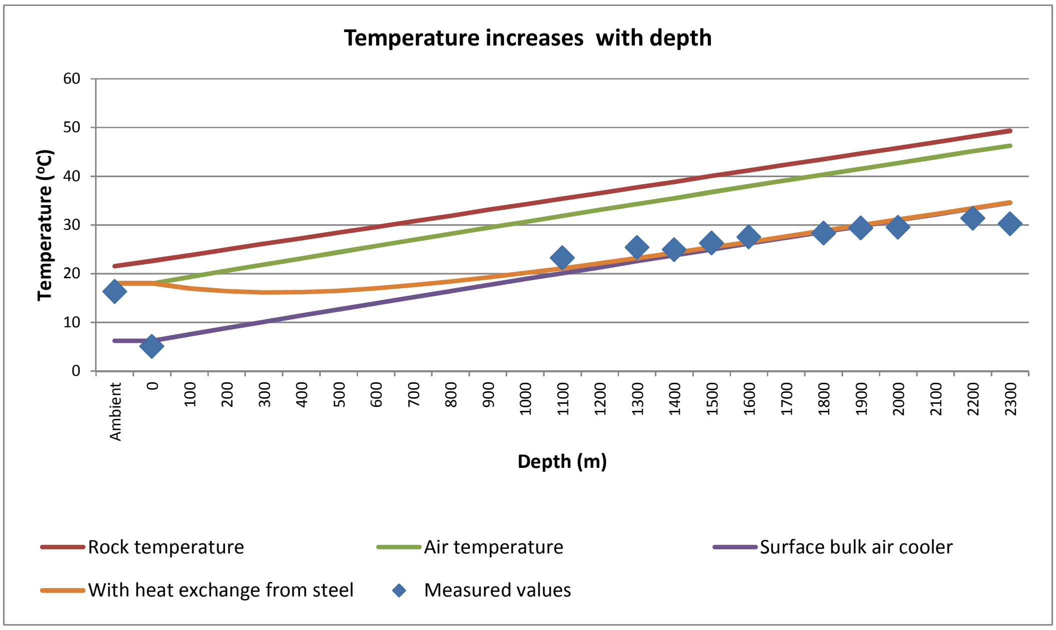


Figure 4-19: Temperature increases with depth

What is seen in Figure 4-19 can be attributed to the steel infrastructure, as well as the rock face that is sufficiently cooled when the BAC is operational. It will take time for these temperatures to increase. If the BAC is switched off for a prolonged time, the second line from the bottom will eventually match the second line from the top.

The infrastructure in the shaft acts like a capacitor. This thermal storage will cool the air during the two hours when the BACs are stopped. The level values are shown in Table 4-8.

Table 4-8: Implementation parameters

Simulation						
	Baseline			Results		
Level	DB T°	RH	Enthalpy	DB T°	RH	Enthalpy
Ambient	16.43	38.50	30.00	15.30	41.95	29.00
Surface	4.95	94.77	20.00	5.47	92.60	21.00
38 L	22.38	38.57	42.00	22.14	38.57	42.00
75 L	30.64	29.91	56.00	30.66	29.84	56.00

The change in enthalpy of a level is zero according to the simulation results as shown in Table 4-9.

Table 4-9: Implementation level difference in enthalpy

Peak clip investigation			
Level	**BAC on enthalpy**	**BAC off enthalpy**	**Difference**
38 L	42.00	42.00	0.00
75 L	56.00	56.00	0.00
Average change level enthalpy			**0.00**

This then is sufficient evidence to test the peak clip initiative in a case study.

4.4. Case study

The case study mine's systems are extensively controlled by EMSs. Data from the fridge plant project was used for the investigation in the previous section. The BAC project implementation was investigated after an optimisation of the cooling auxiliaries project.

The BAC is a counter flow heat exchanger and draws air from the surrounding air. The air is cooled and discharged under the surface into the mine's MM shaft as shown in Figure 4-20. The mining levels were shown in Figure 4-8 earlier in this chapter.

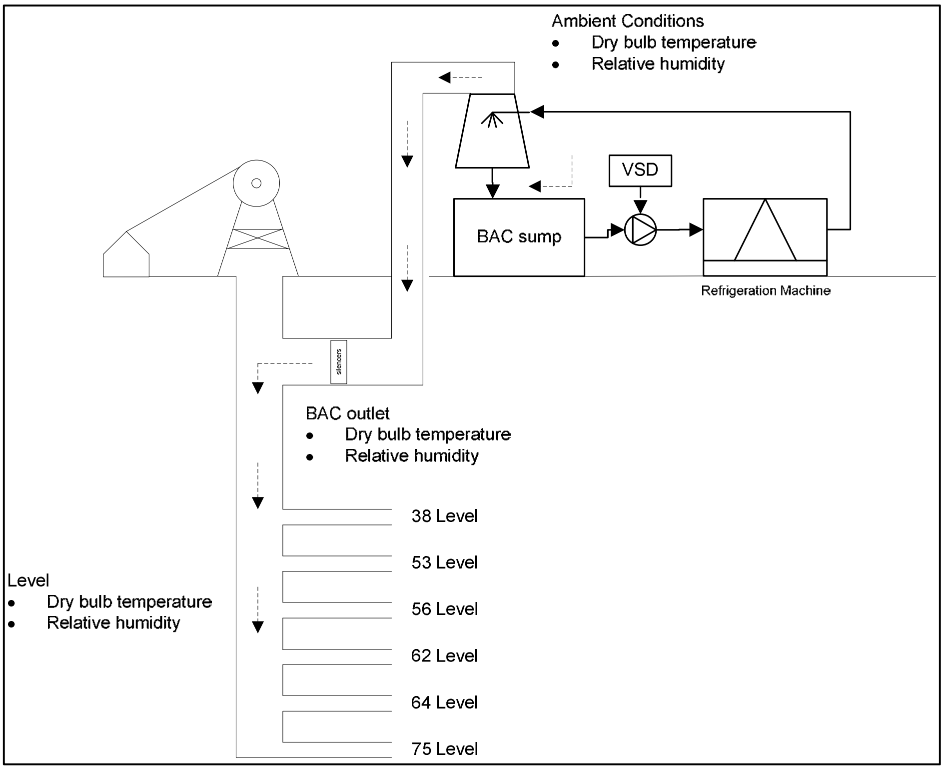


Figure 4-20: Mine A BAC

The BAC fans ensure that the majority of the ventilation air comes from the BAC. Cooling will be wasted if the BAC fans deliver more air than the main extraction fans can draw in. The excess chilled air will escape from the top of the mine shaft and back into the atmosphere.

The water is pumped by three 110 kW pumps with a total flow of 380 ℓ/s. The airflow through the BAC is generated by three 250 kW fans, with a total airflow rate of 500 kg/s. There are three BACs and three refrigeration machines in series.

As calculated in Section 4.2, the BAC absorbs 10 000 kW of thermal energy from the ambient air, turning it into chilled ventilation air. Another 3 360 kW is needed to condensate the 1.35 kg/s of water from the air to dehumidify it. A total of 13 360 kW increases the 380 ℓ/s water temperature from 3 °C to 13 °C. This load then needs to be absorbed by the refrigeration machines' evaporators. With a COP of 4.2, this will require 3 181 kW of electricity.

The refrigeration machines and the BACs were controlled using the infrastructure installed with the fridge plant and optimised cooling auxiliaries project. As shown in Figure 4-21, doing a peak clipping or load-shifting project on mine A's surface refrigeration system will allow for a 3 181 kW reduction in the Eskom evening peak. The results are discussed in the following section.

4.5. Results

The entire mine's surface refrigeration is monitored and the saving is evaluated on the power of the entire system. The fridge plant project's saving strategy was not followed during the testing of the BAC project. The optimisation of cooling auxiliaries project was, however, followed.

Shutting down the BAC in the summer for the Eskom evening peak will save 3.0 MW. This consists of the fridge plant power and BAC auxiliary power. Figure 4-21 shows the load shift for the summer months.

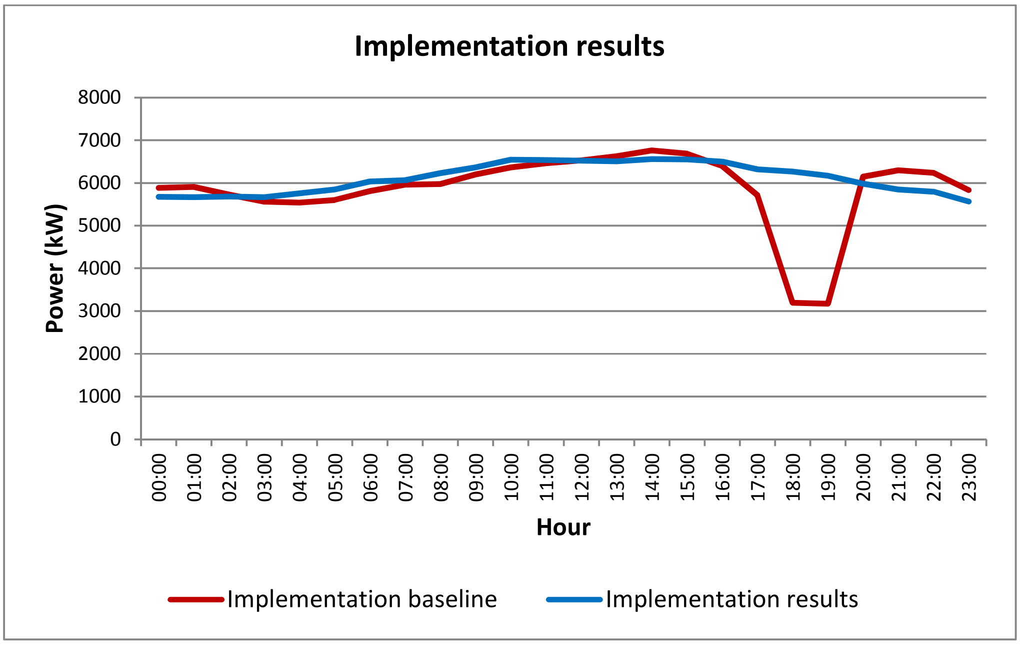


Figure 4-21: Cooling and ventilation summer profile

The effect on underground mining level temperatures over a 24-hour period is shown in Figure 4-22.

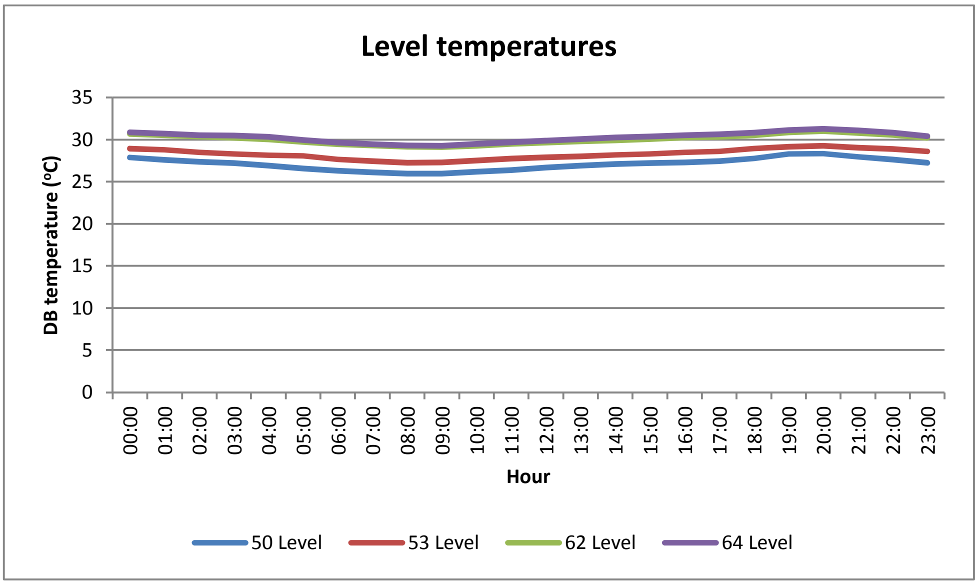


Figure 4-22: Implemented level temperatures

The effect on the RH of the underground mining level over a 24-hour period is shown in Figure 4-23. It can be seen that there is a slight rise in RH between 18:00 and 20:00.

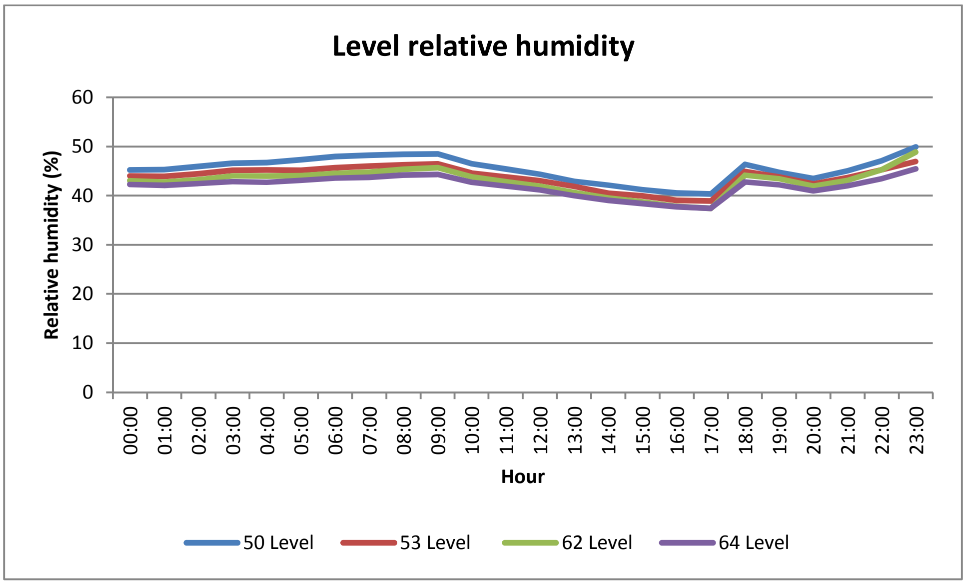


Figure 4-23: Implemented level relative humidity

The average results are summarised in Table 4-10. It can be seen that the daily average DB temperature of the baseline is lower than the daily average DB temperature of the implemented results.

There is, however, a slight decrease in the daily average humidity. This means that the sensible heat increase in DB temperature is countered by latent absorbed energy in increased humidity.

Table 4-10: Implemented level results

Implementation						
	Baseline			Results		
Level	DB T°	RH	Enthalpy	DB T°	RH	Enthalpy
50 L	26.24	48.35	57.00	27.09	45.43	57.00
53 L	27.49	46.67	59.50	28.29	43.81	59.50
62 L	29.31	47.30	64.00	30.06	42.97	65.50
64 L	29.51	44.51	66.50	30.30	41.94	64.50

Looking at the enthalpy, there is no change for the first two levels shown as described above. The sensible heat gain is evened out by the latent heat absorbed. The average change in enthalpy equates to 0.13 kJ/kg. At 500kg/s, this is a reduction in cooling capacity of 65 kW.

Table 4-11: Implemented change in enthalpy

Level	Baseline enthalpy	Results enthalpy	Difference
50 L	57.00	57.00	0.00
53 L	59.50	59.50	0.00
62 L	64.00	65.50	-1.50
64 L	66.50	64.50	2.00
Average			**0.13**

A reject WB temperature of 29 °C gives an enthalpy of 108 kJ/kg. With the resultant average inlet enthalpy of the levels being 43.5 kJ/kg, this gives an enthalpy difference over the mining level of 64.5 kJ/kg. With a 500 kg/s airflow, there is 32 250 kW of cooling power. A 65 kW change will result in a 0.2% decrease in cooling. Considering the cost-saving that can be achieved, this seems to be a negligible reduction in cooling.

Using the measured data, another result that can be established is that for this mine, at an inlet enthalpy of 25.5 kJ/kg, the enthalpy gradient going down the shaft will be as shown in Figure 4-24.

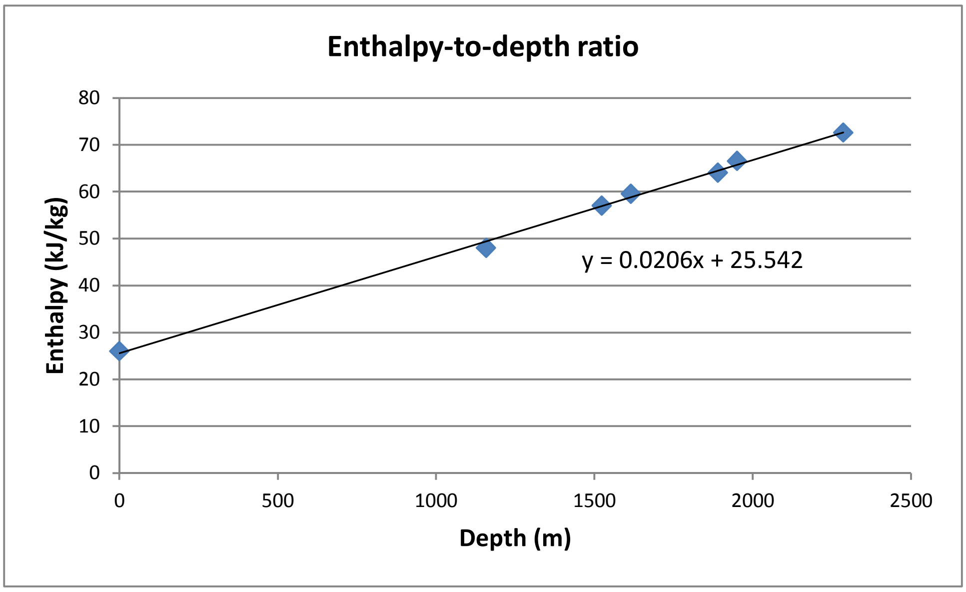


Figure 4-24: Measured enthalpy gradient

The daily average enthalpy will be calculated and this gradient may be used in evaluating future projects.

4.6. Conclusion

It was established from previous chapters that there is a need for a peak clip project on a mine-surface bulk air-cooling system. It was determined that a saving on the BAC would result in a saving on the refrigeration machines. The proposed strategy was unsuccessfully evaluated with available temperature gradients and other equations.

An empirical approach was followed to evaluate what the effect will be on conditions of the underground mining levels. The case study has shown that it is possible to switch off the surface BAC during the Eskom evening peak period. The test results showed that the effect on the underground cooling was insignificant.

It is calculated, using the method contained in Eskom's TOU tariff structure from Chapter 3, that a summer (and hence an annual) saving of R1.38 million can be achieved by the peak clip surface BAC project. Applying these results to the larger South African mining industry will result in the savings shown in Table 4-12.

Table 4-12: Total result of surface BAC peak clipping for South Africa

Mine	Eskom peak period saving (MW)	Capital saving (R million)
Mine A	3.1	1.38
Mine B	2.5	1.11
Mine C	4.1	1.84
Mine D	3.8	1.70
Mine E	3.0	1.33
Mine H	2.6	1.18
Mine I	2.4	1.06
Mine J	3.0	1.33
Total	**24.5**	**10.94**

Implementing this on all the mines will add a capacity of 24.5 MW to the evening peak, as shown in Table 4-12, and will save the mining houses R11 million annually.

4.7. References

[1] Schutte, A.J., Maré, P., Kleingeld, M. Improved utilisation and energy performance of a mine cooling system through control of auxiliary systems. *Proceedings of the 10th International Conference on the Industrial and Commercial Use of Energy*. CPUT, Cape Town, South Africa, August 2013.

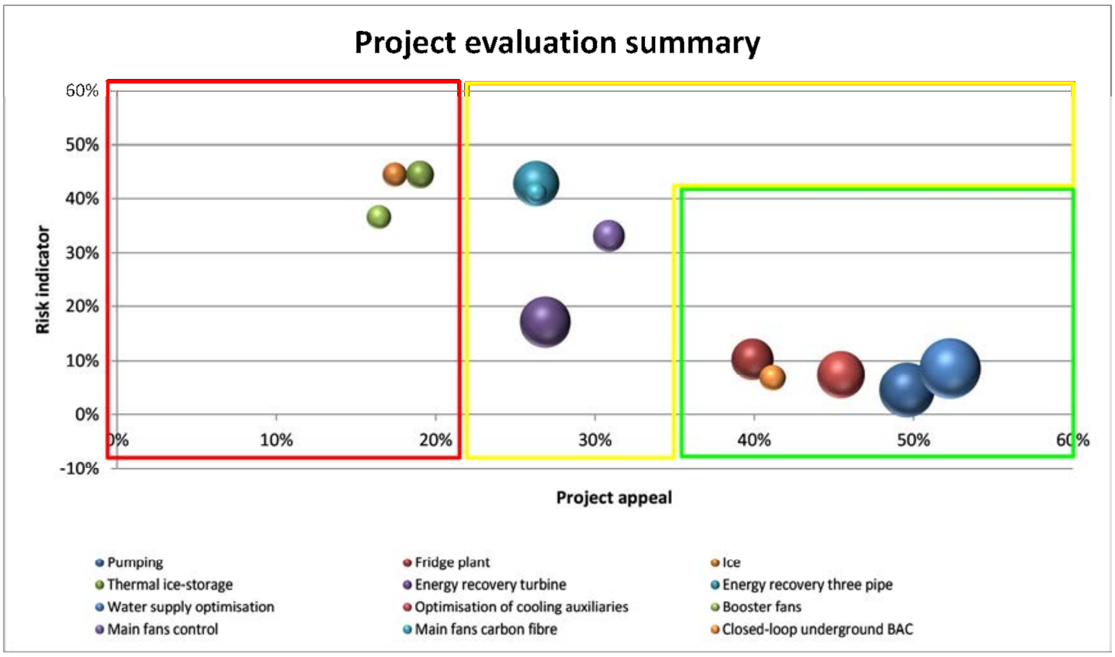
[2] Bluhm, S.J., Marx, W.M., Von Glehn, F.H., Biffi, M. Vuma mine ventilation software. *Journal of the Mine Ventilation Society of South Africa* 54(3):65-72, 2001.

[3] Stone, T. "The critical importance of mine ventilation, Mponeng Mine, AngloGold Ashanti, Fochville", Notes 2.1.40: 1-00, Johannesburg, South Africa.

[4] ASHRAE. HVAC applications. *Mine air condition and ventilation*, *ASHRAE Handbook, Fundamentals*, 2011.

[5] Gosh, D.C., Patterson, H.S. The heat flow into tunnels. *Journal of the Chemical, Metallurgical and Mining Society of South Africa* 41, 1940.

5. Optimised implementation of mine-cooling and refrigeration energy-saving strategies



This thesis presents the research that led to a sequenced combination of energy-saving projects on mine ventilation and cooling systems.

5.1. Prelude

In Chapter 3, the sequenced combination of energy-saving strategies was established. There was a need to research a peak clip initiative on closed-loop surface BACs. Chapter 4 researched and proved that peak clip projects on closed-loop surface BACs are possible, with negligible effect on underground conditions.

The newly developed energy-saving project will now need to be integrated into the sequenced combination developed in Chapter 3. The project will also be evaluated according to cost-saving, risk and PAI. Again, the risk will focus on service delivery, production, EHS and overhead cost.

The PAI is again established by how well the project scores with regard to new equipment, the upgrading of existing equipment, extending the mine's monitoring and networking capacity, displaying and logging mine system variables, short implementation time, little downtime and interaction with other systems.

5.2. New strategy

Continuing with the simulation done in Chapter 3, the new strategy involves stopping the BAC on the surface during the Eskom evening peak period as shown in the cooling system power profile in Figure 5-1.

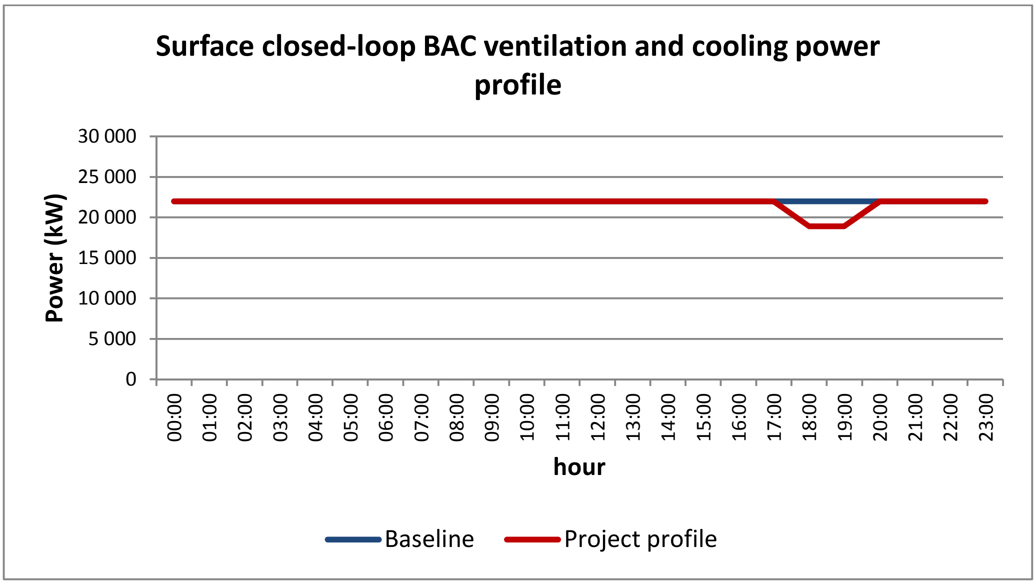


Figure 5-1: Surface closed-loop BAC project power profile

The cost-saving is realised in the summer implementing only this project. The cost profile is shown in Figure 5-2.

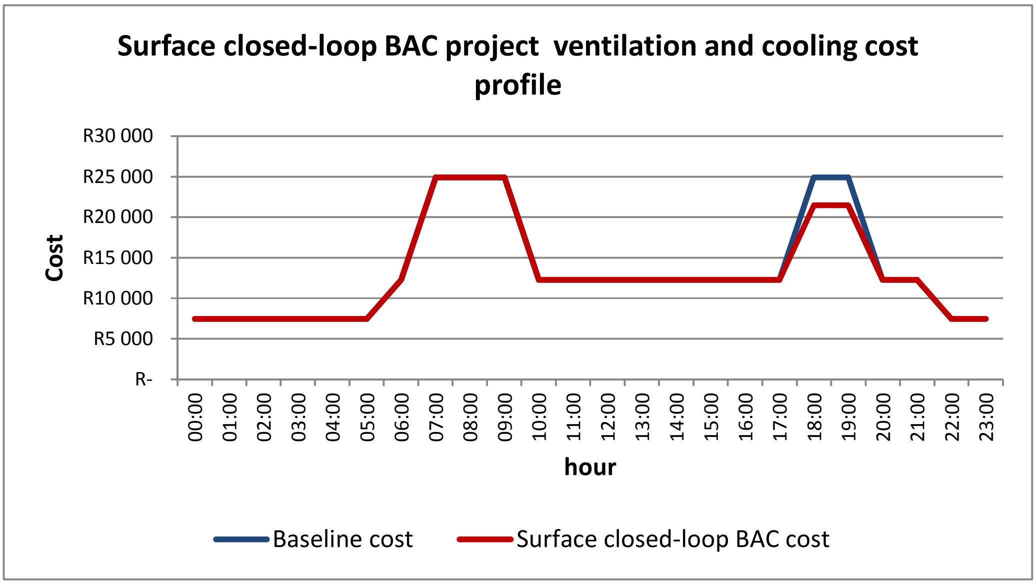


Figure 5-2: Surface closed-loop BAC project ventilation and cooling cost profile

This result gives an annual saving of R2 million and a 2% saving on the total cooling and ventilation energy bill.

From the previous chapter, it is clear that the effect on service delivery is negligible. The surface BAC is still used as usual during the production and cleaning shifts. Switching off during the blasting shift has no effect on production.

The project requires measuring equipment on the inlet of mining levels to monitor the ventilation air conditions. This aids in mine EHS. There is further no effect on EHS. The effect on overhead cost will be the same as a fridge plant project. The risk evaluation sheet is shown in Figure 5-3.

Hazard identification and risk assessment

Project: Closed-loop surface BAC

Section: Surface cooling

Magnitude and severity - Lost production shifts

The severity relates to the resultant lost amount of production shifts due to identified risk
Level 5 - Catastrophic (A month's lost production shifts)
Level 4 - Major (A week's lost production shifts)
Level 3 - Moderate (A production shift)
Level 2 -Minor (A level of a production shift - not recoverable)
Level 1 - Insignificant (A section of a production shift - recoverable)
Level 0 - Not possible

Likelihood - shift interval between occurrences

The likelihood is described as the amount of shifts between occurrence of identified risk event
Level 5 - Frequent (Once on all levels of production shift)
Level 4 - Frequent to moderate (Once at a level of a production shift)
Level 3 - Moderate (Once every 5.5 shifts a week)
Level 2 - Moderate to seldom (Once every 22 shifts a month)
Level 1 - Seldom (Once every 275 shifts a year)
Level 0 - Never

Risk matrix

		Magnitude					
		Level 5 - Catastrophic	Level 4 - Major	Level 3 - Moderate	Level 2 - Minor	Level 1 - Insignificant	Level 0 - Not possible
Likelihood	Level 5 - Frequent	25	20	15	10	5	0
	Level 4 - Frequent to moderate	20	16	12	8	4	0
	Level 3 - Moderate	15	12	9	6	3	0
	Level 2 - Moderate to seldom	10	8	6	4	2	0
	Level 1 - Seldom	5	4	3	2	1	0
	Level 0 - Never	0	0	0	0	0	0

Identification of hazard		Evaluation of risk			Weight	
Aspects	**Hazard / risk**	**Hazard severity or magnitude (S)**	**Likelihood (P)**	**Risk = SXP**	**Aspect weight**	**Weighed Risk**
Service delivery	The BAC project has an insignificant effect on service delivery during the blasting period	2	2	4	1	4
Production	The BAC is stopped during the blasting period and doesn't affect production	1	1	1	2	2
Environmental health and safety	It was shown that the monitoring that comes with this system improved the environmental health and safety conditions underground	2	1	2	3	6
Overhead cost	As with the fridge plant project there may me additional wear on components being stopped and started	2	3	6	1	6

Evaluation of project

Weighed risk indicator	2.57
Maximum possible risk indicator	25
Risk indicator as percentage of maximum possible risk	10%

Rating the resultant percentage risk indicator

No project	100	
	90	
	80	
	70	
	60	
Project with manageable risk	50	
	40	
	30	
	25	
Minimum risk project	20	
	15	
	10	Closed-loop surface BAC
	5	
	0	

Figure 5-3: Closed-loop surface BAC peak clip risk evaluation

The project does not require the installation of new equipment. The existing equipment is upgraded with underground condition monitoring. The underground conditions will need to be displayed, monitored and logged. This project has a short implementation time, as little new equipment and hardware are required. The level monitoring sensors can be installed without affecting production. No weekend labour is required.

The system can be used to determine the load on the underground BAC. It can also be set up to make an alarm if the inlet level temperature varies due to either a burst hot or cold water pipe in the shaft. The effect of the ventilation fan project can also be monitored. The PAI evaluation is shown in Figure 5-4.

Project appeal indicator (PAI)

Project: Surface closed-loop BAC

Sufficiency point out of 10

The sufficiency point indicates how well a project contributes to an aspect out of 10.

Desirability point out of 10

The desirability point is the weight which the aspect carries with 10 indicating that the aspect is highly desirable.

Aspects	Sufficiency point (S)	Desirability (D)	Score (SxD)
New equipment	1	1	**1**
Upgrading existing equipment	5	7	**35**
Monitoring and networking the mine	7	8	**56**
Displaying and logging mine system variables	9	9	**81**
Short implementation time	9	8	**72**
Little down time required for implementation	9	8	**72**
Interaction with other systems	8	5	**40**

Evaluation of project	
Sum of weighed aspect scores	357
Maximum possible score	700
Project appeal indicator (PAI) as percentage of maximum possible appeal	51%

PAI index		
Desirable project	100	
	90	
	80	
	70	
	60	
	50	Surface closed-loop BAC
	40	
Acceptable	30	
	20	
Undesirable project	10	
	0	

Figure 5-4: Surface BAC peak clip PAI

5.3. Implementing the new strategy

The risk evaluation of the surface closed-loop bulk air-cooling strategy is shown with the other projects in Figure 5-5. The risk is equivalent to that of a fridge plant project.

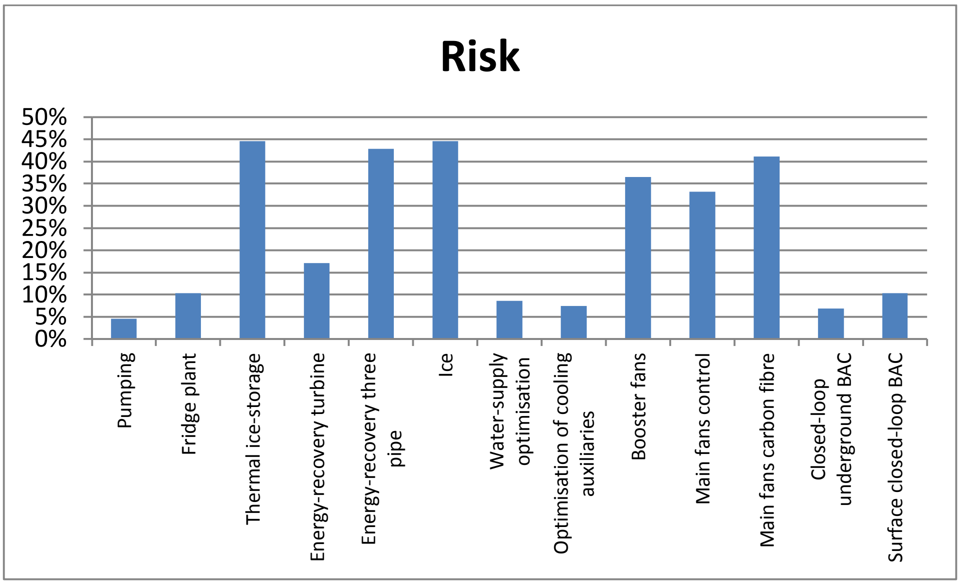


Figure 5-5: All project risk evaluation summary

The PAI of the surface closed-loop bulk air-cooling project, along with all the projects' PAIs, are shown in Figure 5-6. With the underground monitoring of ventilation air conditions and the ease of implementation, this is seen as one of the most appealing projects.

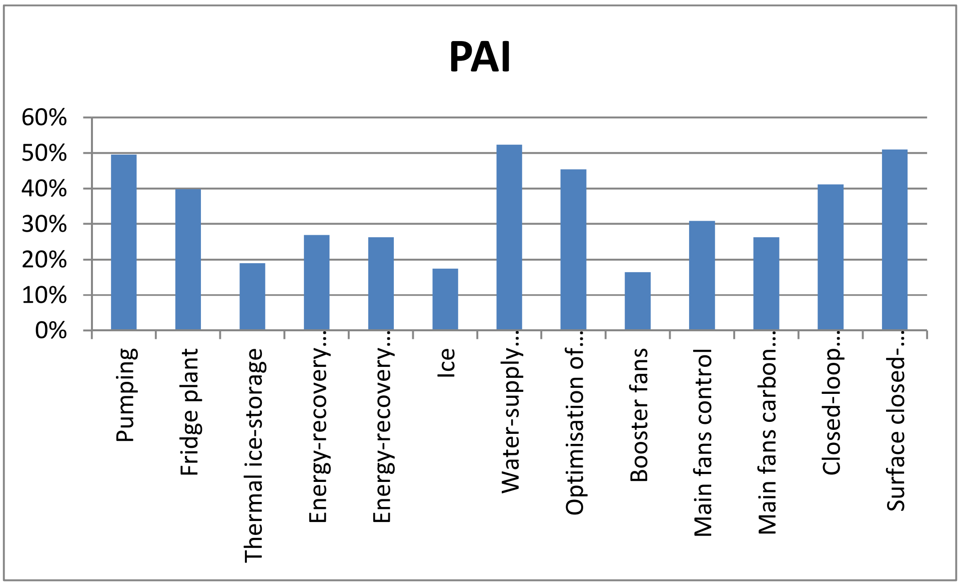


Figure 5-6: All projects PAI summary

The cost-saving of the project is low, since the project only realises a saving on the surface BAC and only in summer. The saving is equivalent to that of the closed-loop underground BAC project.

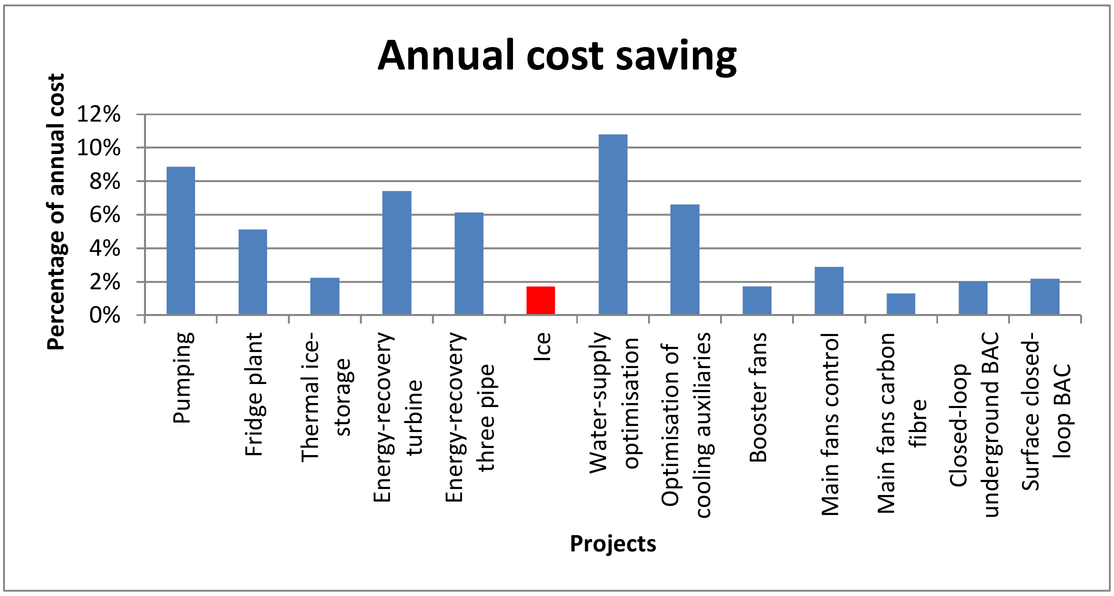


Figure 5-7: Annual cost-saving summary

Table 5-1 shows the final results of the evaluation on load-management and energy-saving projects on the mine-cooling and ventilation system.

Table 5-1: Summary of cost-saving, risk and PAI evaluation

Project	PAI	Risk	Annual cost-saving
Pumping	50%	5%	9%
Fridge plant	40%	10%	5%
Thermal ice-storage	19%	45%	2%
Energy-recovery turbine	27%	17%	7%
Energy-recovery three-pipe	26%	43%	6%
Ice	17%	45%	-2%
Water-supply optimisation	52%	9%	11%
Optimisation of cooling auxiliaries	45%	7%	7%
Booster fans	16%	37%	2%
Main fan control	31%	33%	3%
Main fans carbon fibre	26%	41%	1%
Closed-loop underground BAC	41%	7%	2%
Surface closed-loop BAC	51%	10%	2%

The above table is plotted in Figure 5-8 with the implementation time on the X-axis, the risk on the Y-axis and the size of the ball illustrating the projects' integrated savings impact. From this distribution graph, it can be seen that the two largest balls are the pumping and water-supply optimisation energy-recovery projects.

The highest risk projects are the main fan projects, coupled with risk on mine health and safety. From the graph in Figure 5-8, it can also be seen that higher-risk projects do not result in higher rewards.

It is evident that companies will be rewarded with large savings if long-term projects are implemented. With the present economic uncertainty and the difficulty projecting future mine operation and business cases, these projects are also very unlikely to be implemented.

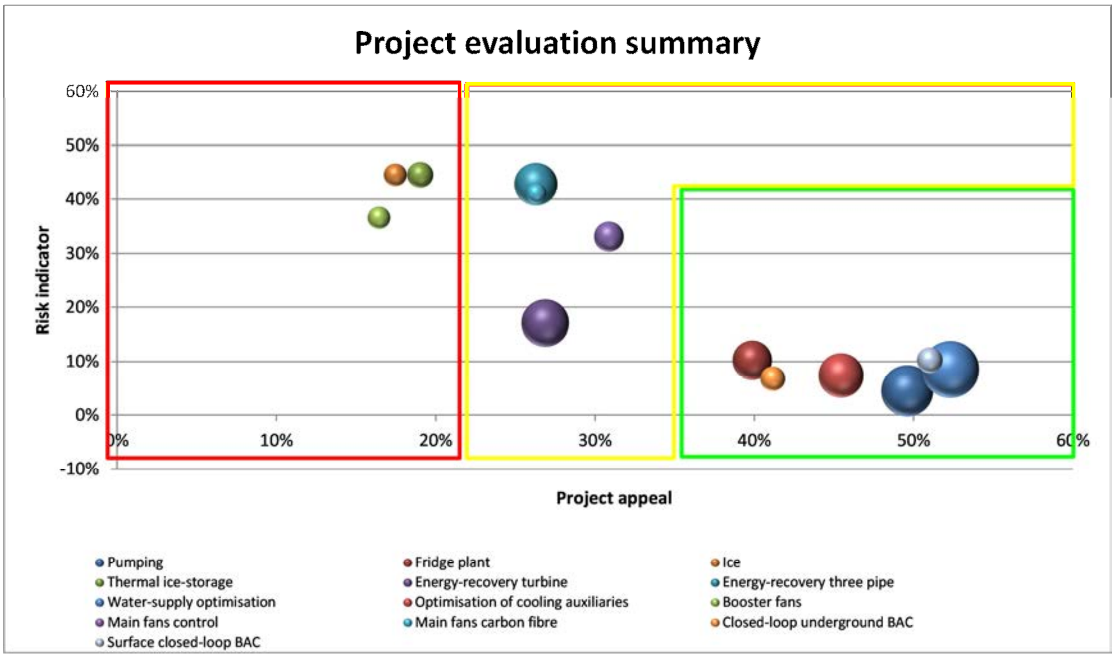


Figure 5-8: Project evaluation summary

The pumping, fridge plant, cooling auxiliaries, optimal use of mine water, closed-loop underground BACs and surface closed-loop BAC projects are all low-risk and high-appeal projects.

5.4. Total impact of sequenced combination

The closed-loop surface BAC project only focuses on the BAC. It can be added to the combination in Chapter 3. With the level condition monitoring, it is, however, suggested that the project should be installed before the fan projects. This will assist with determining the effects of the fan projects on the mine ventilation and cooling.

Table 5-2: Final sequenced combination

Sequence for implementing the best combination	
Sequence	**Project**
1	Pumping
2	Fridge plant
3	Water-supply optimisation
4	Optimisation of cooling auxiliaries
5	Energy-recovery turbine
6	Surface closed-loop BAC
7	Closed-loop underground BAC
8	Booster fans
9	Main fans
10	Main fan carbon blade

The project also requires data from the fridge plant and optimisation of the cooling auxiliaries and can supply data for the closed-loop underground BAC project. Implementing this sequence on the mine-cooling and ventilation system will result in the power profile shown in Figure 5-9.

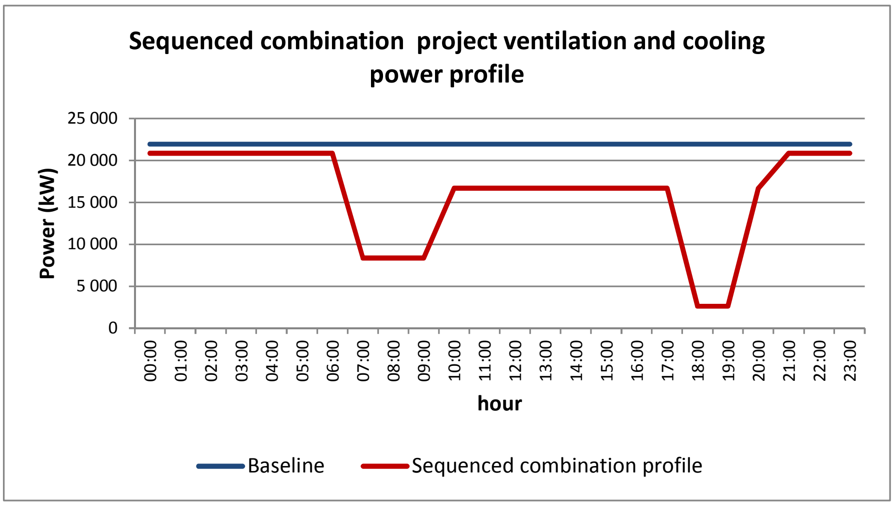


Figure 5-9: Final sequenced combination power profile

The cost profile of the sequenced combination is shown in Figure 5-10. The yearly cost has been reduced from R79 million, to R49 million. That is an annual saving of R30 million and 38% on the ventilation and cooling cost. It is also a saving of 16% on the entire mine's electricity cost.

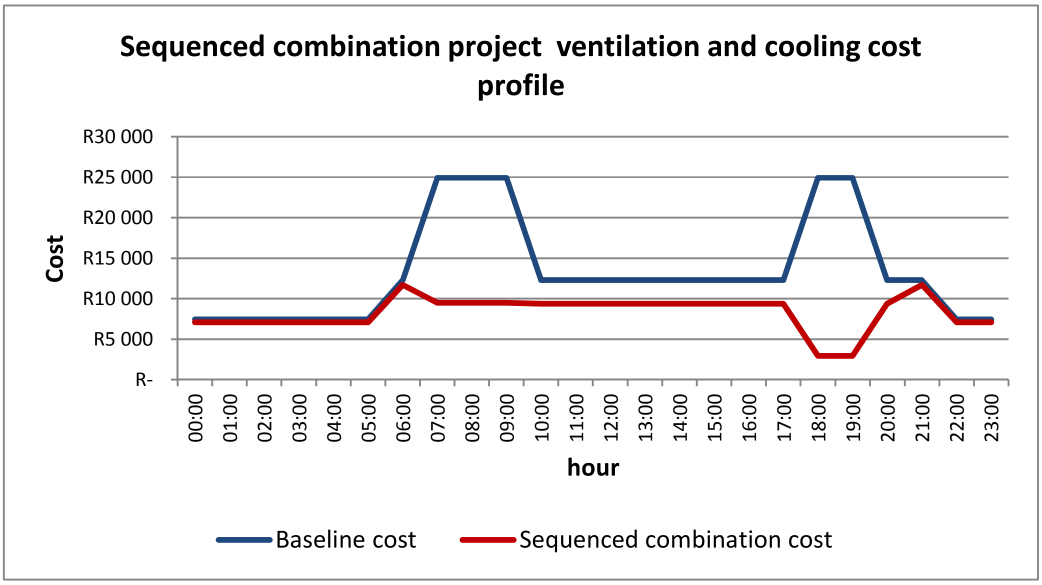


Figure 5-10: Final sequenced combination cost profile

Following the sequenced combination realises a larger saving than any individual project.

5.5. Conclusion

The surface closed-loop BAC project developed in the previous chapter is evaluated according to risk and PAI in this section. It was found that the project did not clash with any other project and could be added to the combination. The project is added to the sequence in the sixth place. It requires data from the other projects and is valuable in supplying data for the rest of the projects in the sequence.

Figure 5-11 shows the mine ventilation and cooling system with each project and its number in the implementation sequence.

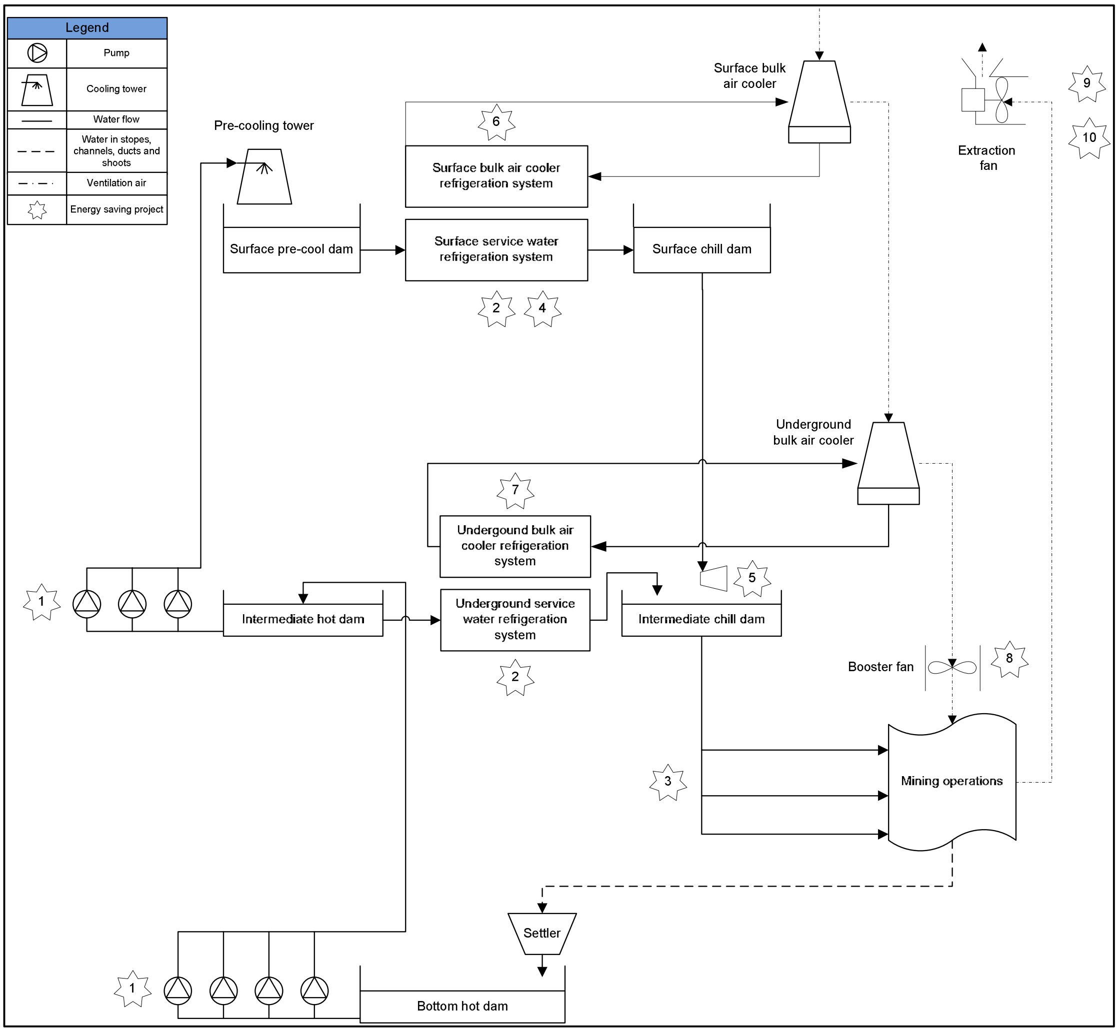
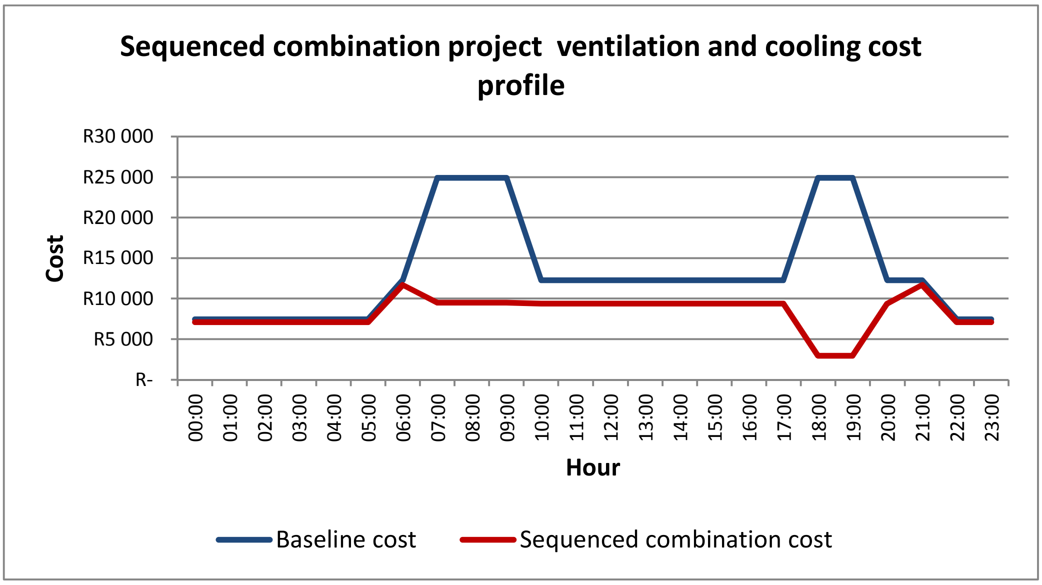


Figure 5-11: System layout indicating projects and project sequence

6. Conclusion



This thesis presented an evaluation of the sequential implementation of existing load-management and energy-saving projects. One more project was identified and added to the sequential combination of projects.

6.1. Conclusion

A thorough literature study was done in Chapter 1 to establish what load-management and energy-saving projects are available on mine ventilation and cooling systems. These projects are implemented individually only considering their cost-saving. The need was established to combine and correctly sequence projects. It was also shown that no research has been done on surface BACs.

Chapter 2 described the mine-cooling and ventilation system components and subsections. South African mines operate at great depths and encounter VRTs of up to 70 ^{o}C. Water, air and ice are currently used to ventilate and cool the underground working environment. The mine is ventilated with large surface extraction fans.

The cooling is done by surface and underground refrigeration machines. A portion of the cooling is used to cool and dehumidify the inlet ventilation air. Booster fans assist with the distribution of ventilation air underground. The water used for drilling, cleaning and dust suppression is also chilled by the refrigeration machines. Dewatering pumps circulate the used warm water back to the refrigeration machines. An energy-recovery device, such as a turbine or three-pipe system, harnesses the potential energy of the system.

In Chapter 3, a cost evaluation of the mine ventilation and cooling system was done, after which the saving of each project on the total cost was determined. A typical mine was simulated with the applicable subsection infrastructure. Projects on the subsections were divided into load-management and energy-efficiency projects. The total mine-cooling and ventilation system uses around 22 MW. The typical annual bill is R79 million.

Chapter 3 developed a risk evaluation matrix based on the risk to service delivery, production, EHS and overhead cost. Usually, the cost-saving of a project is the only variable considered. The appeal of a project was also evaluated by determining the PAI for each project. The PAI is based on new equipment, the upgrading of existing equipment, extending the mine's monitoring and networking capacity, displaying and logging mine system variables, short implementation time, little downtime and interaction with other systems.

The result is that each project was evaluated and compared to each other. It was found that ice is not an energy-saving project. It can be considered to be a more expensive alternative to underground refrigeration. Following the evaluation of all the projects, it was determined which projects could be combined with each other. The projects in the combination were then sequenced. This sequence was verified by the sequence of publications on these projects.

From the above, it was found that the opportunity exists to investigate and develop a peak clip strategy on closed-loop surface BACs.

The energy-saving is realised by reducing the amount of cooling done during the Eskom evening peak. The effect on underground conditions needed to be determined. It is a monumental task to simulate the vast and complex mine working areas underground. The investigation was simplified by considering the effect on the air entering the mining levels.

The available equations for air travelling down the shaft do not take into account the thermal storage of the mine shaft infrastructure. Empirical measurements and equations were used to simulate the effect of stopping the BAC during the Eskom evening peak.

The verified simulation proved that surface BACs can be stopped during the Eskom evening peak and mining blasting shift without adversely affecting underground conditions. The project was implemented on a mine and 3.2 MW was saved during the Eskom evening peak.

All mine-refrigeration systems start with the building of a surface BAC and therefore most South African mines have one. Implementing the BAC peak clip project on other mines will result in a saving of 24.5 MW. This will help Eskom to keep the lights on.

The newly developed project was added to the combination and sequenced accordingly.

Throughout the analysis, it was established that EMSs should be part of all load-management and energy-saving projects. This helps to report the correct saving as with the turbine projects. It is also used to determine the savings on the water-supply optimisation project, and the data is used for follow-up projects, such as the data from the fridge plant project being used for the optimisation of the cooling auxiliaries project.

The thesis showed that the result obtained from the sequenced implementation of projects is larger than the results obtained for individual projects. It also stated that an all-in-one project will not be successful. The integrated energy-efficiency strategy for deep-mine ventilation and refrigeration is shown in Figure 6-1. Each project is a step and the interactions of the projects are shown.

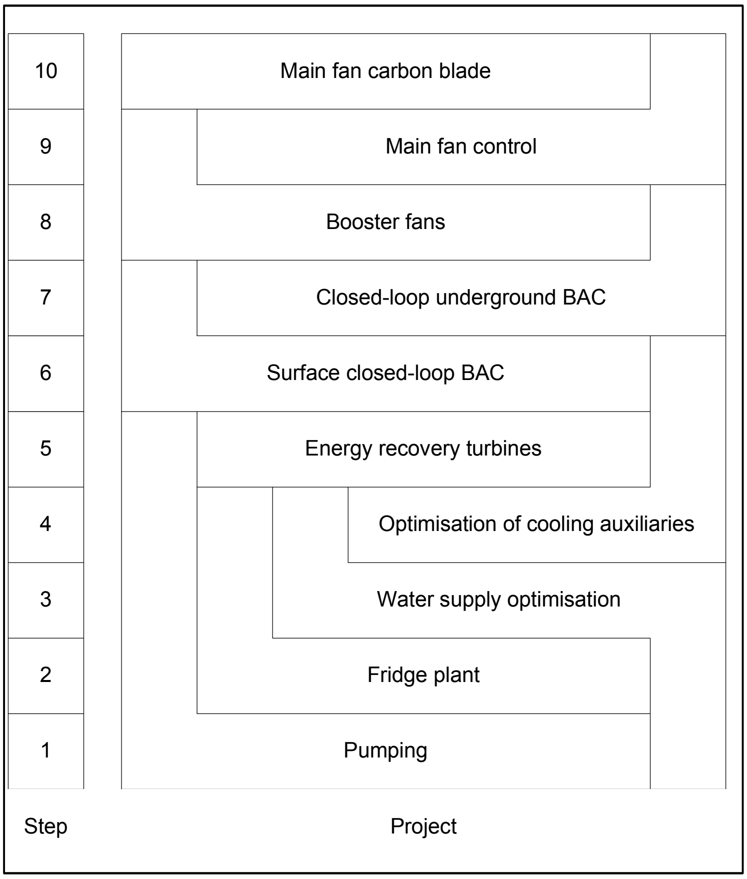


Figure 6-1: An integrated energy-efficiency strategy for deep-mine ventilation and refrigeration

In conclusion, this study summarised energy cost and energy-saving projects for a mine ventilation and cooling system. The study resulted in a sequential implementation guide for a mine energy engineer considering the cost-saving, risk and appeal of a project.

6.2. Suggestions for further research

If more load-management and energy-saving projects are developed, they should be evaluated and correctly added to the sequenced combination.

During this thesis the following suggestions for further research were established:

1. The BAC fans can be controlled using VSDs to limit the amount of cold air wasted. The ventilation air is wasted when the BACs deliver more air than the main extraction fans are drawing in. The chilled air will escape from the top of the mine shaft and back into the atmosphere. Thus, the control on the BAC can be integrated with stopping, controlling and cutting back in energy-saving projects using the main extraction fans.

2. A cooling car cools the immediate area. Cooling cars seem to introduce significant amounts of moisture, which increases the WB temperature of downstream working sections. This causes miners to install multiple cooling cars in series. Open-ended cooling cars should be put in a loop and there should be a system to capture and extrude the condensate from the cooling car. Its effect on the ventilation should be studied.

3. Through this study, different temperatures and RH were noted underground. It is well established what the WB temperature should be. It is proposed that the correlation between relative humidity and the amount of dust be determined. To suppress dust, a minimum RH should be specified.

4. Deep-level mines operate beyond secondary and tertiary air-cooling systems. The working areas are also far from the shaft. The potential energy-saving to completely stop or significantly reduce the amount of cooling done by the surface BAC should be investigated. There is no sense in cooling old work sections on the top levels. It can be seen that cooling the air on the surface of a South African mine is relatively inefficient due to the low climatic heat load and the fact that the colder the air that is sent underground, the more strata heat it will absorb from the long intake airways prior to arriving at the workplace.[b]

i. Brake, D.J., *Design of the world's largest bulk air cooler for the enterprise mine in northern Australia*, Mine Ventilation: Proceedings of the North American/Ninth US Mine Ventilation Symposium, Kingston, Canada, 8-12 June 2002, Taylor & Francis, 2002 (also available in *Mine Ventilation*, De Souza (ed.), Page 381-387, Swets & Zeitlinger, Lisse, ISBN 90 5809 387 5)