

# Identification model for cost-effective electricity savings on a mine cooling system

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

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Graduation May 2018

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# Abstract

Title: Identification model for cost-effective electricity savings on a mine cooling system

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Degree: Master of Engineering (Mechanical)

Keywords: Cooling systems; bulk air cooler; cost-effective; load management

South Africa has the world's largest reserve of platinum and gold. Despite this, the mining sector is struggling to stay economically viable. Increased costs in mining are one of the main contributors to the struggle of South African mines. Electricity is one of the fastest growing expenditures in the mining environment and there remains scope for electricity cost savings.

Cooling systems are one of the larger electricity consumers on deep-level mines; often consuming 20% or more of the total electricity supply. These systems consist of numerous interconnected units. A need was identified to reduce the electricity costs of mine cooling systems without exceeding the cooling system constraints.

Various strategies have been implemented to reduce the electricity cost of mine cooling systems. Improving the efficiency of cooling systems was identified as a desirable option for electricity cost savings on mine cooling systems. Reduced initial funding from Eskom has however limited ESCOs to load shifting or bulk air cooler peak clipping projects.

An integrated methodology was needed to identify scope for electricity cost savings on mine cooling systems due to the interconnected nature of these systems. Existing studies do not provide such a methodology. A decision diagram was developed to assist ESCOs with the identification of possible electricity cost savings projects.

The methodology was validated by testing it on a deep-level mine. An existing load shifting electricity cost saving initiative has already been implemented on the cooling system of the case study mine. The identification model was applied to this cooling system. The model showed that additional electricity cost savings could be achieved by incorporating a peak clipping initiative on the bulk air cooler.

An average daily energy reduction of 14 000 kWh was achieved during summer and 6700 kWh during winter. This amounted to an electricity cost saving of R495 000 over a three-month period. Underground conditions remained within acceptable limits. Extrapolated over a year, an estimated annual saving of R2.1 million can be expected.

# Acknowledgements

I would like to thank:

- My Creator for blessing me with the ability to complete this study.
- Enermanage (Pty) Ltd and its sister companies for the financial support to complete my study.
- My colleagues, especially Janco Vermeulen, for his support.
- Dr Johan Marais, Dr Jan Vosloo and Dr Rudy Joubert for their academic support.
- My friends and family for their prayers and support.

I apologise for anyone who has been omitted.

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# Abbreviations

BC	Below Collar
BAC	Bulk Air Cooler
CCT	Condenser Cooling Tower
COP	Coefficient of Performance
DBT	Dry-bulb Temperature
DSM	Demand Side Management
ECSI	Electricity Cost Savings Initiative
EnMS	Energy Management System
ESCo	Energy Service Company
FRP	Fibre reinforced Plastic
GDP	Gross Domestic Product
HTP	High Tariff Period
KPI	Key Performance Indicator
LTP	Low Tariff Period
M&V	Measurement and Verification
OPC	Open Platform Communications
PAI	Project Appeal Indicator
PCT	Precooling Tower
PFD	Process Flow Diagram
PGM	Platinum Group Metals
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
R <sup>2</sup>	Coefficient of Determination
RMSE	Root Mean Squared Error
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-use
VSD	Variable Speed Drive
WBT	Wet-bulb Temperature

# Chapter 1. Introduction

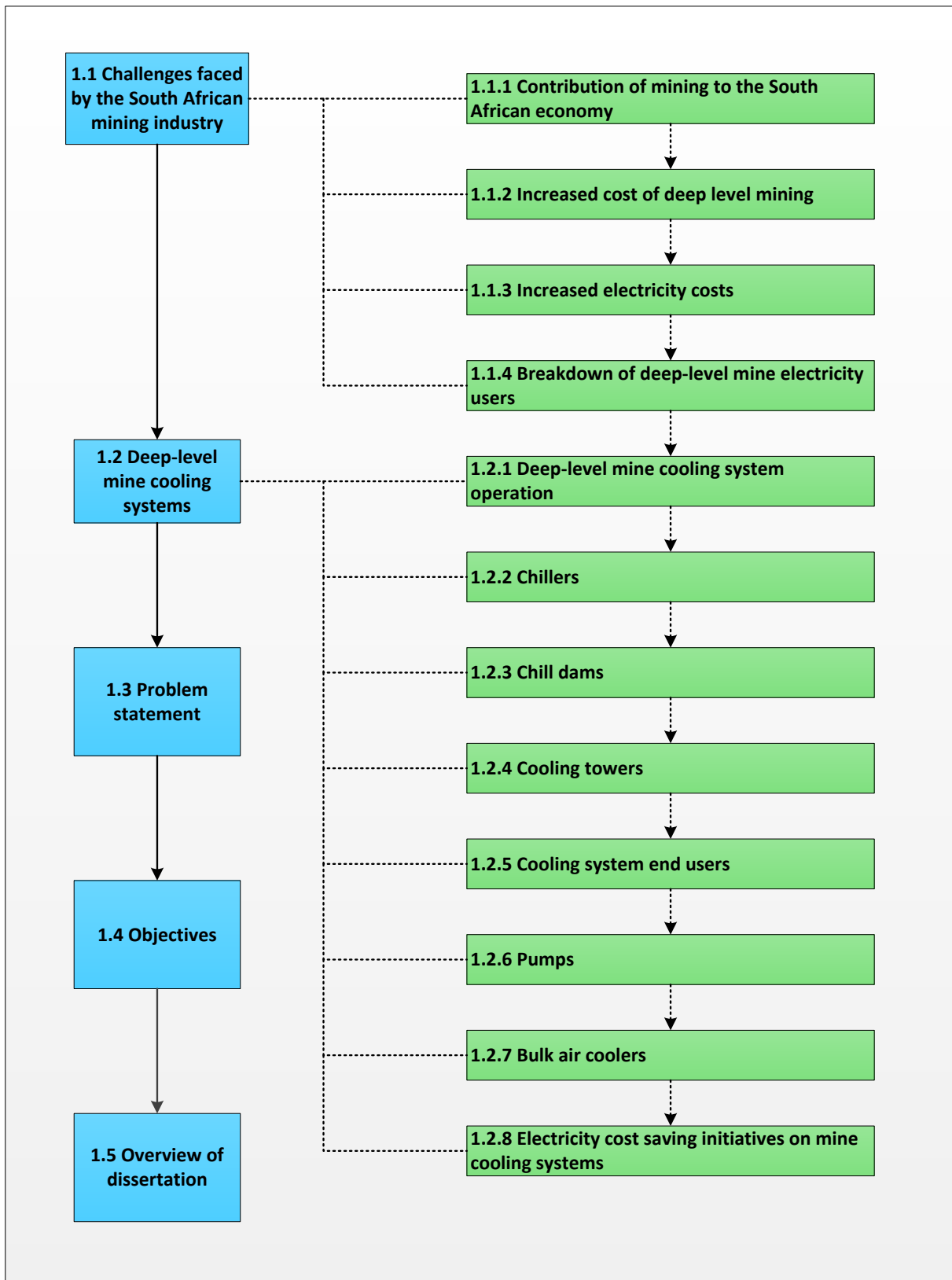


Figure 1: Overview of Chapter 1 content

## 1.1 Challenges faced by the South African mining industry

### 1.1.1 Contribution of mining to the South African economy

A significant quantity of the global platinum group metals (PGMs) and gold comes from South Africa. South Africa is home to the Witwatersrand Basin and Bushveld Igneous Complex. These ore bodies hold the world's largest resources of gold and PGMs respectively [1], [2]. In 2014, South Africa produced 65% of the world's platinum and 5% of the world's gold [3]. The South African mining industry is, however, battling to stay profitable under current economic conditions.

The mining industry has made a notable contribution to South Africa's gross domestic product (GDP). In 2016, the mining industry contributed 7.3% of the national GDP and had nearly 460 000 employees [4]. Refer to Figure 2 for a graph of the mining industry contribution to the South African GDP and the number of people employed by the mining industry over a nine-year period.

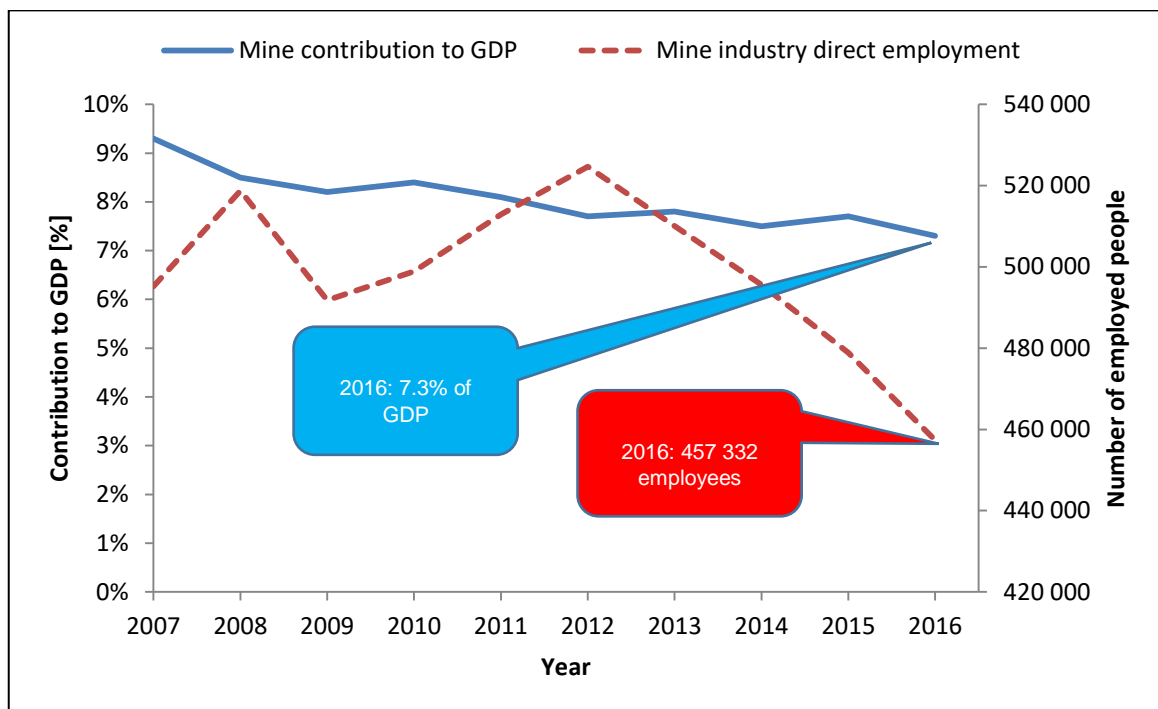


Figure 2: Mining industry's GDP contribution versus number of people employed [4]

From Figure 2, it is clear that South Africa's mining industry is on a decline. In 2007, South Africa was the world's top gold producer [5]. Eight years later, South Africa's gold production ranking dropped to seventh place. Furthermore, the production of platinum has dropped by 18% from 2007 to 2015 [5], [6].

When compared with other major South African sectors, the mining industry is lagging in terms of growth. Figure 3 shows a graph of the growth rate in terms of value add<sup>1</sup> of each major South African sector.

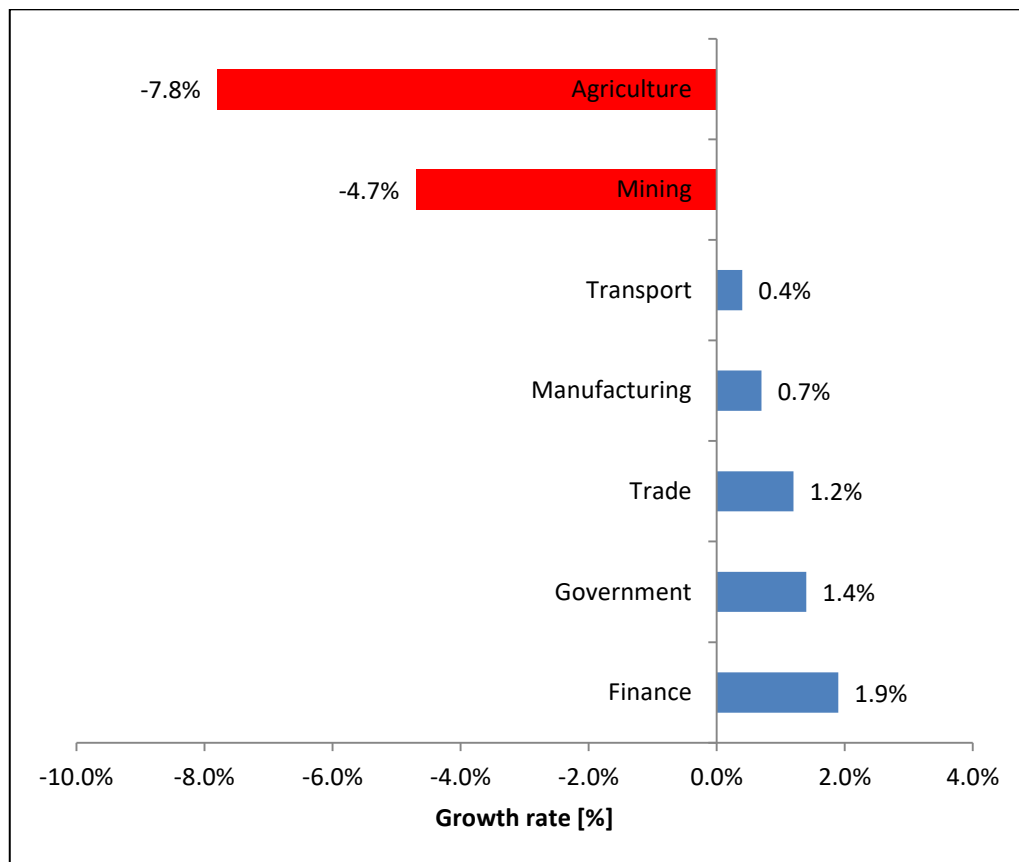


Figure 3: Growth rate in industry value added in 2016 [7]

One of the contributing factors to the mining industry's lagging growth rate is operating expenses. Operating costs on mines are increasing continuously [8]. This not only affects the profitability of a mining company, but it also hinders the implementation of planned business strategies for long-term sustainability [8].

### 1.1.2 Increased cost of deep-level mining

South Africa's gold and PGM production are characterised by deep-level mining. Deep-level mineral mining is a resource-intensive operation [9]. Figure 4 provides a cost breakdown of the operating expenses on mines in 2016. Labour and contractors contribute to the majority of the operating expenses on a typical mine [8]. South African mines have been brought to their knees by labour unions. Unionised staff demand higher

<sup>1</sup> Nominal terms (constant 2010 prices)

wages – often through violent protest actions. Mines have been forced to retrench a large number of workers to compensate for the increased labour costs [10]. Refer to Figure 4 for a cost breakdown of mine operating expenses in 2016.

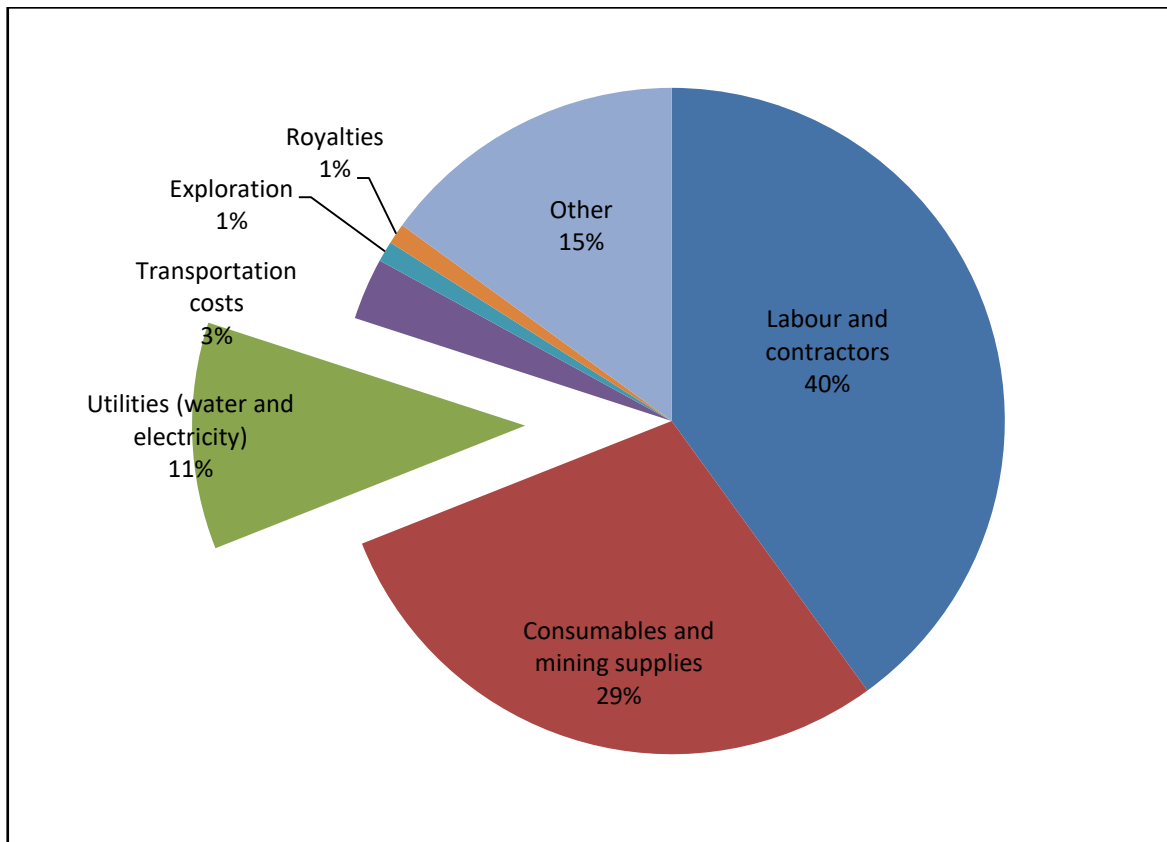


Figure 4: Cost breakdown of mine operating expenses in 2016 [8]

As seen in Figure 4, the second-largest expenditure in the cost breakdown of operating expenditures is consumables and mining supplies. Budget cuts have been made to consumables. From 2015 to 2016, the consumables and supplies expenditure on some mines have increased by 4.4% which is lower than the inflation rate [8].

Utilities, such as water and electricity contribute a significant amount to the operating expenditure on a typical mine (11%). From 2015 to 2016, mines have been spending an estimated 5% more on water and electricity. This price increase was mainly the result of Eskom electricity tariff increases [8]. However, potential remains for electricity cost savings on mines [11].

### 1.1.3 Increasing electricity costs

Eskom is South Africa's primary electricity utility. It satisfies approximately 95% of the country's electricity demand [12]. In reaction to the country's growing electricity demand

Eskom launched its capital expansion programme in 2005 that planned to add an additional 17 GW to its generation capacity by 2018 [13]. A nationwide electricity crunch hit South Africa between 2007 and 2008 [14]. To stabilise South Africa’s electricity grid, Eskom financially supported demand side management (DSM) projects [15]. This funding was used by energy service companies (ESCOs) to implement DSM projects [14].

Eleven years after the capital expansion programme was launched in 2005, Eskom increased its generation capacity by 7 GW [16]. From April 2015 to March 2016, Eskom’s monthly open cycle gas turbine expenditure reduced by 98% [16]. This meant that the stability of the electricity grid increased [17]. Eskom is planning to decommission 11 000 MW of coal power plants by 2020 [18]. The stable grid might thus only be temporary.

Electricity tariffs increased as a result of the higher cost in electricity generation and the capital expansion programme [19]. Eskom reduced its DSM expenditure by R901 million since the 2013/14 year [16]. A performance-based DSM model was introduced by Eskom in 2015. ESCOs are now more reliant on client funding [20]. Figure 5 graphically illustrates major events experienced in South Africa’s electricity supply and how it affected its consumers.

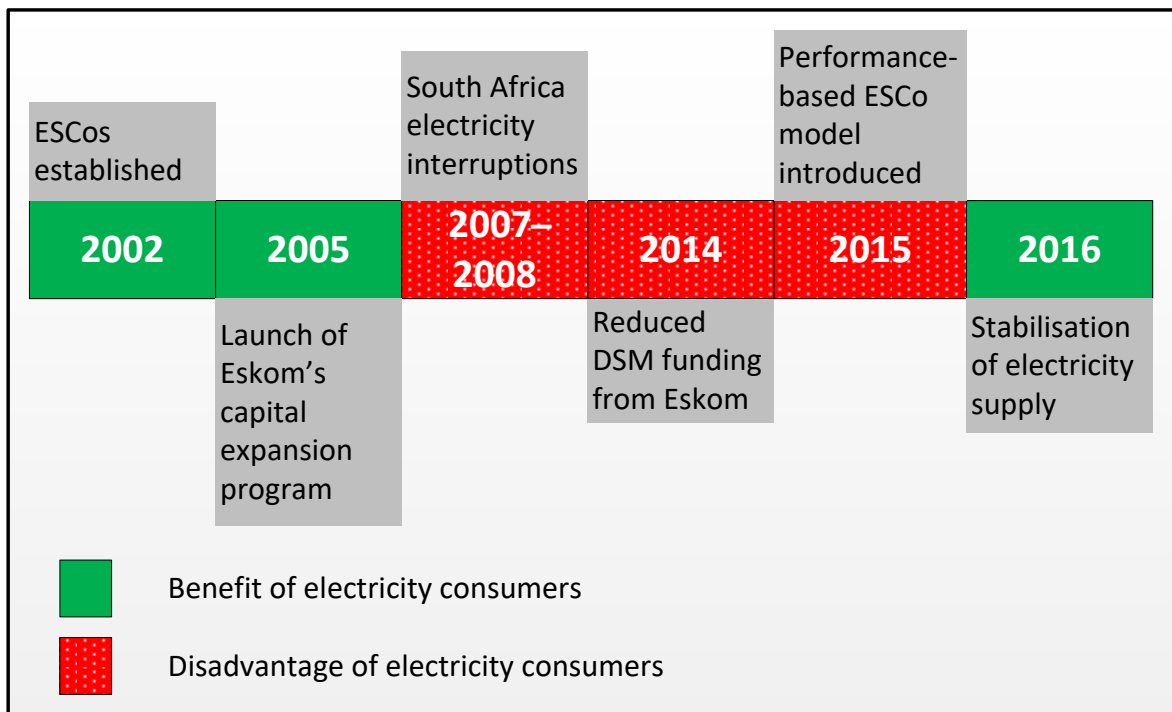


Figure 5: South Africa’s electricity supply timeline

### 1.1.4 Breakdown of deep-level mine electricity users

Mining operations consume a significant amount of energy. In 2016, mines contributed 14.3% of Eskom's total electricity sales [16]. A breakdown of electricity usage differs between mines. Main electricity consumers on a typical deep-level mine include the following [21], [22]:

- Air compressors,
- Dewatering pumps,
- Ore processing,
- Winders, and
- Cooling and ventilation.

Several studies have been done to reduce energy costs on compressed air networks [23]; [24], dewatering pumps [25]; [26], ore-processing units [27] and winders [28]; [29] on mines.

High underground temperatures is a common problem on deep-level mines as it can negatively affect the safety of workers [30]. The increasing depth of South African mines has resulted in cooling systems being installed on mines. A large amount of energy is required to artificially cool the working environment underground [31].

Cooling systems consume a significant amount of electricity, often more than 20% of the total mine electricity usage [21], [22], [31], [32]. Electricity consumers on a mine cooling system mainly consist of chiller compressor motors, fans and transfer pumps. Mines can thus reap a considerable benefit from cooling system electricity cost savings.

## 1.2 Deep-level mine cooling systems

### 1.2.1 Deep-level mine cooling system operation

Mine cooling systems can be divided into different units. Figure 6 provides an illustration of a simplified mine cooling system. A list of the typical functions performed by the cooling system units follows below [33]:

- **Heat absorption:** The main purpose of the mine cooling system is removing unwanted heat from ambient air or underground working areas.
- **Heat rejection:** Mine cooling systems normally reject the removed underground heat into the atmosphere. This is done using of cooling towers and extraction fans.



- **Chillers:** Heat rejection from cooling towers is limited to atmospheric conditions. Chillers are used to further cool the cooling medium before it is transferred underground.
- **Thermal heat storage:** Fluctuations in the cooling system operation can be reduced by using thermal storage units. These units typically consist of chilled water dams, but it is known that underground infrastructure and rockfaces can also store thermal heat [32].

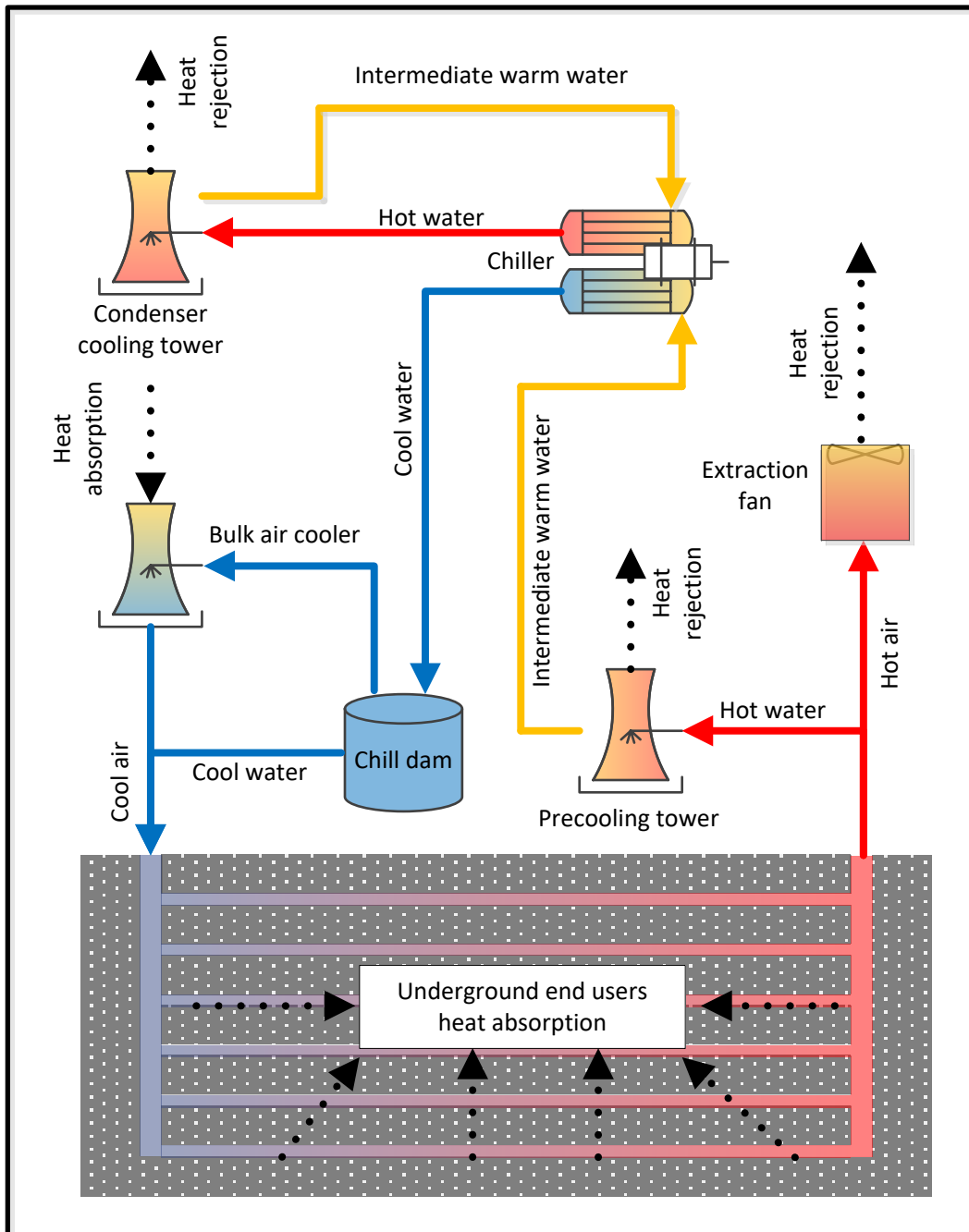


Figure 6: Typical mine cooling system layout

Cooling systems consist of numerous complex interconnected units. Changes made to one unit may affect the operation of upstream or downstream units [34]. A short description of the cooling system process shown in Figure 6 follows:

Hot water from underground is pumped into precooling towers (PCTs) where it is cooled using ambient air. Water from the PCTs, together with chilled water from the bulk air cooler (BAC), is mixed before it is pumped to the chillers at about 15°C. The chillers cool the water to between 3°C and 8°C. Chilled water from the chillers is stored in chill dams before it is transferred to the BAC and underground mining levels. The BAC utilises the chilled water to cool air going underground. Hot and humid air, together with water between 25°C and 35°C is extracted from underground.

A description of the units illustrated in Figure 6 will be discussed in Paragraphs 1.2.2 to 1.2.7. It should be noted that this study only focuses on chilled water supply and demand. Ventilation fans and underground pumps will thus not be covered.

### 1.2.2 Chillers

Mines typically use vapour-compression or ammonia absorption chillers to artificially cool the underground environment. These machines can have a combined power rating of up to 20 MW [35]. The main components found on a chiller include:

- **Refrigerant:** A refrigerant is chosen based on its properties to produce chilled water within a desired temperature range [36]. Typical refrigerants found in chillers include R134a or ammonia.
- **Compressor:** The refrigerant is compressed with the chiller compressor. Compressors used in mine cooling systems can either be centrifugal or screw-type compressors. The compressor is usually driven by an electric induction motor, which is the main electricity consumer of the chiller.
- **Partial load mechanisms:** The installed capacities of compressors are selected based on the full-load operation of the cooling system. Most of the time, the compressors will only be required to run at partial load which corresponds with the operating condition of the cooling system. Guide vanes and slide valves are used to operate the compressors at partial load on centrifugal and screw-type compressors respectively [37].
- **Condenser:** The condenser is a heat exchanger (typically shell and tube heat exchanger) that transfers heat from the refrigerant to the condenser liquid (typically water).

- **Expansion valve:** The refrigerant is transformed from a liquid phase to a gas phase by decreasing the pressure using an expansion valve.
- **Evaporator:** Similar to the condenser, the evaporator is a heat exchanger. Heat from the entering evaporator fluid (typically water) is transferred to the refrigerant.

Figure 7 shows photos of the side and front view of typical chillers found on a deep-level mine. Some of the above-mentioned chiller components can be identified from the photos.

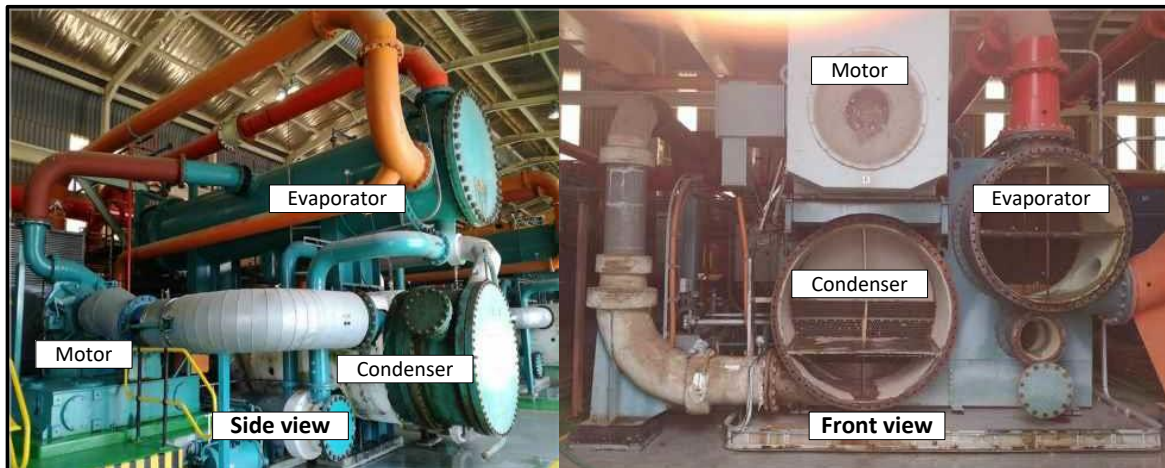


Figure 7: Side and front views of a mine chiller

Cooling systems on mines usually have more than one chiller. There are different configurations in which these chillers can be placed. The chiller configuration is engineered to meet the chilled water temperature and volume requirements of the mine. Four of the main chiller configurations will be discussed [38]:

- **Series:** A fridge plant is constructed in series to support variable temperature chilled water demands. The chilled water flow demand on such a mine is relatively constant. Chiller operation is varied to meet the chilled water temperature demand [36].
- **Cascade chillers:** Chillers separated by chill dams are known as cascade chiller configurations. This configuration provides a dual-step cooling solution [39].
- **Parallel:** Chillers in a parallel configuration aids varying chilled water flow demand. Chilled water can be passed back to the inlet of the chillers for chilled water temperature control [40]. An additional means of chilled water temperature control can be achieved with variable speed drive (VSD) control on the chiller evaporator pumps.

- **Parallel-series:** Chillers in a parallel-series configuration combines the advantages of a series and parallel configuration. A parallel-series configuration allows the chillers to provide sufficient chilled water for varying seasonal chilled water demand and temperature control of the chilled water [33].

Figure 8 illustrates the different chiller configurations.

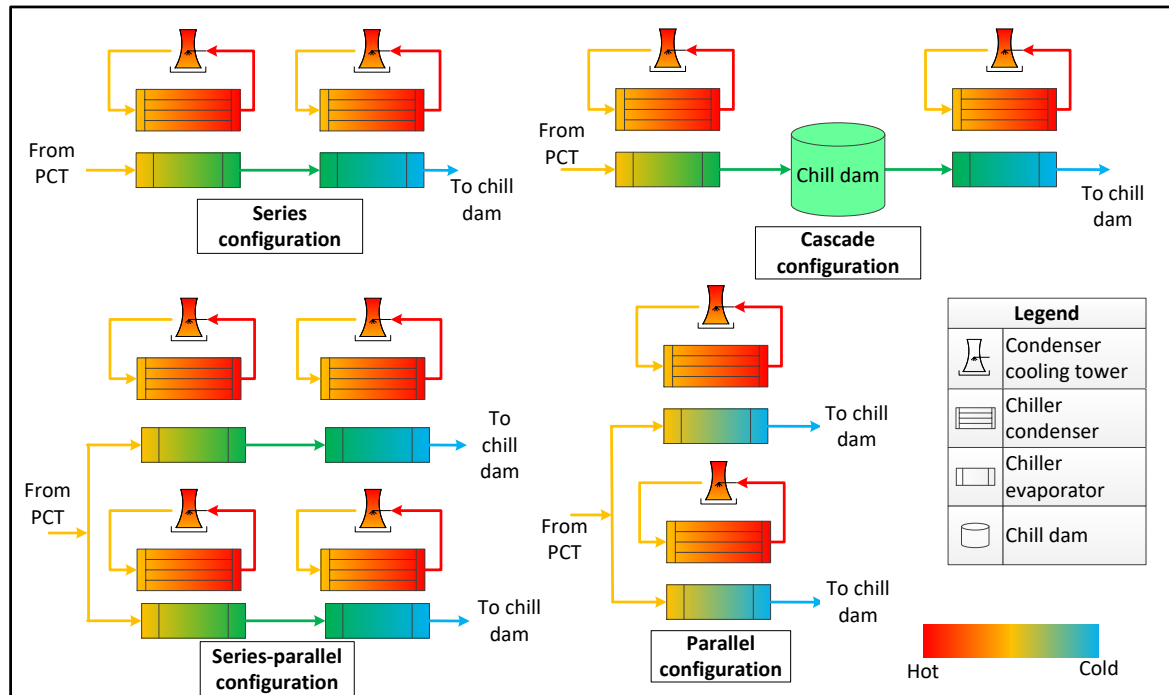


Figure 8: Different chiller configurations [38]

In order to reduce the South African electricity demand, Eskom introduced an energy efficiency induction motor programme. Through this programme, Eskom motivates motor end users to replace inefficient motors by providing a rebate on more efficient motors [41].

The energy efficient motor programme could be utilised to replace inefficient chiller compressor motors. A study has, however, shown that replacing standard motors with high efficiency motors only has a small benefit. The electrical consumption of a high efficiency motor was only 0.3% less than a standard induction motor [42].

Replacing a 90 kW standard efficiency motor with a high efficiency motor has a 20-year payback period<sup>2</sup> [43]. From personal experience, South African mines avoid cost savings projects with payback periods longer than 1.5 years. Alternative methods for reducing the electricity cost of chillers will be discussed in Chapter 2.

<sup>2</sup> Assumptions:

- Eskom 2017/18 Megaflex tariffs;
- The motor is operated 24/7 and
- Maintenance costs on the high efficiency and standard efficiency motors are equal

### 1.2.3 Chill dams

Variations in the chilled water demand or supply can be eliminated with chill dams. Chill dams serve as thermal storage for mine cooling systems. These units have a limited capacity. Mine personnel should strive to maintain a high chill dam level as an insufficient chilled water supply can raise safety concerns and lead to a loss in production [34], [44]. Chilled water supply and demand should be monitored and controlled to avoid low chill dam levels [34], [44]. There are mainly four different chill dam layouts (Figure 9).

- **Buffer for service water:** The lack of buffering for BACs means that the performance of the BACs is influenced directly by the chiller operation. Typically, the chill dam and/or BAC has some form of flow control [33], [34]. If the flow to either the BAC or the chill dam is restricted, the other component will receive more chilled water [33], [44].
- **Buffer for BAC:** Chill dams can also be found on applications where service water is not required. When stopping chillers, the air entering the BAC can still be cooled with water from the chill dam. This chill dam configuration can be found on building chiller systems and closed-loop mine cooling systems [32], [40].
- **Cascade configuration:** Chill dams are in a cascade configuration if the water from the one chill dam flows to another before the water is transferred to the end users. Chilled water from the first set of chill dams will typically be further cooled before entering the next set of chill dams [39].
- **Buffer for service water and BAC:** A chill dam can serve as a buffer for the both the chilled water to the BAC and the service water sent underground [34], [44].

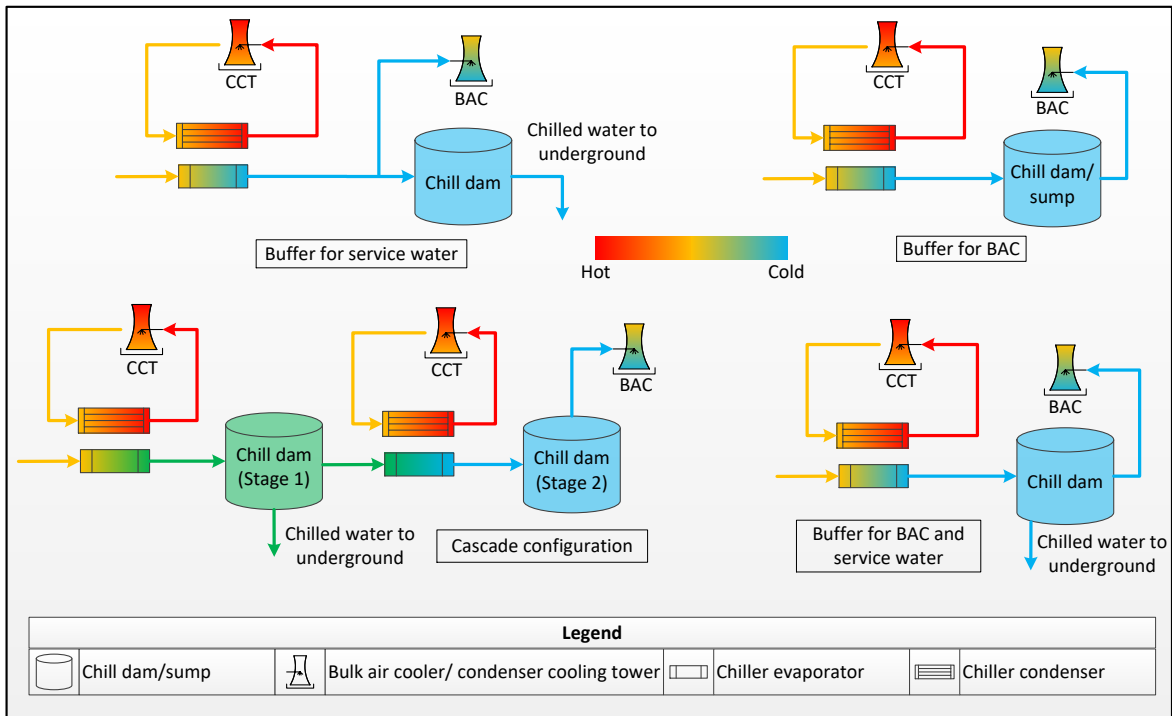


Figure 9: Chill dam configurations

Eskom implemented time-of-use (TOU) tariffs to motivate its consumers to use less electricity during high electricity demand periods [45]. The thermal storage capacity of chill dams can be used to shift electrical load from high tariff periods (HTPs) to low tariff periods (LTPs). Load shifting on mine cooling systems can be automated to improve the project sustainability [46]. This is a promising method for reducing electricity consumption of deep-level mine cooling systems cost-effectively as existing infrastructure can be utilised to achieve megawatt-scale electricity savings [33]. Load shifting will be discussed in more detail in Chapter 2.

### 1.2.4 Cooling towers

Mine cooling towers consist of PCTs and condenser cooling towers (CCTs). PCTs cool hot water from underground; CCTs cool chiller condenser water. These mine cooling towers are typically mechanical draft cooling towers. Inlet hot water is cooled by coming into direct contact with ambient air. The performance of these cooling towers is dependent on the ambient dry-bulb temperature (DBT) and relative humidity. During the cold winter months, PCTs provide the majority of the cooling [38]. Refer to Figure 10 for a diagram and photo of typical cooling towers found on a deep-level mine.

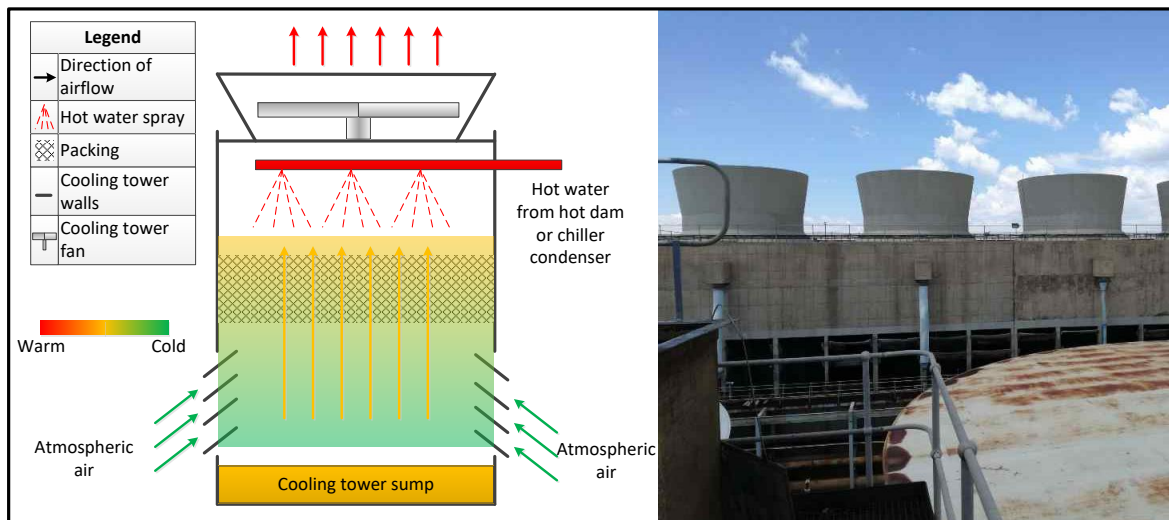


Figure 10: Cooling tower diagram and photo

One of the main factors affecting the efficiency of cooling tower fans is the profile of the blade. It is difficult to manufacture aluminium and stainless steel fan blades with an ideal aerodynamic profile for efficient fan power usage [47].

Fibre-reinforced plastic (FRP) fan blades can be hand-moulded to meet the cooling duty need of the cooling tower efficiently. Replacing metal fan blades with FRP blades has been proven to reduce fan energy consumption by 20–30%.

FRP blades have a higher initial capital cost than metal blades [47]. Furthermore, fan induction motors have a relatively smaller electricity consumption than chiller compressor motors or pumps (3% of chiller electricity consumption) [44]. ESCos will thus most likely consider cooling tower fan replacement as being an unfavourable option.

Improving the efficiency of cooling towers will reduce the load on other cooling system units such as chiller compressors. A one megawatt energy efficiency has been achieved on chillers and pumps by improving the efficiency of mine PCTs [48]. More information on this study will be provided in Chapter 2.

### 1.2.5 Cooling system end users

Underground mining in South Africa requires a significant amount of labour [49]. The safety of these employees is of great concern to the mine [44]. Mines are reluctant to make changes to the operation of cooling systems as they are concerned that these changes might have a negative effect on their employees underground [21], [44]. It is therefore crucial that the end users of the mine cooling system be considered before any alterations are made.

There are various sources of heat in the underground mining environment [30]. The human body can only tolerate a certain amount of heat absorption. At a core body temperature above 38°C, miners may experience fatigue and other serious medical conditions such as heart problems. Raising the body temperature above 40°C can result in death [50].

Ventilation is the first means of heat removal in underground mines [51]. Cooling through ventilation is insufficient at depths exceeding 800 m (depending on the mining design) [51]. At these depths, a surface refrigeration systems needs to be installed to cool ventilation air and transfer chilled water to underground for additional cooling [51].

Near-freezing surface chilled water between 5°C and 3°C is transferred underground to assist with underground activities and cooling. This water will be referred to as service water. There is a complex network of chilled water end users underground [52]. Chilled water is sent underground where it is used for the following purposes [32]:

- Drilling,
- Sweeping,
- Suppressing dust, and
- Cooling.

To understand the underground end user cooling demand, it is necessary to consider the different mining work shifts. A daily mine cycle typically consists of six shifts. A description of each shift follows [53]:

- **Drilling:** Holes are drilled into the rockface for inserting explosives.
- **Explosive preparation and blasting:** The rockface is blasted with explosives. No mining personnel are allowed near the blasting site.
- **No-entry period:** This is a five-hour waiting period where dust from the blasting is allowed to settle and harmful gasses are vented out of the mine. No mine personnel are allowed near the working areas during this period
- **Support and testing:** A support team ensures that the working areas are safe before the next working shift commences
- **Sweeping:** Broken pieces of ore are transported from the blasting area to the ore collection point
- **Shift change:** Personnel enter or exit the working areas



Figure 11 illustrates a graph of the chilled water consumption of a typical deep-level mine. The graph also illustrates the daily mining shifts. The chilled water consumption is at its highest during the sweeping and drilling shift when the chilled water is used for the purposes mentioned above. A constant chilled water flow occurs during the shift changes and no-entry period. This water usage can either be attributed to baseload coolers that are used to keep the rockface cool or chilled water pipe leaks [53].

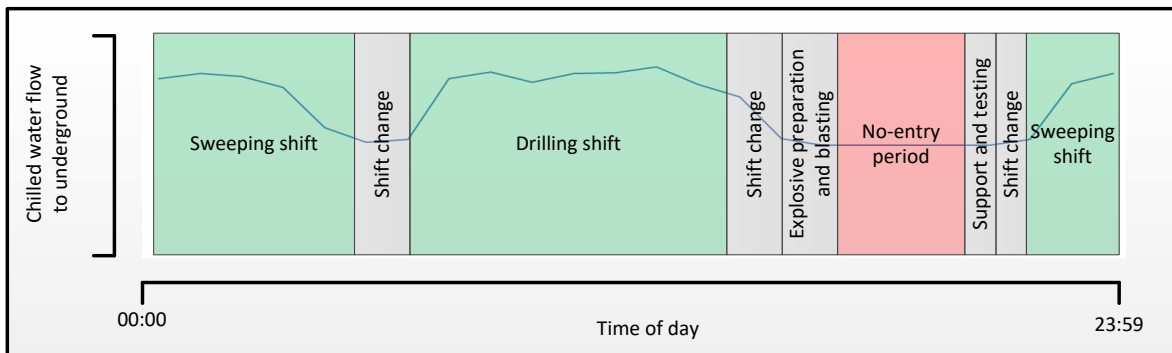


Figure 11: Typical mining schedule and chilled water consumption [53]

Reducing wastage of underground chilled water will reduce the load on surface chillers as less water will need to be chilled. Underground coolers are designed to operate efficiently at a certain chilled water flowrate. Fluctuations in chilled water usage in the working areas results in inefficient cooler operation [36].

Installing mechanical three-way valves on coolers will ensure a constant chilled water flow through the cooler. Theoretical calculations showed that cooler chilled water wastage can be reduced by 67%. This can lead to a 58 kW energy efficiency improvement per cooler, thus resulting in a payback period of 1.9 years [36].

From personal experience it is known that coolers are frequently moved as the underground mining environment develops. If the underground mine personnel do not maintain three-way valves diligently, the project may require constant maintenance from the ESCo, thus resulting in increased payback periods. An alternative method for more sustainable electricity cost savings from underground chilled water management is presented in Chapter 2.

### 1.2.6 Pumps

Mines typically use centrifugal pumps that operate at fixed speeds to transfer chilled water from one component to another [35]. These units can be found on various locations of the

mine cooling system. Refer to Figure 12 for a diagram of the different pump locations on a typical mine cooling system.

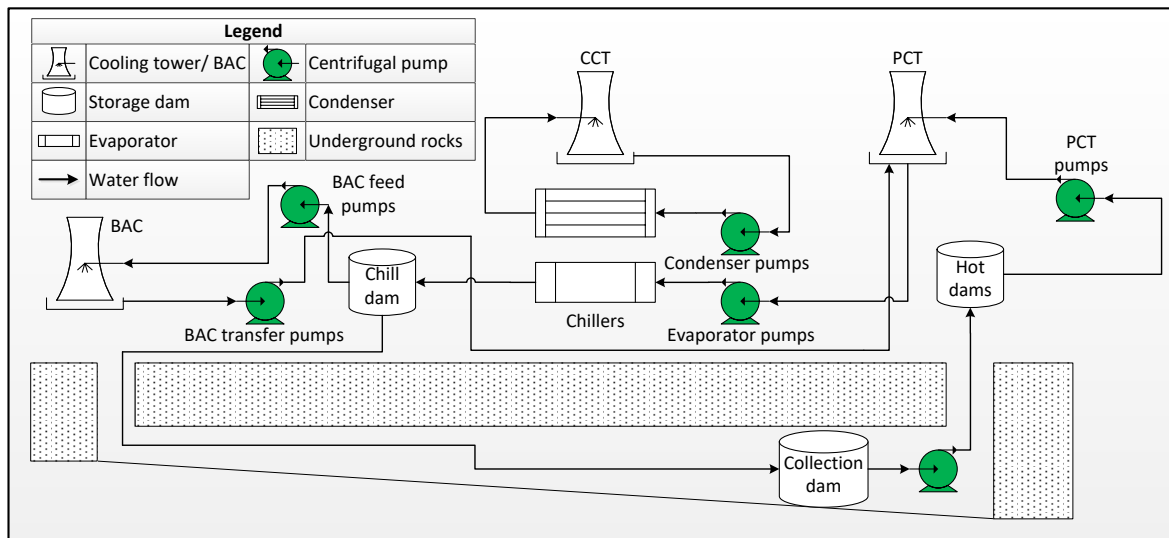


Figure 12: Centrifugal pump locations on a typical mine cooling system

Centrifugal pumps are usually driven by an induction motor. Typical motor sizes of surface cooling system pump motors range between 45 kW and 400 kW [35]. Water entering the centrifugal pump is accelerated by a rotating impeller that is powered by the induction motor. Mechanical energy from the pump is used to overcome the static and frictional head in the pipes [54].

At fixed speeds, the operating characteristics of these pumps are mainly determined by the shape of the impeller and casing. The performance of centrifugal pumps running at full load is governed by the performance curves [54].

Centrifugal pumps are often oversized due to conservative engineering design. The excess flow rate from the oversized pump can be controlled by throttling the flow with valves or recycling the excess flow [55]. These are inefficient pump operating strategies that waste electricity [56]. This operation also causes the pump to operate away from the best efficiency point indicated on the pump performance curve [55].

It is possible to modify the performance curve of a pump by trimming the impeller. Through this modification, it will be possible for the pump to approach the best efficiency point for optimal electricity utilisation and performance [55].

Chilled water demand varies due to changes in ambient conditions and underground demand [36], [56]. It is not feasible to interrupt the cooling system occasionally and

replace the pump impellers for optimal efficiency. An alternative method to improving centrifugal pump operation will be provided in Chapter 2.

### 1.2.7 Bulk air coolers

Air at ambient temperature and humidity is not always sufficient for cooling underground working areas. BACs cool incoming air with chilled water before it is sent underground. Heat is exchanged via direct contact between the chilled water and air. There are mainly two types of BACs, namely, vertical-flow BACs and crossflow BACs [33]. Refer to Figure 13 for a diagram of a vertical- and crossflow BAC [33].

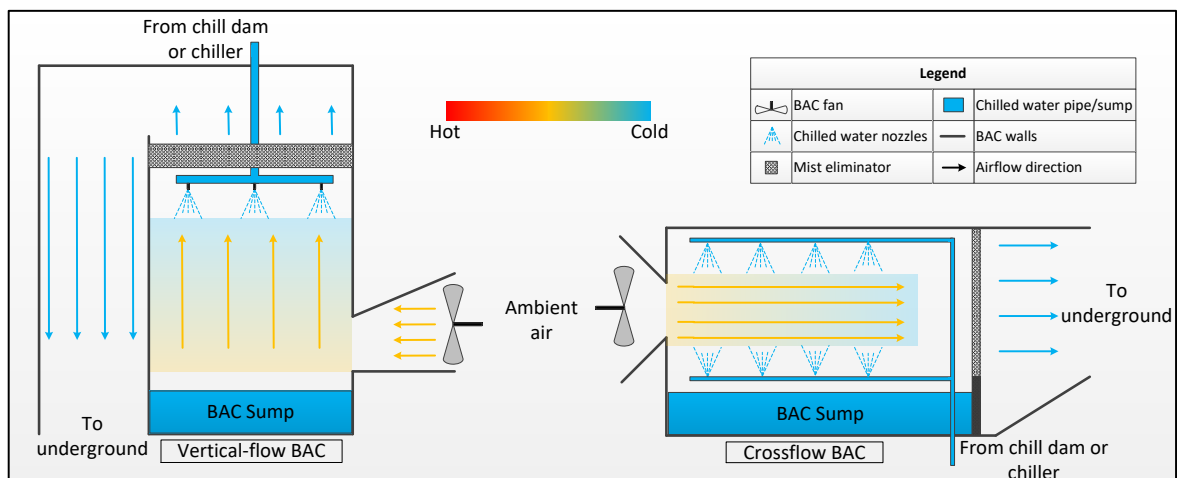


Figure 13: Vertical- and crossflow BAC diagrams [33]

Chilled water can either be gravity-fed from the chill dam to the BAC or pumped to the BAC. The flow of chilled water to the BAC can be controlled by means of valves or pumps. Reducing chilled water flow to the BACs will increase its outlet air temperature; increasing chilled water flow to the BACs will lower its outlet air temperature [34], [44].

Load reduction on the chillers can be achieved by reducing the flow of chilled water to the BAC. This can be achieved by installing VSDs on the BAC feed pumps [36]. BAC cooling load reduction will however result in increased underground temperatures, thus increasing the safety risk to underground workers [32]. More information on BAC load reduction will be covered in Chapter 2.

### 1.2.8 Electricity cost saving initiatives on mine cooling systems

Historically low electricity prices have meant that there was little to no incentives for mines to install and operate the units that were mentioned above efficiently [57]. Cooling systems are often oversized to accommodate future expansion [21]. Most South

African mines use outdated technology and operate cooling systems inefficiently [35]. Electricity cost savings initiatives (ECSIs) spurred due to incentives that include TOU tariffs [45] and government support [15]. Several ECSIs have been identified in Paragraphs 1.2.2 to 1.2.7.

Before Eskom introduced the revised ESCo model in 2015, initial funding was available to obtain equipment, such as high efficiency electric motors and FRP fan blades. Recent studies on mine cooling systems have focussed on cost-effective energy cost savings that utilises existing cooling system infrastructure [33].

Apart from the increased cost of mining, two other concerns on a typical mine are production and safety. Changes made on a mine cooling system can threaten both mine production and safety. Cost-effective control strategies are known to interrupt cooling system operation to underground end users [32]. If the requirements of the end users are not satisfied, the ECSI could be disabled by the client [34].

### **1.3 Problem statement**

South Africa's economy is notably influenced by the performance of its mines. Increased mining costs have made it difficult for mines to remain profitable. Electricity is one of the larger operating expenses. There is a need to reduce mine operating costs in order for mines in South Africa to remain competitive. Mine cooling systems show potential for electricity cost savings. Numerous electricity cost saving measures are available to decrease the electricity cost of mine cooling systems. Some of these methods, however, comes with an increased risk to safety and production and/or require large initial capital investments. There is a need to identify minimal risk, cost-effective ECSIs on mine cooling systems. The aim of this study is to develop a cost-effective electricity savings identification model for a mine cooling system.

### **1.4 Objectives**

As mentioned in Paragraphs 1.2.2 to 1.2.7, there are various existing ECSIs that can be applied to cooling systems. ESCos are limited to low implementation cost initiatives for electricity cost savings on mine cooling systems. The implemented initiatives should also not exceed the cooling system high/low limits.

**Objective 1:** Develop a methodology to identify cost-effective, low risk ECSIs on mine cooling systems.

As mentioned in Paragraph 1.2, cooling systems consist of complex interconnected units. Changing the operation of one unit may influence the operation of upstream or downstream units, thus making it difficult for ESCOs to identify and implement ECSIs without exceeding the cooling system high/low limits.

**Objective 2:** Develop a methodology that will provide ESCOs with a systematic procedure for identifying electricity cost savings potential while taking the cooling system high/low limits into account.

**Objective 3:** Prove that the methodology can be applied to a mine cooling system that results in electricity cost savings without exceeding the cooling system high/low limits.

## 1.5 Overview of dissertation

### Chapter 1

Electricity consumption was identified as a significant contributor to the declining growth rate of mines in South Africa. Cooling systems were identified as one of the larger electricity consumers on mines in Chapter 1. There is a need for a methodology to decrease the electricity cost of mine cooling systems cost-effectively without exceeding the cooling system high/low limits.

### Chapter 2

There are various existing ECSIs for cooling systems. Each of the identified initiatives to be used in the methodology development is reviewed. Chapter 2 is concluded with a study on the typical obstacles ESCOs may face when investigating and implementing ECSIs.

### Chapter 3

A method is presented that firstly identifies the more desirable ECSIs. This is followed by a step-by-step procedure to identify potential for electricity cost savings on the cooling system. The chapter concludes with a strategy to implement and sustain the initiative.

### Chapter 4

The methodology developed in Chapter 3 is applied to a hydropowered platinum mine cooling system. Results from the implementation prove that by implementing the methodology, electricity cost savings can be achieved without affecting the end users of the cooling system negatively.

### Chapter 5

This chapter concludes the study. Recommendations for further research are given.

# Chapter 2. Existing cost saving measures for deep mine cooling

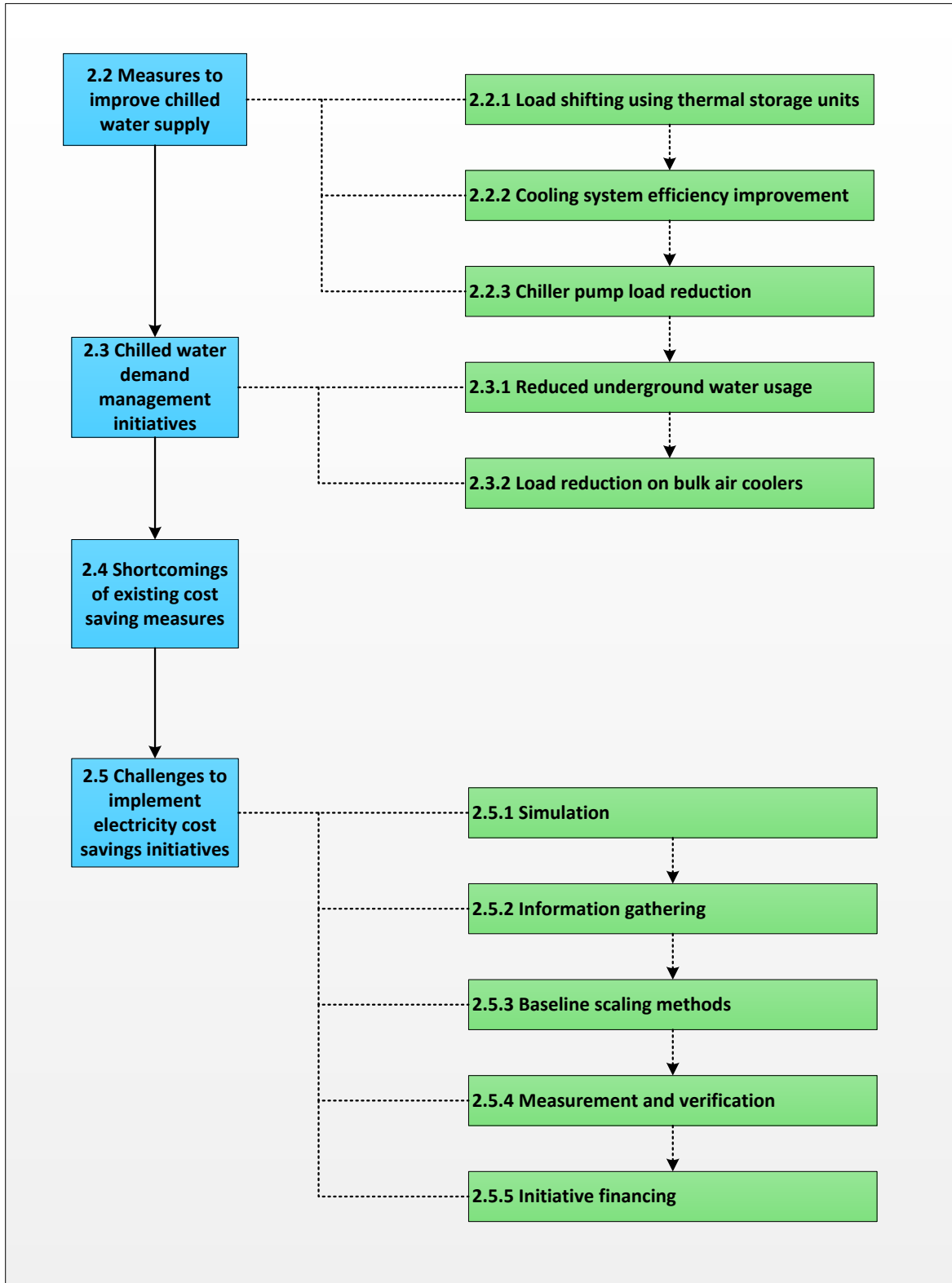


Figure 14: Overview of Chapter 2 content

## 2.1 Introduction

In Chapter 1 cooling systems were identified as one of the larger energy consumers on deep-level mines. A need was identified to cost-effectively reduce the electricity consumption on mine cooling systems. This can be done by means of chilled water supply and/or demand management.

Possible solutions to the problem identified in Chapter 1 will be investigated in Chapter 2. This chapter will start by considering previous studies where the supply or demand of chilled water was managed for electricity cost savings. Technical aspects, such as the effect of the ECSI on cooling systems and the cost-effectiveness of the initiative will be investigated.

The next section will investigate shortages to the existing strategies, followed by some typical obstacles an ESCo has to prepare to face when implementing an ECSI on a mine cooling system. Firstly, the management of the chilled water supply will be discussed.

## 2.2 Measures to improve chilled water supply

### 2.2.1 Load shifting using thermal storage units

As mentioned in Paragraph 1.2.3, Eskom implemented TOU tariffs to charge its customers more during the periods when South Africa's demand for electricity is high. High demand periods typically occur on working weekdays from 7:00–10:00 (Eskom morning peak period) and again from 18:00–20:00 (Eskom evening peak period) in summer<sup>3</sup> and from 6:00–10:00 and 17:00–19:00 in winter<sup>4</sup> [45]. Electricity cost savings are achieved by changing the shape of a system's electricity load profile [52].

There are a variety of load shaping possibilities [58]. A description of three load shaping possibilities, relevant to mine cooling systems follows:

- **Load shifting:** Eskom's TOU tariffs motivate electricity consumers to re-evaluate the time during which electricity is used. Load shifting reduces electricity cost. Electrical energy that would have been used in HTPs is shifted to LTPs.
- **Energy efficiency:** Systems are modified to use electricity more efficiently. Energy efficiency reduces the energy consumption of a system and consequently electricity cost. Energy efficiency projects improve the efficiency of a system by

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<sup>3</sup> Summer ranges from September to May

<sup>4</sup> Winter ranges from June to August

producing more services per unit electricity and/or decreasing the oversupply of services.

- **Load clipping:** The amount of electrical energy used by the consumer is reduced for a specific period. Similar to energy efficiency load shaping, load clipping also improves the system’s energy efficiency by reducing the oversupply of services.

Figure 15 illustrates the load shaping possibilities mentioned above.

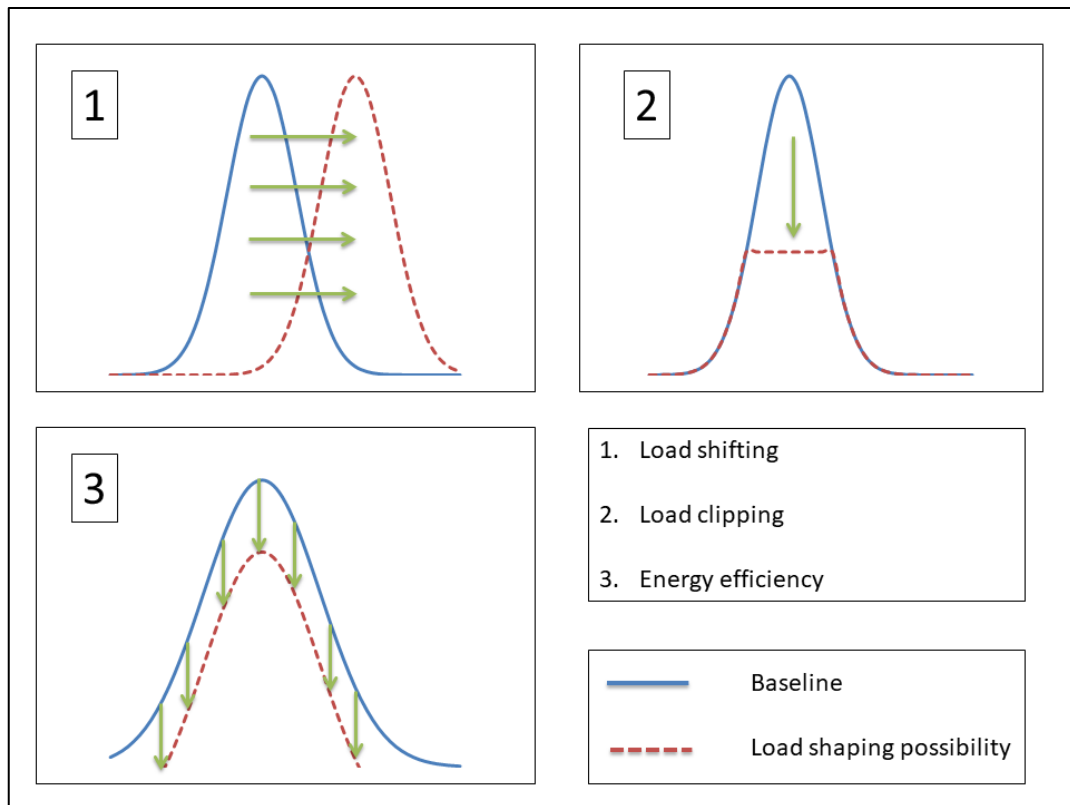


Figure 15: Load shaping possibilities

Load shifting will be discussed in this paragraph. Energy efficiency and load clipping initiatives will be discussed in the Paragraphs 2.2.2 to 2.3.2.

As mentioned in Paragraph 1.2.3, the chill dam on a cooling system is used as a buffer for the BAC and/or service water to underground. The ability of the chill dam to store thermal energy can also be used to shift chiller load from HTPs to LTPs [59].

There are mainly three different load management strategies. In Strategy 1, chillers are operated at a constant load throughout the day (partial storage and load levelling). The chill dam thus serves as a buffer to compensate for the times when the cooling demand exceeds the cooling supply. Strategy 2 involves stopping all chillers for a certain time period. Stored chilled water in the chill dam is used to completely shift the chiller load (full



storage). Strategy 3 is a hybrid of the first and second strategy. The chiller load is thus only shifted partially (partial storage and demand limiting) [59]. These strategies are visually presented in Figure 16.

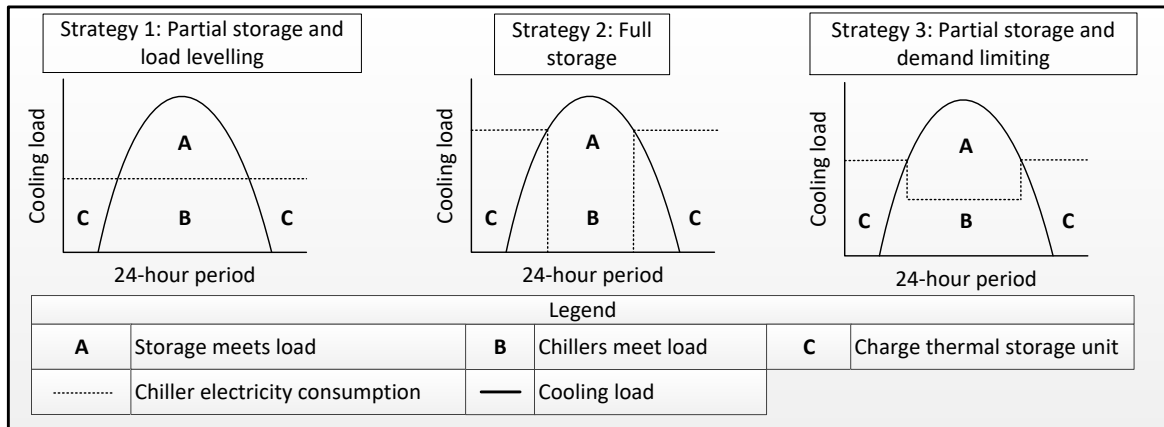


Figure 16: Load shifting strategies [59]

The thermal heat (enthalpy) stored in a chill dam is a function of the temperature and the mass of water in the chill dam<sup>5</sup>. A low chill dam temperature combined with a high water volume results in high thermal energy stored within the chill dam. The thermally stored energy in the chill dam can thus be used by removing water from the chill dam or increasing the chill dam water temperature [39]. No initial capital cost is required to implement load shifting on a mine cooling system as existing infrastructure can be utilised [33]. A discussion follows on two studies where the chill dam level and temperature were used to conduct load shifting on a deep-level mine cooling system.

Study A investigated load shifting on a cascade mine cooling system. During the HTPs, all chillers were stopped. Referring to Strategy 2 in Figure 16, full storage load shifting thus occurred. Thermal energy was used by decreasing the water content of one chill dam and increasing the water temperature of another chill dam by passing hot water from the precooling dam to the chill dam. Load shifting resulted in a R330 000<sup>6</sup> electricity cost saving over a three-month performance assessment period. Refer to Figure 17 for a graphical explanation of the load shifting strategy applied in Study A [39].

<sup>5</sup> It is assumed that the specific heat of water is constant

<sup>6</sup> Based on Eskom Megaflex 2017/18 tariff book

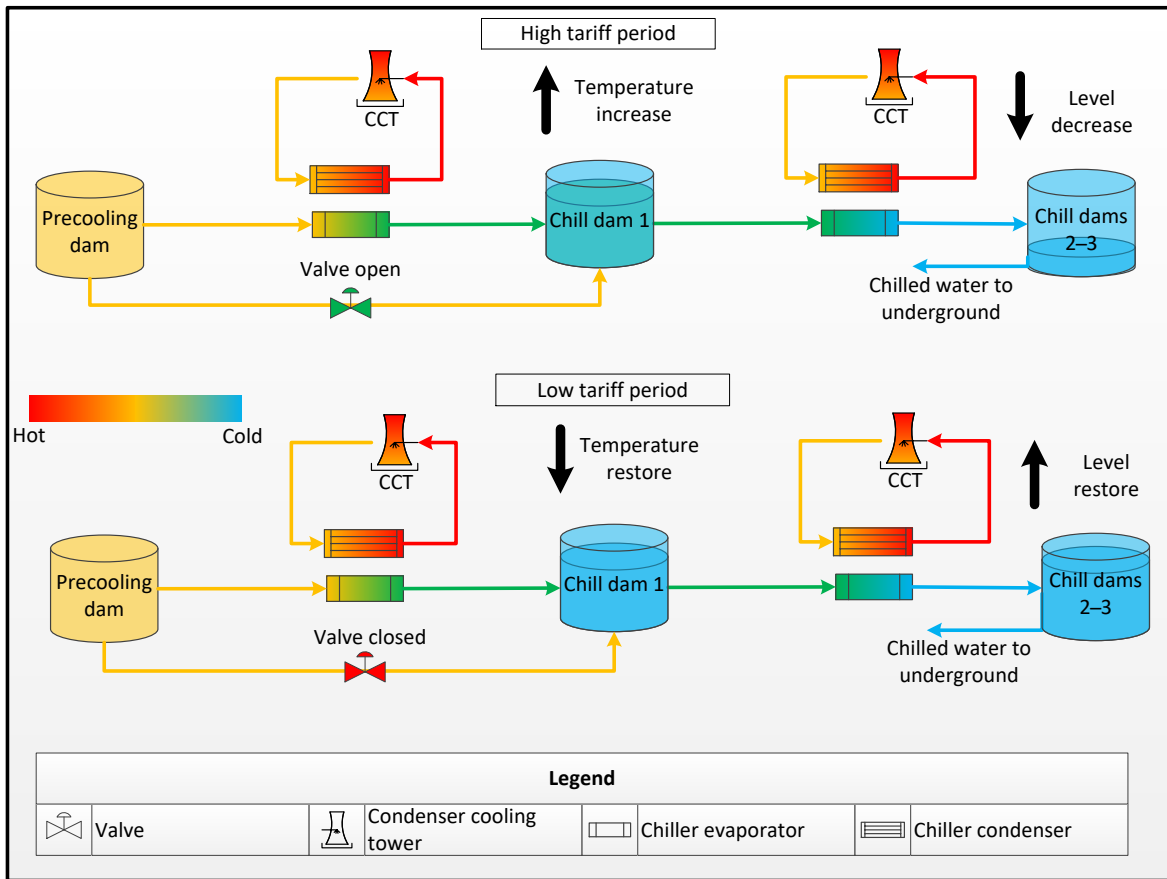


Figure 17: Diagram explaining load shifting on a cascade cooling system [39]

Study B investigated load shifting on a mine cooling system by recycling chilled water. The frequent stopping and starting of chillers can contribute to compressor wear [60]. Recycling chilled water allows load shifting during HTPs without needing to stop chillers. Referring to Figure 16 partial storage and chiller demand limiting thus occurs [21].

During the HTP, a recycling valve was opened to recycle water from the chill dam to the precooling dam. The partial load mechanism of the chiller compensated for the low inlet temperature by reducing the chiller load. Less electrical energy is thus consumed to cool the water to the set point temperature. During the LTPs, the recycling valve was closed, thus allowing the chill dam level to restore. Refer to Figure 18 that graphically shows load shifting through chilled water recycling [21].

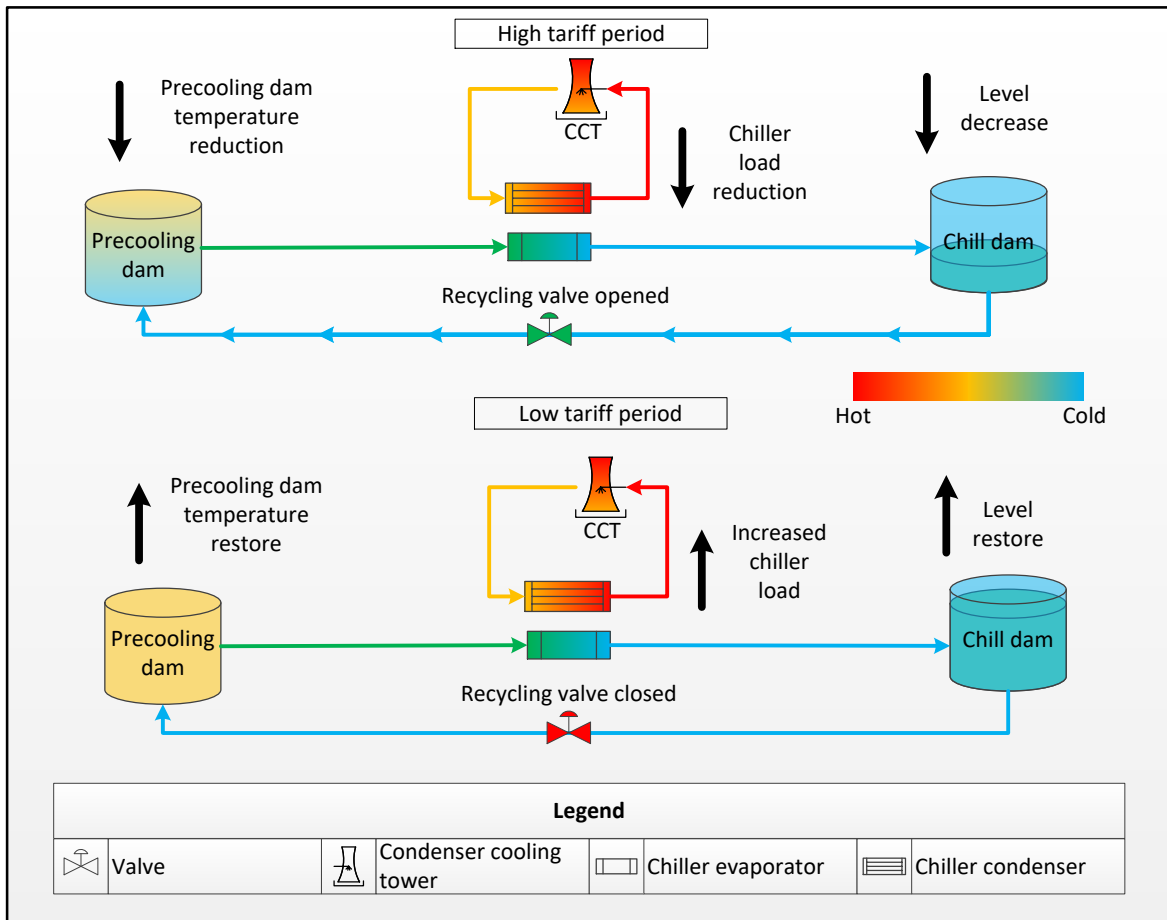


Figure 18: Diagram explaining load shifting by recycling chilled water [21]

Recycling chilled water is, however, considered as an inefficient means of load reduction as more electrical energy is consumed by the pumps that transfer the water [35]. The next two paragraphs will investigate efficiency improvement on cooling systems which include reducing chilled water recycling flow.

### 2.2.2 Cooling system efficiency improvement

Chillers are one of the larger electricity consumers on a mine cooling system [36]. The efficiency of these machines can be determined by calculating the coefficient of performance (COP). Equations 1 and 2 can be used to calculate the COP of a chiller. These equations can be applied on the condenser or evaporator of the chiller.

$$COP = \frac{\Delta H}{P_{motor}} \quad \text{Equation 1}$$

Where:

$COP$  = Coefficient of performance

$\Delta H$  = Heat removal rate over the evaporator or condenser on the water side [kJ/s]

$P_{motor}$  = Power usage of the chiller compressor motor [kW]

$$\Delta H = \dot{m}C_p(T_{wo} - T_{wi}) \quad \text{Equation 2}$$

Where:

$\Delta H$  = Heat removal rate over the evaporator or condenser on the water side [kJ/s]

$\dot{m}$  = Water mass flow rate through evaporator or condenser [l/s]

$C_p$  = Specific heat of water [4.185 kJ/kg × K @ 15°C]

$T_{wo}$  = Outlet evaporator/ condenser water temperature [°C]

$T_{wi}$  = Inlet evaporator/ condenser water temperature [°C]

Chillers on deep-level mines and commercial buildings use similar technologies and techniques to cool an environment [21]. The efficiency of centrifugal chillers in an office building can be improved if the pressure drop over the chiller is reduced [61]. Fouling on the water side of the chiller heat exchangers leads to a pressure drop over the chillers [62]. Early detection of fouling could result in electricity cost savings. A soft sensor for the detection of fouling was created [63].

Domestic water is typically used in the chillers of commercial buildings [64]. It was found that the pipe fouling over a one-year period is negligible in building applications [65]. However, mine water have a high concentration of dissolved solids [66]. Fouling in the mining sector may thus pose a larger problem than in the commercial sector.

An optimal water treatment solution was developed to treat chilled water and prevent fouling. The method incorporated chemical treatment together with high voltage electrical treatment. The chiller COP was increased by 5–6% when this method was applied [67]. The project implementation cost could not be established.

As mentioned in Paragraph 1.2.4, PCTs are used to cool mine water ( $\pm 30^{\circ}\text{C}$ ) from underground before it enters the chillers. These units can have a COP higher than 50 which is almost 10 times higher than that of a typical mine chiller [68]. Increasing the PCT efficiency would result in an overall cooling system energy efficiency improvement [34].

Study C increased the efficiency of a mine cooling system PCT by replacing high-performance fill with a splash-type fill. Sediment and scale build-up deteriorated the efficiency of the high-performance fill. Maintenance could only be conducted during the winter months, which meant that the PCTs operated at a low efficiency during a large portion of the summer months [48].

It was found that the PCTs were oversized. Although the splash-type fill has a lower efficiency than the high-performance fill, it was more resistant against sediment and scale build-up. By replacing the high-performance fill with splash-type fill, the PCTs performed within design specifications throughout the year [48]. Refer to Figure 19 for a photo of the high-performance and splash-type fills.

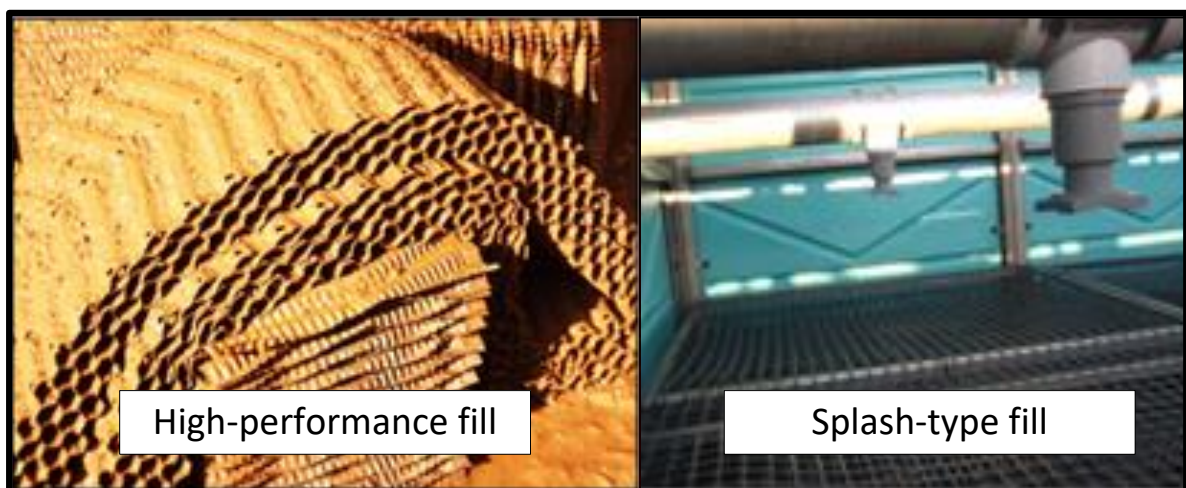


Figure 19: High-performance and splash type fills [48]

The increased PCT performance resulted in a 1 MW cooling system energy efficiency. This amounted to an annual electricity cost saving of R4.6 million<sup>7</sup>. According to the author, the total project cost was R5.6 million [48]. The project cost was adjusted with South African inflation [69]. A payback period of 1.2 years was achieved [48].

<sup>7</sup> 2017/18 Eskom Megaflex tariff

### 2.2.3 Chiller pump load reduction

Cooling system pumps are sized to meet the maximum water flow demand. Chilled water is usually recycled to the PCT sump when the chill dam level nears the 100% level. This results in unnecessary pump operation [35].

Study D investigated the installation of VSDs on mine chiller pumps to reduce chilled water recycling flow. VSDs were installed on both the chiller evaporator and condenser pumps. A test was conducted where the evaporator flow was reduced using VSDs. During the test, the condenser pump operated at full load [70]. The chiller COP resulting from a flow reduction in the evaporator is displayed in Figure 20.

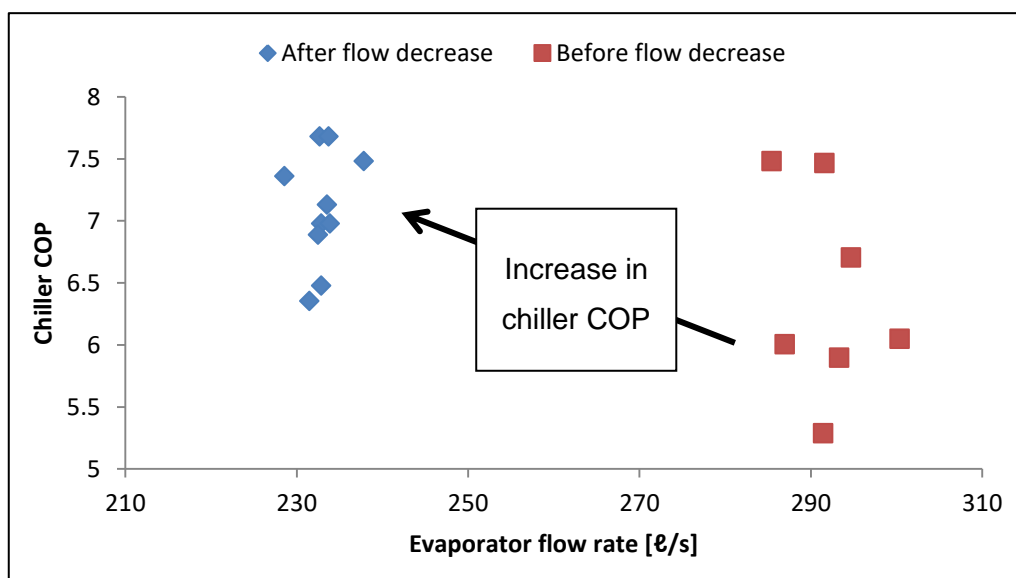


Figure 20: Chiller COP as a result of reduced evaporator flow [70]

In Figure 20, the COP of the chillers was increased while the power consumption of the evaporator pumps decreased. A similar test was done on the condenser pumps. During this test, the evaporator pump operated at full load while the flow of condenser water through the condenser was reduced using VSDs [70]. The chiller COP resulting from a flow reduction in the evaporator is displayed in Figure 21.

Referring to Figure 21, the COP of the chillers was lower after the condenser water flow was reduced. The high condenser water temperature resulted in increased chiller power consumption. The decrease in condenser pump power consumption, however, outweighed the increase in chiller power consumption. When the condenser flow was controlled in conjunction with the evaporator flow, the effect on the chiller COP was negligible. Overall, the pumps consumed less energy, without sacrificing service to its end users. This resulted in an annual electricity cost saving of R2.3 million [70].

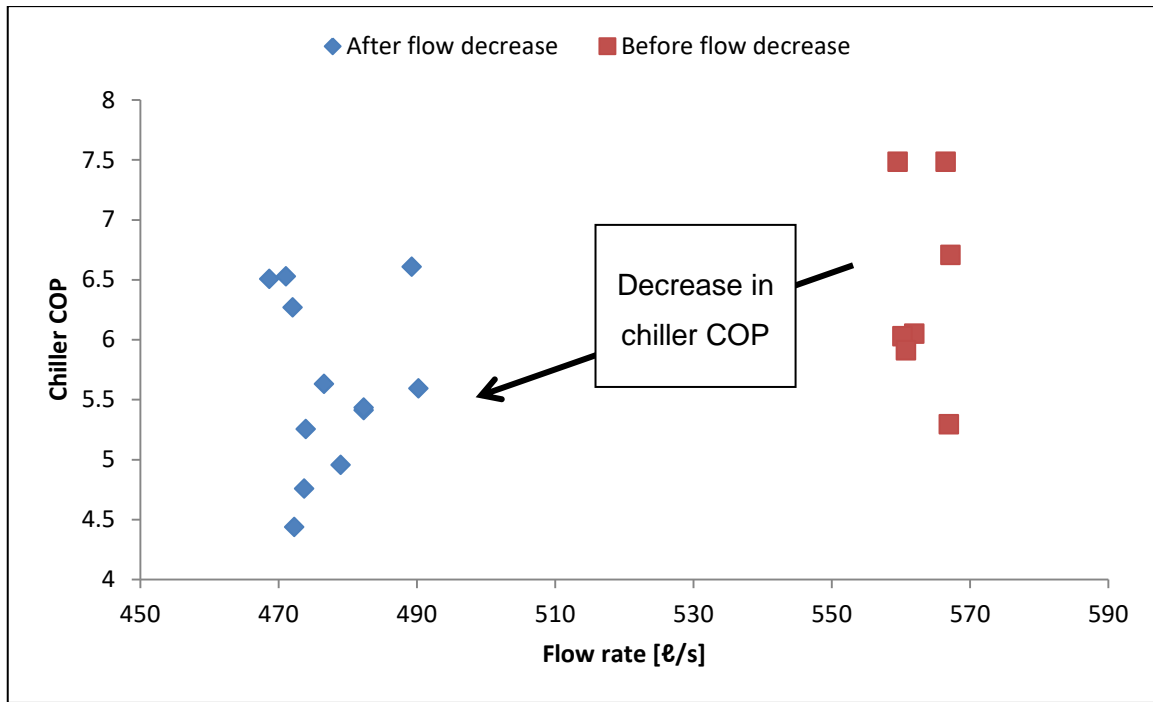


Figure 21: Chiller COP as a result of reduced condenser flow [70]

Numerous other studies have implemented VSD control on chiller pumps. It has been reported that VSDs have a payback period of less than one year. Refer to Table 1 for a list of VSD projects that have been implemented together with their corresponding payback periods. The VSD installation costs presented in Table 1 are calculated with a price estimate based on the size of the centrifugal pumps and adjusted with South African inflation [56], [69].

Table 1: Chiller pump VSD studies

	Annual pump electricity cost reduction <sup>8</sup>	VSD installation cost	Payback period
Study D [70]	R2 300 000	R1 200 000	6 months
Study E [36]	R2 100 000	R1 200 000	7 months
Study F [46]	R5 600 000	R4 000 000	9 months

As mentioned in Paragraph 1.1.3, ESCos are receiving less DSM funding from Eskom since the revised ESCo model has been implemented. The lack of initial funds has resulted in ESCos avoiding the installation of VSDs for cost savings since 2015 [33]. The next section will consider ECSIs on the cooling system demand side.

<sup>8</sup> Electricity cost reduction calculated with Eskom’s 2017/18 tariffs

## 2.3 Chilled water demand management initiatives

### 2.3.1 Reduced underground water usage

As mentioned in Paragraph 1.2.5, chilled water from surface is supplied to underground mining levels for cooling, drilling and sweeping. Chilled water travels through kilometres of pipes before reaching the working areas. These pipes are subjected to harsh conditions that can cause leaks. Fixing leaks is often not considered as a priority by the responsible mining person as production comes first [71].

The chilled water in underground mining pipes is under a large amount of pressure ( $\pm 1000$  kPa). Due to these high pressures, a small hole in an underground chilled water pipe can lead to large water quantities being wasted. Bernoulli's theorem was used to create a graph of the chilled water flow rate versus hole size which is illustrated in Figure 22 [71].

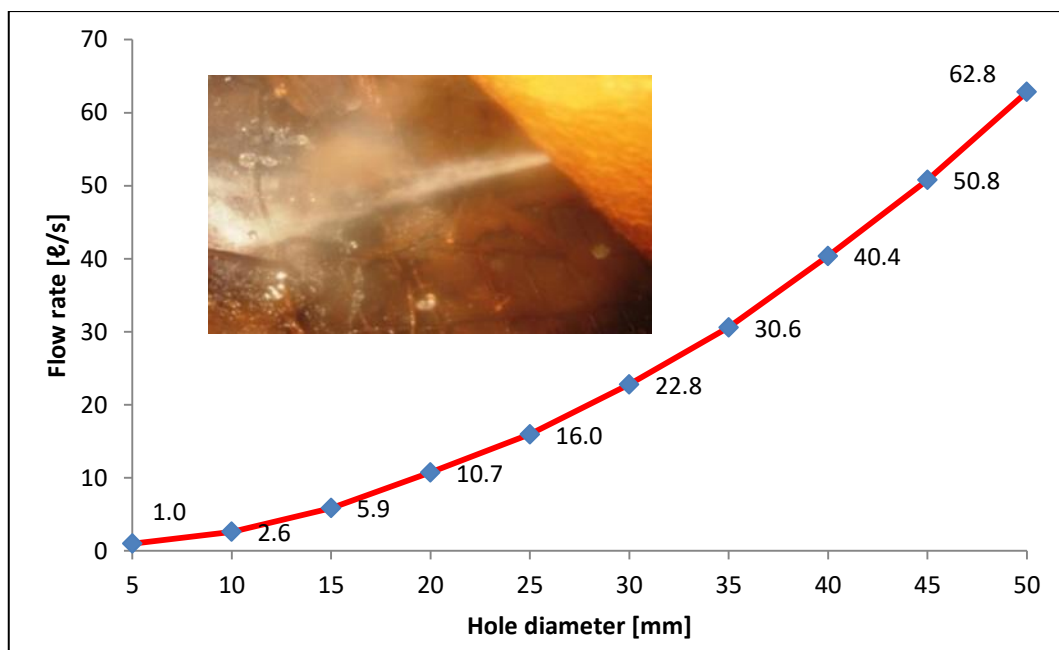


Figure 22: Flow rate versus hole diameter at a pressure of 1000 kPa [71]

Study E investigated the reduction of underground water usage by using the pressure control valves on each level underground [52]. The existing pressure control valves were previously used to stop the flow of chilled water to a certain level during emergencies and on non-working weekends. During the low chilled water demand periods, the downstream pressure of these valves was reduced which resulted in a reduced chilled water flow [52].

Approximately 55% of the chilled water generated by the chillers in Study G was used for the surface BAC; the remaining chilled water was used as underground service water.



Implementing level valve control would result in a 7.6% reduction in chilled water demand underground, thus decreasing the daily power consumption of the chiller by 5.7 MWh. This would result in an annual cost saving of R1.1 million<sup>9</sup> [52].

An initial capital cost is required to modify underground level valves for demand reduction. From personal experience, one valve modification can have a cost as high as R200 000, thus making it an unfavourable option for ESCos.

### **2.3.2 Load reduction on bulk air coolers**

BACs are one of the main chilled water consumers. By decreasing the BAC cooling load, chillers will use less electricity as less chilled water is required. As mentioned in Paragraph 1.2.7, the purpose of a BAC is to cool the underground environment to create a safe working environment for mine workers.

External factors influencing the body temperature of underground workers include the air DBT, relative humidity, velocity and radiant heat [50]. Implementing peak clipping on the BAC affects both the DBT and the relative humidity of underground ventilation air. Velocity is affected when the BAC fans are clipped in conjunction with decreasing the chilled water flow to the BAC. The effect of BAC peak clipping can be monitored using underground wet-bulb temperature (WBT) as DBT and relative humidity are integrated into this value [33], [72].

BAC peak clipping has been avoided in the past as there is a risk of creating safety hazards and consequently losing production if workplaces are not cooled sufficiently [73]. The performance of miners rapidly decrease above a WBT of 30°C [74]. According to the Mine Health and Safety Act of 1996, underground WBTs may not exceed 27.5°C in working areas while mine personnel are present [75]. The optimal time to implement BAC peak clipping would thus be during the periods when there are no people at the working areas.

As mentioned in Paragraph 1.2.5, deep-level mines have about six shifts in a typical working day cycle. Similar to mines, office buildings have specified working hours. The power usage of office cooling systems is dependent on the ambient conditions and office hours. Minimal cooling is required for an office building outside business hours as there are minimal people who require cooling [76]. The cooling requirements of underground

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<sup>9</sup> Based on 2017/18 Eskom Megaflex tariffs

mining areas can also be correlated to the number of people in the working areas [40]. Refer to Figure 23 for a comparison of the cooling system power consumption on a typical deep-level mine with the power consumption of a cooling system of typical office building [76], [77].

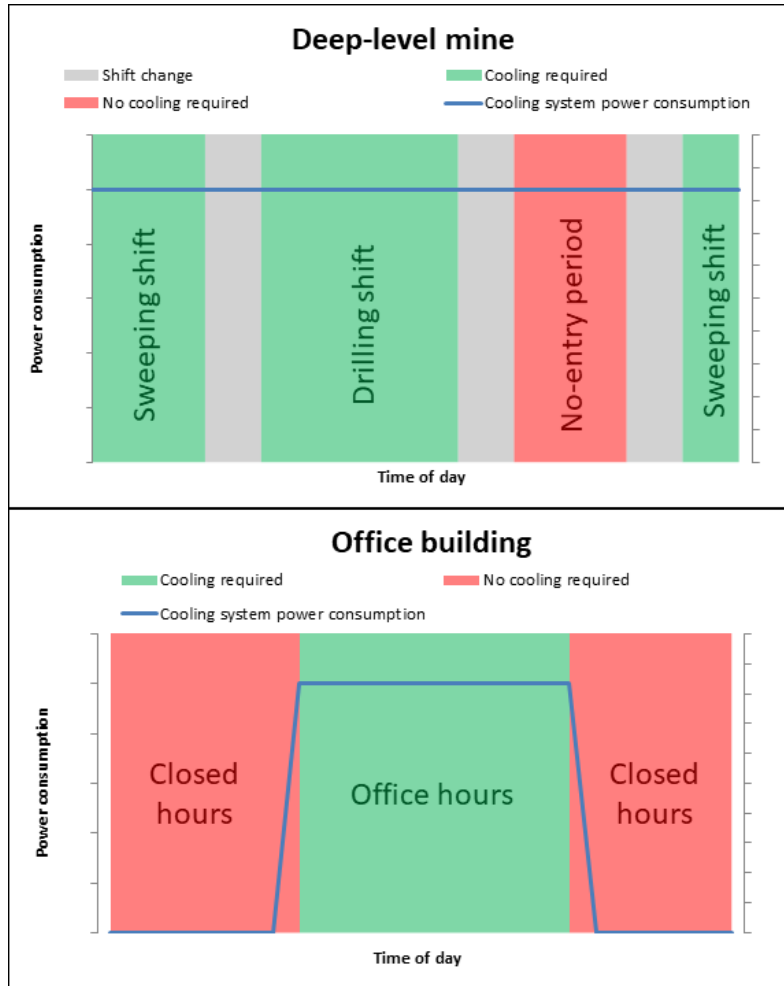


Figure 23: Cooling load comparison of a typical deep mine and office building [76], [77]

As can be seen in Figure 23, cooling systems in office buildings are stopped in the closed hours as there is no need for cooling during this time. Mine operators typically run the mine cooling system throughout the day, thus supplying the underground working areas with unnecessary cooling.

During the blasting shift and no-entry period, all personnel have to be evacuated from the working areas [11]. Minimal underground cooling is required during the blasting period. This period also corresponds with the Eskom evening peak period (HTP). By reducing the cooling load on the BAC, the chilled water demand will decrease. Fewer chillers thus need to be active to meet the chilled water demand.

A number of surface BAC load reduction studies have been implemented after the successful implementation of an underground BAC load shifting project [73]. ECSIs that incorporate the BAC into the control philosophy were found to require minimal start-up funding [33]. A further investigation was conducted on the different surface BAC studies to identify the factors that influence the control philosophy. The factors are listed below:

- Availability of chilled water flow control to the BAC:** BACs are designed to cool air to a specific set point temperature during the hottest days of summer. If the chilled water flow to the BAC cannot be controlled, the air will be overcooled on colder days. The BAC outlet air temperature can be controlled by using VSDs or control valves. In Study D, it was identified that the BAC outlet air was overcooled. Valves were installed to control the outlet air temperature set point which resulted in a reduced chiller load [70]. In Study I, all chillers were stopped during the HTP. Hot water from the precooling dam was diverted to the BAC by stopping the transfer pumps, which resulted in an increased BAC outlet air temperature. Figure 24 illustrates the control philosophy of Study I [33].

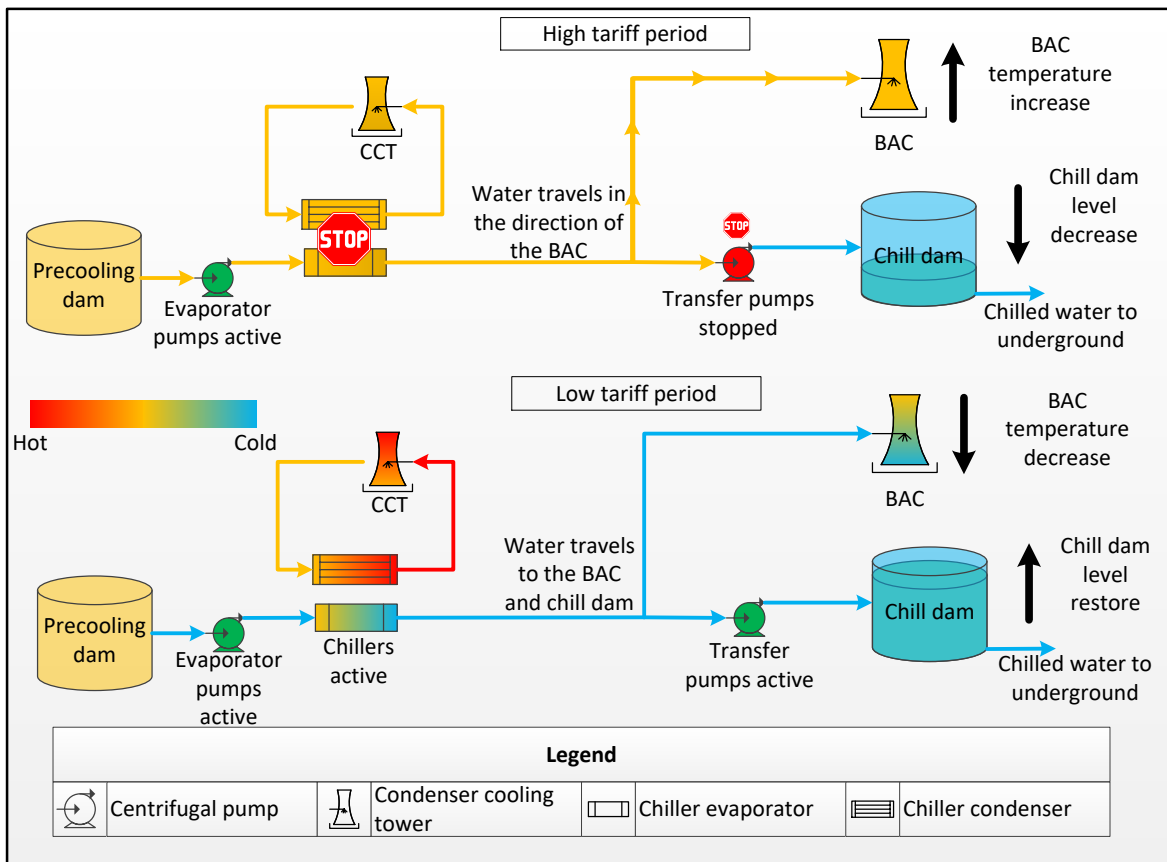


Figure 24: Study I operation during HTPs and LTPs [33]

- **Chill dam temperature requirements:** The cooling load of the BAC can be reduced by increasing the temperature of the chilled water. By operating evaporator pumps while the chillers are stopped, warm water enters the chill dam. In Study J, the chilled water temperature and consequently the outlet air temperature of the BAC were increased, which resulted in an electricity cost saving on the mine cooling system [44]. Study I is an example of an operation where the chill dam temperature had to remain constant. All the hot water from the precooling dam was diverted to the BAC as illustrated in Figure 24 [33].
- **Chill dam location:** Increasing the temperature of the chill dam water is not permitted on all sites. As mentioned in Paragraph 1.2.3, chill dams can be a buffer for chilled water to the BAC and underground operations or just a buffer for the chilled water flow to underground operations. In Study I, the chill dam only served as a buffer for the underground service water. The BAC cooling load could thus be decreased without the chill dam temperature being affected when the chilled water temperature was increased [33]. Study K is an example of a cooling system layout where the chill dam served as a buffer for the service water and the BAC. In this study, the outlet air temperature of the BAC was directly influenced by the temperature of the chill dam as can be seen in Figure 25 [34].

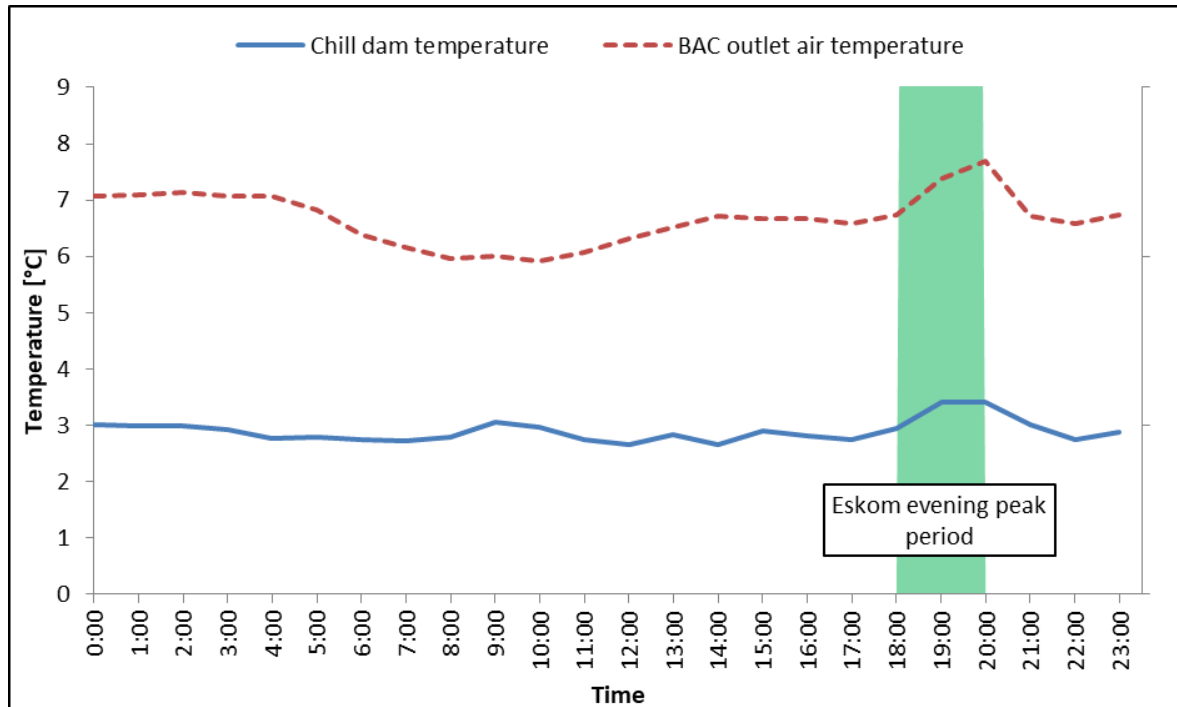


Figure 25: Chill dam and BAC outlet air temperature of Study K [34]

- **Total restriction of chilled water flow to the BAC:** Some mines allow total restriction of chilled water flow to the BAC. The availability of flow control is thus not required on these mines. Air enters the mine at ambient conditions. The BAC fans are also usually stopped in conjunction with the flow of chilled water for additional energy savings. This operation was only identified on gold mines [40], [44].

From the above information, it is clear that the changes made to one of the cooling system components can affect the other components. Raising the temperature of the chill dam can also raise the temperature of the BAC outlet air temperature, while restricting flow can lead to the overflow of dams [39]. Caution should thus be taken before modifications are made to the cooling system.

Load reduction on BACs has been proven to operate in conjunction with other ECSIs. Two strategies where the cooling load on the BAC has been reduced to improve the electricity cost savings of existing ECSIs are discussed below.

Study L installed VSDs to increase the cooling system efficiency throughout the day [78]. In addition to the energy efficiency strategy, a load shifting and peak clipping were also implemented by stopping all the chillers during the Eskom evening peak period. One evaporator pump was operated during this period to supply water to the BAC and the chill dam [78]. Refer to Figure 26 for the performance assessment period power profile and scaled baseline power profile of the combined energy efficiency/load shifting/peak clipping project.

From Figure 26, it is clear that the overall power profile of the cooling system decreased. An additional 3 MW power reduction is visible in the Eskom evening peak period from stopping the chillers.

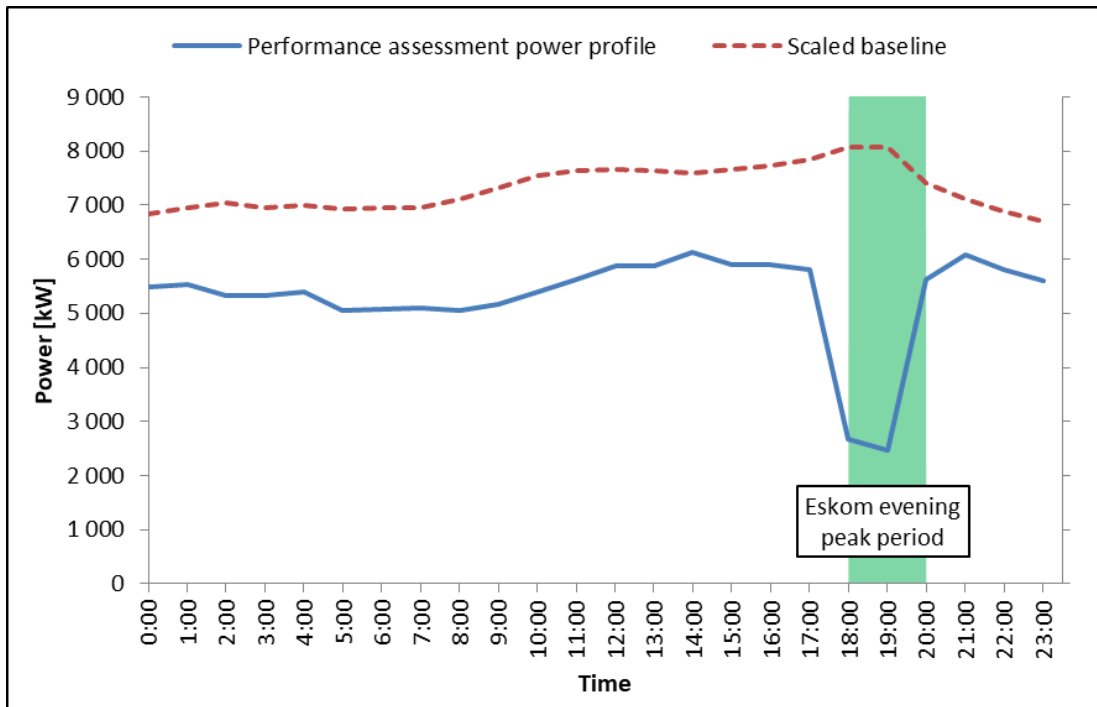


Figure 26: Power profile of a combined energy efficiency and load shifting ECSI [78]

Study M improved a load shifting strategy by reducing the cooling load to the BAC [40]. The baseline power profile in Figure 27 indicates a load reduction during the HTPs. The electricity cost saving was improved by restricting all flow to the BAC during the HTP. This increased the underground temperature. The chiller load was increased during the LTPs to restore the underground temperatures [40].

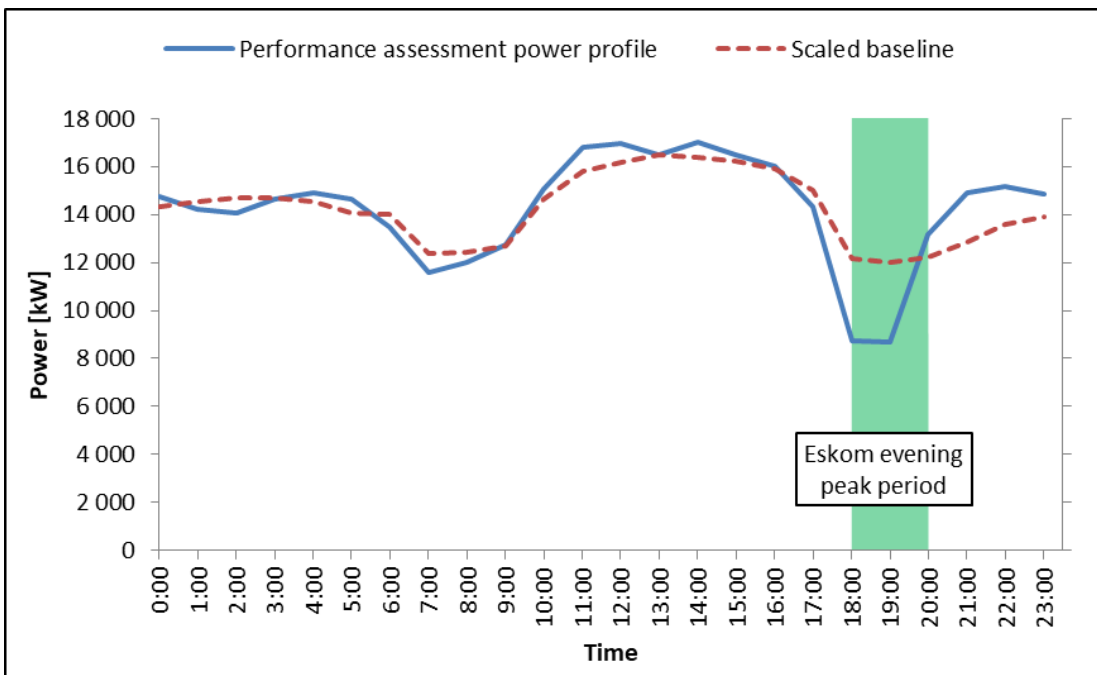


Figure 27: Power profile of improved load shifting using the BAC [40]

## 2.4 Shortcomings of existing cost saving measures

Previous ECSIs implemented on deep mine cooling systems were investigated in Paragraphs 2.2 and 2.3. There are numerous different strategies for reducing the cost of electricity on cooling systems. A summary of these studies is presented in Table 2. The studies were evaluated according to the following criteria:

- **Chiller load reduction/shift:** Did the study investigate and implement load shifting or load reduction on the surface chillers?
- **Pump load reduction:** Did the study consider load reduction on the cooling system? As an example, VSDs can be used to decrease the pump electricity load.
- **Thermal storage units:** Were thermal storage units, such as chill dams or underground storage mediums, used to perform load shifting on the chillers?
- **Underground investigations:** Did the study reduce the flow of chilled water to underground by installing level valves, fixing water leaks or by other means?
- **BAC control:** Did the study actively reduce the BAC cooling load?
- **Methodology:** A detailed, integrated methodology is required to identify electricity cost savings on a complex mine cooling system.

Table 2: Summary of cooling system ECSI studies

	Chiller load reduction/shifting	Chiller pump load reduction	Thermal storage units	Underground investigation	BAC control	Detailed integrated methodology
Study A [39]	Yes	No	Yes	No	No	No
Study B [21]	Yes	No	Yes	No	No	No
Study C [48]	No	No	No	No	No	No
Study D [70]	Yes	Yes	No	No	Yes	No
Study E [36]	Yes	Yes	Yes	No	Yes	No
Study F [46]	Yes	Yes	Yes	No	Yes	No
Study G [52]	No	No	No	Yes	No	No
Study H [33]	Yes	No	Yes	No	Yes	No
Study I [44]	Yes	Yes	Yes	No	Yes	No
Study J [34]	Yes	No	Yes	No	Yes	No
Study K [78]	Yes	Yes	Yes	No	Yes	No
Study L [40]	Yes	No	Yes	No	Yes	No

Table 2 indicates that various strategies have been implemented on mine cooling systems to reduce electricity expenses. Study E reduced chiller and pump load by reducing the BAC cooling load, while Study F introduced BAC control and load shifting into the cooling system control philosophy.

None of these strategies in Table 2 present a detailed, integrated methodology. Existing cooling system electricity cost saving identification methodologies are either high level, case study specific or area specific.

An integrated methodology may have resulted in additional electricity cost savings. Study A, for example, may have achieved additional savings by incorporating the BAC into the control philosophy, while Study F may have achieved additional savings by performing underground investigations.

## **2.5 Challenges to implement electricity cost saving initiatives**

### **2.5.1 Simulation**

It is often difficult to predict the effect of an ECSI on a mine cooling system. Poorly executed ECSIs can result in underperforming projects [79] and insufficient services to cooling system end users. Simulation models of the cooling system are developed to [80]:

- Determine the feasibility of the ECSI,
- Improve the ECSI design,
- Reduce the implementation period, and
- Reduce the implementation cost.

Mathematical models can be used to simulate a cooling system. Simulation packages incorporate these mathematical models to reduce the simulation time. A study was done on the different available simulation packages that can be applied to mine cooling systems [44]. In the study, three software packages were compared. Each software package had advantages and disadvantages. Process Toolbox was selected to simulate the cooling system in this study as it was proven to be user-friendly and could be used to accurately simulate the cooling systems in other studies [33], [44], [68], [81].

The results of the cooling system simulation have to be verified with actual data. These results are only acceptable when it is within 10% tolerance of the actual values [21], [82]. The next section will discuss the acquisition of actual data from the cooling system.



### 2.5.2 Information gathering

As discussed in Paragraph 2.5.1, the simulation of a mine cooling system requires actual measured data. The data quality will determine the quality of the simulation results. High-resolution data is preferred as low-resolution data lacks the ability to capture frequent system changes. Cooling system data in 30-minute intervals is sufficient [39].

Operational data will be used for the baseline development and project tracking. An energy management system (EnMS) was developed in accordance with the ISO 50001 standard for energy management. As part of the developed EnMS, it is important that operational data also be used to track the performance of the ECSI [83].

Various sources can be used to gather data from the mine. Some sources have advantages over others [52]. Table 3 presents possible data sources.

Table 3: Data sources

Source	Data
Manual log sheets and reports [84]	Low-resolution data; Tedious to process data; Not sustainable
Portable, offline loggers [33], [85]	High-resolution; Site visit often necessary; Tedious to process data; Not sustainable
Manual data download from supervisory control and data acquisition (SCADA) historian [33]	High-resolution; Site visit often necessary; Tedious to process data; Not sustainable
Remote data logging from SCADA [84]	High-resolution; Site visits are seldom necessary; Sustainable

From Table 3, it is clear that some data sources are more desirable than others when it comes to the simulation development and initiative performance tracking. A sustainable means of data gathering would be to remotely receive high-resolution data from the SCADA system [84].

### 2.5.3 Baseline scaling methods

An electricity baseline is a measure of the electric power usage before the implementation of an ECSI. The power baseline is an average power profile measured over a certain time period. This profile can be used to determine the effect of the ECSI on the electric power profile. The power usages of all the cooling system components that will potentially be influenced by the ECSI are included into the baseline power measurement.

Changes in external conditions, such as weather, cause the baseline to deviate from what the power usage would have been if no ECSI was implemented. The baseline has to be scaled to compensate for the changes in conditions. A model is developed to scale the baseline. The baseline model uses data from the baseline period and compares it with current conditions. Adjustments are made to predict what the power profile would have been if no ECSI was implemented. Typical baseline scaling models include [86]:

- **Constant baseline model:** The baseline power profile is not adjusted. This model is typically used on systems where the operation is constant.
- **Energy neutral scaling:** Changes in energy consumption are used to quantify operational changes. This scaling model is used where the amplitude of the profile is influenced by external factors. An energy neutral scaling will result in the baseline profile having an average power consumption that is equal to the power profile of the performance assessment period. The scaling factor is calculated with Equation 3.
- 

$$SF = \frac{\sum_0^{23} X[h]}{\sum_0^{23} Y[h]} \quad \text{Equation 3}$$

Where:

$SF$  = Scaling factor

$X[h]$  = Average hourly power usage in assessed period [kW]

$Y[h]$  = Average hourly power usage in baseline period [kW]

The scaling factor calculated in Equation 3 is used to calculate the scaled baseline with Equation 4.

$$SB = SF \times Y[h] \quad \text{Equation 4}$$

Where:

$SB$  = Scaled baseline [kW]

$SF$  = Scaling factor

$Y[h]$  = Average hourly power usage in baseline period [kW]

- Regression baseline models:** With this model, a link is found between the baseline system power consumption and other operational variables. The link is represented by a mathematical formula. During the performance assessment period, operational variables are used to calculate what the power profile would have been if no ECSI was implemented (scaled baseline).

Energy neutral scaling is generally applied when a load shifting ECSI is applied. This scaling method can, however, not be applied to ECSIs where the system’s energy efficiency has been improved. A regression baseline scaling model is used in this case [87]. The next paragraph will discuss the measurement and verification (M&V) process that is required to ensure that the baseline and baseline scaling method is correct.

### 2.5.4 Measurement and verification

Another obstacle to the implementation of ECSIs is the objective quantification of electricity cost savings [20]. M&V teams are appointed to evaluate electricity cost savings achieved through the ECSI. Figure 28 is a diagram of the ESCo and M&V team responsibilities [88].

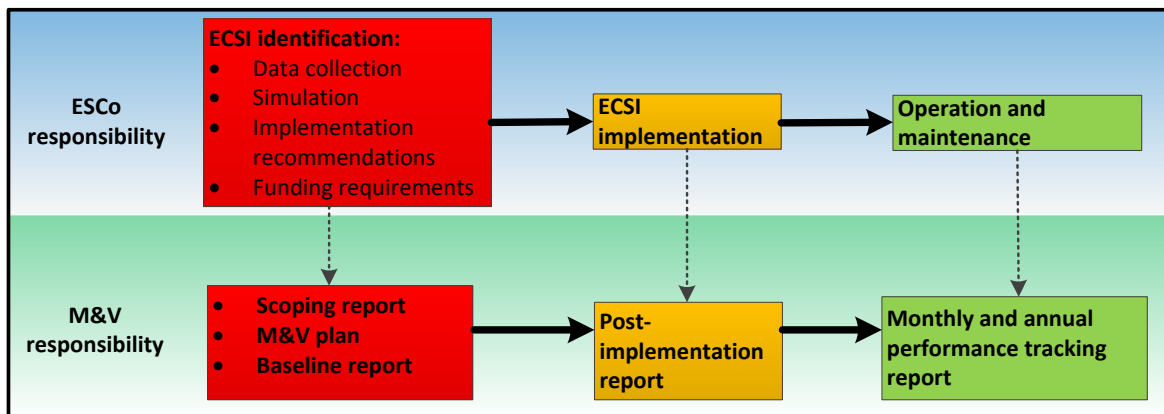


Figure 28: M&V process in alignment with the ECSI [88]

In order to streamline the ECSI, the M&V process should be integrated with the ESCo’s project implementation process. Failure to do so may lead to delays in project implementation [89].

### 2.5.5 Initiative financing

An ECSI cannot continue without funding [20]. As mentioned in Paragraph 1.1.3, ESCOs have been receiving less financial support from Eskom since 2015. South African ESCOs are now thus more dependent on funding from their clients.

An electricity cost optimisation model was developed to help the ESCo in its financial decision-making process [52]. In the event of insufficient Eskom funding, the high initial capital cost of ECSIs can be overcome by implementing manual control and utilising available cooling system equipment. The electricity cost savings from the manual control can then be used to later automate the ECSI [33]. A graph of the cost-effective financing model is illustrated in Figure 29.

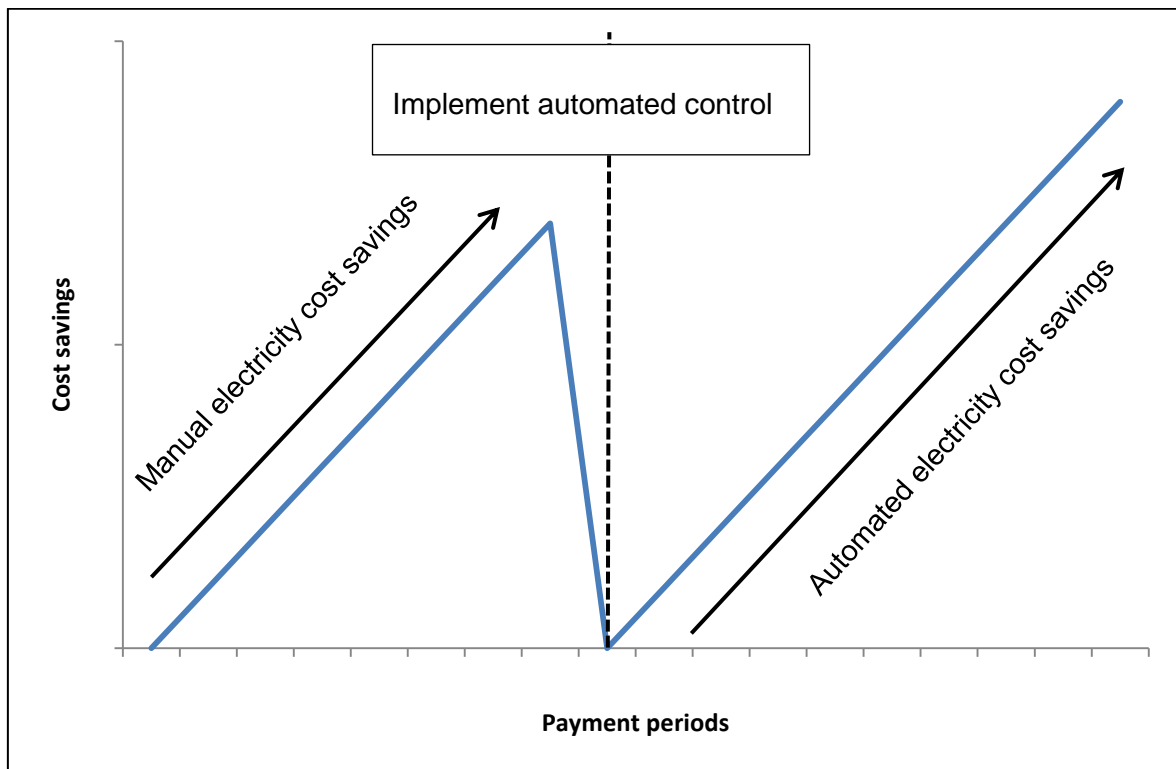


Figure 29: Cost-effective project financing model [33]

Other available financing models include a shared savings model and guaranteed savings model [20]. Both these models are dependent on client funding. The ESCo receives a percentage of the electricity cost saving with the shared savings model. With the guaranteed savings model, the ESCo is paid for guaranteed savings. The ESCo however has to maintain the savings for a predetermined period [20].

## 2.6 Conclusion

Chapter 2 started with an investigation on existing ECSI strategies on cooling systems. The supply of chilled water can be managed for cost savings by increasing the energy efficiency of the cooling systems or shifting the electrical load from HTPs to LTPs. Energy efficiency can be achieved by installing VSDs on cooling system components or improving PCT efficiency. These initiatives, however, come with a high initial capital cost. The thermal storage capacity of chill dams is used to apply load shifting to the cooling system. Existing cooling system infrastructure can be utilised to apply load shifting to the cooling system, thus reducing the need for start-up capital.

As mentioned in Chapter 1, chilled water is used to cool air in the BAC or is used as service water for underground activities. Decreasing the chilled water demand will result in chiller electricity cost savings. Underground automated pressure-regulating valves are installed to reduce the chilled water flow to underground during the low chilled water demand periods. The BAC cooling load is reduced during the no-entry period. Similar to load shifting initiatives, BAC peak clipping can be implemented by utilising existing infrastructure. Underground chilled water demand reduction, however, require start-up capital.

From the literature study, it was identified that an action on one cooling system unit may affect the operation of other units. An integrated methodology is required to guide the ESCo in finding electricity cost savings without exceeding the cooling system constraints. No such methodology was found.

An investigation was done on the obstacles the ESCo might face when implementing a new ECSI on a mine cooling system. These obstacles include:

1. Data gathering,
2. Simulation construction,
3. Baseline scaling,
4. M&V, and
5. Financing.

Sufficient information was gathered to develop a methodology for the identification of cost-effective electricity cost savings on a mine cooling system. This methodology will be developed in Chapter 3.

# Chapter 3. Electricity cost savings identification model for mine cooling systems

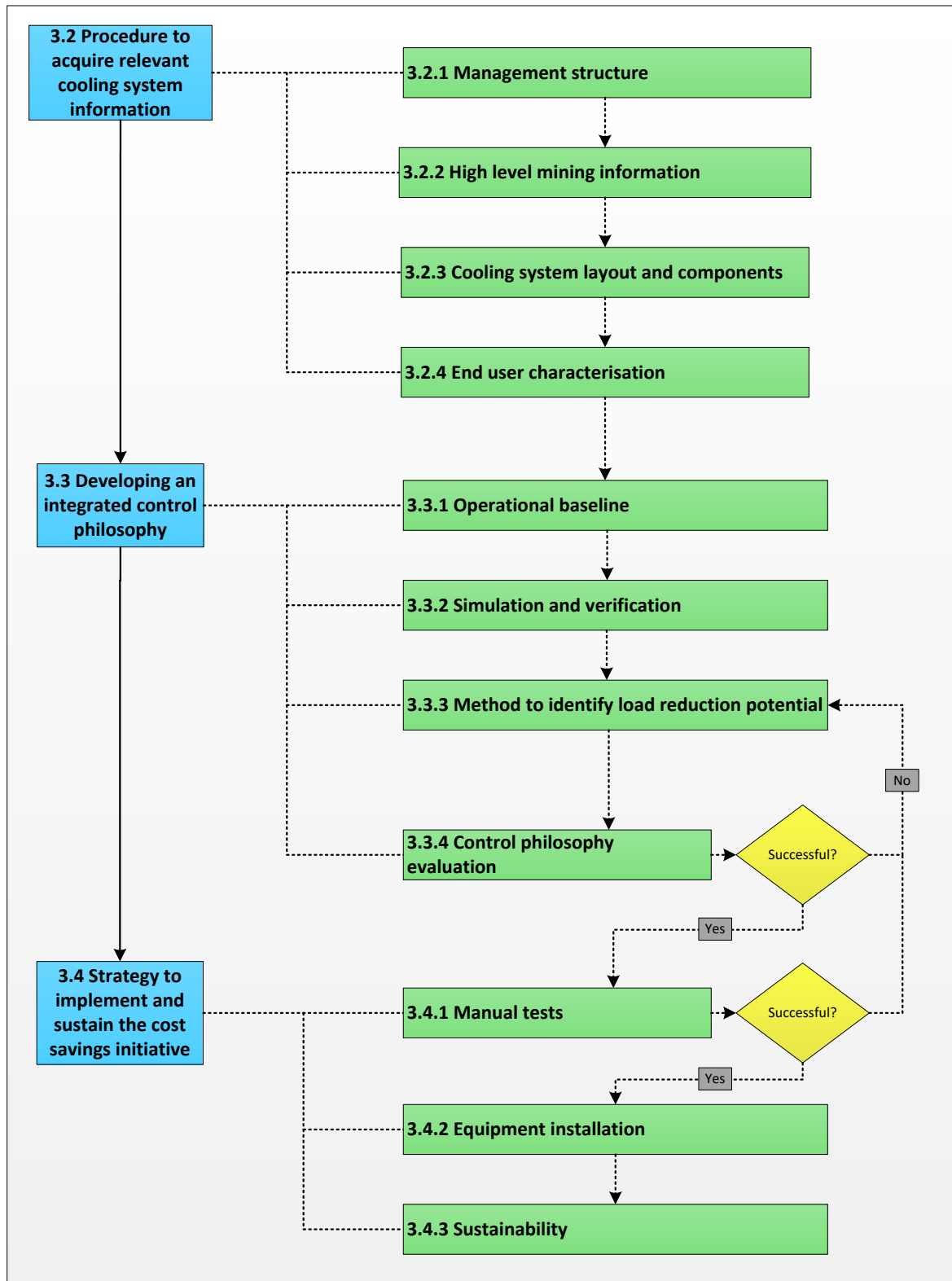


Figure 30: Overview of Chapter 3 content

### 3.1 Introduction

In Chapter 2, a study on existing cooling system ECSIs was conducted. Previous studies used cooling system data to develop a simulation. The simulation could then be used to develop a control philosophy. A method to gather cooling system information and develop a simulation is presented in this chapter.

No integrated methodology for the identification of ECSIs on a cooling system could be found in literature. A methodology for the identification of cost-effective electricity savings initiatives will be developed and discussed. The developed simulation together with the methodology for ECSI identification can be used as tools to develop a control philosophy.

According to literature, a scaled baseline is required to quantify the electricity cost savings resulting from the initiative implementation. If the developed control philosophy is not financially or physically feasible, the ESCo has to revisit the ECSI identification step. The methodology will be developed based on information gathered from previous studies in Chapter 2. Figure 30 illustrates an overview of the Chapter 3 content.

### 3.2 Procedure to acquire relevant cooling system information

#### 3.2.1 Management structure

The top management of the mine should be approached before starting with investigations on the cooling system. The top mine management has the authority to delegate work and provide resources for the implementation of an ECSI. An example of a mine management structure is illustrated on Figure 31 [90].

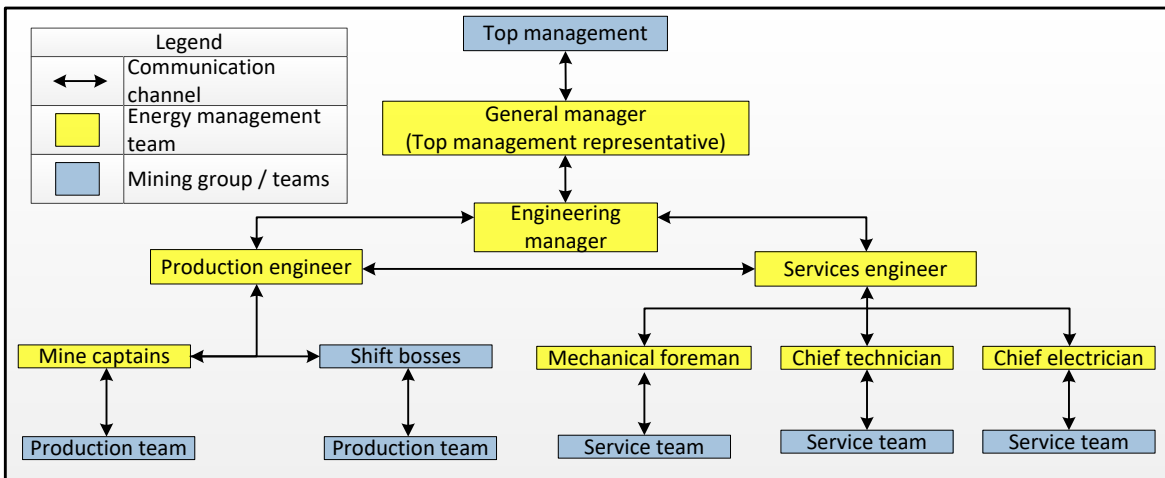


Figure 31: Mine management structure example [90]

The yellow blocks in Figure 31 indicate a proposed energy management team. An ESCo will most likely only work with members from this team. These personnel are directly responsible for the management of energy intensive systems on a mine. Members on this team should frequently communicate with each other to meet production targets while still using energy efficiently [90].

After the management structure and communication channels are determined, a letter of intent is signed. This document gives an ESCo first choice in implementing the project. It also ensures that information from the mine is kept confidential [11].

### **3.2.2 High level mining information**

An ESCo will be allowed to continue with an ECSI investigation after the letter of intent has been signed. High level mine information needs to be obtained which includes:

- Type of mining and technology,
- Life-of-mine, and
- Mine location.

As mentioned in Paragraph 1.2.4, weather has a significant effect on the efficiencies of cooling towers. South Africa has diverse weather conditions over the whole country. An analysis of the weather patterns will be required for the baseline scaling development and simulation of an ECSI.

As mentioned in Paragraph 2.2.1, Eskom tariffs vary based on the time of day, season of the year and day of the week. The electricity price is also based on the distance from the mine to Eskom's transmission zone (Johannesburg) and the voltage at which the mine receives electricity. Table 4 contains the Eskom Megaflex tariffs<sup>10</sup> during the high demand season (winter). The Megaflex tariff usually applies to large electricity consumers, such as mines.

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<sup>10</sup> Excludes value added tax (VAT)



Table 4: Eskom Megaflex tariffs during the high demand season (2017/18 tariffs)

Transmission zone	Voltage	High demand season [Jun–Aug]		
		Peak [c/kWh]	Standard [c/kWh]	Off-peak [c/kWh]
≤ 300 km	< 500 V	278.33	84.68	46.24
	≥ 500 V & < 66 kV	273.96	83.00	45.07
	≥ 66 kV & ≤ 132 kV	265.29	80.36	43.65
	> 132 kV	250.03	75.74	41.14
> 300 km and ≤ 600 km	< 500 V	280.60	85.02	46.16
	≥ 500 V & < 66 kV	276.70	83.82	45.52
	≥ 66 kV & ≤ 132 kV	267.90	81.15	44.06
	> 132 kV	252.53	76.51	41.52
> 600 km and ≤ 900 km	< 500 V	283.40	85.85	46.60
	≥ 500 V & < 66 kV	279.48	84.67	45.98
	≥ 66 kV & ≤ 132 kV	270.63	81.98	44.51
	> 132 kV	255.08	77.26	41.97
> 900 km	< 500 V	286.25	86.74	47.09
	≥ 500 V & < 66 kV	282.26	85.50	46.41
	≥ 66 kV & ≤ 132 kV	273.34	82.80	44.96
	> 132 kV	257.56	78.06	42.41

According to Table 4, the tariffs increase as the distance increases from the transmission zone. This is due to electrical energy losses over large transmission distances [91]. Eskom transmits electricity across the country at a voltage of 132 kV. Eskom can provide the consumer with a lower voltage at a higher tariff [45].

### 3.2.3 Cooling system layout and components

In Paragraph 1.2, the reader was introduced to a typical mine cooling system layout. Each of the components found in the layout was discussed. It is important to understand how the components in the cooling system affect each other before changes are made to the system. This paragraph will provide a step-by-step process to characterise a mine cooling system.

The first step in understanding the system would be to obtain an updated piping and instrumentation diagram (P&ID) of the cooling system. This diagram can be obtained from the drawing office or instrumentation technician. The cooling system components, pipes connecting these components and control loops are illustrated on this diagram. P&IDs are usually complex diagrams, but they can be redrawn in order to create a simplified view of the system. This is known as a process flow diagram (PFD). An example of a cooling system PFD is illustrated in Figure 32.

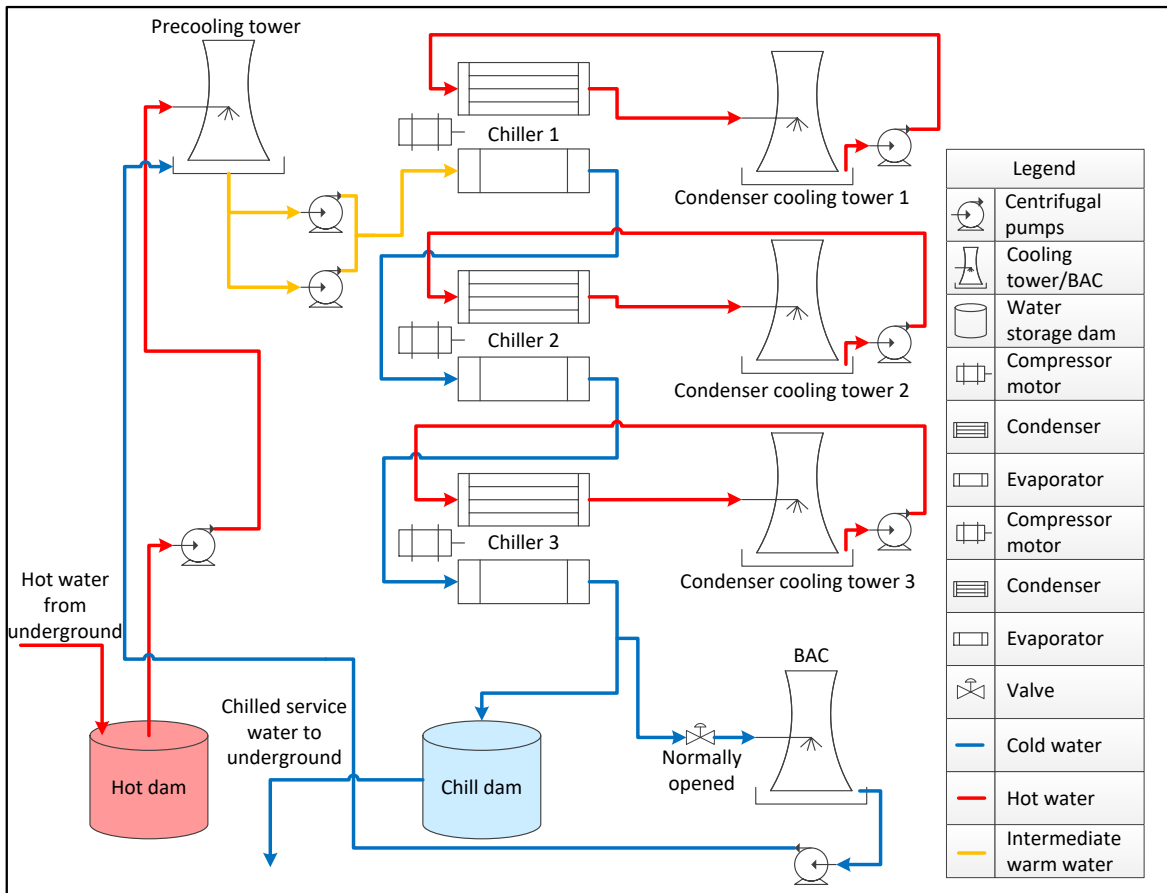


Figure 32: Example of a cooling system process flow diagram

From the cooling system PFD, an ESCo will be able to determine the configuration of the chillers and chill dams which will be important for the identification of ECSIs in Paragraph 3.3.1.

Component specifications can be obtained from P&IDs. This information will be necessary for the cooling system simulation development which will be discussed in Paragraph 3.3.1. The required cooling system information includes:

- Equipment specifications,
- Automated or manual equipment,
- Dam capacities,
- Pipe and valve sizes, and
- Valves that are normally opened or closed.

The information in the P&ID is not always sufficient. An ESCo will then either have to consult with the person responsible for the equipment (engineering supervisor or instrumentation technician) or physically inspect the equipment and specification plates.

Figure 33 illustrates a chiller motor specification plate containing information such as the power rating and efficiency of the motor.



Figure 33: Chiller induction motor specification plate

### 3.2.4 End user characterisation

As mentioned in Paragraph 1.2.5, the cooling system provides cooling and other services to the end users either through ventilation or service water. These cooling mediums have specific requirements that have to be fulfilled in order to meet the needs of its end users. Cooling system high- and low-limit requirements are crucial information needed for the ECSI implementation. The following high/low limits should be obtained:

- Chilled water temperature high limit,
- BAC outlet air temperature high limit,
- Underground air temperature and humidity high limit,
- Underground gas limits (example: carbon monoxide high limits),
- Chill dam level high/low limits, and
- Hot dam high limit.

The first point of contact for the above information is the mine's engineering manager or shaft engineer. Limits that cannot be obtained from these engineers can be obtained from the ventilation engineer or instrumentation technicians. The technicians can assist the ESCo in obtaining set points and limits from the SCADA. Figure 34 shows a SCADA screenshot of a chiller where the outlet evaporator temperature set point is indicated.

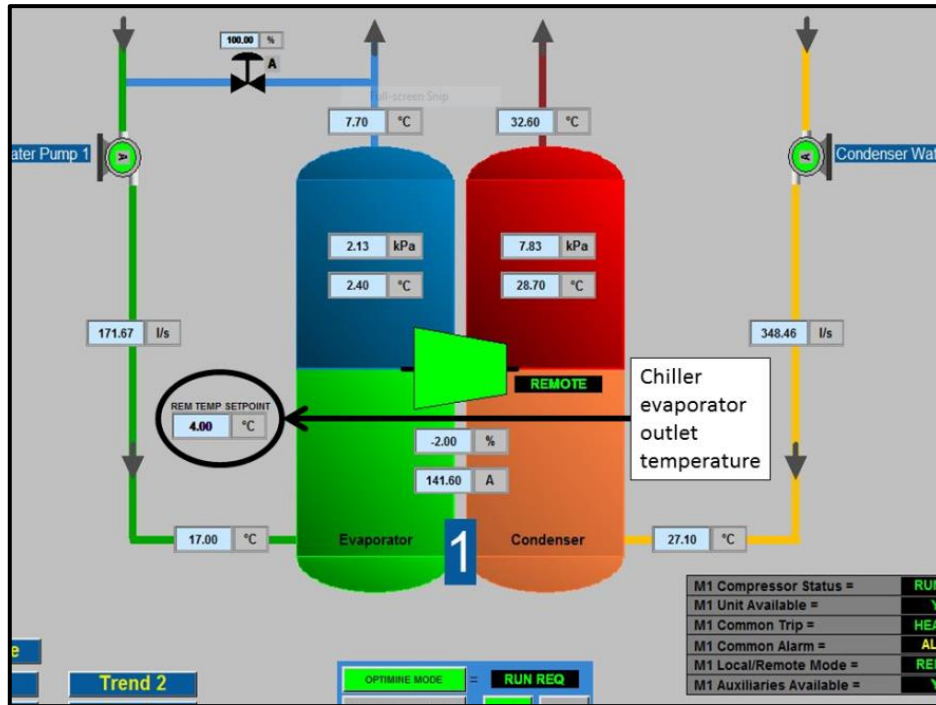


Figure 34: SCADA screenshot of a chiller

The cooling system limits constrain the ECSI. Reasoning behind the specified limits should be noted. Limits are applied based on the design of the mine or to comply with regulations. These limits are frequently overspecified [35]. Mining personnel are often under the impression that the cooling system is utilised optimally and any changes made to the system will lead to deterioration in production and/or cooling system service delivery. The ESCo will need to negotiate with mining personnel to make changes to the cooling system limits. These limits are critical to the success of the ECSI.

### 3.3 Developing an integrated control philosophy

#### 3.3.1 Operational baseline

After the cooling system limits have been determined, ESCos have to investigate the current operation of the cooling system. Key performance indicators (KPIs) are used to measure the performance of the cooling system before and after the implementation of the ECSI. Typical KPIs on a cooling system include:

- Electrical components power consumption,
- Electrical component running status,
- Load reduction mechanism position (VSDs, guide vanes or slide valves),
- Water temperatures,
- Water flow rates,

- Pressures,
- Dam levels,
- Air temperatures,
- Air relative humidity, and
- Underground air composition.

At the start of an investigation, all cooling system variables should be treated as KPIs, as the ESCo has not yet determined the effect of the ECSI. Possible methods for data gathering are discussed in Paragraph 2.5.2. The first source of data for the KPIs in the investigation phase is the SCADA's historian. If the SCADA has insufficient data, the ESCo should either resort to historical data from manual logged sheets or temporary loggers should be installed. Figure 35 illustrates a diagram of the preferred data measurement and collection methods.

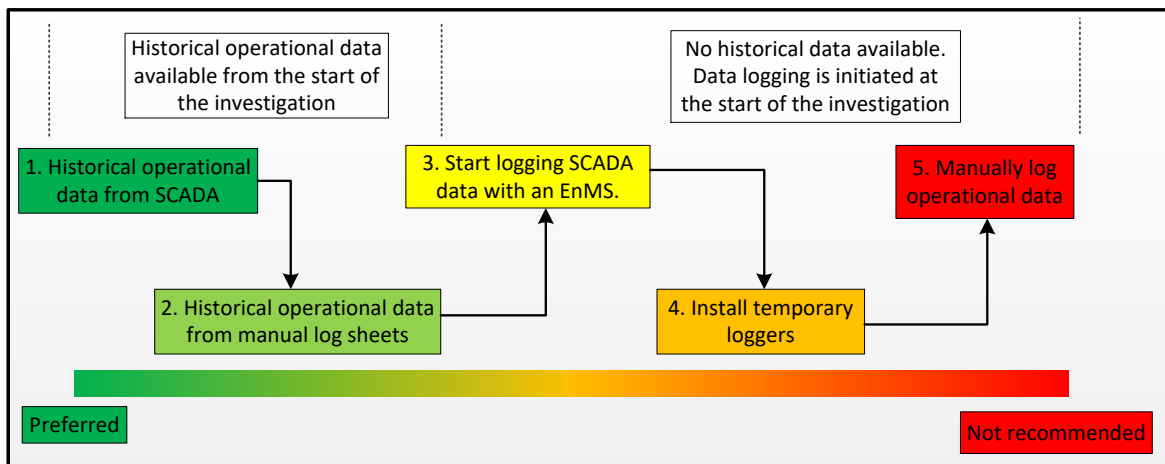


Figure 35: Preferred data measurement and collection methods

### 3.3.2 Simulation and verification

A simulation of the cooling system can be constructed from the gathered data. Process Toolbox was identified as a suitable simulation package for mine cooling systems in Paragraph 2.5.1. A demonstration of the simulation development will be done in Process Toolbox. The method used to construct the simulation could also be applied to other simulation packages.

The gathered data can be separated into controllable and uncontrollable variables. As the names imply, the user has control over the controllable variables, while the control of uncontrollable variables is out of the users hands [92].

Controllable variables can be broken down further into independent and dependent variables. Independent variables can be manipulated. The outcome of the independent variable manipulation will be reflected by the value of the dependent variables (the output). Table 5 is an example of typical controllable and uncontrollable variables found on the mine.

Table 5: Controllable and uncontrollable variables

Controllable variables	Uncontrollable variables
Chill dam level	Ambient temperature
Chilled water temperature	Underground service water usage
BAC outlet air temperature	BAC air flow rate

Time and frustration can be saved if each component of the cooling system is specified separately. Firstly, the design specifications that were gathered in Paragraph 3.2.3 should be inserted in this component. Secondly, the streams going into this component, whether it is water, air or power, should be specified according to the data gathered in Paragraph 3.3.1. These streams will be the independent variables for the time being. Figure 36 illustrates how an individual component can be specified in Process Toolbox.

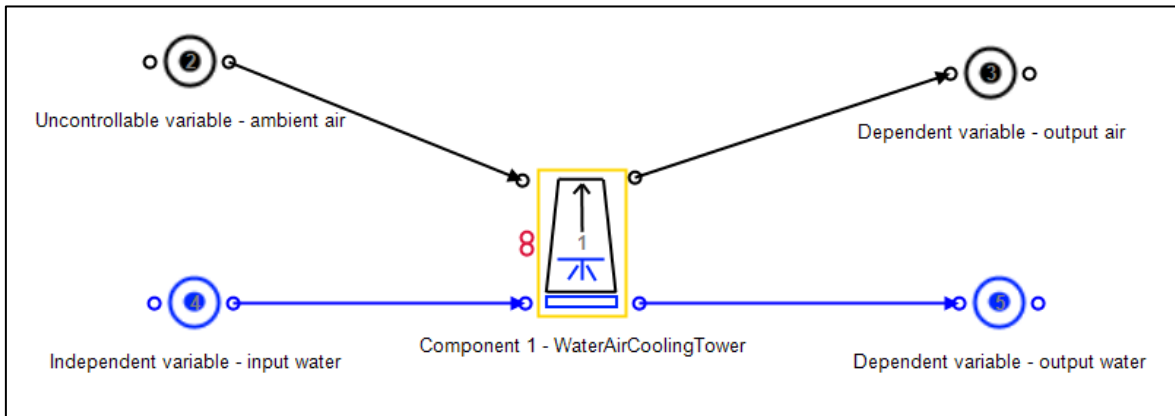


Figure 36: Specification of an individual component in Process Toolbox

Figure 37 shows a process for simulating each cooling system component. The first step in the simulation process is data gathering (see Paragraph 3.3.1). The gathered data (uncontrollable and controllable variables) can be inserted into the simulated component by opening the component window and navigating to the “Input” tab in Process Toolbox.

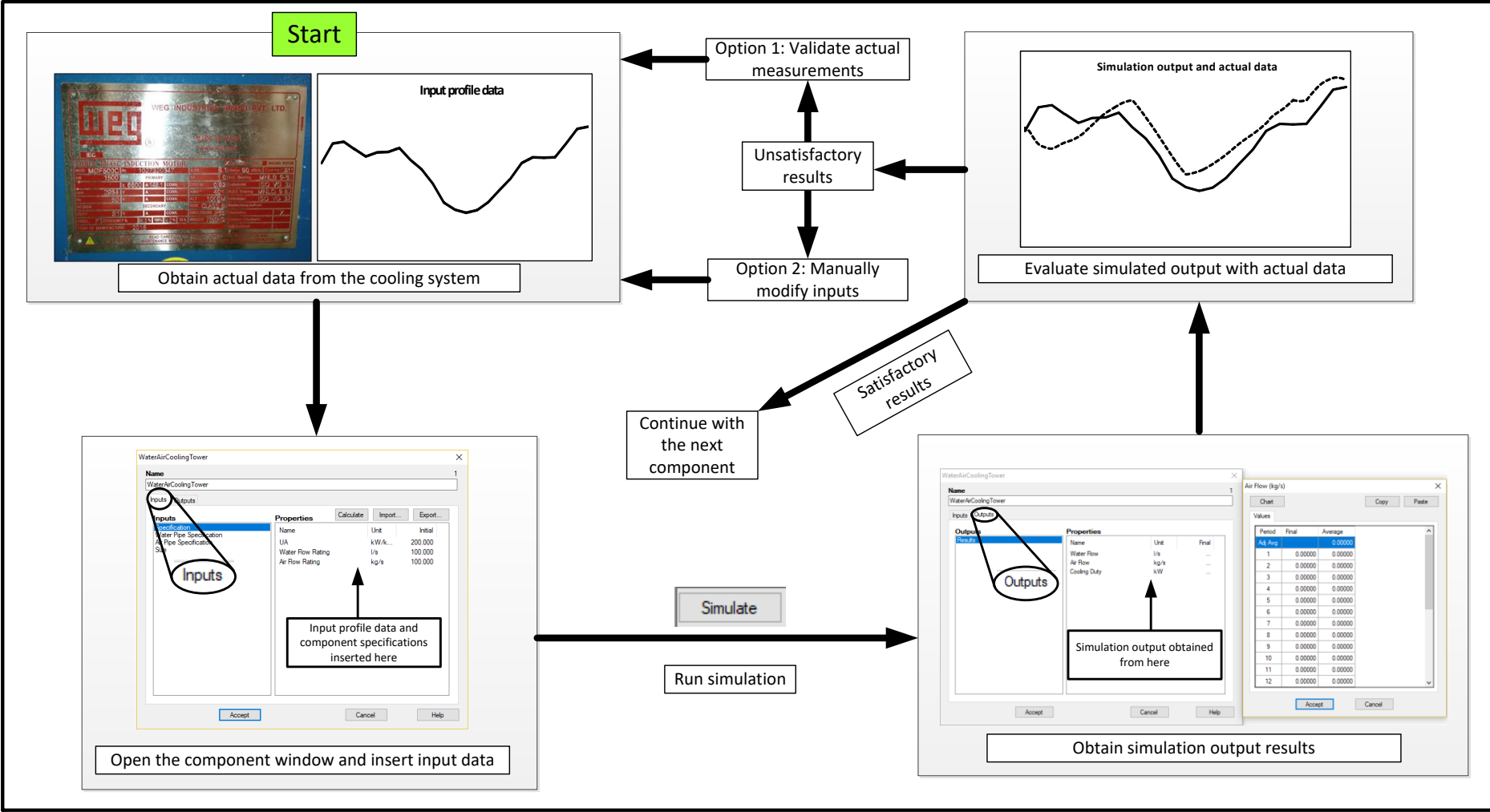


Figure 37: Simulation process

After running the simulation, the user can open the component again and navigate to the “Output” tab. Here, the user can retrieve the simulation output (dependent variables) and paste the output in a spreadsheet.

The simulation output in spreadsheet format can be compared with actual cooling system data. Simulated output from the component can be considered as acceptable if the error between the actual data and simulation output is smaller than 10% (as discussed in Paragraph 2.5.1).

There are two possible explanations for unacceptable output. The first explanation is uncalibrated or malfunctioning mine instrumentation. Portable measurement equipment can be used to verify the measurements from mine instrumentation. The second explanation is incorrect component specifications. As an example, the design pressure drop over a cooling tower may differ from the actual pressure drop due to scale build-up and nozzle plugging. The user then has to resort to trial-and-error to match the actual flow rate with the simulated flow rate by adjusting the simulated pressure drop over the pipe.

After the individual components have been specified, the site layout obtained in Paragraph 3.2.3 can be used to connect the simulated components. A PFD, such as the one illustrated on Figure 32, can be used to construct the simulation layout. Refer to Figure 38 for a simulation layout constructed in Process Toolbox.

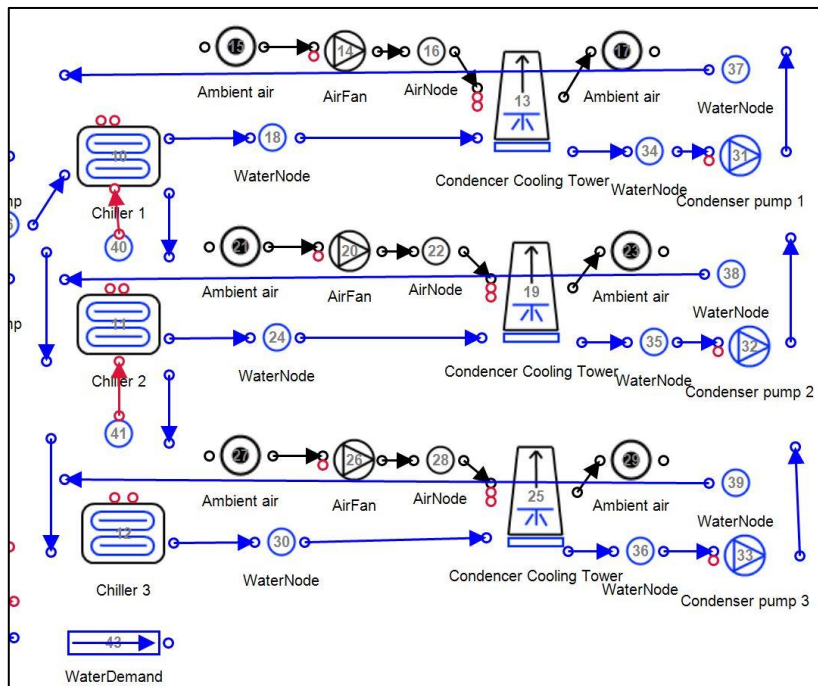


Figure 38: Construction of a simulation layout in Process Toolbox



Process Toolbox is not capable of simulating the effect of the ECSI on the underground temperature and humidity. Manual tests are required to determine the effect on the underground conditions if there are no existing temperature sensors underground. Figure 39 shows a photo of portable DBT and relative humidity loggers that can be used for manual tests.

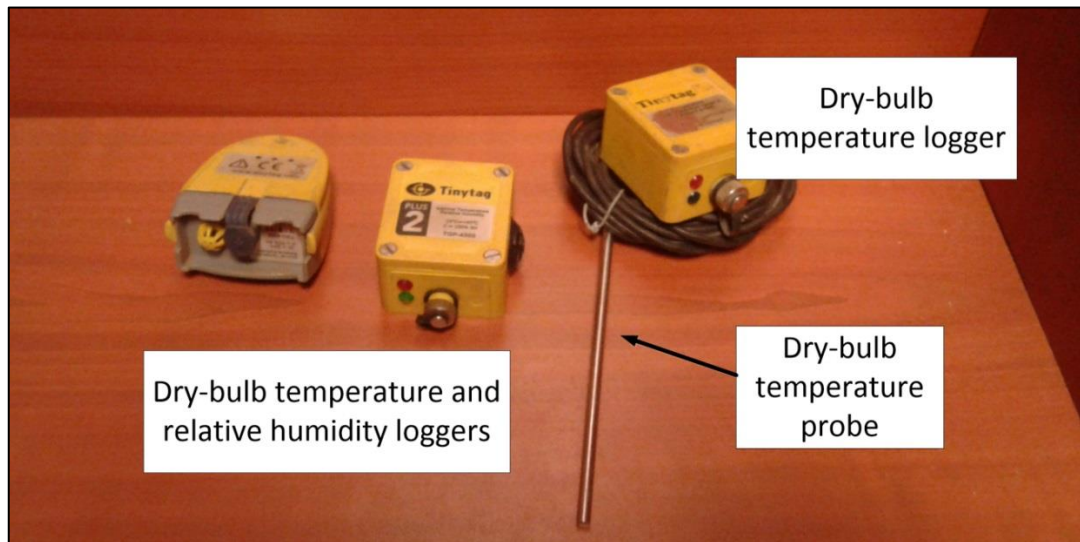


Figure 39: Portable temperature and relative humidity loggers

### 3.3.3 Method to identify load reduction potential

In Paragraph 2.4, it was found that existing studies had a high level, focussed or case study specific methodology of identifying electricity cost savings on a mine cooling system. In this paragraph, a detailed methodology will be developed to help ESCOs identify electricity cost savings without exceeding cooling system limits. Project implementation cost will also have a high importance in this methodology.

It was identified in Paragraph 2.2.2 that energy efficiency projects have high implementation costs (often higher than R1 000 000). Load shifting and BAC projects, on the other hand, can be implemented with little to no cost, but comes with the risk of production loss and safety concerns. Certain projects thus have preference over others.

A study was conducted to determine the sequence in which cooling system ECSIs should preferably be implemented. The ECSIs were rated according to the potential risks involved and the general appeal of the initiative [32].

According to Paragraph 1.1.3, ESCOs are receiving less funding from Eskom to implement ECSIs. In addition, mines are struggling to remain profitable. The criteria used to rate the

ECSIs in the study mentioned above are outdated as the project implementation cost only had a small contribution to the overall ECSI rating. An updated criteria list was used to create new matrixes according to which ECSIs could be rated. The weight values were determined in accordance with similar weighting structures used in Study 1 [32] and Study 2 [93] to rate industrial ECSIs. Information from the literature in Chapters 1 and 2 were also used to support the chosen weights.

The common risks involved in the implementation of cooling system ECSIs are listed in Table 6. Each risk receives a severity value. A severity value of five indicates that the likelihood of a project being cancelled is very high. The opposite is true for a low severity value.

Table 6: Electricity cost savings initiative risk evaluation criteria

<b>Risk</b>	<b>Description</b>	<b>Severity (Max 5)</b>
Production loss	Evaluate the risk of the ECSI leading to production loss on the mine. It was mentioned in Paragraph 1.2.8 that the ECSI can be cancelled if it leads to production loss. For this reason, production receives a high weight.	5
Environmental health and safety	The health and safety of the environment and the underground workers is considered as equally important to production, as it can hold legal consequences for the mine as discussed in Paragraph 2.3.2.	5
Overhead cost	This criterion evaluates whether there will be any additional costs as a result of the ECSI. As an example, maintenance cost on the chillers may increase due to chiller short cycling. Overhead cost has a low severity according to Study 1 [32].	2
Service delivery	Evaluate the risk of the ECSI degrading the cooling system service delivery. Example: The ECSI increases the chilled water temperature. Degrading the service delivery may not necessarily have a negative impact on environmental health and safety, as the mine may, for example, be overcooled below the WBT high limit of 27.5 °C. In such a scenario, it is possible to increase the chilled water temperature without affecting the health and safety of employees. The WBT, however, has to remain below the high limit. Service delivery has a low severity value according to Study 1 [32].	2

The projects were also evaluated according to other factors such as the monetary value of the project. In order for the ESCo and the client to evaluate the desirability of implementing an ECSI a project appeal indicator (PAI) value was used. The PAI will

indicate how sufficient the ECSI will deliver certain functions. Each function has a weight that determines the desirability of the function. A high value for desirability is preferred. The different functions are discussed in Table 7.

Table 7: Electricity cost savings initiative functions

Function	Description	Desirability (Max 10)
Low implementation cost	A large initial capital investment is required to increase the efficiency of chiller pumps. In the past three years, these projects have been avoided by ESCOs due to insufficient funding. This function receives the highest possible weight according to Study 2 [93].	10
Electricity cost savings	Energy efficiency projects are generally known to have high electricity cost savings when compared with load shifting projects. This is thus also a highly desirable trait for an ECSI and receives a high weight according to Study 2 [93].	9
Short implementation time	Some ECSIs require new equipment to be installed or existing equipment to be upgraded. This may lead to a loss in production time. Mines are not always in active production. Projects could thus be implemented and commissioned during non-active periods. Study 1 considers this function as a low desirability, while Study 2 does not use implementation time in its decision matrixes [32], [93].	2
Minimal influence on other systems	Example: Load shifting of the chiller machines may result in a high chilled water temperature which would influence other units such as the BAC negatively. This can, however, be managed by increasing the flow of chilled water. This function is allocated a medium value according to Study 1 [32].	5
Low maintenance	An ECSI with a high maintenance will lead to a reduced return in electricity cost savings. If, for example, the chiller pump VSDs constantly need repairs, it can lead to downtime on the chillers, which may eventually lead to the project being cancelled [34]. This function is more desirable than an ECSI with a low influence on other systems, but not as desirable than an ECSI with a low implementation cost [32], [93].	7

The risk and PAI matrixes that were used to evaluate the ECSIs are illustrated in Figure 70 and Figure 71 respectively. These figures can be found in Appendix A.

Figure 40 illustrates a graph of the resulting risk and PAI of the different project types covered in Paragraphs 2.2 and 2.3.

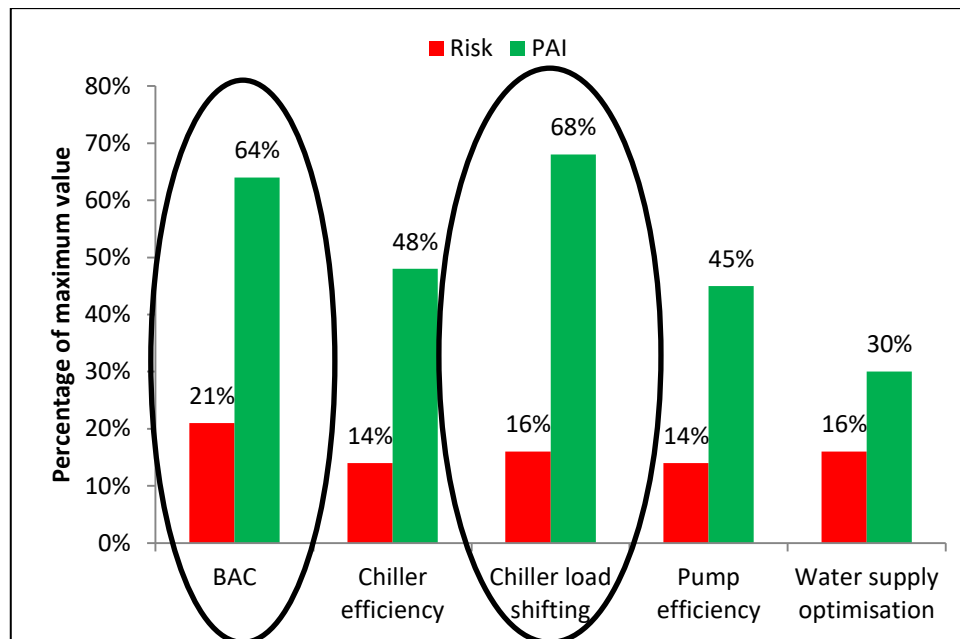


Figure 40: Risk and PAI as a percentage of the maximum value

According to Figure 40, BAC and chiller load shifting ECSIs have the highest PAI scores. The main reason is the low initial implementation cost of these initiatives. This paragraph will only focus on developing a methodology for ECSIs which consist of chiller load shifting or reducing the BAC cooling load.

Identifying ECSIs on a cooling system may prove to be a difficult task. As mentioned in Paragraph 1.2, the cooling system consists of numerous interdependent components. Changes made to one component may affect other components. The decision diagram illustrated in Figure 41 was created based on the background and literature study carried out in Paragraphs 1.2, 2.2 and 2.3.

According to Figure 40, ECSIs on the BAC hold a higher risk than the implementation of load shifting on the chillers. The user will thus first be guided to identify load shifting projects on the chiller. ESCOs may only continue to investigate peak clipping on the BAC if there are no more potential for load shifting on the chillers. ESCOs are cautioned not to use the diagram directly on the mine control philosophy. This diagram only directs the user in finding electricity cost savings potential during the Eskom peak periods.

It is recommended that the actions of this diagram only be applied on the cooling system simulation that was discussed in Paragraph 3.3.1. Actions applied to the simulation should be listed and discussed in an investigation report to develop a control philosophy for electricity cost savings. The investigation report should then be submitted to the relevant mine personnel (preferably top management) for approval.

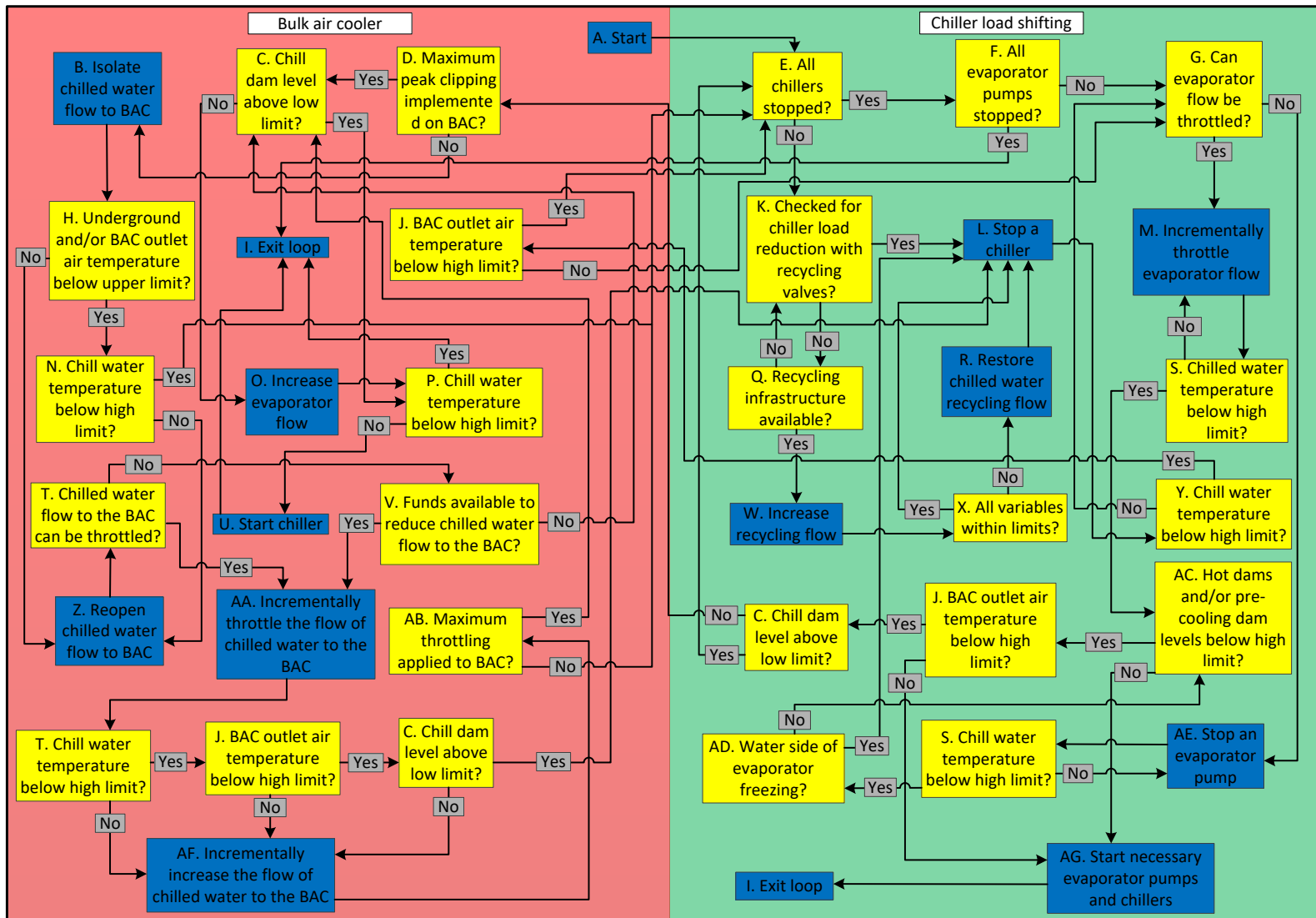


Figure 41: Decision loop for the identification of load reduction on mine cooling systems

The boxes in this diagram are classified into two areas. The green area holds the boxes that are relevant to surface chiller load shifting while the red area holds the boxes that are relevant to peak clipping on the BACs.

The reader will also notice that there are two different coloured blocks in the diagram. Yellow blocks are called decision blocks. When a decision block is reached, the reader has to answer either yes or no to the question in the block. The reader will then be directed to another block. Blue blocks are called action blocks. The action described in the action block should be carried out in the simulation. A description of each block in Figure 41 will be discussed below:

- **Block A:** The decision diagram starts from this block.
- **Block B:** Isolate all flow of chilled water to the BAC in the simulation. Air at ambient conditions will enter the mine. The maximum possible peak clipping/load shifting on the BAC will thus be tested. BAC isolation can be done by setting the speed fraction of the simulated BAC feed pumps to zero as can be seen in Figure 42.

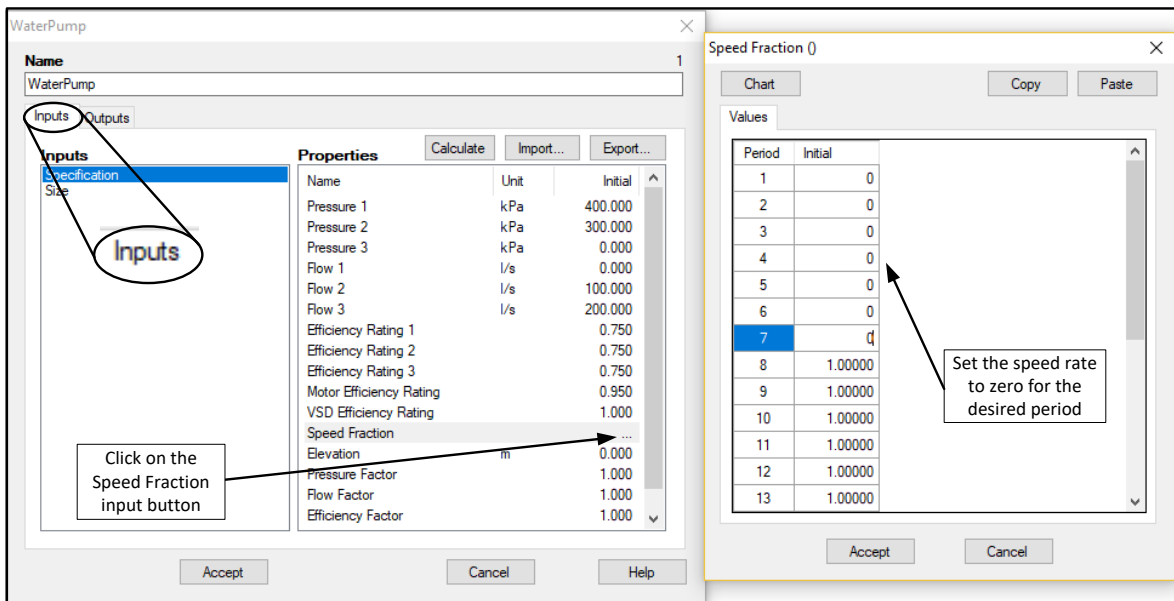


Figure 42: Simulate BAC chilled water isolation

- **Block C:** Check if the chill dam level is above the maximum level.
- **Block D:** The user has to check whether the maximum peak clipping or load shifting has been applied to the BAC. Any further load reduction on the BAC is not possible due to mechanical restriction, underground temperatures exceeding the maximum limit or the BAC outlet air temperature exceeding the maximum limit.

- **Block E:** Chillers are usually the main power consumers on the cooling system. If all the chillers have already been stopped in the HTP, the ESCo should continue to search for electricity savings on the evaporator pumps.
- **Block F:** This block determines whether all evaporator pumps have been stopped in conjunction with the chillers. Further load reduction on the BAC will have minimal cost savings during the HTP.
- **Block G:** The chilled water temperature can be decreased by reducing the evaporator flow. This can be accomplished by reducing the speed of the evaporator pumps using VSDs. A VSD can be simulated by connecting a proportional-integral controller to a centrifugal pump in Process Toolbox as can be seen in Figure 43. The controller reaction can be manipulated by changing the control limits or the integral gain. If there are no VSDs installed on the evaporator pumps, the only option is to stop the evaporator pumps.

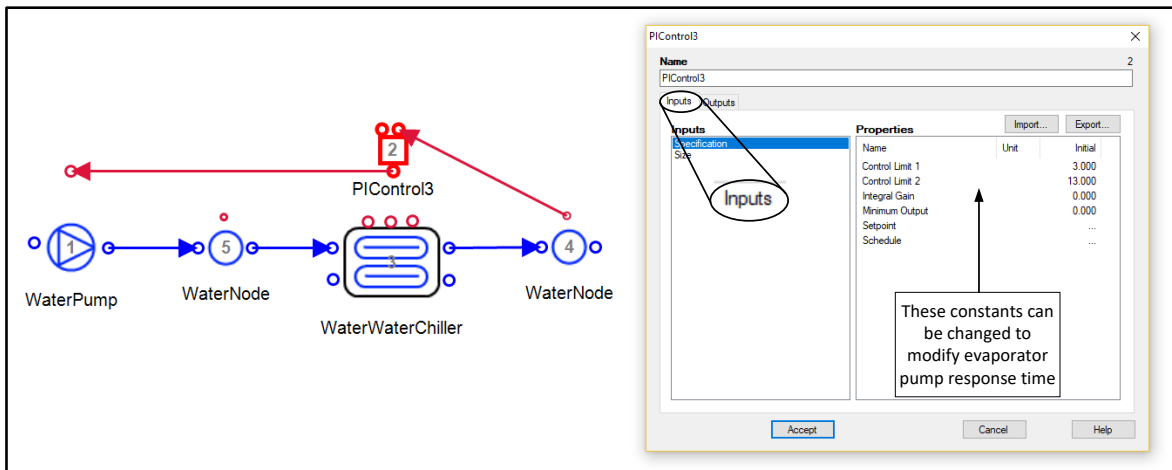


Figure 43: Simulated VSD control on evaporator feed pumps

- **Block H:** There will be a temperature high limit on the BAC outlet air temperature, the underground temperature on some sections, or both the BAC and the underground temperatures. The user should check whether these temperatures are within the desired ranges. As mentioned in Paragraph 3.3.2, Process Toolbox is not capable of simulating underground temperature and humidity. The ESCo is advised to only consider the outlet air temperature limit of the BAC for the purpose of this exercise.
- **Block I:** According to the diagram, minimal scope remains for electricity cost savings on the cooling system. The ESCo should exit the decision diagram and report the findings.

- **Block J:** Check whether the outlet air temperature of the BAC and/or the underground temperatures are within the specified limits.
- **Block K:** Chiller plants do not always have the necessary infrastructure, such as VSDs to reduce the chiller load. The next load reduction choice will then be to recycle chilled water to the chillers. The user should check whether there is available infrastructure to recycle chilled water to the chillers.
- **Block L:** Stopping a chiller involves stopping the induction motor that drives the compressor. A shutdown procedure will be followed to stop the chiller. Stopping the chiller does not include the stopping of an evaporator pump. This means that warmer water will enter the chill dam and/or the BAC. Refer to Figure 44 that graphically illustrates the effect of stopping a chiller on the cooling system.

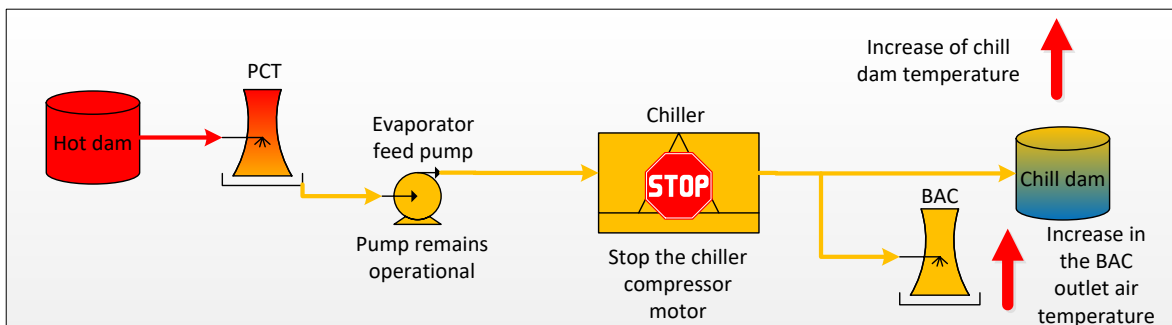


Figure 44: Effect of stopping a chiller

- **Block M:** Incrementally throttle the evaporator flow. The increment with which the evaporator flow has to be decreased is left to the ESCo's discretion.
- **Block N:** Throttling chilled water to the BAC means that the PCT will receive less cool water. Water at a higher temperature will thus enter the chillers. One or a combination of four actions will take place to maintain the outlet chilled water temperature at the set-point:
  - The chiller partial load mechanism will open to increase the cooling load,
  - The rate at which the chilled water is recycled will increase,
  - VSD controlled evaporator pumps will decrease the flow of PCT water to the chiller, or
  - A chiller will be started.

If the chilled water flow rate to the chill dam is reduced, it will result in a lower chill dam level. It may also happen that the chilled water temperature controls are not capable of decreasing the temperature to the set point. The user should thus check the temperature and level of the chill dam. Figure 45 illustrates the effect of decreasing the chilled water flow to the BAC.



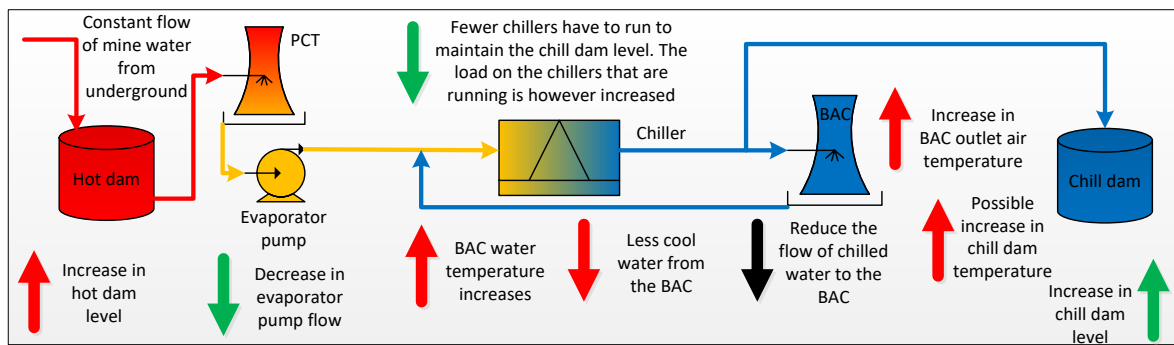


Figure 45: Effect of decreasing the flow of chilled water to the BAC

- **Block O:** Increase the evaporator flow to a point where the chill dam level is above the minimum limit.
- **Block P:** Increasing the evaporator flow to the chillers may increase the chilled water temperature. The user has to check whether the chilled water temperature is below the maximum limit.
- **Block Q:** The user should check whether there are recycling infrastructure available on the cooling system.
- **Block R:** Re-implement the previous chilled water recycling control philosophy.
- **Block S:** After the evaporator flow has been decreased, the user should check whether the chilled water temperature is below the set point temperature. If this is not the case, the evaporator flow should be decreased with the same increment (or stop a pump). This should be done until the chilled water temperature reaches the set point temperature.
- **Block T:** The user should check whether the flow of chilled water to the BAC can be throttled. This can be done by means of VSDs on the BAC feed pumps, decreasing the valve opening of the BAC chilled water inlet pipe or stopping BAC feed pumps. A valve can be simulated with a pipe component in Process Toolbox. The user can manually throttle the flow of chilled water to the BAC by changing the valve fraction over time as can be seen in Figure 46.

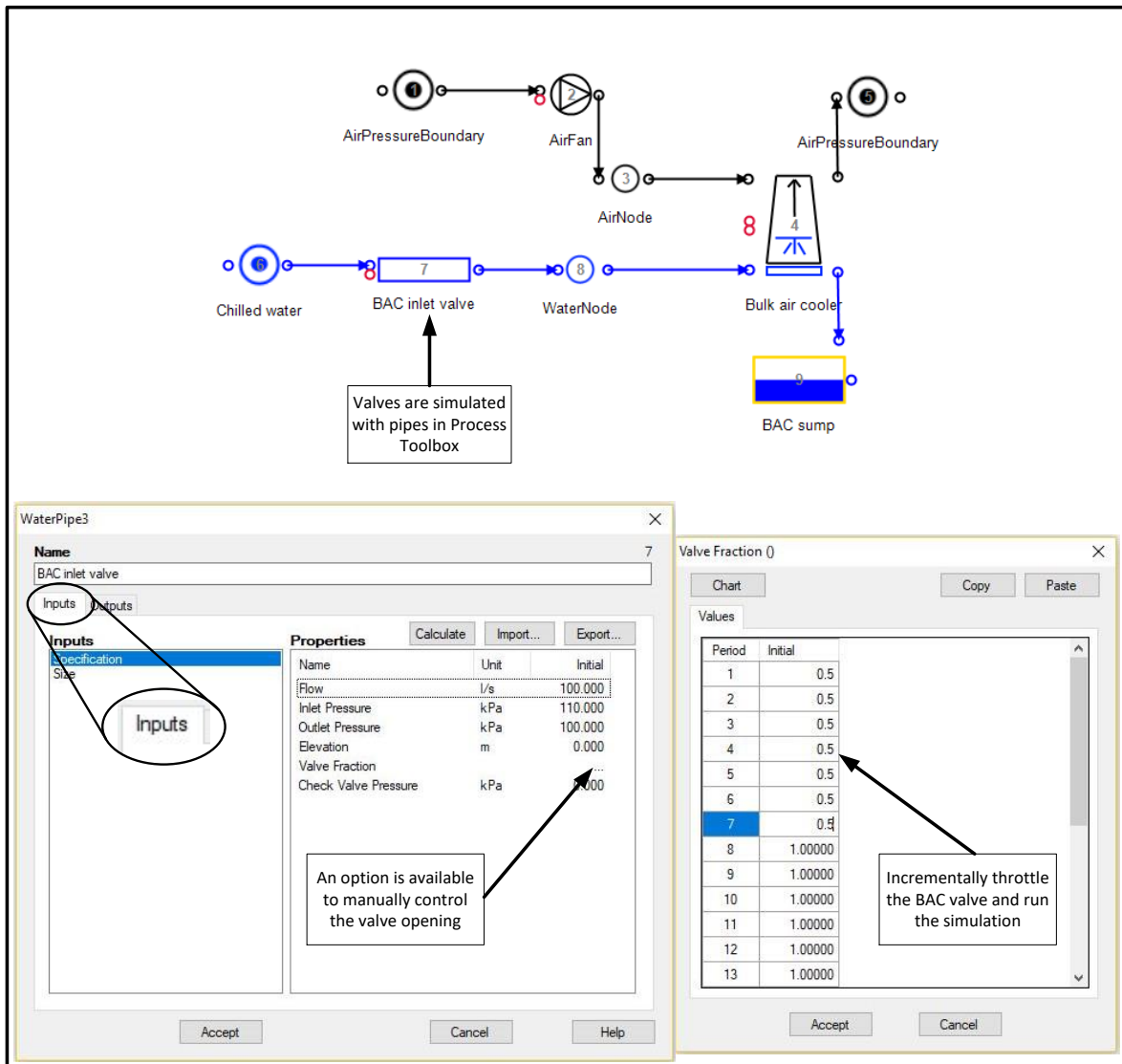


Figure 46: Simulated BAC valve throttling

- **Block U:** The user has to start the necessary number of chillers to decrease the water temperature below the high limit.
- **Block V:** If the client (mine personnel) prefer the option to throttle the flow of chilled water to the BAC, funding has to be made available to install VSDs for the BAC feed pumps or valves on the BAC chilled water inlets.
- **Block W:** Increase the chilled water recycling flow to the chillers. The magnitude with which the chilled water recycling flow is increased is left to the user’s discretion.
- **Block X:** The effect of increasing the recycling flow of chilled water is graphically explained in Figure 47. If the chill dam level is above the low limit, the BAC outlet air temperature is below the high limit and the chillers do not trip, the user may continue to stop another chiller.

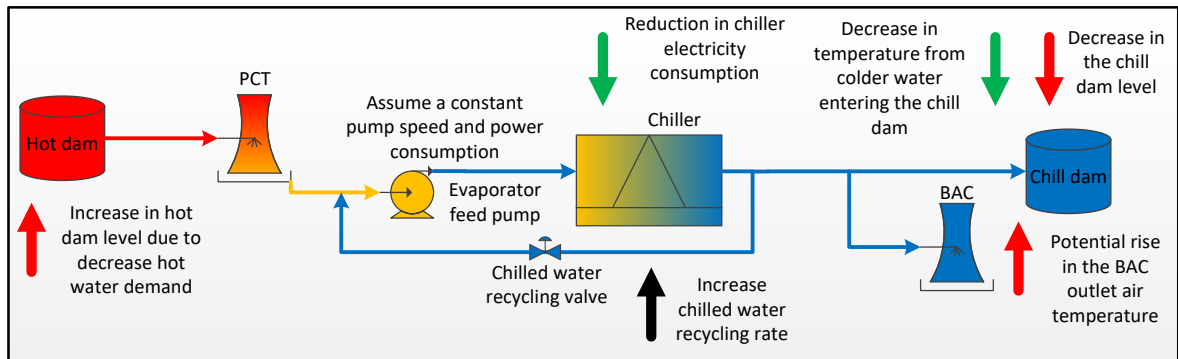


Figure 47: Effect of recycling chilled water

- **Block Y:** Stopping a chiller will result in the chilled water temperature increasing. The user should check whether the chilled water temperature is below the high limit.
- **Block Z:** If either the BAC outlet air temperature or the chilled water temperature is above the high limit, the flow of chilled water to the BAC should be restored. The user will then be directed to check whether the flow of chilled water to the BAC can be throttled.
- **Block AA:** Incrementally throttle the flow of chilled water to the BAC. The increment with which the chilled water is throttled is left to the discretion of the user.
- **Block AB:** Is the BAC mechanically unable to further throttle the flow of chilled water? If this is the case, the user should check whether the chilled water temperature is below the high limit and if the chill dam level is above the low limit and then exit the decision loop.
- **Block AC:** Figure 45 graphically explained that decreasing the evaporator flow to the chillers results in an increase in hot dam and/or precooling dam level. It should be checked whether these levels are within acceptable limits.
- **Block AD:** Reducing the evaporator flow leads to lower temperatures in the water side of the evaporator increasing the risk of water freezing in the evaporator tubes. As a safety precaution, chillers will automatically stop when the temperature approaches 0°C. The user should ensure that the chilled water temperature remain above the low limit programmed into the chiller programmable logic controller (PLC).
- **Block AE:** Stop an evaporator pump.
- **Block AF:** If the chilled water temperature, BAC outlet air temperature or chill dam limit has been exceeded, the chilled water flow to the BAC should be increased with the same increment it was throttled in Block AA.

- **Block AG:** Start the necessary chillers and pumps to restore the hot dam level, precooling dam level, chill dam level or chilled water temperature.

After the decision loop has been completed, all the action blocks that were applied to the cooling system simulation should be combined. This will form the cooling system control philosophy. Adjustments to the overall cooling system control philosophy may also be necessary outside the load reduction period in preparation of the load reduction period.

### 3.3.4 Control philosophy evaluation

The result of Paragraph 3.3.3 is a control philosophy with a lower electricity cost than the simulation of the operational baseline information. As mentioned in Paragraph 2.5.3, an electrical baseline and baseline scaling method are required to measure the electricity cost savings effect of the ECSI.

Each component affected by the ECSI has to be incorporated into the baseline. The simulation discussed in Paragraph 3.3.2 can be used to identify the affected components. This is done by monitoring the simulated electricity profile before and after the implementation of the ECSI. If the component's simulated electricity profile is affected by the ECSI implementation, it has to be incorporated into the electrical baseline.

There may also be cases where the load on some cooling system components is increased to compensate for the components that were stopped. As an example, the underground chiller load may be increased to compensate for the load reduction of the surface BAC. Typical cooling system components that have to be considered include:

- Surface chillers,
- Underground chillers,
- Water transfer pumps,
- Condenser cooling tower fans,
- Precooling tower fans, and
- BAC fans.

As mentioned in Paragraph 2.5.3, the electrical baseline is a sum of all the affected component power profiles over a specified period. The electrical baseline is usually a three month averaged 24-hour profile [35], [46]. It has been mentioned numerous times that the ambient conditions have a considerable influence on the operation of the cooling system.

As a solution a three-month average baseline profile can be created for both summer and winter [68].

After the baseline construction, a baseline scaling method has to be chosen. Three baseline scaling methods were discussed in Paragraph 2.5.3. It was found that a constant baseline model will most likely not be suitable for a mine cooling system. An energy neutral baseline scaling is used for a load shifting project, while a regression model is preferred for energy efficiency and load clipping initiatives. Figure 48 displays a decision diagram for choosing the appropriate scaling method.

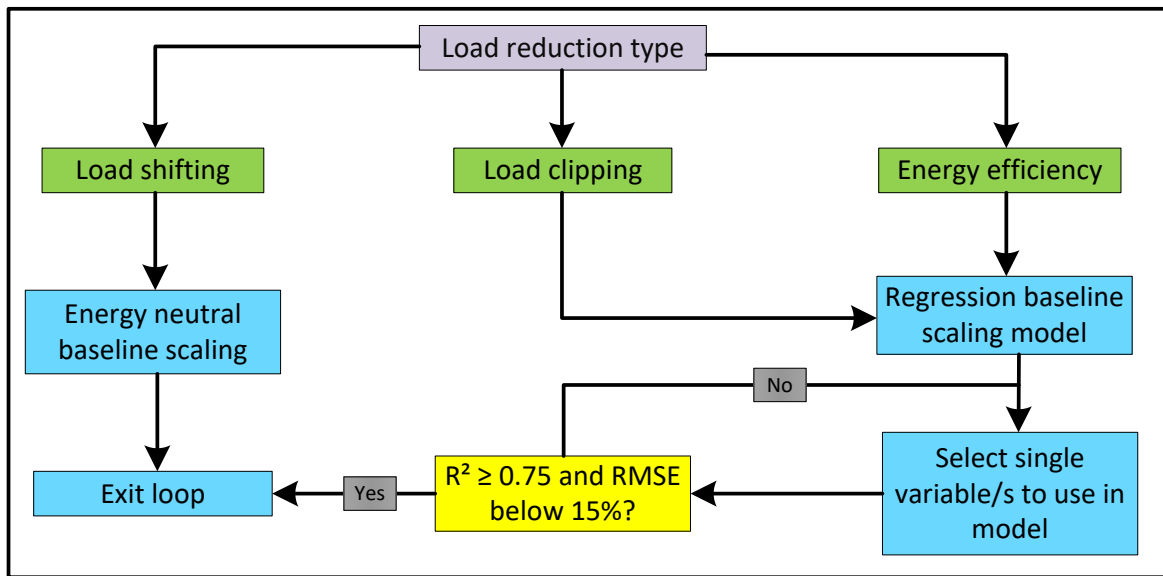


Figure 48: Baseline scaling model decision diagram

The regression baseline model can be evaluated by considering the coefficient of determination ( $R^2$ ) and root mean squared error (RMSE). A suitable regression baseline scaling model will have a coefficient of determination above 0.75 and an RMSE below 15% [86].

The baseline with the baseline scaling model can now be used to evaluate the simulated ECSI. Figure 49 is a graph of the scaled baseline and the actual power profile during the performance assessment period. The green areas in the graph display the periods where the scaled baseline has a power usage that is more than the actual power profile. This means that a reduced amount of energy is used in these periods. The blue areas display the periods when the power is higher than the baseline period.

The day under assessment should be divided into periods where the electricity tariff is constant. The graph in Figure 49 was divided into HTPs (a to b and c to d) and LTPs (d to

a and b to c). Equation 5 can then be used to calculate the reduction or increase in energy during certain periods.

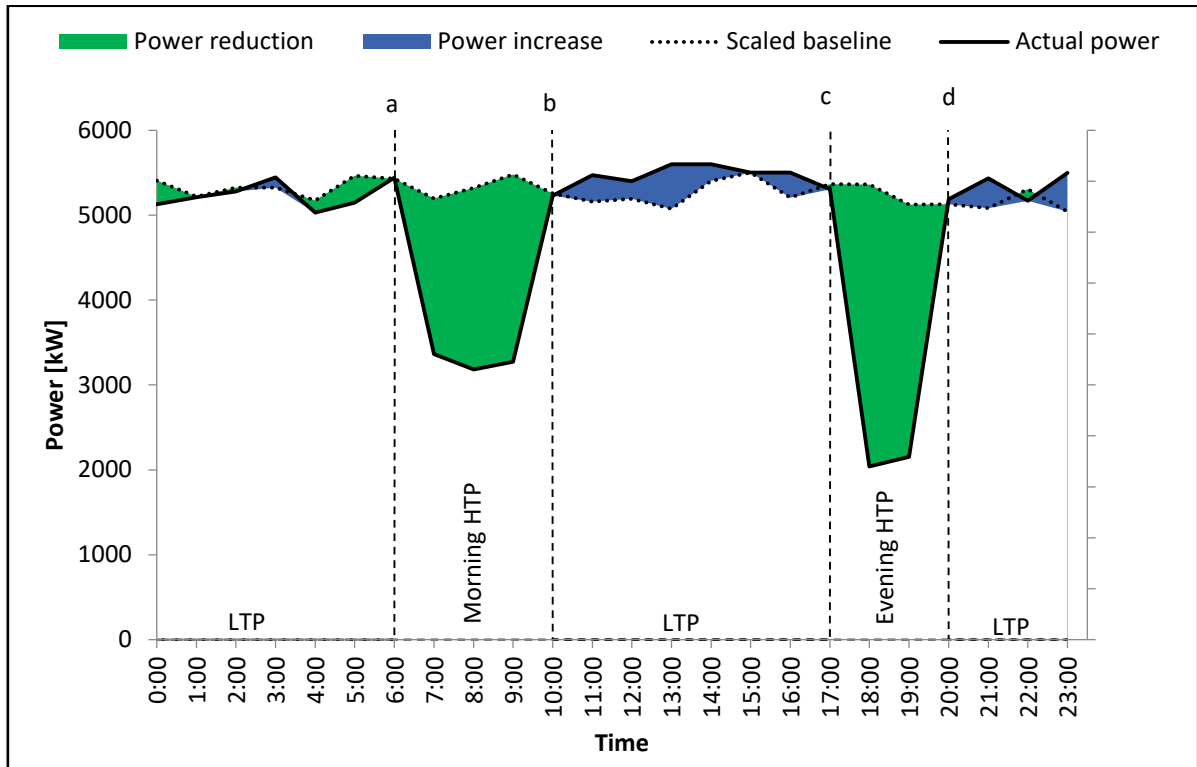


Figure 49: Example of baseline and actual power graph

$$E_i = \int_a^b g(x)dx - \int_a^b h(x)dx \quad \text{Equation 5}$$

Where:

$x$  = Hour

$g(x)$  = Scaled baseline power profile as a function of time [kW]

$h(x)$  = Actual electrical power in the ECSI performance assessment period as a function of time [kW]

$a$  = Start hour

$b$  = End hour

$E_i$  = Electrical energy reduction in period  $i$  [kWh]

Equation 6 is used to calculate the electricity cost for period  $i$ .

$$C_i = E_i \times T_i \quad \text{Equation 6}$$

Where:

$C_i$  = Electricity cost saving in period  $i$  [R].

$E_i$  = Energy reduction in period  $i$  [kWh].

$T_i$  = Tariff during period  $i$  [R/kWh].

Adding the cost saving of each tariff period using Equation 7 will result in the total daily electricity cost saving.

$$C_T = \sum C_i \quad \text{Equation 7}$$

Where:

$C_T$  = Total daily electricity cost saving [R]

$C_i$  = Electricity cost saving in period  $i$  [R].

The total daily electricity cost savings determine if the project will be financially feasible to implement. If the ECSI's payback period is longer than the planned payback period, the decision diagram illustrated in Figure 41 should be used to find a more cost-effective ECSI. Once it has been determined that the ECSI is feasible, the next steps would be to conduct further tests, if necessary, and permanently implement the initiative.

## 3.4 Strategy to implement and sustain the cost savings initiative

### 3.4.1 Manual tests

Building a physical scaled model of the mine cooling system for testing purposes is impractical. These tests are usually physically conducted on a full-scale mine cooling system. A risk assessment needs to be completed before manual tests are conducted.

The ideal time for manual testing is usually during the weekly maintenance period. Minimal activities take place underground during this period. All the relevant parties should be notified before the tests are conducted.

### 3.4.2 Equipment installation

To avoid unnecessary expenses, equipment should preferably only be obtained after the manual tests have been successful. In the event of the manual tests not being feasible, equipment should be obtained based on the results of the simulation. As an example, it is difficult to manually test the effect VSDs would have on the cooling system without installing VSDs.

### 3.4.3 Sustainability

It is difficult to determine the long-term effects on the cooling system through manual tests as these tests are only temporarily implemented. All KPIs that were identified in Paragraph 3.3.1 should be logged and reported in regular intervals. Figure 50 illustrates a screenshot of an EnMS used to log cooling system tag data.

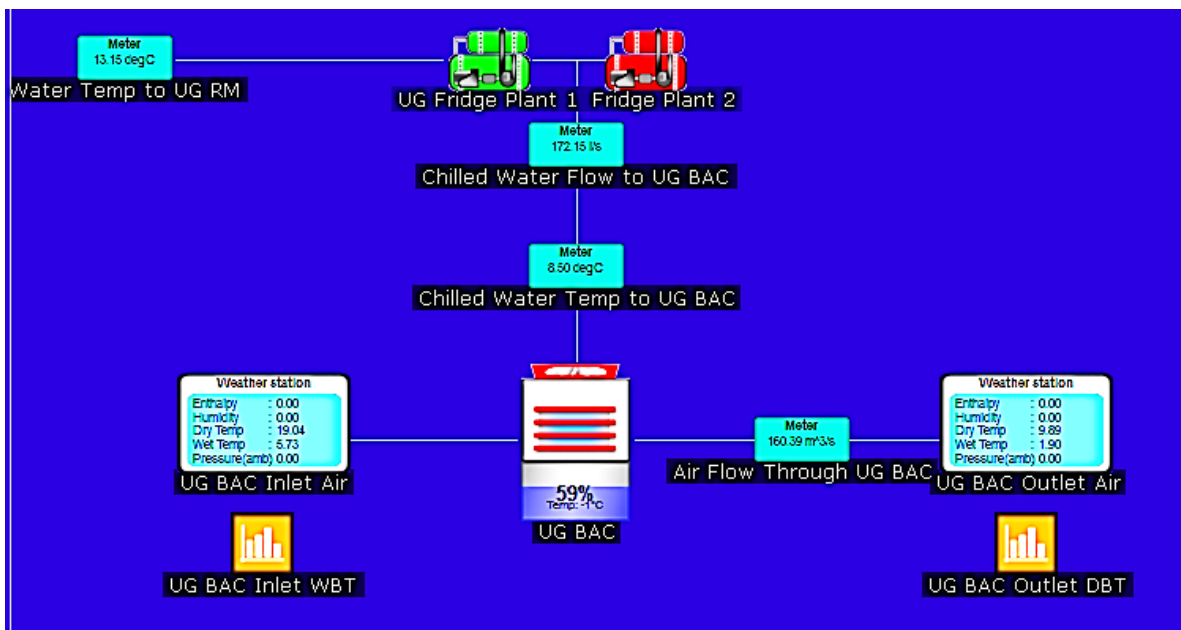


Figure 50: Screenshot of EnMS

Figure 51 shows the monitoring of the long-term effect of the ECSI on the chilled water temperature is monitored. The chilled water temperature increased a month after ECSI implementation. If the temperature continues to rise, the ECSI has to be revised or cancelled.



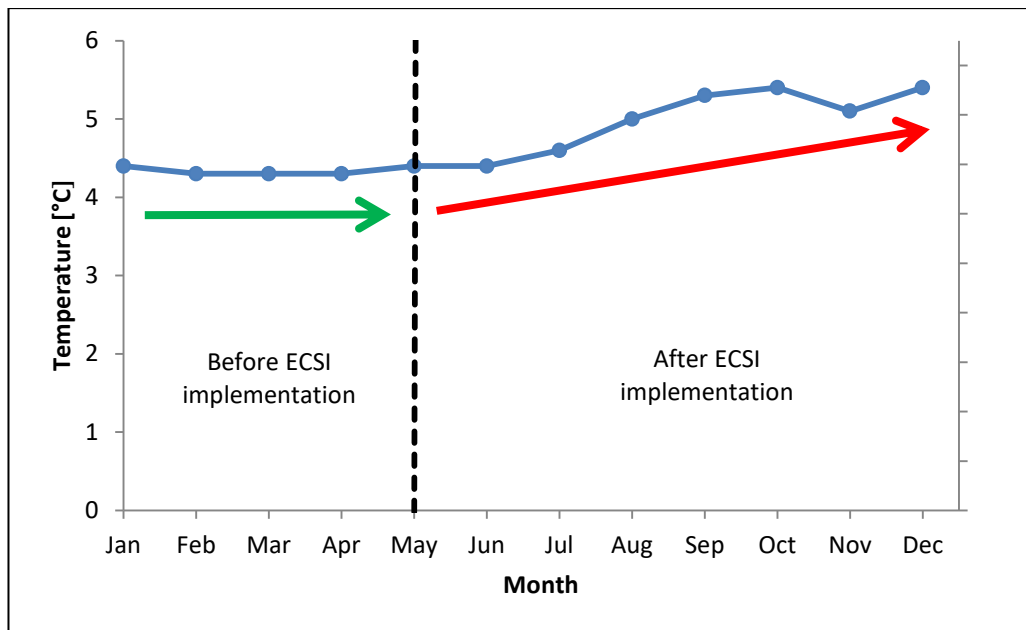


Figure 51: Example of monitoring the long-term effect of the ECSI on the chilled water

### 3.5 Conclusion

**Objective 1:** Develop a methodology to identify cost-effective, low risk ECSI on mine cooling systems.

**Objective 2:** Develop a methodology that will provide ESCOs with a systematic procedure for identifying electricity cost savings potential while taking the cooling system high/low limits into account.

Chapter 3 provided ESCOs with a detailed guide for obtaining holistic cooling system information. This information included:

- Mine management structure,
- High level mining information (location, weather),
- Cooling system component specifications, and
- End user requirements.

The holistic cooling system information together with operational baseline data can be used to construct a simulation of the cooling system. Actual cooling system data is used to validate the simulation outputs.

The core of Chapter 3 is a decision diagram that will guide the ESCo in the identification of electricity cost savings on a mine cooling system. The decision diagram together with the cooling system simulation can be used to develop a control philosophy.

A baseline scaling model needs to be developed to evaluate the control philosophy. After the control philosophy has been proven to be feasible, it can be manually implemented. Thereafter it can be implemented permanently. In the following chapter, the methodology developed in Chapter 3 will be applied to a real-life mine cooling system.

# Chapter 4. Implementation of solution

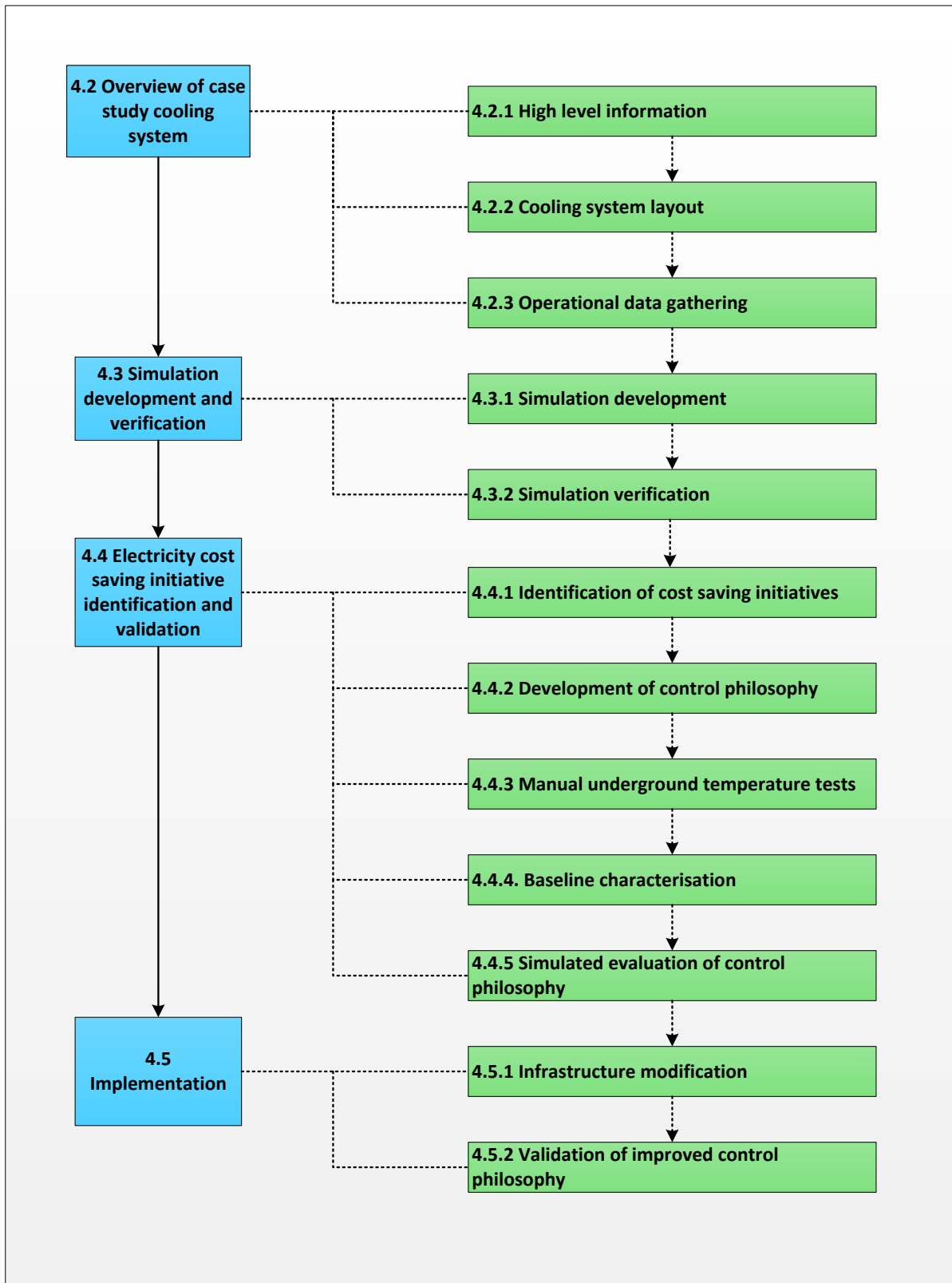


Figure 52: Overview of Chapter 4 content

## 4.1 Introduction

A methodology for the identification and implementation of an ECSI was developed in Chapter 3. This methodology guided the user through information required to characterise the cooling system. After the cooling system characterisation, the developed decision diagram can be used to identify ECSIs on the cooling system.

Chapter 4 covers the implementation of the methodology developed in Chapter 3. The ESCo decided to implement the methodology on Mine X<sup>11</sup>. The reader will be guided through a step-by-step identification and implementation process. These steps include:

1. Information gathering: A discussion on the site and historical data gathering process.
2. Simulation: Development and validation of simulation results.
3. ECSI identification: Use the decision diagram developed in Chapter 3 to identify ECSIs on the cooling system and develop a control philosophy.
4. Validation of simulated ECSI.

## 4.2 Overview of case study cooling system

### 4.2.1 High level information

Mine X is a platinum mine located in the Limpopo province. It has been in operation since 1993 with a life of mine greater than 30 years at the time of writing. There is thus minimal danger of an ECSI being cancelled due to the mine closing.

Unlike other mines that use compressed air for drilling and other functions, operations on Mine X depend on high-pressure chilled water to power underground drills, coolers and sweeping operations. This technology is referred to as hydropowered mining.

The hydropowered equipment of Mine X consumes a vast amount of chilled water. Large electricity consumers, such as chillers and pumps are used to chill and transport the water respectively. The cooling system of Mine X is thus an ideal target for ECSIs.

A letter of intent was signed off by the engineering manager of the mine. There was no need to involve the general manager of the mine in the ECSI. The production engineer was informed about the project, but was not considered as part of the energy management

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<sup>11</sup> The mine name is kept confidential

team. The structure of the energy management team for Mine X with the responsibilities of each team member is illustrated in Figure 53.

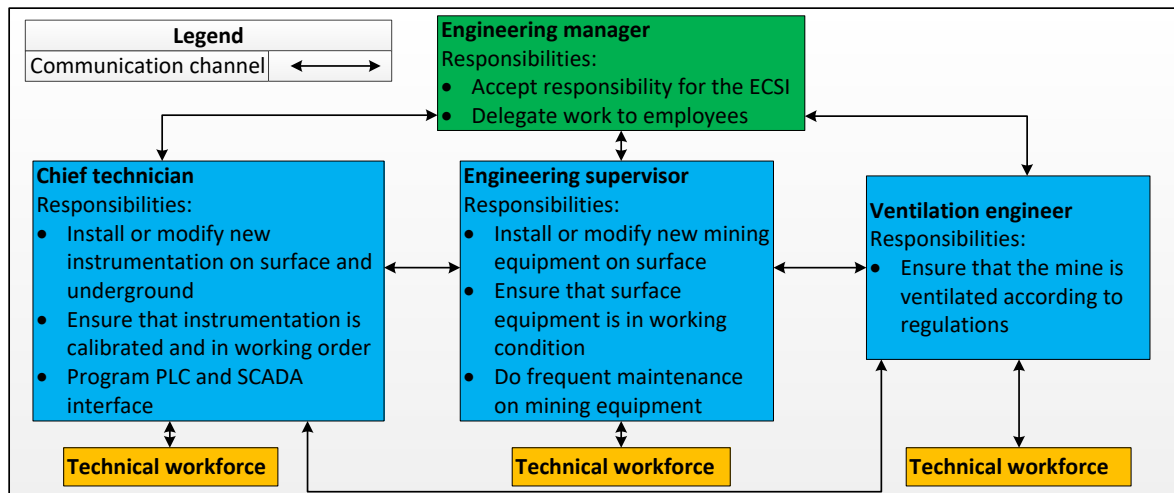


Figure 53: Energy management team structure of Mine X

#### 4.2.2 Cooling system layout

The P&ID of the cooling system was obtained from the chief technician of the mine. This diagram illustrated how major units, such as pumps, chillers and cooling towers, are connected. Instrumentation governing the operation of these major units can also be identified from the P&ID. Specifications of major units can be found in Appendix B. The cooling system P&ID was redrawn to a PFD as can be seen in Figure 54.

The cooling system of Mine X consists of two parallel chiller sets. Each chiller set has four chillers in parallel. Chilled water from the chillers is pumped directly into one of four connected chill dams. Chilled water from the chill dams is pumped to the BAC to cool the air sent underground. Chilled water is also gravity-fed underground to be used as service water. The chill dams thus serve as a buffer for the service water and the BAC.

The chilled water demand on Mine X varies throughout a normal working day. As mentioned in Paragraph 1.2.2, chillers in parallel are designed for variable flow purposes. Parallel chillers are thus ideal for the operations of Mine X.

VSDs and/or chilled water recycling should be applied to control the outlet evaporator water temperature of chillers in parallel. None of the chillers on Mine X has VSDs installed on the chiller pumps. A two-stage chilled water recycling loop is used to control the evaporator outlet temperature.

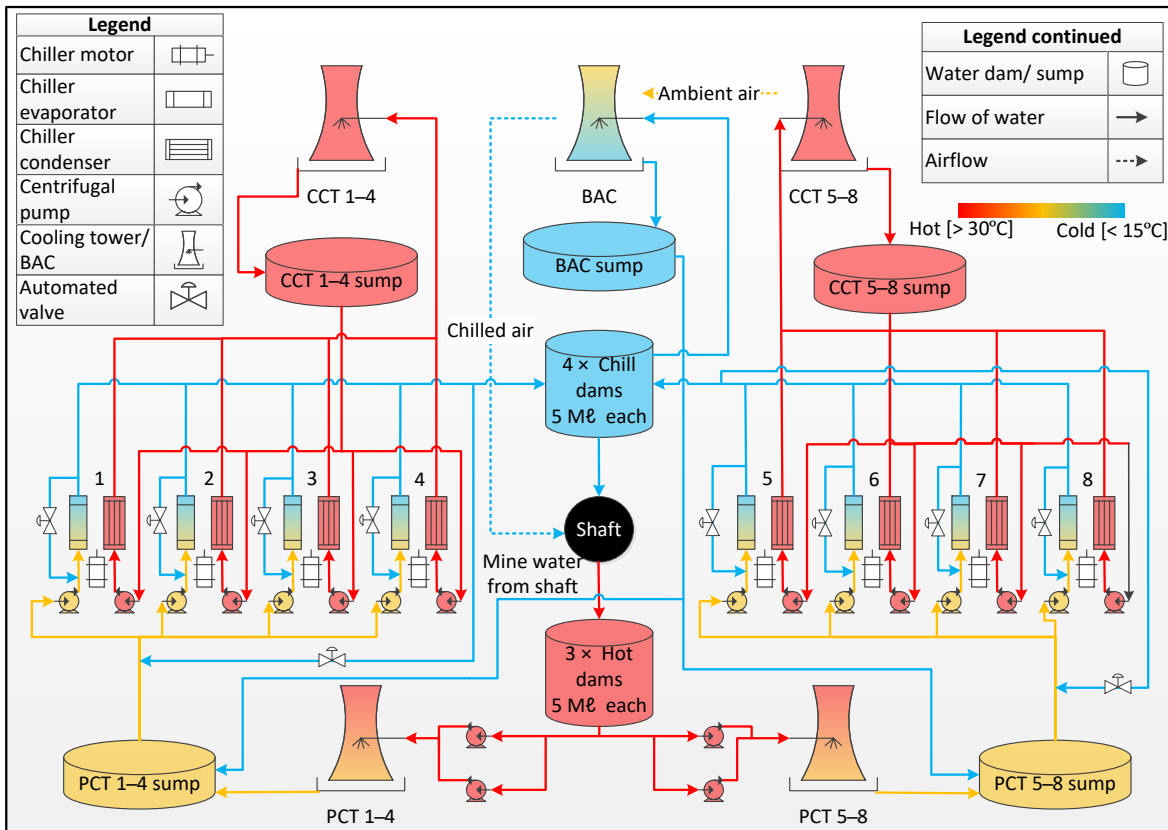


Figure 54: Mine X cooling system PFD

The first stage of the chilled water recycling loop recycles water from the inlet chill dam pipe to the common pipe of the chiller evaporator pumps. Each set of chillers has one chilled water recycling loop. This chilled water recycling stage is used to ensure that the water entering the evaporators is at  $\pm 15^{\circ}\text{C}$ . This is considered as the ideal inlet evaporator temperature for an average air chiller on Mine X.

Each chiller has unique characteristics. The outlet temperature of Chiller 1 will not necessarily be equal to the outlet temperature of Chiller 2 for the same evaporator inlet temperature. Fine temperature control is achieved with a second chilled water recycling stage. Chilled water from the outlet of each chiller is recycled to the inlet of the evaporator. The recycling flow of chilled water in the second recycling stage is controlled by the outlet evaporator temperature.

There are two BACs on Mine X. One of the BACs is located on surface while the other is located underground. The underground BAC operates in a closed loop, which means that the water used for this BAC remains in circulation. Two underground chillers with a combined power rating of 3 MW are used to chill the water for the underground BAC. Chilled water from surface is used as make-up water in the underground BAC. The make-

up chilled water flow rate to this closed-loop BAC is considered as negligible. This study will only focus on the operation of the surface BAC.

Mine X uses a vertical-flow BAC on surface. Four centrifugal pumps are used to pump chilled water ( $< 7^{\circ}\text{C}$ ) from the chill dam to the BAC. Chilled water comes into direct contact with ambient air which is transferred using four fans. Used BAC chilled water ( $> 10^{\circ}\text{C}$ ) collects in the BAC sump. Four return pumps are used to pump water from the BAC sump to the PCT sumps. Figure 55 is a diagram of the surface BAC on Mine X.

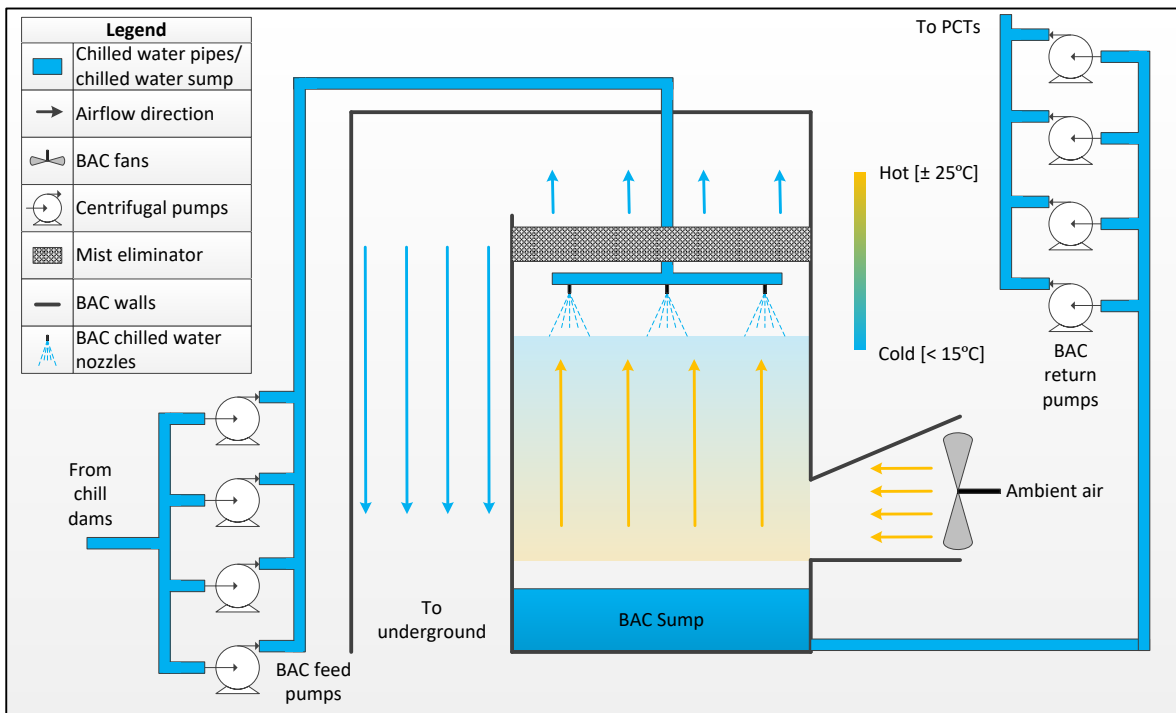


Figure 55: Diagram of the surface BAC on Mine X

### 4.2.3 Operational data gathering

Mine X electronically logs cooling system KPIs. These values are logged in one-second intervals. To avoid exhaustion of the server hard drive, data older than three months are automatically deleted by the historian software.

Historical data for three months was downloaded from the SCADA and processed. Not all the tags needed for the simulation construction were logged. An additional source of data was manually logged using spreadsheets. Only 11 cooling system KPIs were logged each hour by an operator on duty. Manually logged spreadsheets were obtained for two years.

An EnMS, like the one seen in Figure 50, was installed by the ESCo and allowed to read tag values from the SCADA via an open platform communications (OPC) connection. All

the cooling system tags visible on the SCADA were logged in two minute intervals, stored on the EnMS and sent to the ESCo in real time. Data for nine months was required from the EnMS to develop a baseline scaling method. The project was thus delayed for nine months due to a lack of sufficient data. Once sufficient data was obtained, a simulation was constructed.

## **4.3 Simulation development and verification**

### **4.3.1 Simulation development**

As discussed in Paragraph 2.5.1, Process Toolbox is a suitable simulation software package for mine cooling systems. It was thus decided to simulate the cooling system of Mine X with this software package. The following assumptions were made regarding the simulation:

- No heat exchange between ambient air and water pipes, and
- No heat exchange between water in dams and ambient air.

A detailed description of the simulation design together with the specifications of major components are given in Appendix B.

### **4.3.2 Simulation verification**

A typical day in the baseline period was simulated. Data from Paragraph 4.2.3 was used to construct the simulation. As discussed in Paragraph 3.3.2, these cooling system variables have to be divided into dependent, independent and uncontrollable variables. These variables are listed in Appendix B.

One dependent variable listed in Appendix B is the cooling system power consumption. Refer to Figure 56 where the power profile of a typical day in the baseline period is verified with actual data. Figure 56 shows that load shifting was applied during the morning and evening peak period ( $\pm 2$  MW load shifting). Six chillers ran during the peak periods while seven chillers ran outside the peak periods. The load shifting did not exactly correspond with the peak periods. Delayed responses from the existing ECSI were a common occurrence.



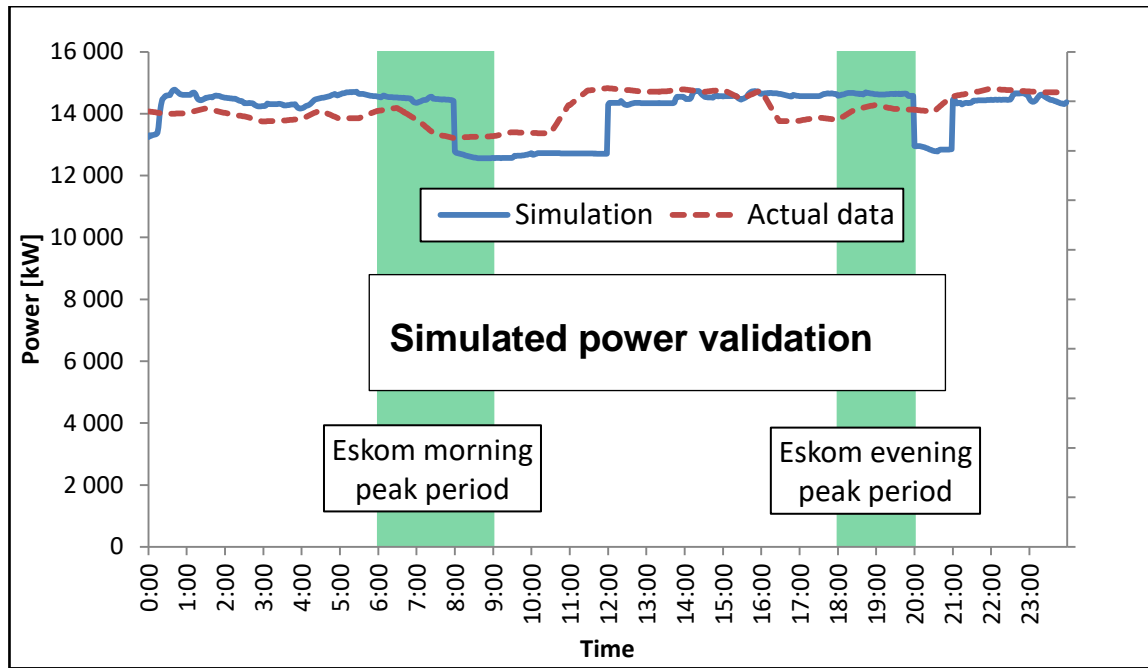


Figure 56: Validation of the simulated power profile in the baseline period

The simulated power profile has an average error of 4.3% compared with the actual cooling system power profile. According to the literature study conducted in Paragraph 2.5.1, the acceptable error between the simulated and actual values is 10%. The simulated power profile is thus in an acceptable range. All other variables were also found to be within acceptable limits. As an example, the chill dam level was also monitored. Figure 57 illustrates a graph of the simulated and actual chill dam level.

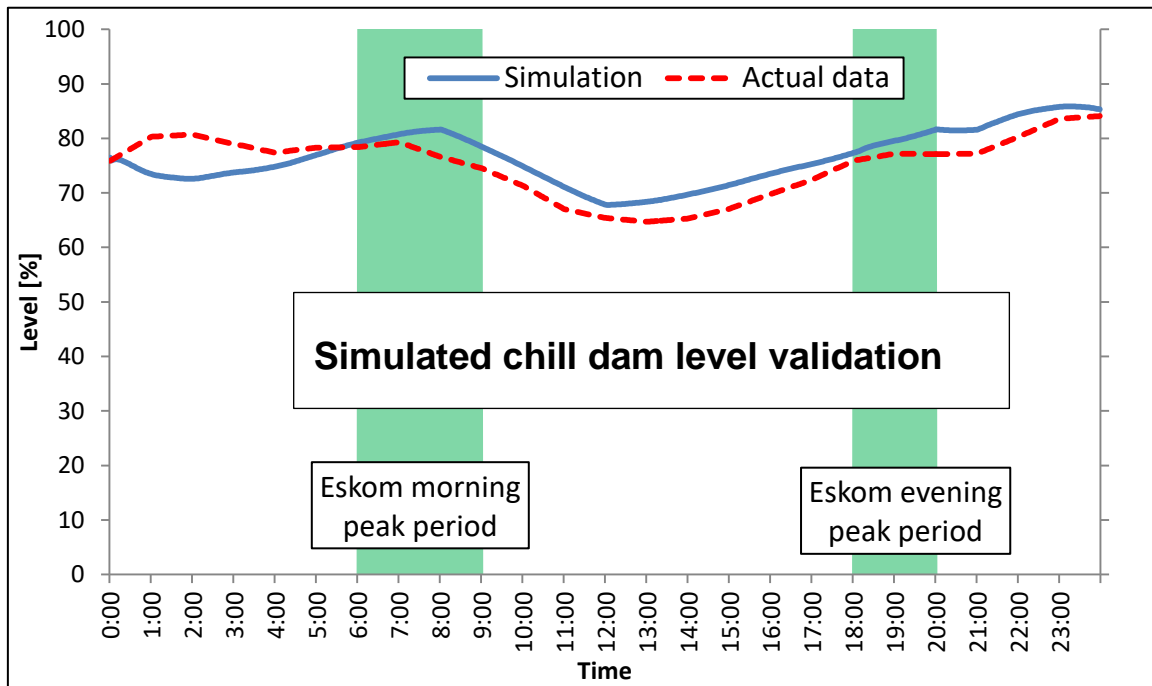


Figure 57: Validation of simulated chill dam level profile in the baseline period

The simulated chill dam level has an average error of 4.6% when compared with actual data. Table 8 lists of some dependent variables with their corresponding errors when compared with actual data. The simulated cooling system results of Mine X have thus proven to be valid.

Table 8: Simulated dependable variables error

<b>Uncontrollable variable</b>	<b>Error</b>	<b>Uncontrollable variable</b>	<b>Error</b>
PCT temperature	5.3%	BAC sump temperature	2.8%
BAC chilled water usage	10%	Chill dam level	4.6%
Chill dam temperature	6.1%	CCT temperature	3.1%

## 4.4 Electricity cost saving initiative identification and validation

### 4.4.1 Identification of cost saving initiatives

The decision diagram developed in Paragraph 3.3.3 was used to identify scope for additional electricity cost savings on the cooling system of Mine X. Refer to Appendix C which explains how the decision diagram was applied to the simulation.

There were no VSDs present on the cooling system, nor was there sufficient funding available to purchase VSDs or pursue any other energy efficiency initiative. The next step was for the ESCo to consider load reduction by using existing cooling system infrastructure.

From the operational data gathered in Paragraph 4.2.3, it is known that not all the chillers were stopped during the Eskom peak periods. Maximum load shifting has however already been achieved by the existing ECSI. The chill dams storage capacity was used to stop chillers during the Eskom peak periods and run more chillers during the LTPs. Stopping more chillers would result in the chill dam level dropping below the low limit.

The existing ECSI used a third party software package to stop and start chillers while monitoring the cooling system variables. Evaporator pumps were stopped in conjunction with the chillers. Depending on the chill dam level, the third party software would run four chillers during the HTPs and seven chillers during the LTPs periods to restore the chill dam level. The ESCo's final alternative was to consider peak clipping on the surface BAC.

From 15:00 on weekdays, mine personnel are cleared from the underground working areas to prepare for the blasting shift. No mining personnel are allowed at the underground working areas from 16:00 to 21:00 on working weekdays and on Saturdays.

After negotiations with the mining personnel, it was decided that the BAC outlet air temperature may be raised during the Eskom evening peak period which corresponds with the no-entry period. Refer to Table 9 for the BAC outlet air DBT set points during the day.

Table 9: Surface BAC outlet air DBT set points

<b>Time</b>	<b>Surface BAC outlet air DBT set point</b>
Summer 00:00 to 16:00	9°C
Summer 16:00 to 18:00	12°C
Summer 18:00 to 20:00	13°C
Summer 20:00 to 00:00	9°C
Winter 00:00 to 16:00	9°C
Winter 16:00 to 17:00	12°C
Winter 17:00 to 19:00	13°C
Winter 19:00 to 00:00	9°C

According to the results of the decision diagram applied to the cooling system of Mine X in Appendix C, peak clipping on the BAC will enable the ESCo to stop two additional chillers during the Eskom evening peak period without exceeding the cooling system limits.

Chilled water flow to the BAC is reduced two hours prior to the Eskom evening peak period in summer and an hour prior to the Eskom evening peak period in winter. This allows the chill dam levels to increase before the start of the Eskom evening peak period.

Raising the BAC outlet air temperature during the Eskom evening peak period has a low risk, as there are minimal mine personnel underground during this period. The mine however required that the underground temperatures be maintained under the high limit temperatures provided by the ventilation engineer.

As mentioned in Paragraph 2.3.2, WBT is used to measure the underground conditions as it incorporates the relative humidity and DBT of air. The temperature limits set by the ventilation engineer are given in Table 10.

Table 10: Underground temperature high limits

Location	WBT high limit
2-Level station	22.0°C
7-Level station	25.0°C
10-Level station	24.5°C
12-Level BAC inlet	28.0°C

There were neither valves nor VSDs that could be used to control the outlet air temperature of the BAC. The only means of controlling the BAC outlet air temperature was by stopping and starting the BAC feed pumps. A control philosophy for controlling the outlet air temperature will be discussed in Paragraph 4.4.2.

#### 4.4.2 Development of control philosophy

The surface BAC on Mine X has four feed pumps as can be seen in Figure 55. Chilled water flow to the BAC can be reduced or increased by changing the number of BAC feed pumps running as identified in Paragraph 4.4.1. There are thus five BAC outlet air temperature settings. Setting 1 entails running four BAC feed pumps to achieve a specific BAC outlet air temperature. Setting 2 entails running three BAC feed pumps etc.

Each BAC feed pump operates at a certain BAC outlet air temperature. As an example, BAC Feed Pump 1 will run when the temperature is 7°C or higher, Feed Pump 2 will run when the temperature is 8°C or higher etc. A considerable amount of attention has to be given to the temperature range selection of each pump. Incorrect range selection can lead to undercooling, overcooling or pump short cycling<sup>12</sup>.

The BAC feed pumps share a common manifold. Stopping and starting the BAC feed pumps will change the manifold pressure and thus the pressure over the BAC feed pumps. The flow of chilled water to the BAC and the number of BAC feed pumps running are thus not linearly correlated. Refer to Figure 58 for a graph that illustrates the effect of four BAC feed pumps sharing a common manifold. The graph was constructed using BAC data for four months from Mine X.

<sup>12</sup> Pump short cycling occurs when a pump is frequently stopped and started. According to the mine personnel, this operation deteriorates the pump condition.

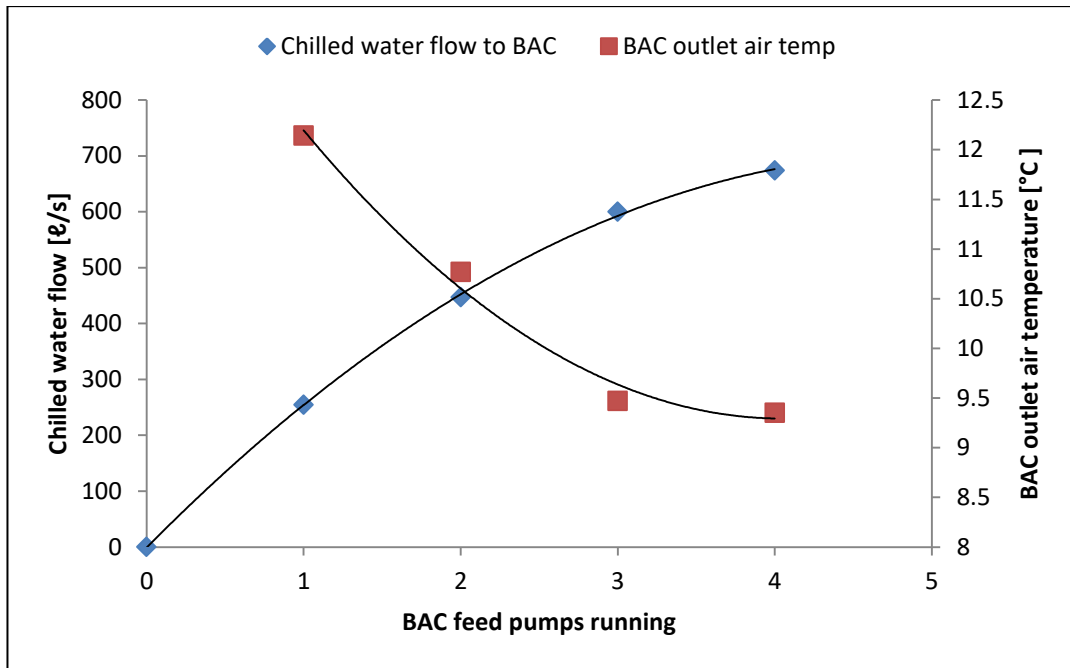


Figure 58: The effect of four BAC feed pumps sharing a common manifold

From Figure 58, it is clear that an increase in the chilled water flow per pump decreases with an increase in feed pump operation. The new set point of each BAC feed pump was determined through trial-and-error on low risk days (Sundays).

The BAC feed pump control will be divided into three periods. These three periods correspond with the three different BAC outlet air temperature set points:

- Period 1 (Set point = 8°C): 00:00–16:00 in summer and winter; 20:00–23:59 in summer and 19:00–23:59 in winter.
- Period 2 (Set point = 12°C): 16:00–18:00 in summer and 16:00–17:00 in winter.
- Period 3 (Set point = 13°C): 18:00–20:00 in summer and 17:00–19:00 in winter.

Table 11 shows the baseline period temperature set point and the new temperature set point for each feed pump in each period.

Table 11: BAC outlet air DBT set point

Feed pump number	Baseline period	Period 1	Period 2	Period 3
1	7.00°C	7.00°C	9.00°C	9.00°C
2	7.50°C	8.00°C	10.00°C	12.50°C
3	8.00°C	8.50°C	11.75°C	13.25°C
4	9.00°C	9.00°C	12.25°C	13.50°C

As illustrated on Figure 58, the effect on the BAC outlet air DBT becomes smaller as more BAC feed pumps are started. The temperature increment between the feed pump set points are thus decreased with more pumps starting. This will avoid feed pump short cycling.

A schematic of the BAC feed pump control philosophy can be seen in Figure 59. Similar to Figure 41, there are two different block types in this schematic, namely decision blocks (yellow) and action blocks (blue). In decision blocks, the statements in the blocks are either true or false. Actions such as “switching on a pump” are illustrated in action blocks. As soon as an action block is reached, the sequence is repeated from the green “a) Action block/ begin” block.

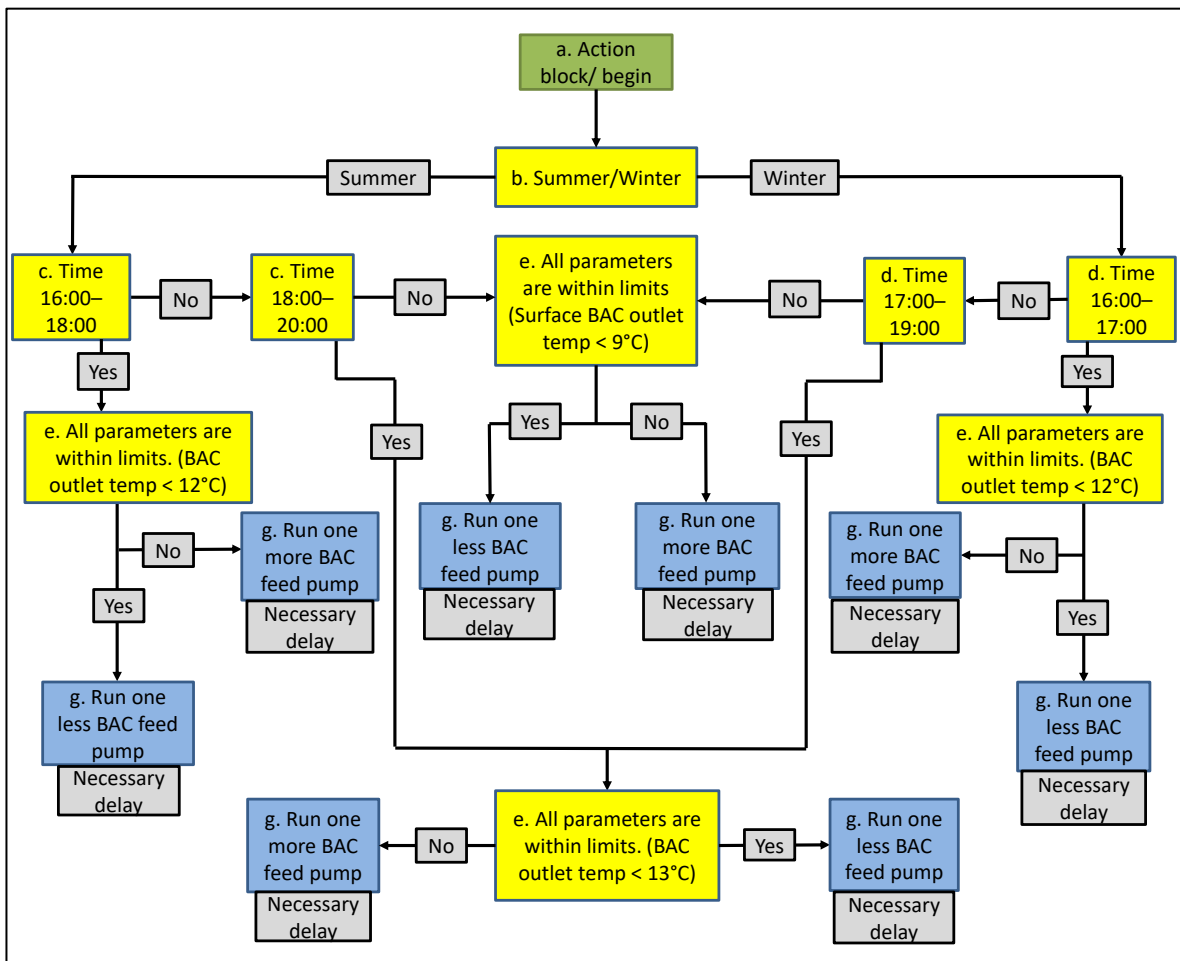


Figure 59: Schematic of the BAC feed pump control philosophy

A description of each block (a–g) follows:

- a) The iteration starts from Block A. As soon as an action block (blue block) is reached in the schematic control philosophy, the iteration repeats from this block (green block).
- b) Eskom's evening peak period spans from 18:00–20:00 in summer (September–May) and 17:00–19:00 in winter (June –August). The peak period is only applicable during working weekdays (Monday–Friday).
- c) Each day in summer between 16:00 and 18:00, the set point of the surface BAC outlet air temperature is 12°C DBT. From 18:00–20:00, the set point increases to 13°C DBT. For the remainder of the day, the BAC outlet air temperature set point is 9°C DBT.
- d) Each day in winter between 16:00 and 17:00, the set point of the surface BAC outlet air temperature is 12°C DBT. From 17:00–19:00, the set point increases to 13°C DBT. For the remainder of the day, the BAC outlet air temperature set point is 9°C DBT.
- e) The temperature limits provided in Table 9 and Table 10 should constantly be monitored. Appropriate actions are taken to restore these parameters to their set points.
- f) These action blocks indicate that an additional surface BAC feed pump should either be stopped or started. To prevent pump short cycling, the necessary delays are implemented in the control. After the implementation of one of these action blocks, the iteration repeats itself from the green “a) Action block/begin” block.
- g) One BAC feed pump is started after the necessary delay<sup>13</sup>.

As mentioned earlier, fewer chillers need to operate to maintain the chill dam above the required level of 65% if BAC feed pumps are stopped. The existing chiller control operated a minimum of three chillers during the Eskom evening peak period. Simulation results revealed that the chill dam is maintained if two chillers are operated during the evening peak period.

The chiller operation was adjusted to accommodate the new BAC control philosophy. Refer to Table 12 that indicates the minimum number of chillers that can be operated during the Eskom evening peak period without the chill dam level dropping below 65%.

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<sup>13</sup> A countdown timer in the PLC avoids the pumps from stopping or starting for five minutes

Table 12: Minimum chiller operation during the Eskom evening peak period

Chill dam level at the start of the Eskom evening peak period	Number of chillers operated during the Eskom evening peak period
< 65%	Run all available chillers
65–68%	6
68–74%	5
74–80%	4
80–85%	3
85–100%	2

Figure 60 illustrates the difference between the pre- and post-implementation control philosophy. In the previous operation, four chillers and four BAC feed pumps were operated during the evening peak period on a typical baseline period day. With the improved control philosophy, two BAC feed pumps together with two chillers can be operated during the Eskom evening peak period without exceeding the cooling system limits. The cooling system operation may differ from day to day as a result of changes to weather conditions and/or chilled water demand.

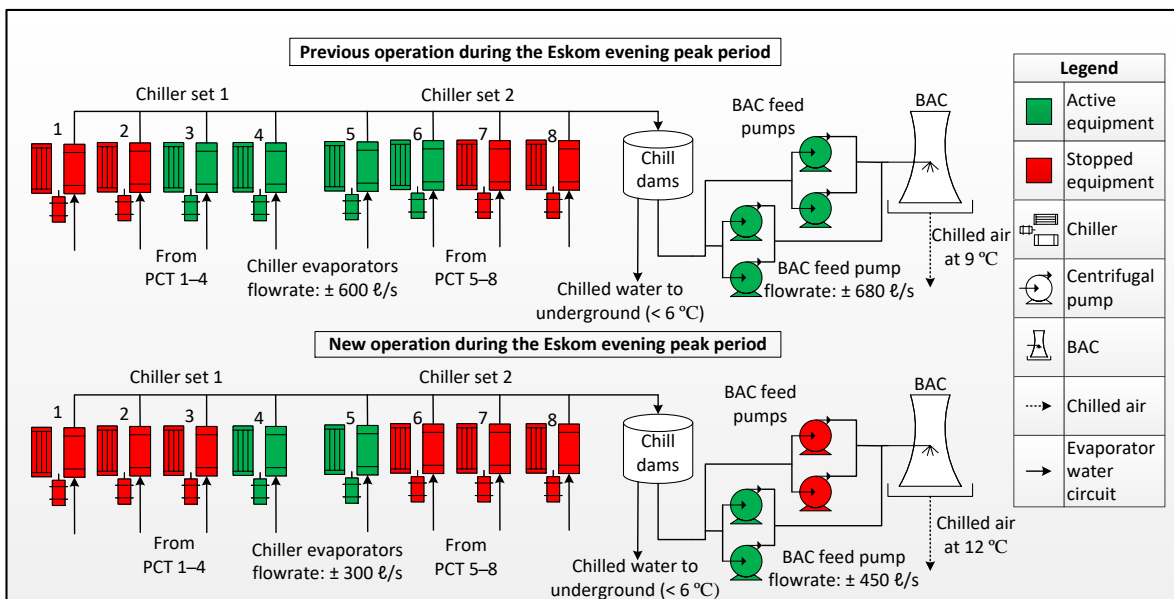


Figure 60: Improved cooling system operation on a typical summer day

As discussed in Paragraph 2.5.1, Process Toolbox is incapable of simulating the underground environment. Physical tests are needed to determine the effect on the underground conditions. Manual testing of underground temperatures will be discussed in the following paragraph.



### 4.4.3 Manual underground temperature tests

According to Paragraph 4.4.1, additional electricity cost savings can be achieved on the cooling system by reducing the flow of chilled water to the BAC. This will result in an increased air temperature going underground. Temperature high limits were obtained for four underground levels as given in Table 10.

Before the tests were conducted, the ESCo first had to establish whether there was sufficient measurement instrumentation underground. It was found that Mine X lacked weather stations<sup>14</sup> underground. Underground temperatures and humidity were logged manually.

The ventilation engineer pointed out four underground levels where the air temperature and humidity were a frequent problem. Portable weather stations (as illustrated in Figure 39) had to be installed on these levels. The locations of these weather stations are illustrated in Figure 61.

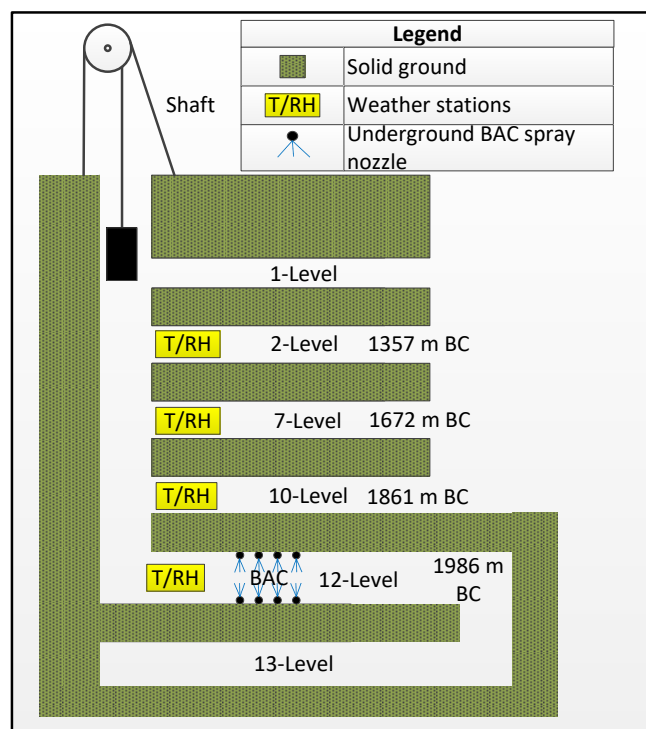


Figure 61: Temporary weather station locations underground<sup>15</sup>

<sup>14</sup> Instruments that are able to measure the relative humidity and DBT of air will be referred to as weather stations.

<sup>15</sup> Some levels on Mine X were omitted from this diagram.

The underground BAC, located 1986 m below collar<sup>16</sup> (BC) provides chilled air to the levels beyond 12-level. Temperatures on these levels are manually logged on a daily basis. The installation of temporary weather stations beyond 12-level is thus not necessary.

The tests were conducted in periods when there were no people in the working areas. Three of the BAC feed pumps were stopped during blasting period, which corresponds with the Eskom evening peak period. Figure 62 illustrates how the BAC was operated during the test day. Problems were experienced with two of the BAC feed pumps between 4:00 and 14:00 on this day. Load clipping during the evening peak period assisted the mining personnel in fixing the pumps. All the pumps were able to run after the blasting shift.

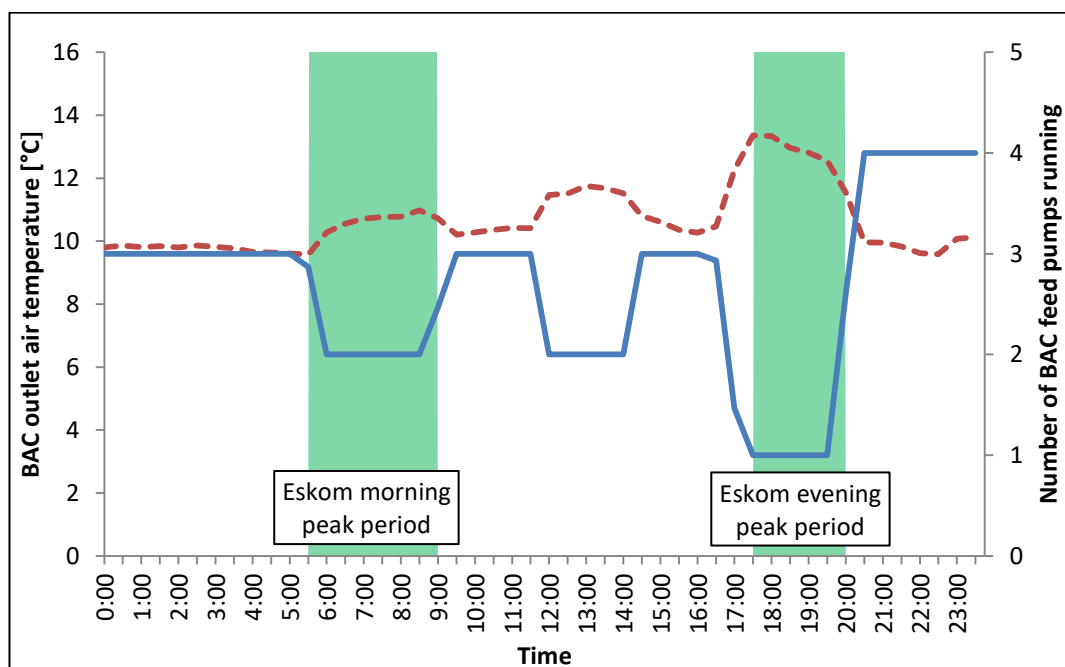


Figure 62: BAC load clipping test operation

Figure 63 is a graph illustrating the temperature as a result of the BAC peak clipping on 2-level. A rise in WBT is clearly visible after the BAC feed pumps were stopped. The WBT increased to 0.11°C below the WBT limit. It is thus not possible to isolate the chilled water flow to the BAC during the evening peak period without exceeding the WBT limits. The WBT of 2-level took 24 minutes to restore to the value it had at the start of the peak clipping.

<sup>16</sup> The collar is also known as the shaft deck and is located on ground level. Workers, services and material enter the mine through the collar.

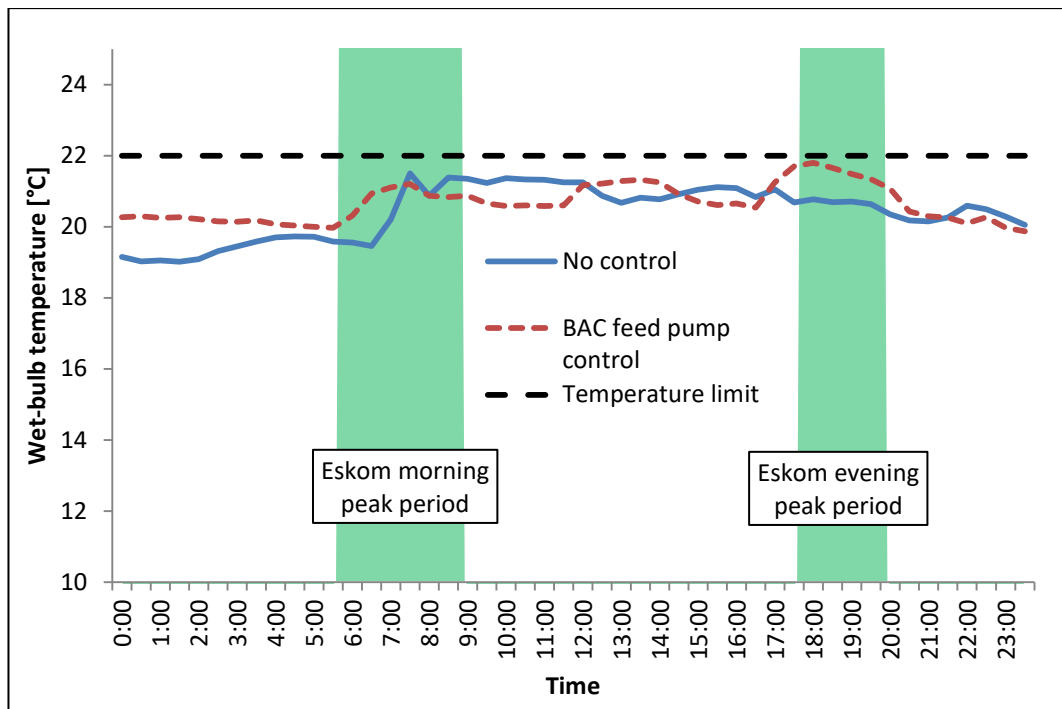


Figure 63: Effect of the BAC peak clipping on the WBT of 2-level

The WBT information of four levels as a result of BAC peak clipping is given in Table 13. As explained in Paragraph 4.4.2, all BAC feed pumps are started when the maximum WBT is reached underground.

Table 13: Underground WBT as a result of BAC peak clipping

	WBT at peak clipping start – 16:00 [°C]	Maximum WBT during peak clipping [°C]	WBT limit [°C]	Recovery time [min] <sup>17</sup>
<b>2-Level</b>	20.47	21.89	22.00	24
<b>7-Level</b>	22.79	23.81	24.50	42
<b>10-Level</b>	22.28	23.85	24.50	46
<b>12-Level BAC inlet</b>	26.22	27.35	28.00	86

Referring to Table 13, the recovery time increases with an increase in depth. An explanation of this occurrence may be the increase in heat capacitance of walls and mining infrastructure as the air passes to deeper levels. An increase in capacitance leads to a decrease in response time. The next mining shift starts work at 22:30. An hour-and-a-half is thus sufficient time for the underground WBTs to recover.

<sup>17</sup> Time needed for the WBT to restore to the value at the start of the BAC peak clipping

It was confirmed that the chillers at the 12-level BAC did not consume more electricity during the performance assessment period. However, there was a concern regarding the WBTs of the levels deeper than 12-level which depended on cool air from the underground BAC. Daily ventilation reports revealed that the cooling on these levels remained sufficient throughout the day.

#### **4.4.4 Baseline characterisation**

A three-month (September–November) electrical baseline was developed for the cooling system. The simulated power profile of the following equipment was affected by the ECSI and was thus incorporated into the baseline:

- Chiller compressor motor,
- Evaporator feed pumps,
- Condenser pumps,
- CCT fans,
- PCT fans,
- PCT pumps,
- BAC feed pumps,
- BAC return pumps, and
- BAC fans.

Figure 64 shows the unscaled baseline power profile. Valleys in the baseline can be seen during the Eskom morning and evening peak periods. These valleys are the result of the active, existing load shifting ECSI on Mine X.

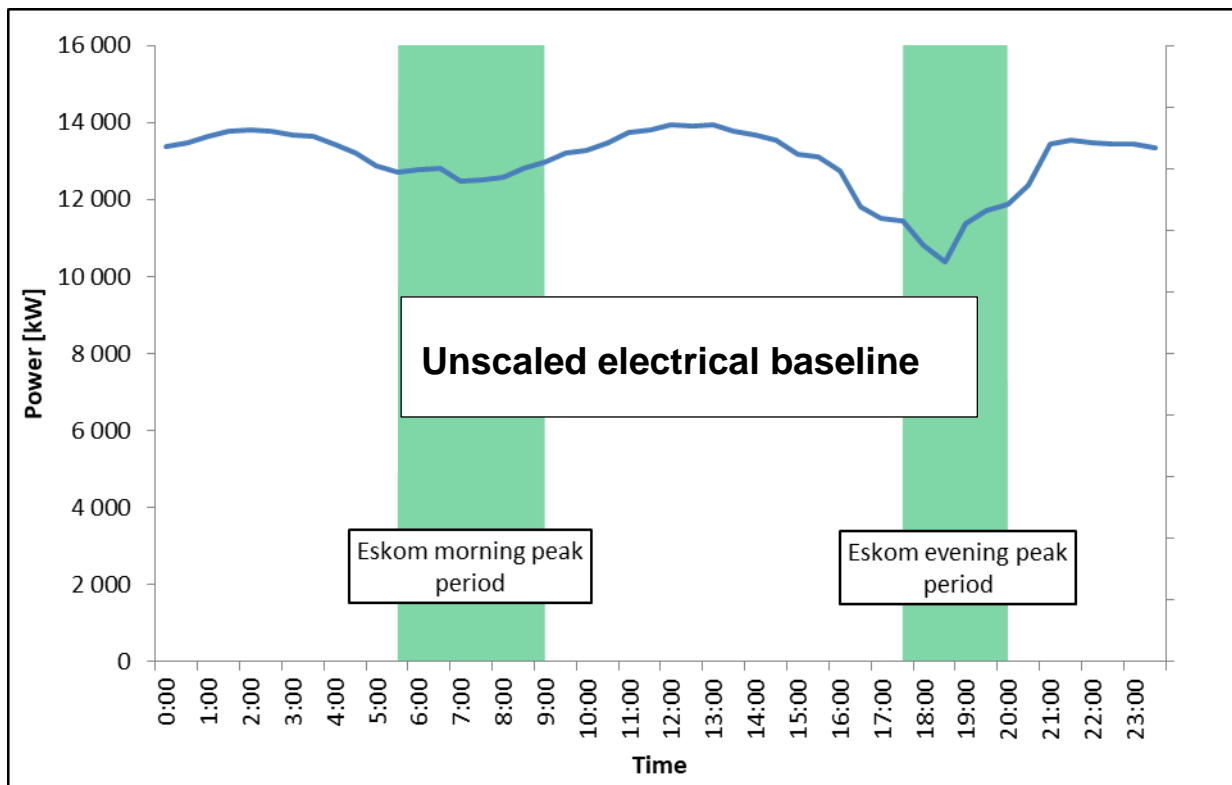


Figure 64: Unscaled electricity baseline

The control philosophy developed in Paragraph 4.4.2 will reduce the BAC service delivery in the Eskom evening peak period. Peak clipping is thus implemented on the cooling system. According to the diagram in Figure 48, a regression scaling model is the preferred baseline scaling method.

A regression scaling model based on ambient conditions was the apparent choice as manually logged data gathered in Paragraph 4.2.3 showed a clear correlation between the ambient conditions and the surface cooling system power usage. Data had to be logged over a year period to determine the weather's effect on the operation of the cooling system.

Underground service water usage increased dramatically during the logging period. The cause of the high chilled water usage was pinpointed to poor management of underground coolers. Figure 65 illustrates how the chilled water flow increased from the baseline period to the period when the demand for chilled water underground increased.

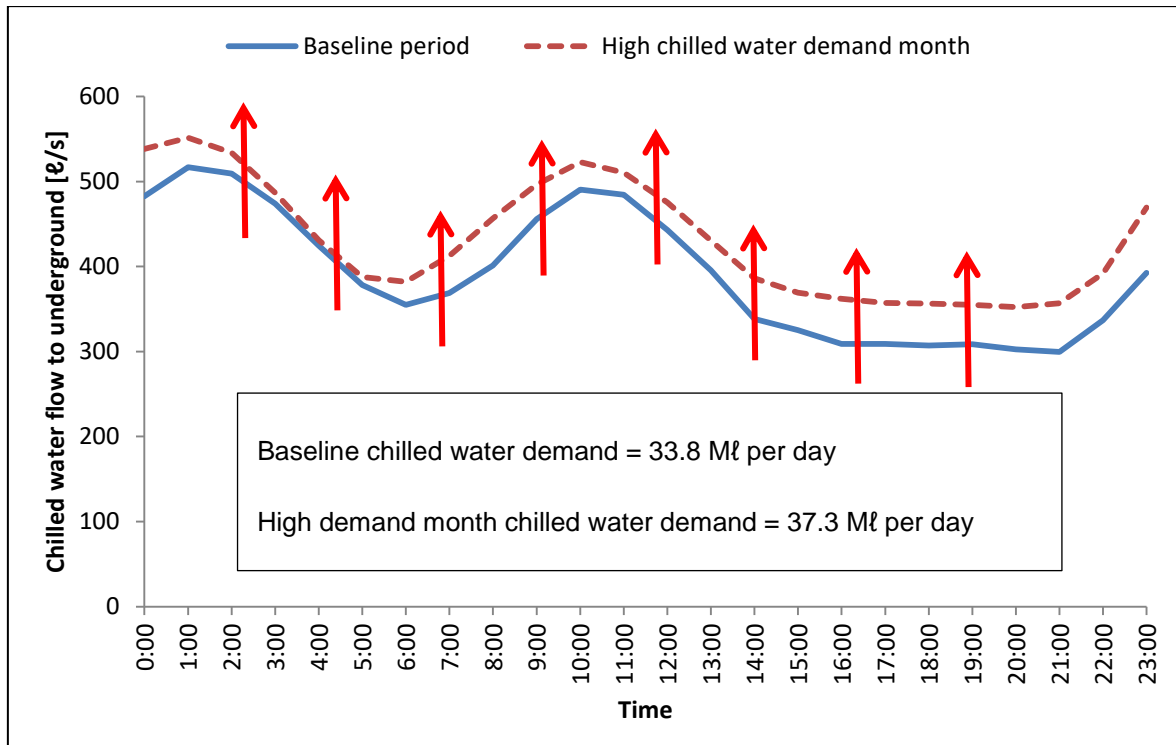


Figure 65: Increase underground chilled water demand

Different regression models were developed and tested. Microsoft Excel® Analysis toolbox was used to develop these regression models. Table 14 lists the tested regression models with their corresponding  $R^2$  values.

Table 14: Regression models comparison

Regression model	Description	$R^2$
1	Daily energy versus enthalpy	0.750
2	Daily energy versus enthalpy and chilled water volume to underground	0.794
3	Daily energy versus enthalpy, chilled water volume to underground and chilled water temperature	0.810

Referring to Table 14, it is clear that the  $R^2$  value increases with an increase in regression model variables. The independent M&V team approved Regression Model 3 in Table 14. Refer to Equation 8 for the regression scaling model.

$$E = -5847.18 \times CWT + 2544.803 \times CWV + 1989.639 \times H + 154056.02 \quad \text{Equation 8}$$

Where:

$E$  = Daily cooling system energy usage [kWh]

$CWT$  = Daily average chilled water temperature [°C]

$CWV$  = Daily chilled water volume sent underground [Mℓ]

$H$  = Daily average enthalpy [kJ/m<sup>3</sup>]

#### 4.4.5 Simulated evaluation of control philosophy

Figure 66 illustrates the effect on the simulated power profile after the implementation of the ECSI identified and developed in Paragraph 4.4.1 and Paragraph 4.4.2 respectively. More chillers could be stopped as a result of the decreased chilled water demand without exceeding the cooling system limits. This resulted in a 6500 kWh peak clipping during the Eskom evening peak period amounting to an expected annual electricity cost saving of R2.7 million<sup>18</sup>.

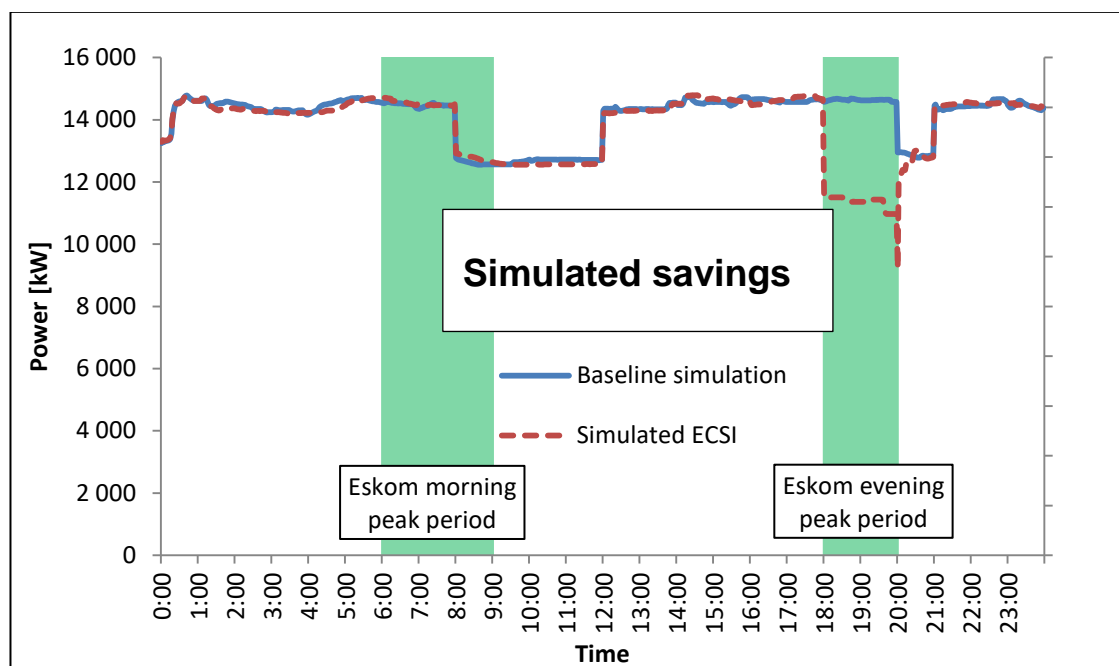


Figure 66: Baseline simulation versus simulated ECSI

The manual underground WBT test in Paragraph 4.4.3 together with the control philosophy evaluation in this paragraph have proven that the ECSI is feasible. After

<sup>18</sup> Based on Eskom's 2017/18 Megaflex tariffs

presenting the results to the engineering manager and his co-workers, the ECSI was signed off for implementation.

## 4.5 Implementation

### 4.5.1 Infrastructure modification

As mentioned in Paragraph 4.4.3, Mine X has insufficient weather stations underground. The ESCo purchased six weather stations for permanent installation underground (two spare weather stations). These weather stations were installed on the same locations as the temporary weather stations. Figure 67 illustrates a photo of the weather station installed at the 10-level station.



Figure 67: Weather station installed at the 10-level station

The ESCo also purchased a 500 m communication cable to connect the weather stations to the SCADA using existing fire detection communication infrastructure.

The ESCo requested to install a third-party software for automating the ECSI. Mine personnel preferred using their own SCADA software for automation. Troubleshooting on the cooling system could then be done without the ESCo's assistance. A sub-contractor was appointed to modify the cooling system control to incorporate the new ECSI. A summary of the items purchased by the ESCo for the ECSI implementation is given in Table 15.



Table 15: Implementation cost

Item	Quantity	Cost
Weather stations	6	R47 702. 16
500 m two pair halogen-free fibre optic cable	1	R25 200. 00
Server with software (EnMS)	1	R9 900. 00
Control system modification	1	R10 500. 00
<b>Total cost</b>		<b>R93 302.16</b>

After the new control philosophy was implemented, the ESCo was required to monitor the project for a three-year period. At the time of writing, the project has been active for a three-month period.

#### 4.5.2 Validation of improved control philosophy

The control philosophy developed in Paragraph 4.4.2 is validated by applying it to the cooling system of Mine X. Actual cooling system results are compared with the simulated results to prove that the developed control philosophy and therefore the methodology to identify electricity cost saving on the mine cooling system are valid.

Figure 68 shows a graph of the actual weekday power profile and scaled baseline of two summer months in the performance assessment period. An average daily energy reduction of 14 000 kWh was achieved during this period. This resulted in an electricity cost saving of R385 000 over the two-month period.

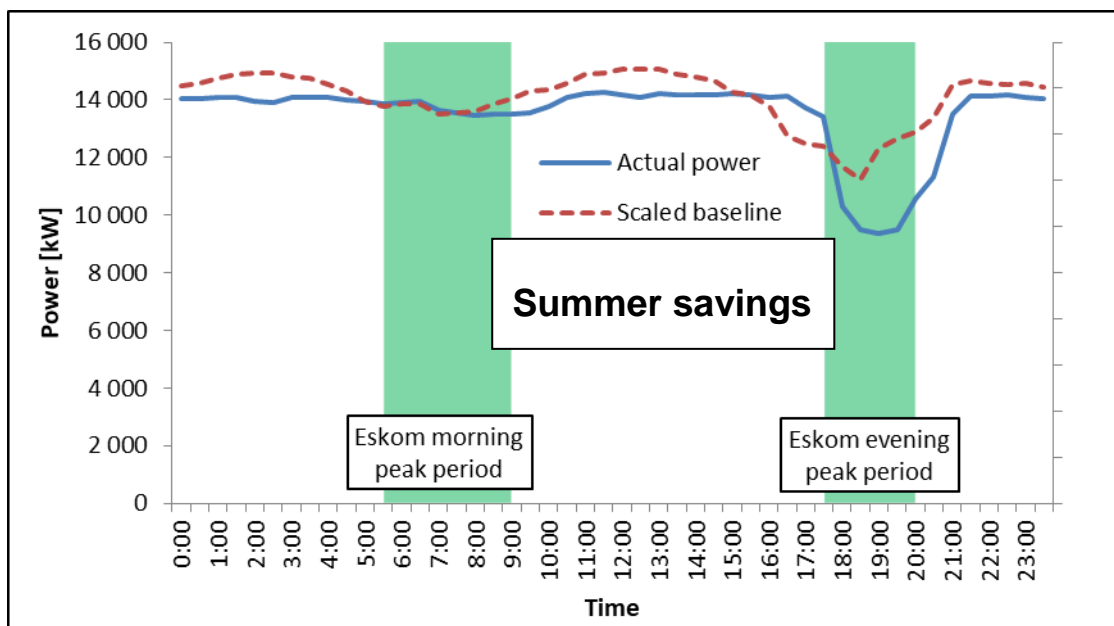


Figure 68: Weekday scaled baseline and actual power over two summer months

According to the simulated ECSI, a daily energy saving of 6000 kWh is expected. The overperformance can be attributed to the rise in chilled water temperature described in Paragraph 4.4.4. The BAC was incapable of reaching the outlet air temperature set point with the high chilled water temperature. This resulted in an all-day BAC load reduction.

Figure 69 shows the actual power profile and scaled baseline during one month in winter. An average daily energy reduction of 6700 kWh was achieved during this period. The ECSI resulted in a R110 000 electricity cost saving over this winter month.

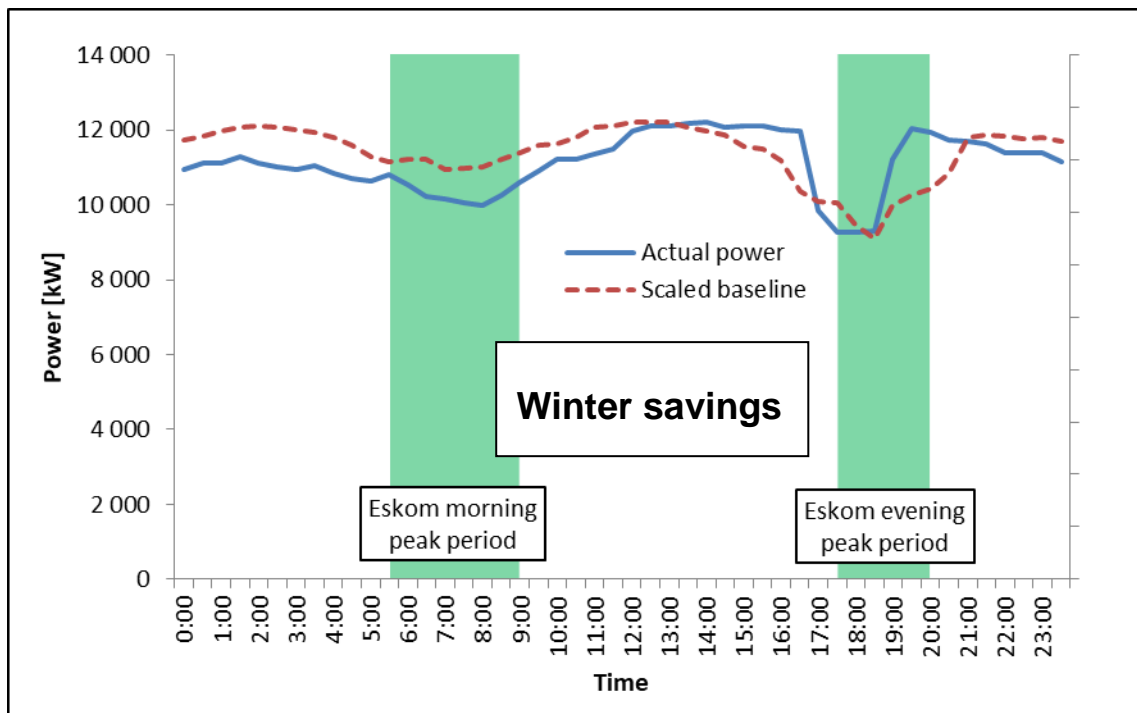


Figure 69: Weekday scaled baseline and actual power over one winter month

The chillers were operated manually during the winter month for maintenance purposes. In contrast to the summer performance assessment period, fewer chillers were stopped during the Eskom evening peak period as can be seen in Figure 69. This operation filled the chill dams for the chiller maintenance of the next day.

The energy efficiency experienced during winter was lower than that experienced during summer. A  $\pm 30$  kJ/kg ambient air enthalpy reduction from summer to winter enabled the BAC to cool the incoming air to the set point temperature in winter. Less water also needed to be recycled to the PCT sump as more cooling could be provided by the PCTs during winter.

The ECSI overperformed with an average daily energy saving of 700 kWh. The overperformance can be attributed to the constant operation of Chiller 7 and Chiller 8 during the maintenance periods. It is known that these are the more efficient machines.

If the operation described above is maintained throughout the year, an estimated annual electrical cost saving of R2.1 million can be realised. Mine personnel have however realised the consequences of the high chilled water usage underground. The ventilation department have been tasked to remove unnecessary coolers and find chilled water leaks underground.

## 4.6 Conclusion

**Objective 3:** Prove that the developed methodology can be applied to a mine cooling system that results in electricity cost savings without exceeding the cooling system high/low limits.

Information on Mine X was gathered in the first section of Chapter 4. The cooling system was identified to be one of the larger energy consumers on the shaft. An electricity cost saving investigation was launched on the cooling system. A lack of operational data delayed the project's implementation. The ESCo installed an EnMS for data logging purposes.

The equipment specifications and operational data were used to construct a simulation of the cooling system. Actual operational data was used to verify the simulation output. The maximum error between the simulated and actual data was 10%. This is an acceptable error for the simulation to be used in the identification of an ECSI.

The decision diagram developed in Chapter 3 was used to identify an ECSI on the cooling system. A load shifting project was currently implemented on the surface cooling system. Scope for additional savings was however identified by incorporating the BAC into the current control philosophy. Reducing the flow of chilled water to the BAC was challenging as there were neither VSDs nor valves to control the flow. A new cost-effective control philosophy for controlling the BAC feed pumps was developed.

A baseline scaling method was needed to adjust the baseline according to the change in conditions. Several operational adjustments occurred since the start of the baseline measurement period. A multi-variable regression baseline scaling model was developed to incorporate these adjustments.

The new control philosophy resulted in an annual simulated electricity cost saving of R2.7 million. Weather stations and communication cables were purchased for critical underground levels. Manual tests during the baseline measurement period revealed that the WBTs of the underground levels remained within acceptable limits. The savings achieved over a three month period were extrapolated over a whole year. An annual saving of R2.1 million was calculated.

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# Chapter 5. Conclusion and recommendations

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## 5.1 Summary of work

In 2016, South Africa's mining industry contributed to 7.3% of the country's GDP and provided work to more than 450 000 people. The high operating cost of mining has resulted in a negative mining growth rate. Electricity has been identified as a notable operating expenditure with the potential to be reduced.

Cooling systems on mines can contribute up to 20% of a mine's electricity bill. Various energy intensive units were identified on a typical mine cooling system. There are available measures to achieve electricity savings on deep-level mine cooling systems. Changes made to the Eskom DSM funding model constrained ESCos to low initial capital cost initiatives. Low cost initiatives come with a risk to safety and production. There is a need to develop a low risk, low initial capital cost electricity savings strategy for mine cooling systems.

The literature study revealed that there were various strategies to manage the supply and demand of chilled water for electricity cost savings. Energy efficiency initiatives, such as PCT performance improvement and VSD control on chiller pumps can lead to high electricity cost savings on mine cooling systems. These initiatives however come with a high initial capital cost which makes them unattractive to ESCos.

Low initial capital cost initiatives utilise existing cooling system infrastructure for electricity savings. These initiatives include chiller load shifting and BAC peak clipping. Changes made to the operation of existing infrastructure can affect the operation of upstream and downstream units. A detailed integrated methodology is thus required to identify electricity cost savings opportunity on a mine cooling system. No such methodology could be found in literature.

Apart from identifying ECSIs on mine cooling systems, ESCos have to face numerous other challenges before an ECSI can be implemented. These challenges include information gathering, simulation development, baseline scaling methods, M&V and initiative financing. Methods to overcome these challenges were found in literature.

A generic methodology was developed to address typical obstacles to ECSIs and identify electricity cost saving potential on mine cooling systems. A systematic approach to the characterisation of the mine and its cooling system was presented. The gathered information could then be used to construct a model of the cooling system. Objective 1 and Objective 2 stated in Paragraph 1.3 was thus met.

The first step in the identification process was to select desirable initiatives with low risks. Cooling system risk and project appeal matrixes found in literature were modified to identify such initiatives. Chiller load shifting and BAC peak clipping were identified as the more desirable projects with manageable risks.

The ESCo decided to implement the integrated methodology on Mine X, which is a hydropowered platinum mine. The cooling system on Mine X had an existing chiller load shifting initiative in operation. The methodology developed in Chapter 3 was applied to the cooling system of Mine X. Additional scope for cost-effective electricity savings was identified by applying BAC peak clipping.

A lack of valves and VSDs made it difficult to control the BAC outlet air temperature. The BAC feed pump operation was used to control the outlet air temperature. A simulation of the cooling system revealed that the BAC feed pump control can result in an annual electricity cost saving of R2.7 million.

The new control philosophy was implemented permanently by installing weather stations on critical levels underground and hard-coding the BAC peak clipping control philosophy into the existing cooling system control philosophy. An electricity cost saving of R495 000 was achieved three months after the ECSI implementation. Extrapolating, this would result in an annual cost saving of R2.1 million. No negative long-term effects were detected on the underground environment. Objective 3 in Paragraph 1.4 was thus met.

## **5.2 Recommendation for future work**

The methodology developed in this study was successfully implemented on a platinum mine cooling system. Below is a list of recommendations for future work:

- The methodology developed in Chapter 3 was developed for mine cooling systems. It is recommended that a similar methodology be developed for residential and commercial cooling systems.
- In the case study, motors had to be stopped and started to meet the cooling demand, as funding for VSDs was not available. A study is needed to evaluate the long term maintenance requirements on the chillers and centrifugal pumps.
- The purpose of the developed methodology is to reduce the electricity usage during the Eskom peak periods by either applying peak clipping or load shifting to the cooling system. It is recommended that a similar methodology be developed for energy efficiency projects on mine cooling systems.

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# Appendix A Risk assessment matrix and project appeal indicator matrix

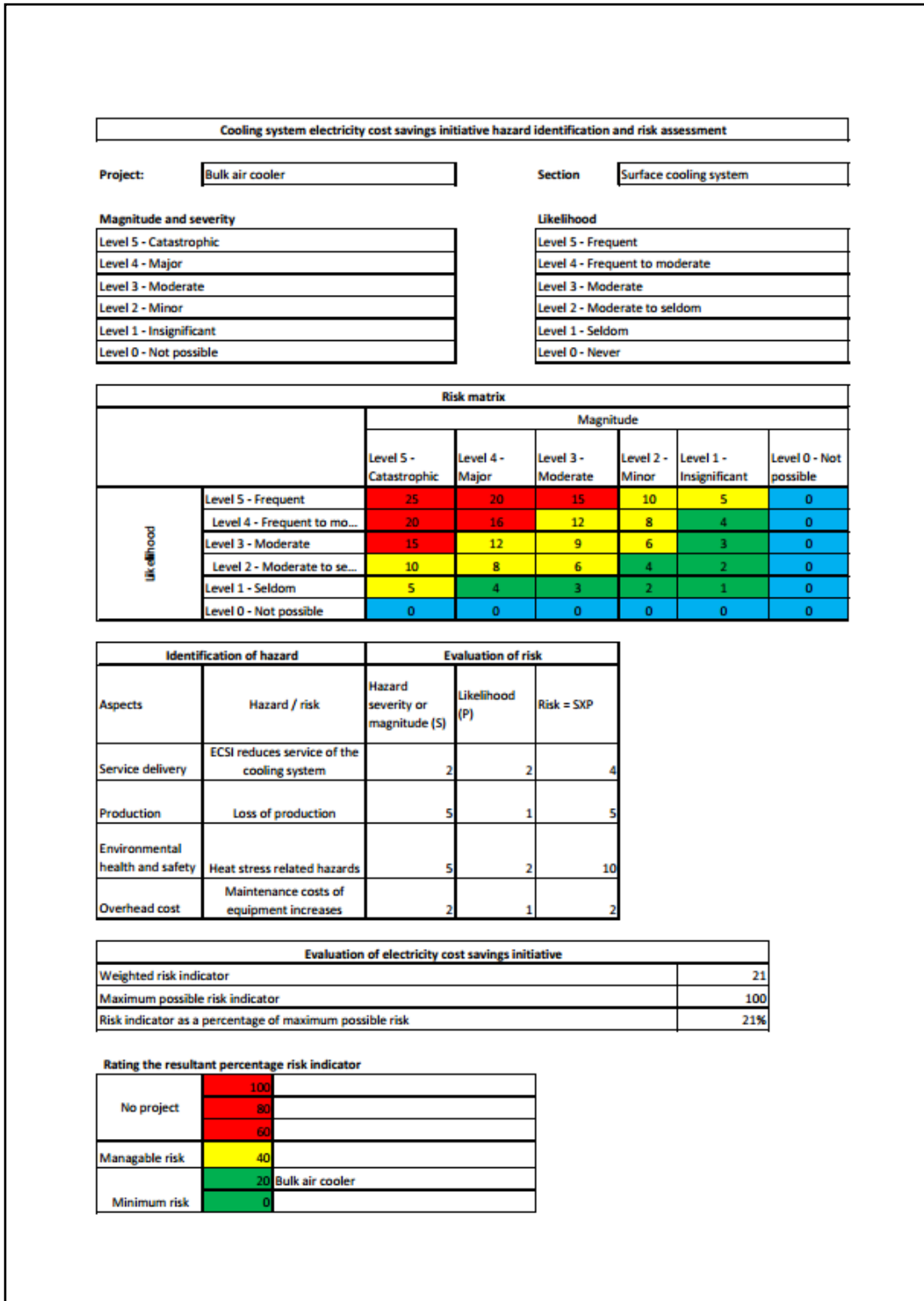


Figure 70: Electricity cost savings initiative risk matrix

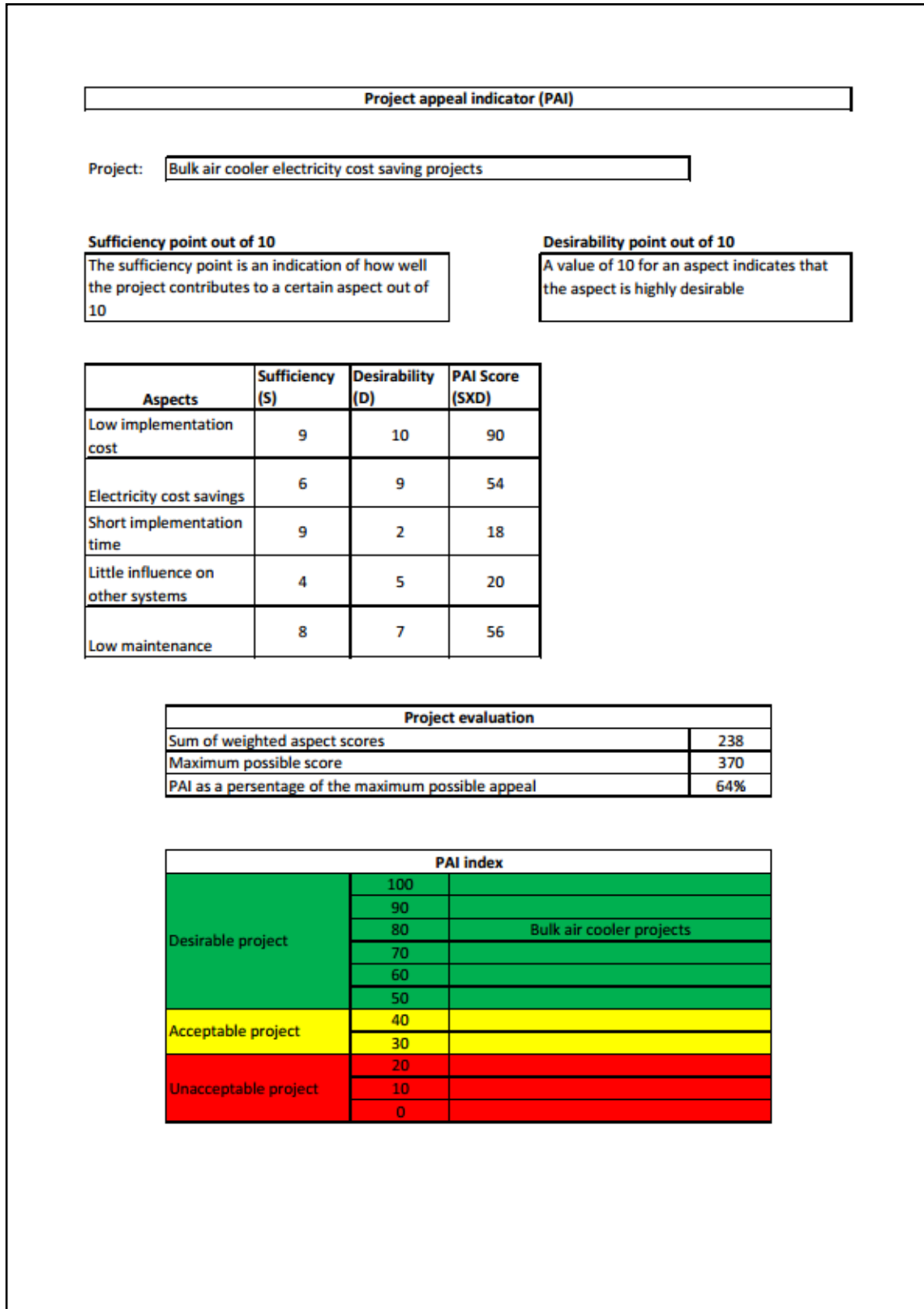


Figure 71: Electricity cost savings initiative PAI

## Appendix B Mine X simulation

The cooling system on Mine X consists of distinct components. The components are:

- Chillers,
- CCTs,
- PCTs,
- BACs, and
- Dams.

The simulation of each component can further be broken down into sub components. In this section, the components, together with their sub-components will be discussed.

Mine X has eight chillers that are connected in parallel. Each simulated chiller has been customised to suite their unique characteristics. Refer to Figure 72 for an illustration of the chiller simulation.

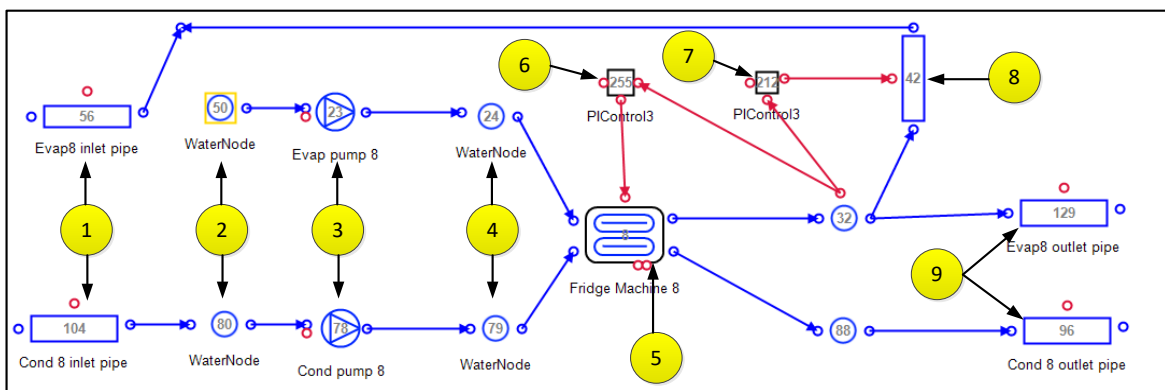


Figure 72: Chiller simulation layout

An explanation of the sub-components numbered in Figure 72 follows below:

1. Pipes transfer water from the PCT sumps to the evaporator pumps and cooled condenser water from the condenser sumps to the condenser pump.
2. Water nodes connecting water pipes to the pumps.
3. Centrifugal pumps are simulated to transfer water from the PCT sumps and CCT sumps to the evaporator and condenser pumps respectively.
4. Water nodes connect the pumps to the chiller condenser and evaporator.



5. The chiller sub-component in Process Toolbox simulates the chiller compressor, evaporator and condenser tubes.
6. The chiller guide vanes are controlled by a proportional-integral controller. The controller reduces the power consumption of the chiller with a decrease in the evaporator outlet temperature.
7. The second stage of the recycling valves are controlled with proportional-integral controllers. The chiller guide vane controller reaction time is faster than the recycling valve controller.
8. The pipe component in Process Toolbox can also be used to simulate the recycling valves. Chilled water is recycled to the inlet of the chiller to reduce the evaporator outlet temperature.
9. Outlet evaporator and condenser pipes connect the evaporator and condenser to the chill dam and CCTs respectively.

A list of the sub-component specifications used in the simulation is given in Table 16. Note that these values may differ slightly from chiller to chiller.

Table 16: Chiller components specifications

<b>Description</b>	<b>Actual value</b>	<b>Description</b>	<b>Actual value</b>
Evaporator pump rated power	75 kW	Condenser pump rated power	125 kW
Evaporator pump measured flow rate	155 l/s	Condenser pump measured flow rate	330 l/s
Chiller evaporator outlet temperature	5.5°C	Chiller condenser outlet temperature	33°C
Chiller evaporator inlet temperature	14°C	Chiller condenser inlet temperature	28°C
Chiller power consumption	1400 kW	Recycle valve measured flow rate	20 l/s

As mentioned in Paragraph 3.3.1, dividing the cooling system variables into uncontrollable, independent and dependent variables can help with simulation development. Each simulation component (chiller, PCTs, etc.) are simulated separately. The input streams from other components are considered as uncontrollable variables before the components. A list of the uncontrollable, independent and dependent variables follows:

Uncontrollable variables:

- Evaporator inlet temperature, and
- Condenser inlet temperature.

Independent variables:

- Chiller power,
- Evaporator and condenser pump power,
- Evaporator and condenser pressure drop,
- Recycle valve pressure drop, and
- Chiller COP.

Dependent variables:

- Recycle water flow rate,
- Evaporator and condenser water flow rate, and
- Evaporator and condenser outlet temperature

Heat from the chiller condenser water outlets are removed in the CCTs. There are four CCTs per chiller set. Each set of CCTs was simulated with one cooling tower component. The first set of CCTs is an exact duplicate of the second set. Refer to Figure 73 for the simulation layout of the second CCT set.

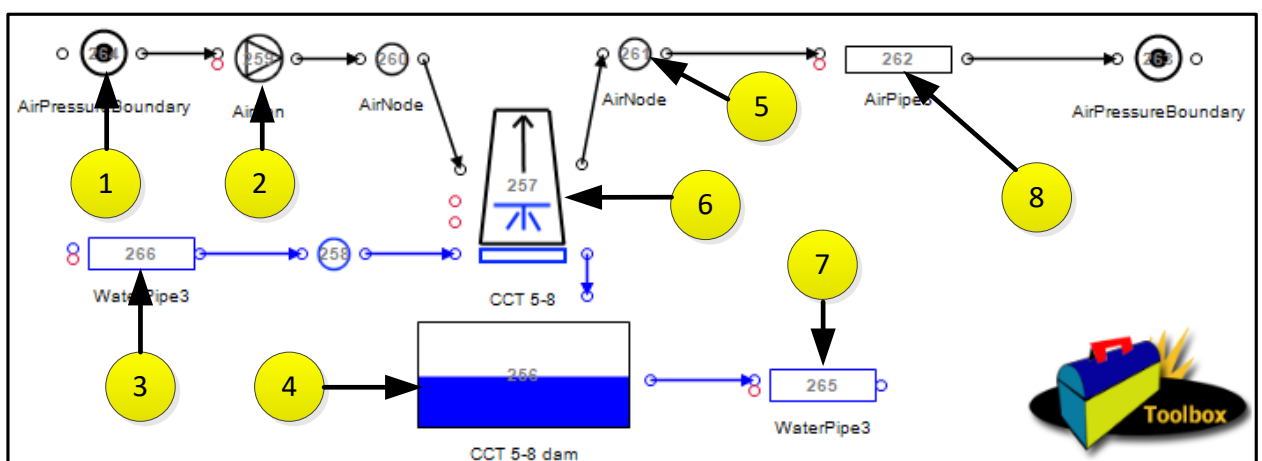


Figure 73: CCT simulation layout

An explanation of the sub-components numbered in Figure 73 is given below:

1. The simulated air pressure boundary contains the pressure, DBT and relative humidity information of the ambient air.
2. Air is displaced through the CCT with an air fan.
3. Warm water from the chiller condensers is transported to the CCTs via a pipe network.
4. Cooled water from the CCT collects in the CCT sump.
5. Similar to water nodes, air nodes connect other components, such as CCTs and air fans. Air nodes also hold information such as air pressure, DBT and relative humidity.
6. Heat exchange between the incoming condenser water and the ambient air is simulated with an air-water heat exchanger.
7. Water is carried from the CCT sumps to the chiller condensers.
8. An air pipe carries heated air from the CCTs to the atmosphere.

Table 17: CCT 5–8 component specifications

Description	Actual value	Description	Actual value
Cooling duty (varies)	30 000 kW	Power rating of each fan (four fans)	150 kW
Air flow rate	800 kg/s	Air outlet temperature	33°C
Cooled condenser water temperature	28°C	Condenser water flow rate	1 400 l/s
Condenser sump volume	500 m <sup>3</sup>		

A list of the uncontrollable, independent and dependent variables follows:

Uncontrollable variables:

- Ambient conditions,
- Incoming condenser water flow rate, and
- Incoming condenser water temperature.

Independent variables:

- Condenser cooling duty,
- Fan power usage, and
- Air pressure drop over CCT.

Dependent variables:

- Air flow rate through CCT,
- Cooled condenser water temperature, and
- CCT sump level.

As mentioned in Paragraph 4.2.2, there are two sets of PCTs, each containing four PCTs. Each set of PCTs was simulated with one cooling tower component. Figure 74 illustrates the components used to simulate PCTs 5–8 (second set of PCTs). The first set of PCTs is an exact duplicate of the second set.

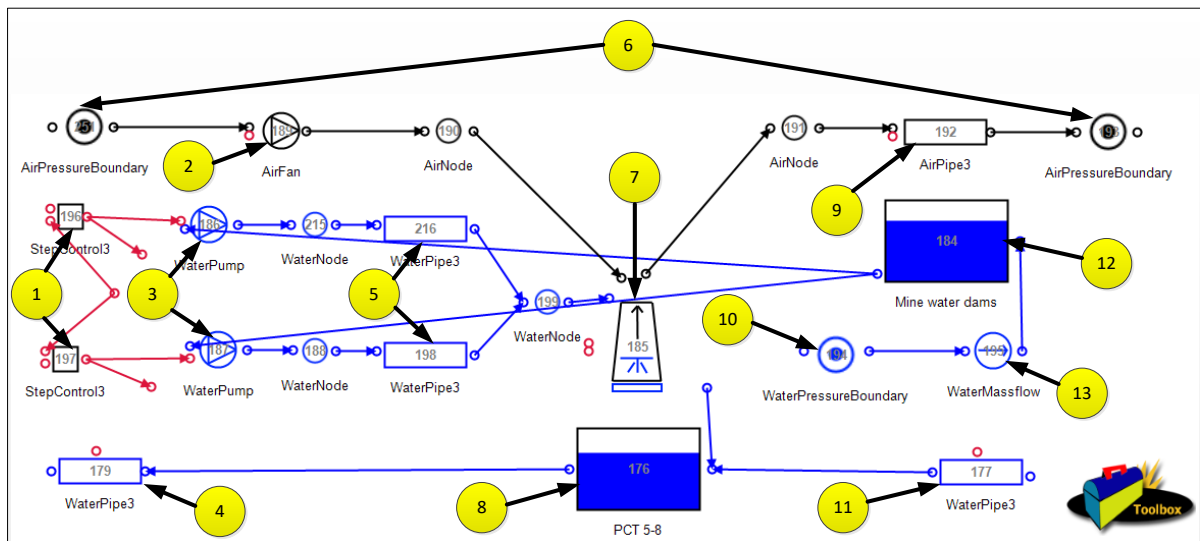


Figure 74: Precooling tower simulation layout

An explanation of the sub-components numbered in Figure 74 follows below:

1. Step controllers are used to stop and start PCT pumps to control the mine water dam levels.
2. Heat exchange between the incoming mine water and the ambient air is simulated with an air-water heat exchanger.
3. Centrifugal pumps pump mine water from the mine water dam to the PCTs.
4. Water pipe transferring water from the PCT sump to one set of chillers.
5. Pipes transferring water from the pumps to the PCTs. The pumps are not connected to a common manifold.
6. Air pressure boundaries simulating the ambient conditions. Ambient pressure, relative humidity and DBT are accepted as inputs.
7. Heat exchange between the incoming mine water and the ambient air is simulated with an air-water heat exchanger. Water from the PCT drops into the PCT sump.
8. The PCT sump is simulated with the dam component.

9. An air pipe is used to simulate the pressure drop over the PCT fans.
10. The water pressure boundary, simulates the temperature and pressure at which the mine water is received on surface.
11. A water pipe transfers water from the BAC sump to the PCT sump.
12. The three mine water dams are simulated with one dam that has a combined volume of all three dams.
13. A water mass flow component simulates the flow of mine water to surface.

A list of the component specifications used to simulate PCT 5–8 is given in Table 18.

Table 18: PCT 5–8 components specifications

Description	Actual value	Description	Actual value
Mine water dams (three dams simulated as one)	15 Mℓ	PCT 5-8 sump volume	500 m <sup>3</sup>
Mine water temperature	32°C	PCT 5-8 sump water temperature	19°C
PCT cooling duty	18 000 kW	Fans combined power rating (four fans)	400 kW
Mine water flow rate	400 ℓ/s	PCT pump motor rating	75 kW

A list of the uncontrollable, independent and dependent variables follows:

Uncontrollable variables:

- Water flow from BAC,
- Water temperature from BAC,
- Water flow rate from underground,
- Water temperature from underground,
- Ambient conditions, and
- PCT water demand.

Independent variables:

- PCT cooling duty,
- Pressure drop over PCT fans,
- Water pressure drop over PCT

- PCT fan power, and
- PCT pump power.

Dependent variables:

- Air flow rate through PCT,
- PCT temperature, and
- PCT sump level.

Mine X has a vertical-flow BAC on surface. Similar to the PCT and CCT simulation, the BAC is simulated with an air-water heat exchanger. Four centrifugal feed and return pumps pump chilled water from the chill dams to the BAC and the BAC sump to the PCTs respectively. Refer to Figure 75 for the BAC simulation layout.

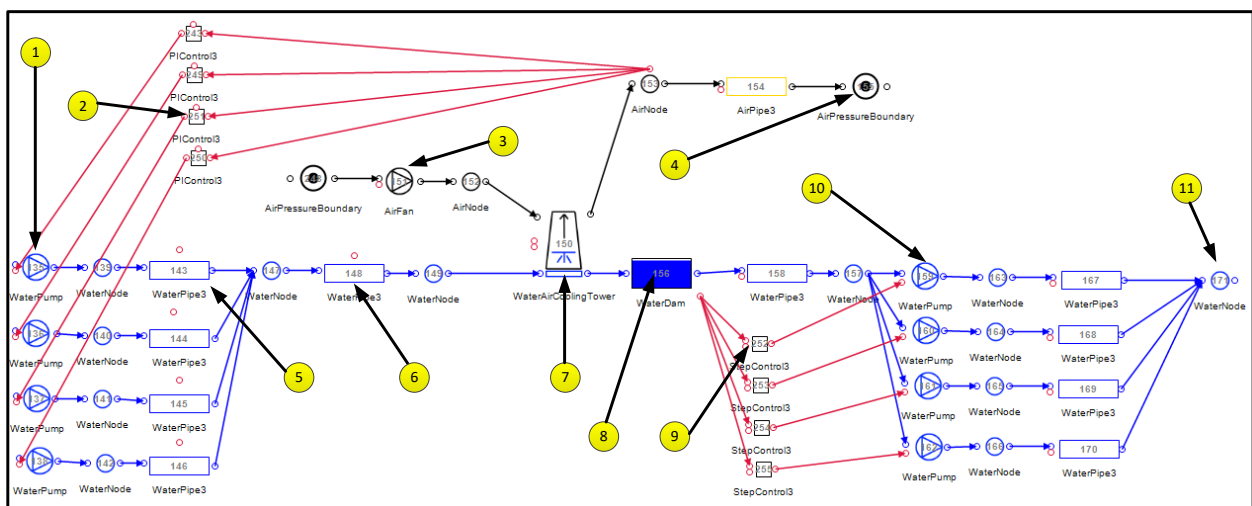


Figure 75: BAC simulation layout

An explanation of the sub-components numbered in Figure 75 follows below:

1. BAC feed pumps pump chilled water from the chill dam to the BAC.
2. Step controllers control the BAC outlet air temperature by stopping and starting BAC feed pumps.
3. Air fans supply ambient air to the BAC.
4. Chilled air is sent underground.
5. Water pipes transfer water from individual BAC feed pumps to the BAC.
6. All the individual chilled water pipes from the feed pumps connect to a common manifold.
7. Heat exchange between the ambient air and chilled water takes place in the BAC which is simulated with an air-water heat exchanger.

8. Chilled water from the BAC collects in a BAC sump.
9. Step controllers are used to control the BAC sump level by stopping and starting BAC return pumps.
10. BAC return pumps pump water from the BAC sump to the PCT sumps.
11. Water going from the BAC sump to the PCT sump.

A component specification list of the BAC is given in Table 19.

Table 19: BAC components specifications

Description	Actual values	Description	Actual values
BAC feed and return pump rated power	75 kW	BAC sump volume	500 m <sup>3</sup>
Individual BAC feed/return pump flow rate	245 l/s	BAC return water temperature	10°C
Air flow rate	400 kg/s	BAC fans combined power	400 kW
Outlet air temperature	8.5°C		

Uncontrollable variables:

- Ambient air conditions, and
- Incoming chilled water temperature.

Independent variables:

- BAC cooling duty,
- Pressure drop over water pipes,
- Air pressure drop over BAC,
- Pump electricity consumption,
- Fan electricity consumption, and
- Pump operation.

Dependent variables:

- Air flow rate through BAC, and
- BAC outlet air temperature.

Mine X has four connected 5 Mℓ chill dams. The chill dams receive chilled water from Chiller Set 1 and 2. Chilled water is recycled to the chillers using mixing valves. Chilled water from the chill dams is either demanded by underground users or the surface BAC. Refer to Figure 76 for an illustration of the simulated chill dam layouts.

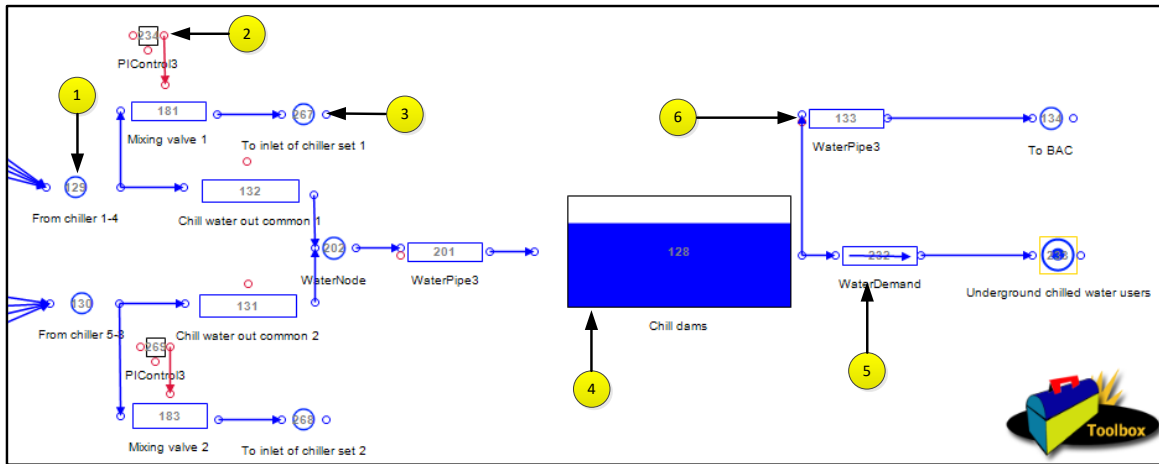


Figure 76: Chill dams simulation layout

A description of the numbered sub-components follows below:

1. Chilled water is received from Chiller Set 1 and Chiller Set 2.
2. Proportional-integral controllers are used to control the chiller set inlet water temperature by recycling chilled water.
3. Chilled water recycled to one of the chiller sets.
4. Chill dams simulated as one 20 MI chill dam.
5. Simulated underground chilled water demand.
6. BAC chilled water demand.

Table 20 lists the chill dam component specifications.

Table 20: Chill dam components specifications

Description	Actual values	Description	Actual values
Combined size of the chill dams	20 Mℓ	Chilled water flow to chill dams (varies)	1200 ℓ/s
Chilled water temperature (varies)	5.5°C	BAC chilled water demand	650 ℓ/s
Underground chilled water demand (varies)	400 ℓ/s	Chilled water recycled to chiller sets	200 ℓ/s





Figure 77 illustrates how the decision diagram, developed in Chapter 3, was applied to the cooling system of Mine X. The path followed in the diagram is indicated by the bold coloured arrows. The yellow arrows indicate arrows only followed once. The orange arrows were followed twice, while the red arrows were followed three times. Each block that was reached in the diagram is discussed below.

1. **Block A:** Start at the start block.
2. **Block E:** Not all the chillers on Mine X are stopped during the evening peak period.
3. **Block K:** There has not been an investigation on chilled water recycling valves for chiller load shift.
4. **Block Q:** Mine X has existing chilled water recycling infrastructure.
5. **Block W:** As described in Paragraph 4.2.2, there are two stages of chilled water recycling valves. All recycling valves (Stage 1 and Stage 2) have already been fully opened during the summer period. During the winter period, the Stage 1 recycling valves were fully closed to avoid water freezing in the evaporator tubes. Increasing the chilled water recycle flow rate could thus not be used to reduce the chiller load during the evening peak period.
6. **Block L:** One of the chillers was stopped with the evaporator feed pump of the stopped chiller still active.
7. **Block Y:** The chilled water temperature of the chill dam was raised above the high limit of 6°C. Action had to be taken to reduce the chilled water temperature.
8. **Block G:** There were neither valves nor VSDs to throttle the flow of chilled water through the chiller.
9. **Block AE:** The evaporator pump of the stopped chiller was stopped.
10. **Block S:** The chilled water temperature is below the high limit of 6°C.
11. **Block AD:** The chilled water was above 0°C, which meant that water would not freeze in the evaporator tubes.
12. **Block AC:** The hot dams and precooling dam levels were below the high limit.
13. **Block J:** The BAC temperature has remained unchanged since the start of the decision diagram, as the chill dam was a buffer for both the chilled water to underground and the BAC.
14. **Block C:** Stopping the evaporator pump resulted in the chill dam level dropping below the low limit of 75%. Actions were thus needed to restore the chill dam level above the low limit.

15. **Block D:** After negotiations with mine personnel, permission was granted to increase the BAC outlet air temperature during the evening no-entry period. No peak clipping has previously been implemented on the surface BAC.
16. **Block B:** The chilled water flow to the BAC was isolated by stopping all BAC feed pumps in the simulation.
17. **Block H:** The BAC outlet air temperature exceeded the high limit that was negotiated with mine personnel.
18. **Block Z:** The chilled water flow to the BAC was restored by starting the BAC feed pumps.
19. **Block T:** Chilled water flow to the BAC can be throttled by stopping one or more BAC feed pumps.
20. **Block AA:** Two BAC feed pumps were stopped in the simulation to throttle the flow of chilled water to the BAC.
21. **Block T:** The chilled water temperature slightly increased with 0.5°C over the course of the evening peak period. The temperature was however still below the high limit of 6°C.
22. **Block J:** The maximum BAC outlet air temperature reached during the evening peak period was 13°C which is 1°C lower than the BAC outlet air temperature high limit.
23. **Block C:** The chill dam level was above the low limit.
24. **Block L:** An additional chiller was stopped with the evaporator feed pump still active.
25. **Block Y:** Chilled water temperature was above the high limit.
26. **Block G:** Refer to Step 8.
27. **Block AE:** The evaporator pump of the second stopped chiller was stopped.
28. **Block S:** The chilled water temperature was below the high limit.
29. **Block AD:** The water side of the evaporator was not freezing.
30. **Block AC:** The hot dams and precooling dams were below the high limit.
31. **Block J:** The BAC outlet air temperature was below the high limit.
32. **Block C:** The chill dam level was above the high limit.
33. **Block E:** Not all the chillers were stopped.
34. **Block K:** Chilled water recycling flow was checked in Step 3.
35. **Block L:** A third chiller was stopped.
36. **Block Y:** The chilled water temperature was above the high limit.
37. **Block G:** Refer to Step 8.
38. **Block AE:** The evaporator pump of the third chiller was stopped.
39. **Block S:** The chilled water temperature was below the high limit.
40. **Block AD:** The water side of the evaporator was not freezing.

41. **Block AC:** The hot dams and precooling dams were below the high limit.
42. **Block J:** The BAC outlet air temperature was below the high limit.
43. **Block C:** The chill dam level was below the low limit.
44. **Block D:** If an additional BAC feed pump was stopped, the high limit of the BAC outlet air temperature would be exceeded. Maximum peak clipping was thus applied to the BAC.
45. **Block C:** The chill dam level was below the high limit.
46. **Block O:** The last evaporator pump that was stopped was started to restore the chill dam level.
47. **Block P:** After starting the evaporator pump, the chilled water temperature increased above the high limit.
48. **Block U:** The third stopped chiller was started again.
49. **Block I:** The decision loop was completed.