

A holistic approach to evaluate the feasibility of implementing ice thermal storage on deep mines

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ABSTRACT

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Over the past decade, the mining industry has been faced with several challenges that have contributed towards dwindling profit margins across many South African deep-level mines. One of the major, if not the most significant contributing factor has been attributed towards ever-increasing operating costs, primarily resulting from escalating prices in electricity.

Refrigeration systems have been identified as one of the largest single energy consumers in the mining sector, contributing up to 24% of a mine's total electrical energy consumption. To assist in offsetting low commodity prices and reducing margins for profit, optimising cooling systems on existing mining operations has become critical for the current and future sustainability of gold mining operations in South Africa. Although a wide variety of load management initiatives have already been extensively implemented on mine refrigeration systems, the subsequent load-shifting capability and cost-saving potential remains limited. The sustainability and profitability of deep-level gold mining in South Africa remains under threat.

To alleviate financial strain prompted by ever-increasing electricity tariff rates, a need was identified to implement more effective load management strategies and techniques capable of maximising the cost-saving potential of mine refrigeration systems. Ice thermal storage has the potential to make up the shortfall. Ice thermal storage systems represent a relatively new technology utilised on mines and as a result, studies are limited. Through widespread utilisation in the building industry, ice thermal storage systems have revealed countless benefits, of which the most instrumental is the cost-saving potential. By storing energy in the form of ice during periods when electricity tariffs are cheapest and releasing it during periods when electricity is most expensive, lucrative cost savings can be achieved.

The aim of the study is to prove whether it is worthwhile to implement ice thermal storage on mines as an alternative, more effective cost-saving solution. Therefore, extending the knowledge in the field of ice based thermal storage, contributing to the development and wider utilisation of such systems in the mining

industry. To accomplish this, a generic methodology that can be utilised to evaluate and sustainably implement ice thermal storage as an alternative cost-saving technique within the mining industry was developed. Through application of a simulation strategy incorporating analytical approaches, a feasibility analysis was incorporated to predict system behaviour and determine project feasibility without capital expenditure. Improved implementation strategies and operation approaches are also provided to assist in the sustainability of future installations within the mining industry.

A South African deep-level gold mine was chosen as the case study mine. Mine P was selected as it represents one of the only mines in South Africa currently employing ice thermal storage to capitalise on a variable time-of-use electricity tariff structure. Due to extended periods of downtime throughout the 2018/2019 financial year, Mine P's ice thermal storage system afforded a unique opportunity for this study to analyse the operational and financial impact on the holistic cooling system, with and without the use of ice thermal storage.

Through case study implementation, the analytical approaches in constructing an accurate predictive simulation model on the use of ice thermal storage on mines was verified and validated. Validation results revealed an average percentage error of 6.5%. Actual implementation results with and without the use of ice thermal storage were critically analysed and compared, quantifying the financial impact and benefits gained by incorporating ice thermal storage on a mine cooling system. A holistic approach was adopted. Actual implementation results revealed significant load reduction and cost-saving potential. An average hourly load shift of 6.0 MW was achieved for the morning Eskom peak period during weekdays. Whereas, for Eskom's evening peak period, an average hourly load shift of 7.1 MW was achieved. This translates to an annual cost-saving potential of R 4.5 million. A reduction of R 502 per megalitre of water cooled was revealed when comparing a conventional refrigeration system to that incorporating the use of ice thermal storage. In addition, an average decrease of 42 kWh per megalitre of water cooled was realised. Consequently, service delivery requirements were compromised, with an overall deterioration of 7.1%. Represented by the global systems coefficient of performance, a reduction in the performance of the holistic refrigeration system of 14.3% was revealed. Comparing estimated cost savings to-date to that of the initial capital investment, a return on investment of just under 123 months (10.3 years) has been approximated.

Based on the findings obtained throughout this study, it is clear that ice thermal storage systems remain expensive with an unfavourable payback period. Since the majority of deep-level gold mines across South Africa are suffering with dwindling profit margins, ice thermal storage does not pose a feasible cost-saving strategy for many mining operations. However, ice thermal storage systems should be considered for implementation on profitable mines with a life of mine greater than 10 years. Not only does ice thermal storage offer significant cost-saving potential, but with mines planning to dig deeper in search of gold-rich ore deposits, ice thermal storage allows for expansion without the need to invest in additional refrigeration units.

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TABLE OF CONTENTS

ABSTRACT	I
ACKNOWLEDGEMENTS.....	III
TABLE OF CONTENTS	IV
LIST OF FIGURES	VI
LIST OF TABLES	IX
LIST OF EQUATIONS	XI
CHAPTER 1: BACKGROUND AND LITERATURE.....	1
1.1 Energy demand in South Africa	2
1.2 Challenges faced by the South African gold mining industry	4
1.3 Deep-level gold mining in South Africa.....	9
1.4 Background of refrigeration and cooling systems on deep-level mines.....	11
1.5 Investigating cost-saving potential on mine refrigeration systems.....	20
1.6 Thermal energy storage	33
1.7 Problem statement and study objectives.....	49
1.8 Overview of study	50
CHAPTER 2: METHODOLOGY TO EVALUATE ICE THERMAL STORAGE ON DEEP- LEVEL MINES	52
2.1 Introduction	53
2.2 Step 1: Characterising the system.....	55
2.3 Step 2: Constructing baseline models.....	60
2.4 Step 3: Developing a cost-saving strategy utilising ice thermal storage	71
2.5 Step 4: Implementation of proposed solution	87
2.6 Conclusion	94
CHAPTER 3: STRATEGY IMPLEMENTATION THROUGH PRACTICAL APPLICATION...95	
3.1 Introduction	96
3.2 Step 1: Characterising the system.....	96
3.3 Step 2: Constructing baseline models.....	101
3.4 Step 3: Developing a cost-saving strategy utilising ice thermal storage	105
3.5 Step 4: Case study implementation.....	119

3.6	Conclusion	154
CHAPTER 4: CONCLUSION AND RECOMMENDATIONS.....		156
4.1	Conclusion	157
4.2	Recommendations for future work	159
LIST OF REFERENCES		162
APPENDICES		172
Appendix A: Additional literature		172
Appendix B: Simulation output variables		189
Appendix C: Mine P's system specifications		190
Appendix D: Baseline modelling		194
Appendix E: Theoretical ice plant simulation modelling		199
Appendix F: Eskom's MegaFlex ToU tariff structure		203
Appendix G: Mine P's cooling system layout incorporating an ITS system		206
Appendix H: Ice thermal storage risk assessment		208
Appendix I: Actual implementation results Mine P		208

LIST OF FIGURES

Figure 1: IDM verified MW savings [9]	3
Figure 2: Eskom's variable ToU tariff structure [10].....	3
Figure 3: Number of employees vs annual employee earnings for the gold mining industry in South Africa [22][23]	5
Figure 4: Underground wet-bulb temperature vs corresponding production loss [29][31].....	7
Figure 5: Comparison of South Africa's gold production vs total gold and electricity price increases [22][23][35][36]	8
Figure 6: Virgin rock temperatures of South African deep mines [46].....	10
Figure 7: Mining processes as a percentage of the total electricity consumption (adapted from [51]).....	11
Figure 8: Generic layout of a surface mine cooling system	13
Figure 9: Cooling infrastructure requirements for various depths and temperatures [44][54].....	15
Figure 10: Operation strategies of TES systems (adapted from [69])	34
Figure 11: Charging and discharging procedure of ice-mass storage systems (adapted from [105])	37
Figure 12: Charging and discharging process of encapsulated ice (adapted from [105])	39
Figure 13: Ice harvesting system (adapted from [105])	40
Figure 14: Schematic of an ice slurry system [116].....	40
Figure 15: Methodological approach to evaluate and implement ITS on deep-level mines	54
Figure 16: Step 1 - Characterising the system.....	55
Figure 17: Simplified mine surface cooling system layout.....	56
Figure 18: Step 2 - Developing baseline models.....	60
Figure 19: Load reduction and operation strategy identification flow diagram	62
Figure 20: Cooling load profile example.....	63
Figure 21: Ambient dry-bulb temperatures for 2018	67
Figure 22: Example application of SLA and scaled baselines	69
Figure 23: Step 3 - Developing a cost-saving strategy utilising ice thermal storage	71
Figure 24: Methodology to analyse pre-existing energy and cost-saving initiatives	74
Figure 25: Step 4 – Implementation of proposed solution	88
Figure 26: Surface cooling system process flow diagram - Mine P.....	98
Figure 27: Electrical power baselines - Mine P.....	102
Figure 28: Electrical power baselines - Mine P.....	103
Figure 29: Ice dam outlet temperature simulation results - baseline 1.....	112

Figure 30: Simulated surface chill dam water temperature - baseline 1	113
Figure 31: Simulated system power consumption - baseline 1	114
Figure 32: Ice dam overview - Mine P	122
Figure 33: Ice coil circuiting	122
Figure 34: Comparable boundary conditions - baseline period 1	125
Figure 35: Refrigeration system power consumption - Mine P, baseline period 1	126
Figure 36: Running status of installed chillers - Mine P, baseline period 1	127
Figure 37: Ice dam outlet temperature during morning ice melt - Mine P, baseline period 1	128
Figure 38: Ice dam outlet temperature during evening ice melt - Mine P, baseline period 1	129
Figure 39: Surface chill dam temperature - Mine P, baseline period 1	130
Figure 40: Combined COP of installed chillers - Mine P, baseline period 1	131
Figure 41: Pre-cooling sump and chill dam levels - Mine P, baseline period 1	133
Figure 42: Global system COP - Mine P, baseline period 1	135
Figure 43: Refrigeration system power consumption - Mine P, baseline period 2	137
Figure 44: BAC air outlet WB temperature comparison - Mine P, baseline period 2	139
Figure 45: Surface chill dam temperature comparison	152
Figure 46: Overall system power consumption comparison	153
Figure 47: Eskom's week-on-week energy availability [137]	172
Figure 48: Vertical forced draught cooling tower [138]	173
Figure 49: Multi-stage horizontal forced draft BAC [138]	175
Figure 50: Various chiller configurations used in industry (adapted from [28])	176
Figure 51: Schematic of a 3CPFS [150]	180
Figure 52: Schematic overview of a back-pass valve control [72][77]	182
Figure 53: External melt ice-on-coil operation [135]	182
Figure 54: Monthly energy consumption with and without ITS [121]	185
Figure 55: Monthly energy cost with and without ITS [121]	185
Figure 56: Integrated simulation model - Mine P's surface cooling system	194
Figure 57: Power profile verification – baseline 1	195
Figure 58: Power profile verification – baseline 2	195
Figure 59: Power profile verification – baseline 3	196
Figure 60: Power profile verification – baseline 4	196
Figure 61: Surface chill dam verification - baseline period 2	197
Figure 62: BAC air outlet temperature verification - baseline period 2	197

Figure 63: Pre-cooling towers verification - baseline period 2	198
Figure 64: Integrated simulation model - incorporating an ITS system.....	199
Figure 65: Simulated system power consumption - baseline 2	201
Figure 66: Simulated system power consumption - baseline 3	201
Figure 67: Simulated system power consumption - baseline 4	202
Figure 68: Mine P's surface cooling system during the ice-making cycle (preparation period).....	206
Figure 69: Mine P's surface cooling system during the ice-melting cycle (peak periods)	207
Figure 70: Refrigeration system power consumption - Mine P, baseline period 3	209
Figure 71: Refrigeration system power consumption - Mine P, baseline period 4	213

LIST OF TABLES

Table 1: Evaluation of existing load management initiatives on mine refrigeration systems	29
Table 2: Primary features of energy storage mediums (adapted from [102][105])	35
Table 3: Comparative summary of ITS techniques	47
Table 4: Identified constraints influencing the implementation of ITS systems on deep-level mines	58
Table 5: Required system specifications	59
Table 6: Electrical baseline development through the application of statistics	66
Table 7: Cooling system process variables	70
Table 8: Ice plant model simulation input variables [130]	81
Table 9: Operational status of Mine P's cooling system components throughout the year	99
Table 10: System constraints - Mine P	100
Table 11: Chiller utilisation percentages - Mine P	102
Table 12: Application of Equation 6	103
Table 13: Process variables - Mine P	104
Table 14: Process parameters simulated versus actual comparison – baseline period 2	107
Table 15: Application of analytical approach for simulation model - baseline period 1	110
Table 16: Simulation input variables for ITS system calibration: baseline period 1	111
Table 17: Summary of simulated ITS implementation results – baseline 1	114
Table 18: Summary of simulated hourly load shifts	117
Table 19: ITS system requirements	117
Table 20: Basic overview of equipment requirements for Mine P's ITS system	118
Table 21: Summary of baseline period 1 implementation results - baseline and assessment period	135
Table 22: ITS system characteristics - baseline period 1	136
Table 23: Summary of baseline period 2 implementation results - baseline and assessment period	138
Table 24: ITS system characteristics - baseline period 2	140
Table 25: Summary of weekday electricity cost savings - baseline period 1	143
Table 26: Summary of annual electricity cost savings - Mine P	144
Table 27: Cost saving comparison	145
Table 28: Approximate cost savings achieved to-date	145
Table 29: Cost and energy comparisons to cool water	147
Table 30: Comparison of theoretical and actual ITS system requirements – Mine P	150
Table 31: ITS simulation validation – operational impact of baseline 1	151
Table 32: ITS simulation validation - economic evaluation	154

Table 33: Commercially available simulation packages	189
Table 34: Simulation model output variables [130].....	189
Table 35: Technical specifications of Mine P	190
Table 36: Operating control limits - Ammonia chillers	192
Table 37: Operating control limits - Hitachi chillers.....	193
Table 38: Simulated load shift control philosophy – Mine P.....	200
Table 39: Application of analytical approach for simulation model - baseline period 2	202
Table 40: Eskom's 2018/2019 MegaFlex ToU winter tariff structure [36]	204
Table 41: Eskom's 2018/2019 MegaFlex ToU summer tariff structure [36]	205
Table 42: Eskom's MegaFlex ToU tariff history [36]	205
Table 43: Ice thermal storage risk assessment matrix	208
Table 44: Summary of baseline period 3 implementation results - baseline and assessment period	210
Table 45: ITS system characteristics - baseline period 3	211
Table 46: Summary of baseline period 4 implementation results - baseline and assessment period	212
Table 47: ITS system characteristics - baseline period 4	213

LIST OF EQUATIONS

Equation 1: Global coefficient of performance of entire integrated cooling system [81]	24
Equation 2: Thermal load absorbed by entire cooling system [81]	24
Equation 3: Chiller machine utilisation	63
Equation 4: Service level adjustment factor	68
Equation 5: Scaled baseline calculation	68
Equation 6: Melting rate of stored ice	83
Equation 7: Required mass of ice	83
Equation 8: Ice building cooling duty	84
Equation 9: Required ice building rate	84
Equation 10: Amount of stored energy in the form of ice	86
Equation 11: Payback period	86
Equation 12: Energy consumption required to cool daily water volumes	92
Equation 13: Total cost to cool daily water volumes	93
Equation 14: Coefficient of performance of vapour-compression refrigeration cycles [81]	177
Equation 15: Coefficient of performance of ammonia-absorption refrigeration cycles [81][145]	178
Equation 16: Thermal energy absorbed in the evaporator	178
Equation 17: Quartile formulas	188
Equation 18: Standard deviation of a sample	188

NOMENCLATURE

List of units

Symbol	Description	Units
°C	Measure of temperature	Degrees Celsius
c	Measure of currency	South African cent
G	Denotes 1×10^9	Giga
g	Measure of mass	Gram
J	Measure of energy	Joule
k	Denotes 1×10^3	Kilo
L	Unit of measure	Level
<i>l</i>	Measure of volume	Litre
M	Denotes 1×10^6	Mega
m ²	Measure of area	Square metre
m ³	Measure of volume	Cubic metre
m	Measure of distance	Metre
mm	Measure of distance	Millimetre
Pa	Measure of pressure	Pascal
R	Measure of currency	South Africa rand
t	Measure of mass	Ton
W	Measure of power	Watt
Wh	Measure of energy	Watt-hour

List of symbols

Symbol	Description	Units
α	Expansion coefficient	-
η_w	Water-side efficiency	-
ρ	Density	kg/m^3
σ	Standard deviation of sample	-
$C_{cooling}$	Daily cost of cooling	R
$Cooling\ ratio_{cost}$	Cost to cool a specific volume of water	R/l
$Cooling\ ratio_{energy}$	Energy required to cool a specific volume of water	kWh/l
COP_{global}	Coefficient of performance of integrated cooling system	-
$C_{p,w}$	Specific heat constant of water	$kJ/kg.K$
$E_{cooling}$	Daily energy consumption due to cooling	kWh
h_{fg}	Latent heat of fusion	kJ/kg
kWh_{actual_i}	Half-hourly actual energy consumption	kWh
$kWh_{baseline_i}$	Half-hourly unscaled baseline	kWh
Q_1	Lower quartile range	-
Q_2	Median	-
Q_3	Upper quartile range	-
Q_4	Maximum value in sample	-
$\dot{Q}_{evaporator}$	Thermal load absorbed in the evaporator	kW
$\dot{Q}_g$	Thermal load supplied by the generator	kW
$\dot{Q}_{ice}$	Cooling capacity of ice	kW
Q_{ice}	Amount of stored energy in the form of ice	kWh
$\dot{Q}_{ice-build}$	Refrigeration cycle cooling duty	kW
$\dot{Q}_{cooling\ system}$	Total thermal load of integrated cooling system	kW
$\dot{Q}_w$	Cooling capacity of water	kW

m_{ice}	Mass of ice	kg
$\dot{m}_{ice,b}$	Ice building rate	kg/s
$\dot{m}_{ice,m}$	Melting rate of stored ice	kg/hr
$\dot{m}_w$	Mass flow rate of water	kg/s
$\dot{m}_{w,daily\ avg}$	Daily average mass flow rate of water	kg/s
n	Number of terms in sample	-
$Scaled_{baseline_i}$	Half-hourly adjusted baseline	kW
SLA_i	Half-hourly SLA factor	-
$T_{ai(WB)}$	Air inlet WB temperature	°C
$T_{cold\ dam}$	Cold dam water temperature	°C
$T_{hot\ dam}$	Hot dam water temperature	°C
$T_{ice-build}$	Ice building water temperature	°C
$t_{ice-build}$	Duration of ice building process	Hours
t_{peak}	Duration of peak period	Hours
$T_{w,i}$	Inlet water temperature	°C
$T_{w,o}$	Outlet water temperature	°C
$Unscaled_{baseline_i}$	Half-hourly unscaled baseline	kW
V_{sys}	Total volume of water cooled per day	l
W_c	Compressor electrical power	kW
W_{in}	Total electrical power consumed	kW
W_p	Pump electrical power	kW
$W_{cooling.\ system}$	Electrical power consumption of integrated cooling system	kW
$\bar{X}$	Mean of the sample set	-
X_i	Each value in the sample	-

LIST OF ABBREVIATIONS

Symbol	Description
3CPFS	Three chamber pipe feeder system
AISC	All-in sustaining costs
ARS	Ammonia-absorption refrigeration cycle
BAC	Bulk air cooler
BAU	Business-as-usual
BRICS	Brazil, Russia, India, China and South Africa
CAPEX	Capital expenditure
COP	Coefficient of performance
DB	Dry-bulb
DSM	Demand side management
EAF	Energy availability factor
EMS	Energy management system
EPI	Energy performance indicator
ESCO	Energy service company
FY	Financial year
GDP	Gross domestic product
GUI	Graphical user interface
HVAC	Heating, ventilation and air conditioning
HIP	Howden ice plant
IDM	Integrated demand management
IGV	Inlet guide vane
ITS	Ice thermal storage
KPI	Key performance indicator
M&V	Measurement and verification
MR	Melting rate

MWt	Mega watt thermal
NERSA	National Energy Regulator of South Africa
OPC	Open platform communication
P&ID	Proportional-integral-derivative
PB	Payback
PCM	Performance-centered maintenance
PI	Proportional-integral
PLC	Programmable logic controller
PTB	Process Toolbox
SCADA	Supervisory control and data acquisition
SD	Standard deviation
SLA	Service level adjustment
TES	Thermal energy storage
ToU	Time-of-use
VRT	Virgin rock temperature
VSD	Variable-speed drive
VUMA	Ventilation of Underground Mine Atmospheres
WB	Wet-bulb

GLOSSARY

<i>Air agitation</i>	Process of adding turbulence to the ice water by bubbling air through the tank. This ensures that the water in the storage tank is mixed evenly, resulting in a constant temperature throughout.
<i>Auto-compression</i>	Commonly referred to as adiabatic compression, is a process whereby air entering and descending down the shaft is compressed by the weight of atmospheric air, causing the pressure and temperature of the air to increase.
<i>Deep-level mining</i>	Represents a method of extracting mineral deposits utilising underground mining methods, typically reaching depths in excess of 1.5 km.
<i>Demand limiting strategy</i>	A type of thermal energy storage strategy, representing a system that turns off operational chillers during periods when electricity rates are highest, relying on the stored ice to provide the required cooling load.
<i>Energy availability factor</i>	Defined over a specified period; the energy availability factor is a measure of the plant availability incorporating energy losses. The factor represents a ratio of the available energy generation to the reference energy generation.
<i>Financial year</i>	In the context of this study, a financial year corresponds to Eskom's billing dates.
<i>Full storage strategy</i>	Full storage systems are one in which the entire design load is generated and stored during off-peak periods or at night, ready for use during peak periods. This implies that the chillers will be standing during the day when the cooling load is maximum, with the provision of adequate cooling supplied by the stored thermal energy.
<i>Millennium ice</i>	Ice remanence attached to the ice coils proceeding the ice-melting process.
<i>Mine cooling system</i>	In the context of this study, the pumping, air-cooling and refrigeration systems are collectively defined as the mine cooling system.
<i>Partial storage strategy</i>	In partial storage systems, only a portion of the design load is generated and stored during the off-peak period. The chillers operate continuously

throughout the day, with part of the cooling load satisfied by the thermal energy storage system.

Refrigeration

Involves the process of artificial cooling, removing heat from one source and rejecting it to another.

Supercooling

Occurs when a substance is rapidly cooled to below its freezing point in the absence of phase change.

Sustainability

The ability to maintain a process at a certain rate for an extended period of time.

Thermal energy storage

A technology that reserves energy, typically stored in a thermal reservoir for later use. Energy, in the form of chilled water, ice or eutectic salts, is charged and stored during periods of low-demand, thereafter, during peak demand periods, the energy is discharged and used as required.

Validation

Involves the process of checking whether the identified problem is solved by the proposed solution.

Verification

Confirms that a proposed methodological or analytical approach provides the expected results.

CHAPTER 1: BACKGROUND AND LITERATURE



1, 2

This chapter summarises the challenges faced by the South African gold mining industry. An overview of deep-level mine cooling systems is provided. Existing load management strategies implemented on mines and in industry are identified and critically evaluated. Ice utilised as an alternative cost saving technique is explored.

¹ <https://www.miningreview.com/jobs/finance-manager-ca-pastel-cashflows-finance-south-africa/>

² <https://thesa-mag.com/features/mining/departments-mineral-resources-protecting-nations-interests-assets/>

1.1 Energy demand in South Africa

One of the major challenges the South African power utility, Eskom, has had to face in the past and foreseeable future, is ensuring a secure and sustainable energy supply [1]. Over the years, the South African power grid has been subjected to immense strain. The rapid expansion of the public, mining and industrial sectors has been identified as one of the contributing factors straining the national power grid [2].

In 2008, Eskom experienced a severe electricity crisis, struggling to match the consumers' electricity demands due to insufficient power generation. In response to this, Eskom embarked on a massive expansion programme to alleviate power supply shortages through the construction of two new coal-fired power stations, Medupi and Kusile [3]. The expansion programme was due to be completed by 2015 with an estimated cost of R 163.2 billion [4]. However, due to various oversights, poor execution and inadequate planning, project completion has been delayed until 2023 [4]. In addition to oversight discrepancies, technical problems experienced with the current boiler units in commercial operation at Medupi and Kusile power stations have only added fuel to the fire. According to the general manager of the National Energy Regulator of South Africa (Nersa), for the financial year (2018/2019), the commissioned units have tripped in total 84 times [5][6]. This marks for further concern over the future sustainability and reliability of Eskom's planned power supply. In the context of this study, a financial year corresponds to Eskom's billing dates. Therefore, the 2018/2019 financial year commenced on 17th June 2018 and ended on 16th June 2019.

Figure 47 found in Appendix A1 illustrates Eskom's energy availability factor (EAF) between 2016 and 2018, as well as for the first 12 weeks of 2019. Significantly, it may be observed that the EAF is on the decline over this period. As measured by the EAF, Eskom's plant performance dropped by approximately 7.4% for the first 12 weeks of 2019 when compared to 2018 for the same period. Taking into consideration that continuous maintenance and upgrades are still required on Eskom's ageing fleet of power stations, Eskom is faced with a significant challenge to meet the consumers' demand and supply sufficient electricity.

In an effort to alleviate strain on the power grid, reduce electricity consumption and ensure energy security, Demand Side Management (DSM) initiatives have gained substantial focus over the past decade. DSM or Integrated Demand Management (IDM) is an energy management method driven through the application of load management and implementation of energy efficiency strategies [7]. Since their inception, DSM initiatives have proven to be successful with significant reductions in the electricity demand in South Africa. Further studies suggest that these initiatives implemented in the industrial and mining sectors possess the capability to improve machine efficiency and processes [8]. Figure 1 illustrates the year-on-year demand savings from 2003 until the financial year end 2018 [9]. Although DSM initiatives have effectively displaced the capacity equivalent to an entire power station (approximately 3 600 MW), to ensure the sustainability of Eskom and accommodate further economic development, substantial reductions in power

usage are still required. More emphasis needs to be placed on creative energy efficiency technologies and load reduction strategies.

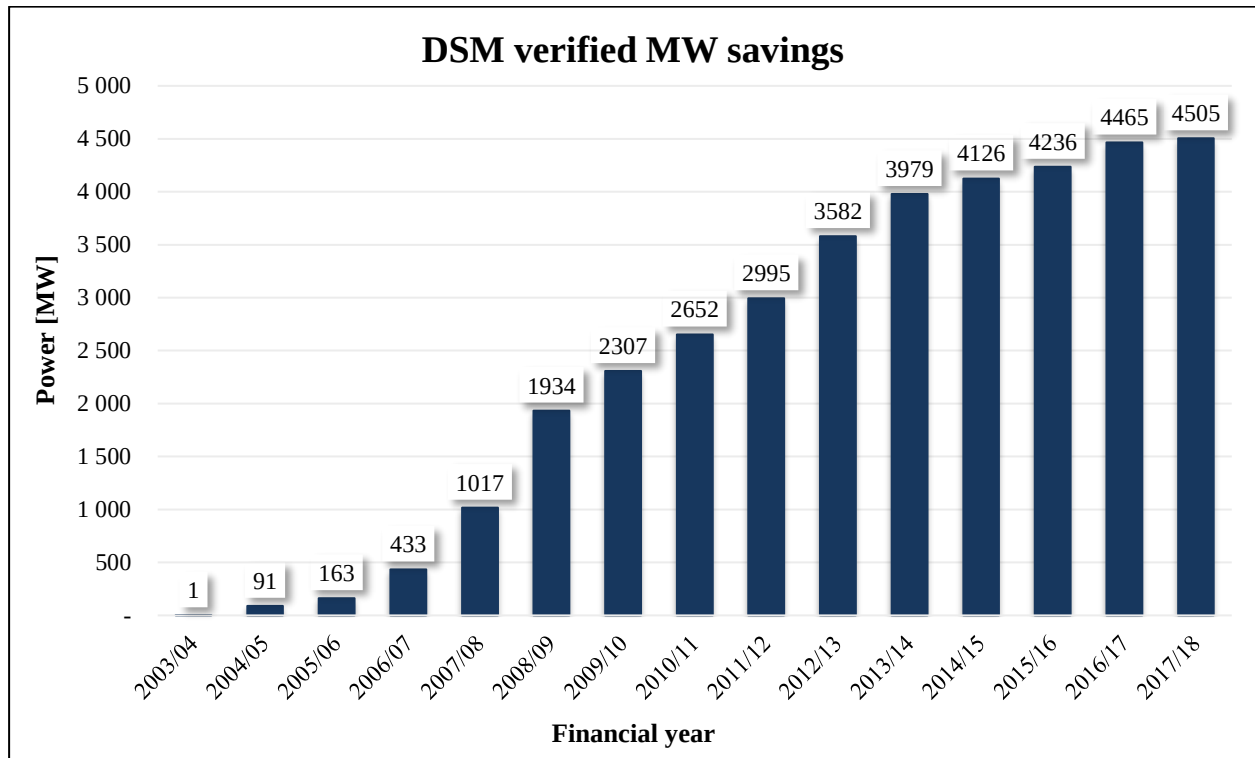


Figure 1: IDM verified MW savings [9]

To assist the struggling power grid during periods of high-demand, Eskom has devised a Time-of-Use (ToU) tariff structure. Based on the time of day and corresponding power usage, the schedule is categorised into off-peak, standard and peak hours. Figure 2 displays how the Megaflex ToU tariff is structured during both summer (low-demand season) and winter months (high-demand season).

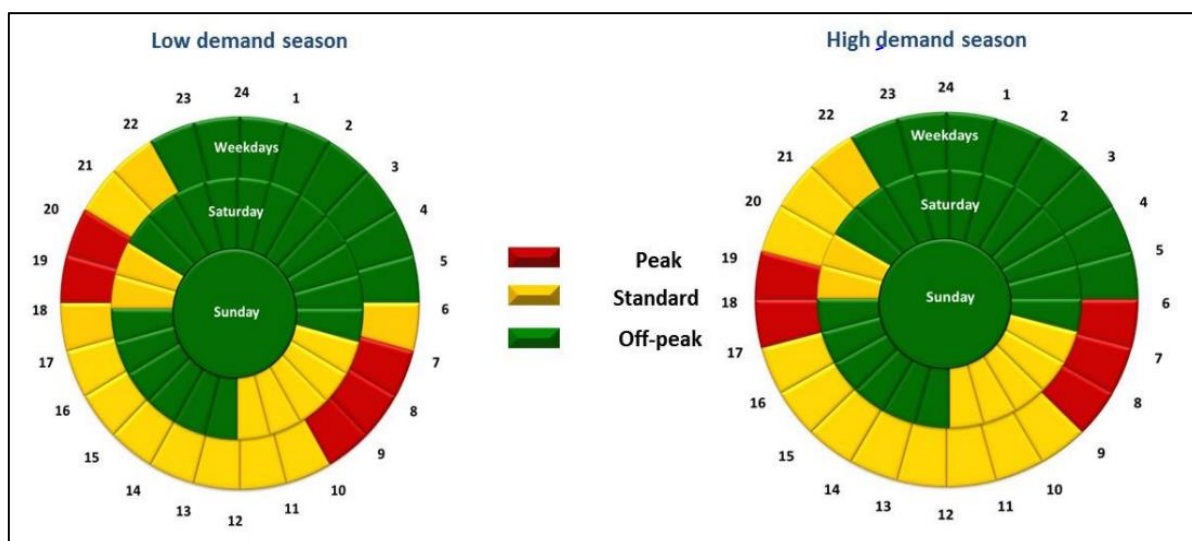


Figure 2: Eskom's variable ToU tariff structure [10]

Eskom considers “peak” periods most devastating to the national power grid, therefore, subsequently charging consumers to pay more during these periods [10]. As of April 2019, according to the Megaflex tariff schedule, under which mining operations are characterised, consumers will be expected to pay up to 500% more for electricity usage during peak periods than during off-peak periods [11]. The variable tariff structure was implemented by Eskom to force large consumers of electricity to reduce their power usage during peak periods, thereby providing stability to the national power grid.

Traditionally, compared to international standards, over the past three decades, electricity prices in South Africa have been relatively low. Between 2007 and 2017, electricity prices have increased by approximately 356%, severely exceeding inflation which has increased by just over 74% over the same period [12]. With Nersa confirming a further electricity price increase of 27.1% between April 2018 and 2021, compared to the BRICS countries, South Africa’s electricity will be the least affordable [12][13][14].

For the financial year 2017/18, the mining industry made up 14.2% of Eskom’s total 212 190 GWh electricity sales [15]. Compared to the various mining firms present in South Africa, gold mining operations are the most vulnerable to fluctuations in the price of electricity. This is mainly due to the energy-intensive nature of deep-level mining and the ever-decreasing competitiveness within the global markets ensuring they are unable to influence the price of gold [3].

1.2 Challenges faced by the South African gold mining industry

1.2.1. Introduction

Historically, compared to international standards, South Africa’s economy is energy-intensive [16][17][18]. This implies that the country consumes a large amount of energy per unit of Gross Domestic Product (GDP) output. This was particularly true for the industrial and mining sectors largely due to low electricity prices and equally low commodity prices. In a survey conducted in 2010, it was found that the non-ferrous metals and gold mining industries were responsible for approximately 25% of the country’s total electricity consumption, with just 4% contribution to GDP [3]. This confirms that the mining industry has historically been extremely wasteful of electricity. With recent electricity price tariff increases and future projections, mining industries are experiencing a significant increase in operational costs and cannot afford to abuse energy.

Together with improving asset productivity, reducing the cost to operate are the most important drivers for innovation within the South African mining industry [19]. Although energy usage and electricity price increases have become one of the most prominent reasons for dwindling profit margins in the gold mining industry, there remain several other challenges restraining the profitability of gold mining operations across South Africa. As a result, South African mining companies are struggling to remain financially competitive.

1.2.2 Socio-economic challenges

Since the gold rush, the gold mining industry has been one of the primary providers of employment in South Africa. Many of the gold deposits found in these mines are characterised by narrow reefs with an approximate stoping width of 1 m [20]. This implies that mechanisation is either difficult or not possible, therefore, yielding a highly labour-intensive sector [20]. Due to high levels of unemployment and poverty, the mining industry is largely responsible for the socio-economic development of local mining communities through job creation [21]. This implies that any economic impact felt directly by the mining industry will be equally conveyed throughout local mining communities. This creates for fragile labour relations between employer and employee.

Figure 3 illustrates the number of employees vs the annual average employee earnings for the gold mining sector in South Africa between 2007 and 2018. Due to the increase in labour costs, mines have been forced to retrench employees in an attempt to reduce operating costs. The progressive decline in employment and rapid increase in annual employee earnings has adversely impacted labour costs which further exaggerates the financial strain experienced by gold mining operations.

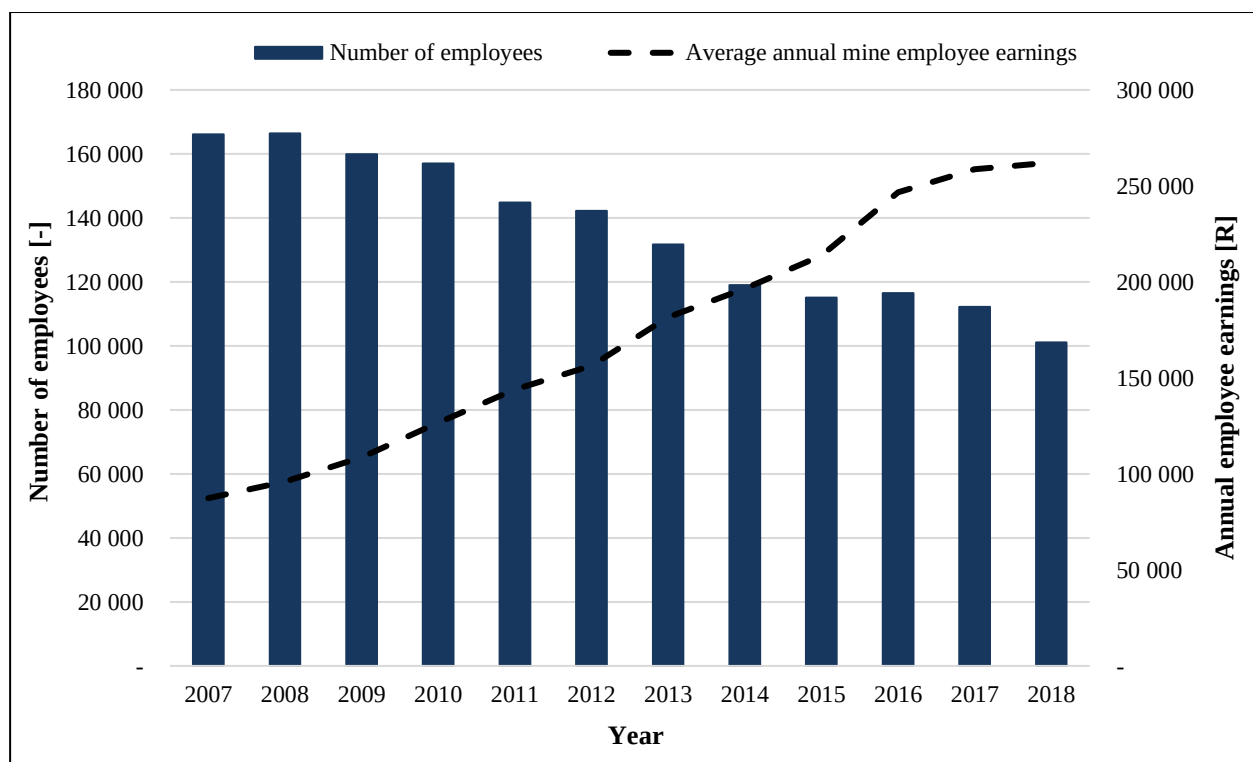


Figure 3: Number of employees vs annual employee earnings for the gold mining industry in South Africa [22][23]

1.2.3 Declining gold grade

Since the inception of the South African gold mining industry in the early 1900's, gold mining operations were able to exploit high-grade gold deposits at relatively shallow depths. However, since these ore deposits

have already or are busy being mined out, mining companies have been forced to mine deeper in search of new ore deposits. Therefore, increasing the cost of extraction.

Between 2004 and 2015, the gold grade recovered for both open-cast and underground mining operations in South Africa has decreased by approximately 43% [23]. Müller and Frimmel (2010) predicted that by the year 2050, gold ore grades could be as low as 0.9 g/t if current trends remain unchanged [24]. According to precious metal analyst Leon Esterhuizen, since the 1990's, the South African deep-level gold mining industry has lost the ability to compensate low tonnage with higher ore grades due to the depletion of the best high-grade resource deposits [25]. This further exemplifies the need for optimisation in gold mining operations in order to obtain maximum value from current low-grade deposits. Declining ore grades of existing deposits have only amplified the looming demise of the gold mining industry in South Africa [26].

1.2.4 Increasing costs in production

It has previously been discovered that there is an exponential relationship between the grade of ore and corresponding processing costs. In an investigation conducted by Mudd (2007), it was concluded that the lower the grade of gold, the higher the cost per unit gold produced [27]. This implies that due to declining gold ore grades, the resource intensity of gold production increases at an exponential rate. In addition to the energy consumption required to extract a unit of gold increasing quite significantly, the costs associated with mining processes have also increased. Along with cost-saving initiatives, the implementation of modern technologies and processes is imperative to offset increasing operational and processing costs [25].

1.2.5 Mining at increasing depths

Home to some of the deepest mines in the world, in excess of 3 km, South African gold mining companies are mining deeper and deeper in search of new gold ore deposits. With rock face temperatures reaching up to 60°C, mining at such depths requires extensive cooling and ventilation [28]. Coupled with increases in the cost to cool and ventilate the mine at increased depths, the necessity of additional rock support to ensure a safe working environment have contributed quite significantly towards ever-increasing operational costs.

To add to the challenge of increased extraction costs, mining deeper underground adversely impacts productivity. Whillier (1971), as cited by Belle and Biffi (2018), mentioned that there is a relationship between a miners' performance and underground wet-bulb (WB) conditions [29]. Once working conditions reach a WB temperature of 27.5°C, it becomes mandatory to introduce artificial cooling [29]. Figure 4 indicates the relationship between underground WB temperatures and a workers' physical performance. To encourage a productive shift, WB temperatures should not exceed 27.5°C. Once exceeded, the physical and mental performance of mine workers significantly decrease, therefore reducing productivity [30].

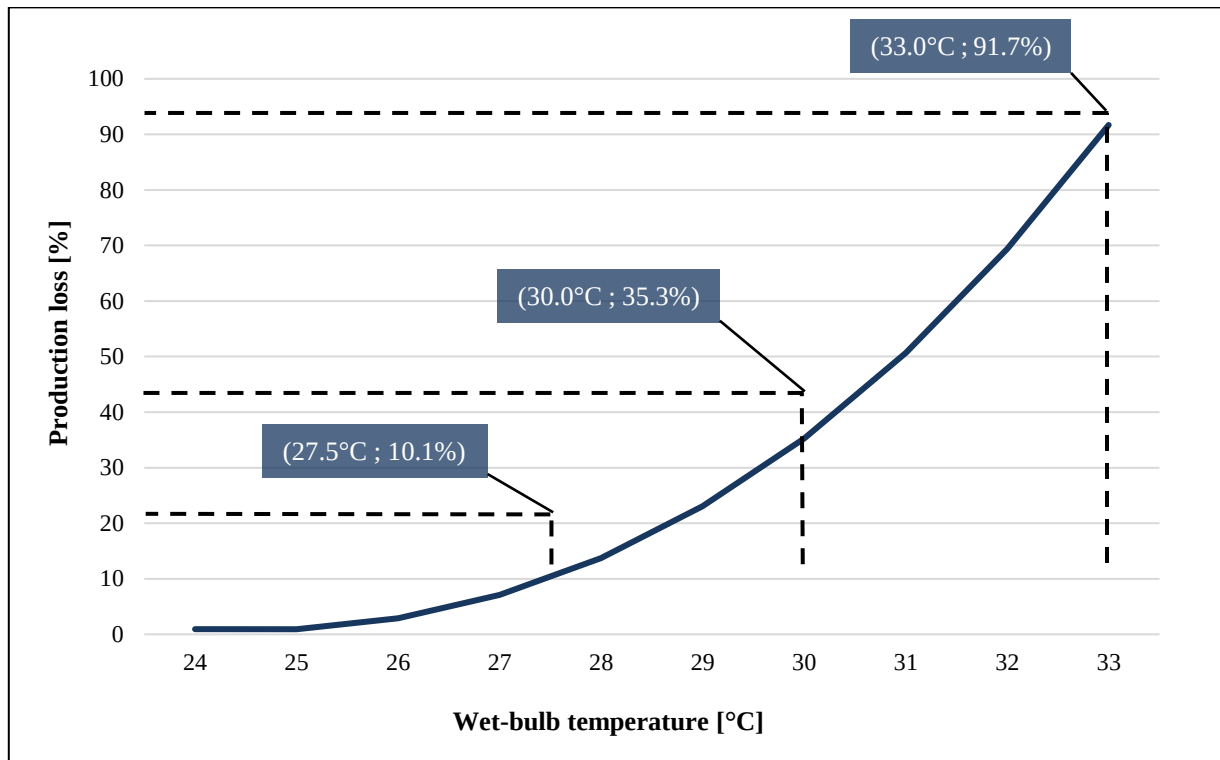


Figure 4: Underground wet-bulb temperature vs corresponding production loss [29][31]

Mining deeper does not only increase the travel time to reach rock faces but imposes additional safety issues. This implies that further production time is lost due to the requirement of additional safety procedures that need to be followed and adhered to.

1.2.6 Declining gold production trends

Although the gold mining industry offers a relatively small contribution towards the GDP in South Africa, it still plays a vital role in the socio-economic development of the country. Gold mining companies are finding it increasingly difficult to remain internationally competitive, accounting for only 4% of the global gold production in 2018 [32].

According to recent declining gold production trends and rapidly increasing input costs, approximately 71% of all gold mining operations across South Africa were unprofitable or marginal towards the end of 2018 [21][33]. Figure 5 illustrates a comparison of South Africa's annual gold production vs total gold and electricity price increases between 2007 and 2018. Between 2007 and 2018, the total amount of gold produced in South Africa has decreased by 47%. This is partly due to the reliance on older, inefficient mining equipment and a rapid decrease in the workforce involved in the gold mining sector as depicted in Figure 3. Through further observation of Figure 5, it is evident that the average price increase of electricity far exceeds that of increases in the gold price. Without changing the cost structure of a mine, lower production will only result in higher unit costs.

In the absence of profitability, the position isn't sustainable. On 31st December 2018, commenting on interim results sustained for the first half of the 2018/19 financial year, Harmony Gold reported heightened all-in sustaining costs (AISC) expected to be in the range of between R 520 000/kg and R 530 000/kg for the remainder of the financial year [34]. With the rand gold price ranging between R 564 136/kg and R 613 795/kg for the third quarter of the 2018/19 financial year, mine margins are under pressure due to volatile commodity prices [35]. The volatility in the rand gold price has made it increasingly difficult for mining companies to plan ahead. It is clear that the South African gold mining industry is rapidly declining to a point where the economic viability of gold mining in the country is at risk.

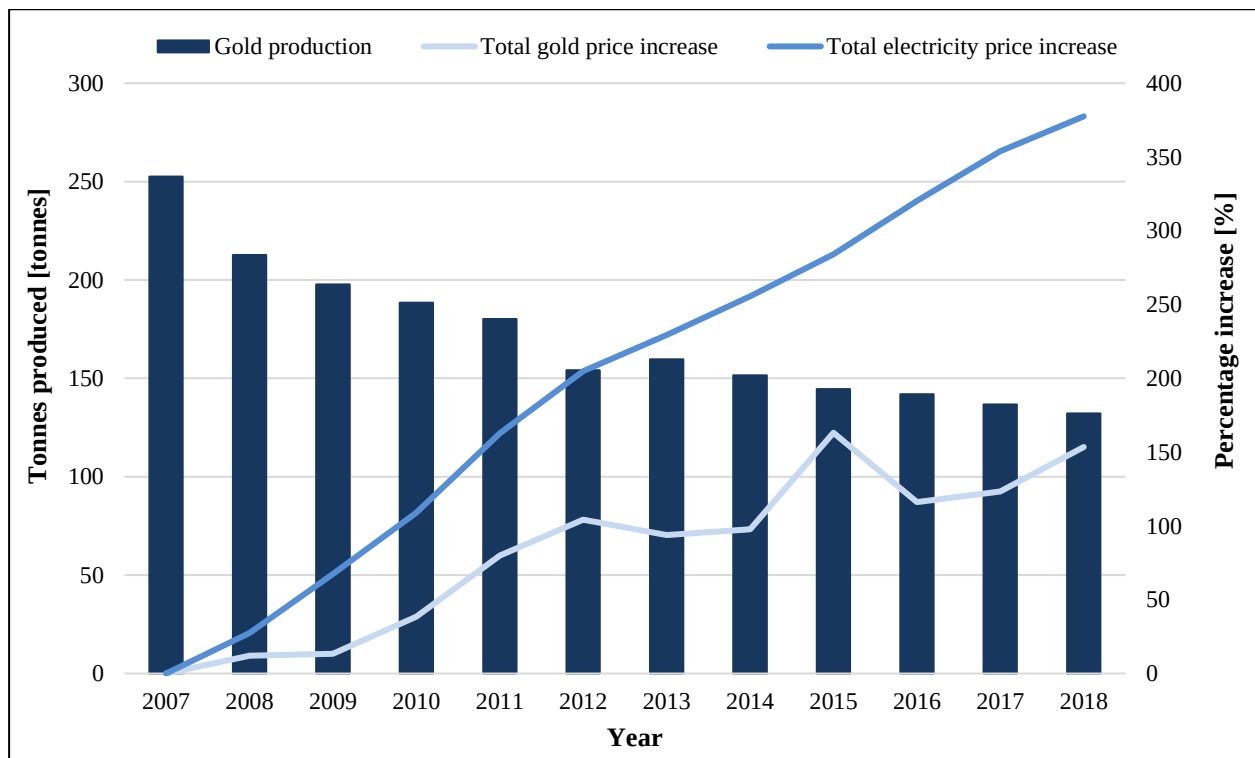


Figure 5: Comparison of South Africa's gold production vs total gold and electricity price increases [22][23][35][36]

With approximately 95% of South Africa's gold production originating from underground mines, the future of the gold mining industry in the country is highly dependent on the economic sustainability of deep-level mines [20]. With ever-increasing input costs, gold mining operations in South Africa are facing insolvency with rapidly dwindling margins for profit. A weakening in the solvency ratio between 2017 and 2018 reiterates the current stance of the South African gold mining industry and their ongoing struggle to deal with an underperforming gold price and increased operational costs [37].

Rapidly escalating electricity and labour costs have in recent years been the main reason behind the dwindling profitability of many gold mines. Since deep-level gold mining is labour intensive, labour-related costs are by far the highest, accounting for up to 53% of total costs [38]. As a short-term solution, when mines become marginal or unprofitable, large-scale retrenchments are inevitable. As a result of

restructuring the workforce, downscaling of mining operations and subsequently reducing production is unavoidable. In essence, in an attempt to reduce operating costs, a mine sacrifices a portion of its revenue stream. The solution is unsustainable. Focus should be aimed on implementing more efficient technology and cost-effective energy management initiatives with the ability to reduce unit costs. To ensure continuous improvement of mining practices and the efficient use of energy, modernisation is essential [25].

Coupled with escalating energy consumption and electricity costs, the gold mining sector has recently been compounded by the questionable sustainability of Eskom's power supply. Consuming just over a seventh of electricity supplied by Eskom, gold mining operations are heavily reliant on an affordable and stable energy supply. Further sporadic supply disruptions and the looming possibility of load-shedding continue to cast concern within mining companies across South Africa [34].

With electricity costs already accounting for approximately 16% of a mine's expenditure [39], in addition to increased energy consumption, mining operations have also been impacted by continuously increasing electricity tariffs. In a country with variable electricity price tariffs, there exists significant potential for mines to invest in innovative cost saving solutions and modern technologies that will not only reduce costs of operation but will assist the power grid by shifting load out of peak demand periods, reducing strain on the grid. Since deep-level mines consume a vast amount of electricity for cooling and ventilation, booming energy costs have become the principal driver for mines to seek alternative optimisation strategies and energy management solutions in order to promote both short- and long-term profitability and reduce energy consumption by becoming more energy efficient in their operations [40].

1.3 Deep-level gold mining in South Africa

As the search for gold takes mining operations beyond shallow, low-lying orebodies, South African mines have been directed towards deeper underground operations. With the introduction of deeper working environments, miners are subjected to various hazards that pose a threat to productivity, health, safety and morale. Of these hazards, the most detrimental is excessive heat.

The main sources of heat contributing to elevated underground environmental temperatures include: mechanical processes, machinery, oxidation of the orebody and/or timber used for bracing, human metabolism, auto-compression, steep geothermal gradients and blasting [41][42]. Typically, the effects of auto-compression and steep geothermal gradients offer the most significant contribution to heat loads in deep-level mines [41]. Auto-compression, also commonly referred to as adiabatic compression, is a process whereby air descending down the shaft is compressed by the weight of atmospheric air, causing the pressure and temperature of the air to increase. As air descends down a shaft, its potential energy is converted into enthalpy [43]. An increase in enthalpy will either cause an increase in pressure or internal energy or both,

therefore, increasing the temperature of air. The temperature gradient of air descending down a mine shaft due to auto-compression is approximately $1^{\circ}\text{C}/100\text{m}$ [44].

Measured in $^{\circ}\text{C}/\text{m}$, steep geothermal gradients result in elevated virgin rock temperatures (VRTs), with the rate of increase dependent on the thermal conductivity of the rock [45]. Figure 6 illustrates the geothermal temperature gradients experienced in South Africa's deep-level mines. The thermal conductivity of rock found in platinum mines is typically lower than that found in gold mines. At a depth of 2.2km, platinum mines experience VRTs of up to 70°C , compared to 40°C experienced in gold mines at the same depth.

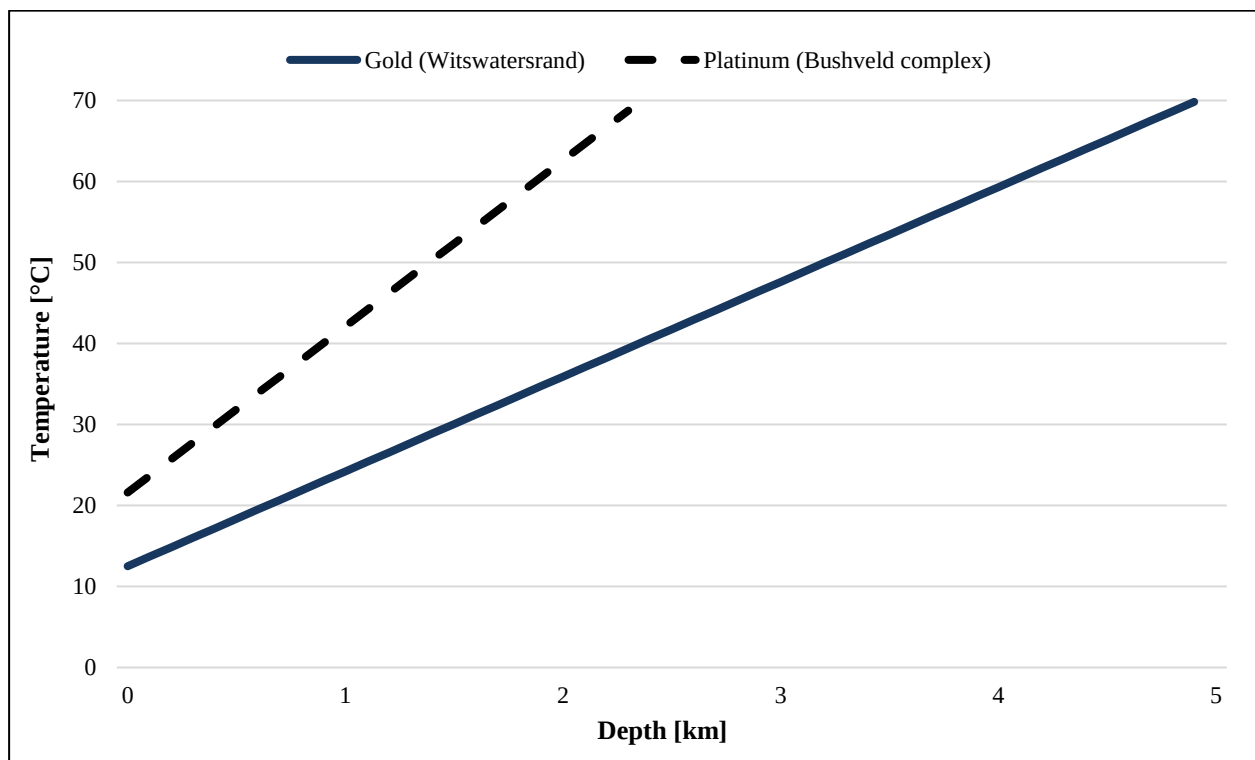


Figure 6: Virgin rock temperatures of South African deep mines [46]

According to data analysed and reported by Jones (2018), VRTs associated with deep mines easily reach up to 50°C [46]. With legislation in South Africa prohibiting underground working conditions from exceeding a WB temperature of 27.5°C [47], coupled with steep geothermal gradients and ever-increasing depth at which ventilation air must reach, deep mines are faced with a significant challenge to cool underground networks at various depths.

In recent years, mining for gold at depths of 3 km has become the norm. It is believed that many gold mines in the Witwatersrand region have already begun detailed planning to accommodate for production at a depth in excess of 4 km [48][49]. To meet stringent legislation and ensure a comfortable, habitable working environment, the required cooling load is heavily dependent on VRTs and mining depths. According to Els (2000), the cooling of underground networks is solely reliant on its refrigeration system [50]. Bluhm et. al (2000) suggested that at depths greater than 3 km, between 370 kW and 570 kW of refrigeration per kiloton

per metre (kt/m) is required [48]. This implies that as development continues, and mines become deeper, more complex and energy-intensive mine refrigeration systems are required to mitigate the effects of escalating heat loads and provide chilled water for mining processes. Figure 7 displays the electricity consumption of various deep-level mining processes as a percentage of the total consumption. Of all the mining operations, mine refrigeration systems consume up to 24% of the total electrical energy [51].

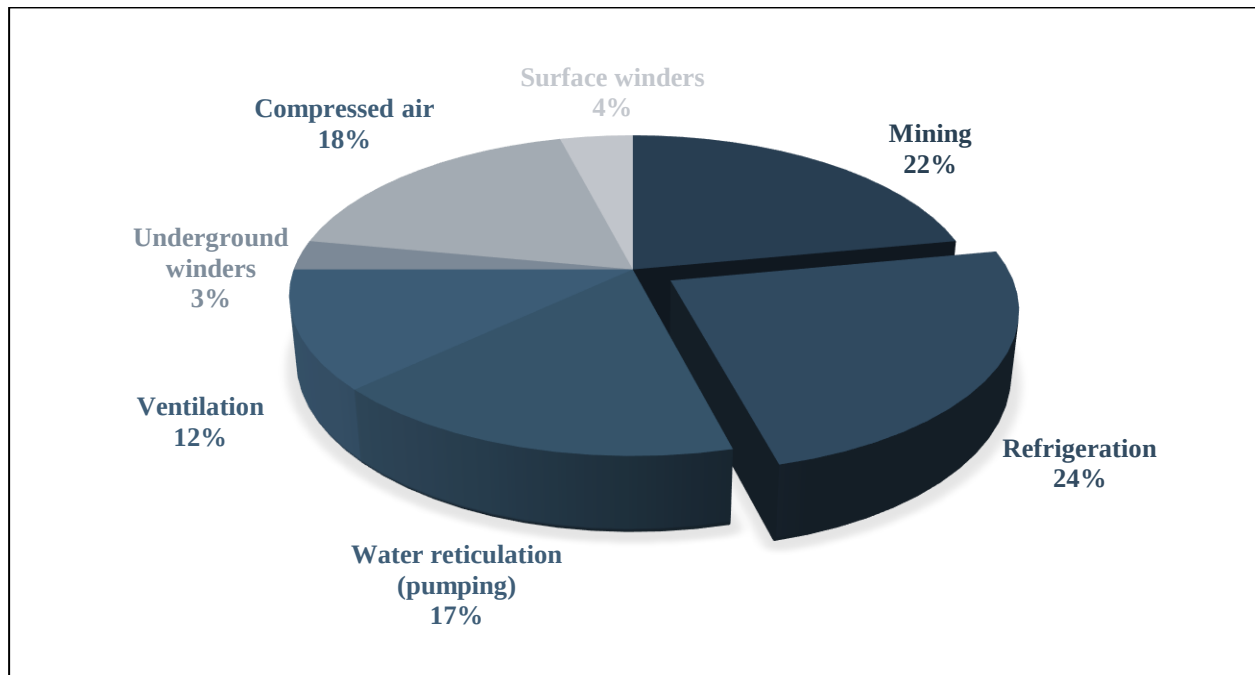


Figure 7: Mining processes as a percentage of the total electricity consumption (adapted from [51])

Due to the escalating price of electricity, mines have been forced to proactively look at reducing the cost of cooling. It is clear that implementation of innovative optimisation initiatives on mine refrigeration systems can yield significant energy and cost savings.

1.4 Background of refrigeration and cooling systems on deep-level mines

1.4.1 Overview

As of April 2019, with the current price increases in electricity, South African gold mining company, Mining group A, is estimated to pay an additional R 300 million in annual energy expenditure across their deep-level mining operations³. In order to off-set the rising cost of electricity, Mining group A will need to produce an additional 500 kg of gold annually. With production trends on the decline, it is clearly evident that the future sustainability of deep-level gold mining operations remains in the balance. The South African mining operation is named Mining group A due to confidentiality agreements.

³ “Annual energy expenditure”, Personal Communication, Energy Manager, Mining group A, South Africa

Due to depleting gold reserves, gold mining companies have chosen to dig deeper in search of gold-rich ore-deposits. However, as the depth of mines increase, so do the technical challenges and operational costs associated with maintaining acceptable underground environmental conditions. Larger, more energy-intensive refrigeration systems are required to supply sufficiently cool ventilation air and chilled service water to cool elevated rock surface temperatures. With refrigeration systems consuming up to 24% of the total electricity consumed by a typical deep-level gold mine, corresponding to electricity price increases, the cost of operating Mining group A's entire fleet of refrigeration units will increase annually by R 72 million.

It has been shown that due to the deepening and widening of mining operations, larger, more complex and energy-intensive refrigeration systems are required. In addition to this, due to the depletion of shallower, high-grade ore deposits, the need for gold mining operations to continuously review and redesign cooling systems is becoming more and more evident. Not only does the installed capacity of mine refrigeration systems place a huge financial burden on mines but, coupled with declining ore grades, challenges associated with mining at greater depths highlight the importance of implementing cost-effective energy management measures.

Before one may evaluate present energy and cost-saving initiatives on mine refrigeration systems, it is imperative to understand the fundamental operational principles, performance capabilities and constraints of key components contributing to an integrated mine refrigeration system. Understanding the operation of individual subsystems and how they contribute to the holistic cooling system is significant when developing sustainable cost and energy saving strategies.

In the context of this study, a combination of the pumping, air-cooling and refrigeration sub-systems are defined as the mine cooling system. The mine refrigeration system, however, collectively refers to system components that makes use of a secondary coolant or refrigerant to cool or freeze water, such as chillers or an ice-plant. This includes auxiliary components such as the condenser towers and pumps.

1.4.2 Mine cooling system

Chilled water plays a vital role in the sustainability and operation of deep mines. As mines deepen, the importance of supplying underground operations and working sections with sufficiently cool water and air dramatically increases.

Layout and operation

Each integrated mine cooling system is unique and designed according to various parameters including; mining depths, geographical location and underground mining operations. Depending on these parameters, different mine cooling system configurations may be preferred. Figure 8 displays a generic layout of a

typical surface deep-level mine cooling system. Mine cooling systems typically consist of the following components: pre-cooling towers, bulk air coolers (BACs), condenser towers, chillers, pumps and thermal storage dams. Working in unison, these cooling components enable mines to provide sufficient cooling and ventilation to underground end-users.

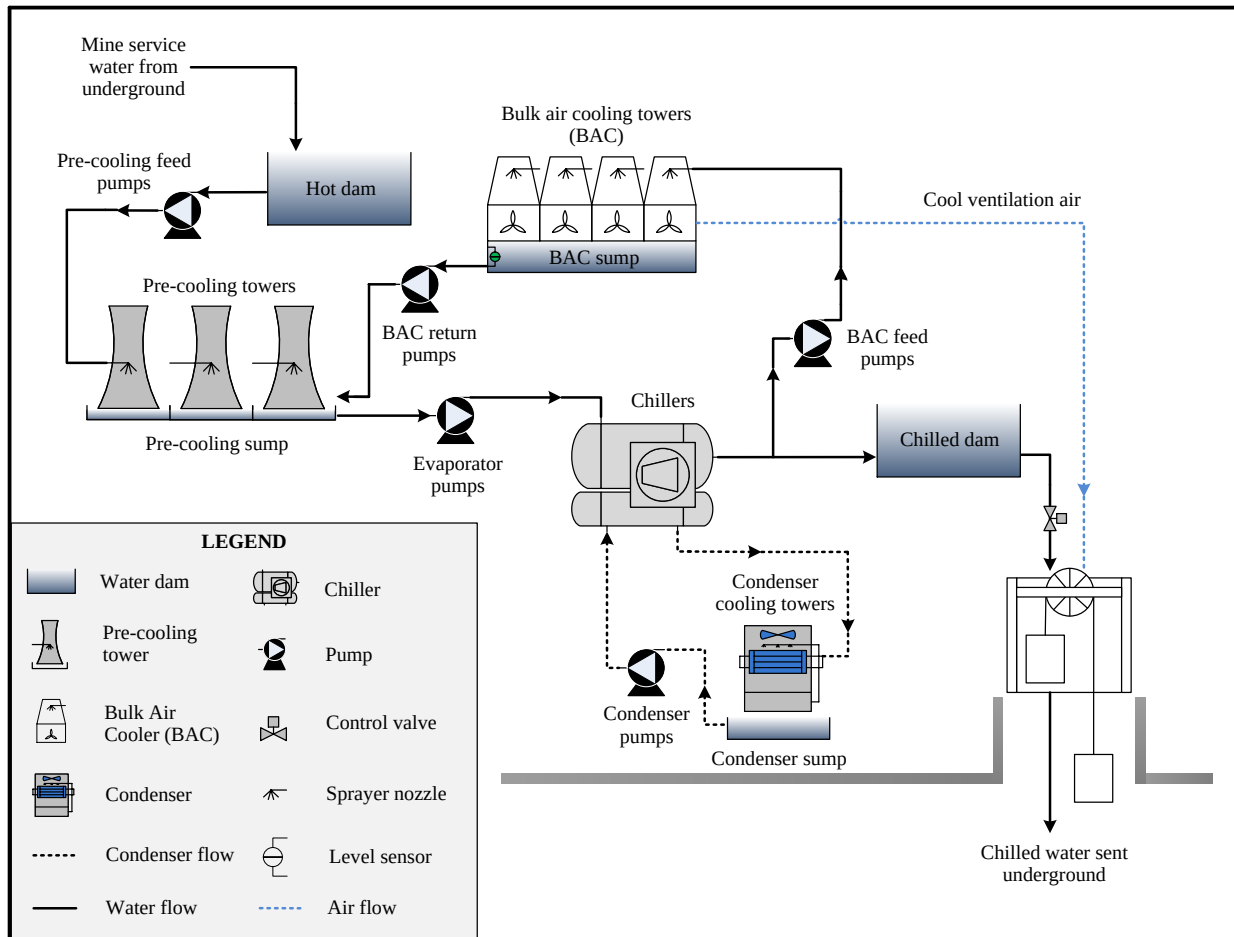


Figure 8: Generic layout of a surface mine cooling system

Hot mine service water pumped from underground dewatering dams enters a surface storage dam between 26°C and 28°C [52][53]. Thereafter, it is pumped through the pre-cooling towers' spray nozzles whereby the water is adiabatically cooled by the ambient air via heat rejection into the atmosphere. The water is temporarily stored in the pre-cooling tower sump before being pumped to the chillers via dedicated evaporator pumps. Using indirect heat exchangers, the water is subsequently cooled to between 3°C and 6°C by the chillers [30]. Depending on the system configuration and mining application, the arrangement of chillers may vary between several possible layouts involving series and/or parallel chiller configurations. Similar to the pre-cooling towers, condenser pumps circulate condenser water through the spray nozzles of the condenser cooling towers for heat rejection, after which it is stored in the condenser sump.

Chilled water leaving the chillers is either stored in the chilled dam before being sent underground or circulated through the surface bulk air coolers (BACs) using dedicated BAC feed pumps. The surface BACs

use the chilled water to provide cool and dehumidified ventilation air to underground working sections. To offset significant heat loads associated with deep mines, BAC outlet air temperatures can be required to be as low as 7°C wet-bulb [30]. Suction created by main ventilation fans circulate the cool air throughout underground networks. The volume of chilled water sent underground at any one time is usually controlled by means of a control valve. This optimises a mine's water utilisation based on demand requirements throughout the day. Additional background regarding the functionality and purpose of each cooling system component is provided in Appendix A2. This will assist in identifying an effective and sustainable solution to mitigate ever-increasing operating costs.

1.4.3 Mine cooling strategies

The installed capacity of cooling systems is heavily dependent on size and depth of the mine. Integrated infrastructure ranging from conventional air coolers (ventilation only) to complex cooling systems consisting of chillers, air coolers and cooling towers, provide the backbone of cooling in mining operations. Figure 9 provides the depths at which the efficacy of available cooling technologies run out in ultra-deep platinum mines. It can be utilised as a guideline to ensure the most cost-effective and optimal cooling strategy is implemented at various depths.

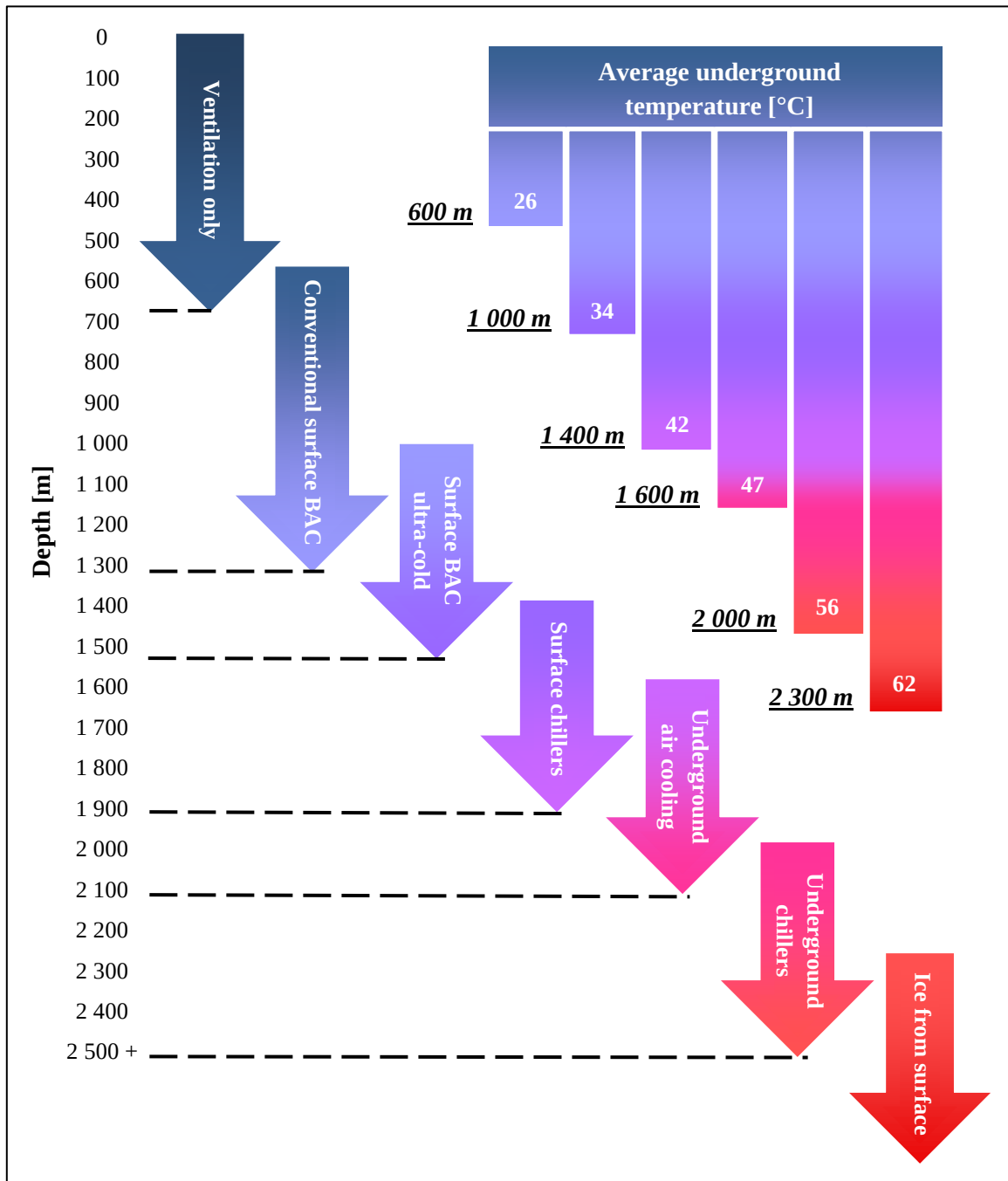


Figure 9: Cooling infrastructure requirements for various depths and temperatures [44][54]

As an example, beyond a depth of 2 km, underground chillers are more cost-effective than surface chillers. The main reason for this is the energy loss in sending cold water down from surface and then having to pump it back to surface again. Although the cooling methods and technologies remain the same throughout other metalliferous mines, the depth at which they are implemented will differ. An example of this is in gold mines. Typically, surface BACs are introduced at a depth of 1400 m and ice at approximately 3000 m [55]. From Figure 9, it is evident that deeper mines require cooling systems of larger cooling capacities, able to provide more effective cooling at depth.

In South Africa, there are currently four proven mine cooling strategies typically implemented on deep-level gold mines. The suitability of each cooling method can be determined by the following factors:

- Depth of mine. As an example, with mines digging deeper, the trade-off between ultra-cold air-cooling vs chilled water sent underground from surface typically falls in favour of the latter.
- Required cooling capacity. The increase in mechanisation and development of work sections further away from the shaft will require additional cooling.
- Type of mine. As illustrated in Figure 6, platinum mines experience significantly higher VRTs at shallower depths compared to gold mines.
- Mine infrastructure and geological constraints. Introducing new cooling methods to an already established system may be challenging, and in some cases impossible. In addition to infrastructure upgrades such as piping networks, large excavations on surface or underground not only require large capital expenditure but due to poor forward planning, there is limited space for expansion.

Considering the financial, operational and socio-economical constraints identified in previous sections, it has become ever-more important for the South African mining industry to reconsider current cooling methods in an effort to optimise their system, reduce energy wastage and ultimately improve profitability margins. The relationship between the ever-increasing depth of mines and associated operating costs is well established. Therefore, provision of suitable cooling techniques and understanding their optimum performance and suitability are critical to South African deep-level mines of the future. A brief overview of the four mine cooling methods to consider on deep mines is provided.

Option 1: Fridge shaft strategy

Once a mine reaches a certain depth, ventilation alone is no longer sufficient to provide adequate cooling. Mines are forced to consider the integration of costly surface refrigeration plants to cool ventilation air before it is sent underground. The fridge shaft approach typically consists of two separate surface BAC units. The first unit supplies ultra-cool ventilation air down the main hoisting shaft at approximately 5°C WB [54]. As depicted in Figure 9, without additional cooling, the efficacy will be lost at a depth of between 1400 m and 1500 m. With the introduction of a second surface BAC supplying ultra-cold air at 3°C WB down a separate dedicated “fridge shaft”, additional supplementary cooling capacity is provided [54]. The ultra-cold air sent down the fridge shaft is delivered to only the deepest levels where it is required. This provides effective positional efficiency.

Option 2: Chilled water from surface

As mining depths increase further, pre-cooling towers are introduced to cool mining service water. With further increases in depth, the pre-cooling towers alone become inadequate, therefore, requiring surface

refrigeration plants to additionally cool the mine service water. In addition to the surface BAC supplying ultra-cool ventilation air down the main hoisting shaft, additional cooling capacity is provided by chilled water. Chilled water produced by the surface refrigeration plants, at a cold set point of approximately 3°C, is gravity-fed from surface to underground air coolers in the form of BACs and/or tertiary cooling methods such as spot coolers [52]. Return water from underground coolers then flows under gravity to the main pump station, before being pumped out of the mine to the pre-cooling towers on surface.

Option 3: Underground refrigeration

Due to large pumping costs associated with surface plants, installation of underground refrigeration plants is a viable alternative solution with depth. A proportion of water is still cooled on surface and sent back down underground to an intermediate dam. Water that is not returned to surface will be “redirected” to the underground plants where it will be cooled to approximately 3°C before entering the intermediate dam. From the intermediate dam, water is distributed to respective underground coolers and working sections.

Option 4: Ice from surface

It has been well documented that the breakeven point at which ice becomes more efficient than underground plants is around 3 km for gold mining operations [55]. Chilled water from the surface refrigeration plant/s enters the ice-plant where it is cooled to form either hard ice or a slurry mixture. From here it is sent underground and received by the intermediate dam. A proportion of the return water leaving the mine is then added to the intermediate dam where it is cooled as the ice in the dam melts. Thereafter, chilled water just above freezing point leaves the intermediate dam and is subsequently sent to underground end-users.

Comparison of cooling methods

Down to a depth of 2 300 m, implementation of the fridge shaft approach is perfectly plausible. However, once a mine ventures past this depth, the decision becomes marginal. The major limiting factor of this cooling method is the required fridge shaft diameter with depth. According to Mackay *et al.* (2010), as the depth of the mine increases, so does the required diameter of the fridge shaft [54]. For example, in order to provide sufficient cooling at a depth of 3 000 m, the required fridge shaft diameter becomes unreasonably high, between 16 m and 18 m respectively [54]. Furthermore, with a significant increase in the volume of air flow circulating the mine, additional and/or larger return airways are required. This not only requires extensive excavation of underground networks but may introduce further safety concerns with regards to the overall structural integrity and stability of the mine. Due to the greater surface area of exposed rock resulting from additional excavation, larger than normal heat loads are experienced.

Amongst the remaining three cooling methods, based on service delivery requirements alone, sending ice down from surface is the most favourable solution with depth. According to a study conducted by Schutte (2016), for a mine with working levels between 2 300 m and 3 300 m, the implementation of an ice system will provide more effective cooling to working sections compared to both surface and underground refrigeration systems [52]. Furthermore, sending ice underground will require the least in terms of underground excavations and shaft piping. The main advantage of ice comes from its latent heat of fusion during phase change. This implies that ice has the ability to provide up to four times more cooling compared to that of chilled water per kg [56][57]. As a result, ice plants provide a system with increased cooling capacity, reducing the flow of water circulating the mine [58]. Therefore, costs associated with return water pumping are significantly reduced. The primary focus of these ice systems is to assist in solving the cooling challenges associated with deep-level operations. However, these systems are not only very expensive but also require extensive maintenance. At a mean depth of between 2200 m and 3500 m, the initial capital cost associated with ice systems for these depths can reach upwards of R 163 million [59]. Although such systems are expensive, the benefits associated with ice used for cooling cannot be ignored.

The main advantages of using underground chillers as opposed to surface chillers have been accredited to reduced costs in return water pumping and significant improvements in service delivery outcomes. In a study conducted by Schutte (2016), it was discovered that mine working sections receive up to 91% of the cooling done by underground chillers, whereas this is only 78% for a system consisting of surface chillers [52]. This is largely attributed to the fact that cooling occurs much closer to the working sections. Intuitively, underground refrigeration plants seem more favourable than surface plants. However, be that as it may, mines typically favour the use of surface chillers based on the following factors [60][61][62]:

- Compared to surface chillers, underground chillers do not have the ability to use atmospheric air for heat rejection, but instead make use of exhaust air. Due to the amount of exhaust air available underground, underground chillers are constrained by limitations in heat rejection. In general, surface chillers operate more efficiently than underground chillers with a higher COP.
- Maintenance on surface is of better quality and not as intensive compared to underground installations.
- Before underground refrigeration plants can be installed, significant excavation is required.

The practice of sending chilled water down from surface became economically justifiable due to the introduction of energy-recovery systems and large capital costs typically associated with underground refrigeration plants.

As the temperature difference between the water leaving the mine cooling system and ambient temperature increases, cooling not only becomes more expensive but also less efficient [52]. With mine cooling systems placing a huge financial burden on mining operations, planning for the future is integral to ensure the long-

term sustainability and profitability of the mine. Mine cooling infrastructure not only requires an initial large capital investment, but with increasing electricity costs and maintenance requirements, operational costs result in mines postponing upgrades for as long as possible. Of all cooling system components, surface refrigeration plants, or chillers, require an abundance of electrical energy. Individual chillers can consume anything between 3 MW and 16.4 MW [63]. In an energy audit conducted by du Plessis (2013) on 20 mine systems, it was found that chillers account for approximately 66% of the total electrical energy consumption of a mine cooling system [63]. Due to the sheer magnitude of underground networks and the increasing depth of mines, larger volumes of water are required to provide the necessary cooling. This implies that most deep-level mining operations will require more than one chiller. These systems are generally extremely energy-intensive, demanding a combined cooling load capacity varying anything between 25 to 50 MW [64][65][66]. South Africa is said to be the largest user of chillers, with over 300 units installed [49]. It is evident that although surface refrigeration plants may be the preferred cooling method, they are still extremely expensive to run.

Considering the current financial instability of the mining industry, rapidly increasing prices in electricity and uncertainty surrounding the future of the gold mining industry in South Africa, mining companies are seeking both cost and energy saving initiatives with minimal payback periods. In some scenarios, if the proposed cost or energy saving initiative does not have a payback period of less than one year, the project will not be considered for implementation⁴. This not only solidifies the current financial instability of gold mining companies in South Africa, but also emphasises uncertainty created by declining ore grades, gold price volatility and a severe decline of production trends in recent years.

As mine depth increases, costs associated with large energy-intensive refrigeration systems incorporating the use of several surface and/or underground chillers becomes increasingly excessive. It is evident that cost-effective methods to reduce the load on installed chillers are required. Studies have shown that cooling systems offer considerable potential for DSM [67]. Concerns over escalating operational costs have recently been compounded by the instability of South Africa's national power grid. Load management efforts in this sector promise strong returns [68].

⁴ "Implementation of energy management on deep-mines", Personal Communication, Energy Manager, Mining group A, South Africa Gold

1.5 Investigating cost-saving potential on mine refrigeration systems

1.5.1 Preamble

Considering today's fragile economy and growing instability in the national power grid, energy conservation has become an important issue. With Eskom implementing a variable tariff structure, imposed to shift load out of peak demand periods, consumers have been forced to either foot the bill or seek alternative cost saving solutions to offset rising operational costs. As a result, load management strategies have gained increased attention over the years. Load management strategies are particularly advantageous in that they benefit both the power demand and supply side. The demand side benefits due to a reduction in energy demand during peak ToU periods, therefore, reducing energy usage costs. In terms of the supply side, benefits are obtained from a reduction in power generation requirements [69].

Many efforts have been made by researchers and Energy Service Company's (ESCOs) alike to develop new, optimised load management control strategies to reduce operational costs with maximum affect. Within this section, current employed load management strategies will be analysed to identify areas of improvement and potential innovation. The primary focus of this section investigates the strategies currently implemented on mine refrigeration systems that reduce peak ToU power consumption, enabling significant cost saving possibilities.

1.5.2 Load management on deep-level mine refrigeration systems

Load management strategies do not necessarily reduce the overall power consumption of a mine refrigeration system. These strategies are typically implemented to primarily reduce the operating costs of mine refrigeration systems during the more expensive Eskom peak ToU periods. Essentially, load management involves the process of reducing the power consumption of the consumer by "pausing" certain operations during peak periods, allowing them to continue during standard or off-peak periods. The Eskom ToU tariff structure is depicted in Figure 2.

The success of load management optimisation techniques is generally governed by the Eskom ToU tariff period, thermal storage capacity and environmental circumstances [70]. To ensure the sustainability of load management strategies on deep-level mine refrigeration systems, the following obstacles should be addressed [71][72]:

- Available thermal storage capacity
- Chilled water supply requirements
- The ability to recover normal operational parameters (sufficient comeback load and flow capacity)
- Condition of plant equipment
- Process requirements

- Machine utilisation
- Water reticulation network
- Baseload power profile
- System configuration
- Environmental condition

To measure a mine refrigeration system's response to a load-shifting strategy, a simulation model is required to address the obstacles listed above that may jeopardise the sustainability and success of the strategy. Factors such as quality of production, productivity and mine safety should also be considered [73]. The following load-shifting strategies have been implemented on mine refrigeration systems:

- Thermal storage capacity
- Chiller shutdowns
- Back-pass valves
- Temperature setpoint controllers
- Thermal ice storage

In order to determine the load-shifting potential of a refrigeration system, certain process parameters must be investigated. Process parameters include; chiller flow rates, dam level percentages, temperatures and the machine operating constraints [72]. Adherence to these constraints is imperative; the implementation of a load-shifting strategy should not adversely impact these parameters in any way.

Thermal storage capacity

Dependent on a mine's thermal storage capacity and chilled water requirements, thermal storage dams offer significant load management potential. Based on a variable tariff structure, managing the thermal storage capacity of a system has proven to be a very successful load-shifting strategy in both commercial building and mining applications. Thermal storage dams act as a form of capacitance, storing unwanted cooling energy for later usage [74][75]. Similar to storage tanks in buildings, thermal storage dams utilised within the mining industry increase the cooling capacity of the system, allowing the cooling load to be shifted out of the more expensive peak Eskom ToU tariff periods, therefore, realising significant cost-saving potential.

Chiller shutdowns

With over 300 energy-intensive chillers installed across South African mines, chiller load management strategies promise significant cost-saving potential [49][76]. Load management strategies have been developed to control the chillers operation according to the most cost-effective operating schedule, with close consideration of the installed capacity and thermal storage capacity of a mine. During off-peak ToU

tariff periods, water is chilled and stored in storage dams. During peak ToU tariff periods, storage dams will have accumulated a sufficient capacity of chilled water, allowing the chiller/s and its cooling auxiliaries to be turned off without restricting the chilled water supply required for mining operations [74].

Temperature set points are typically more stringent directly after a load shift has been implemented in order to rapidly stabilise chill water dam temperatures. Set points are updated as requirements change. Real-time control is not only required to ensure an optimal load shift is achieved but will additionally assist to mitigate risks associated with a reduction in the cooling of chilled water done by the chillers [51][77].

Back-pass valves

A chiller's cooling load during the peak ToU tariff periods can additionally be reduced with the installation of a back-pass valve system. An illustration of the back-pass valve control is depicted in Figure 52 found in Appendix A3. Chilled water leaving the chiller/s is transported either directly back to the chiller inlet (direct effect) or into the hot water dam (slower, longer lasting effect). By doing this, the chilled water mixes with the hot return water, therefore decreasing the inlet chiller temperature [78]. With a decrease in cooling requirements, the compressor inlet guide vanes (IGVs) will cutback, thereby reducing the overall power consumption of the chiller. Indirectly, the back-pass valve controls the chiller evaporator discharge temperature by varying the water flow fed back to the chiller inlet.

As illustrated in Figure 52, the back-pass valve can be utilised during both off-peak and peak periods to save energy. However, for maximum load reduction and cost-saving potential, the back-pass valve should only be utilised during peak periods [76]. Efficient back-pass valve control and an adequate supply of chilled water can effectively allow a complete chiller shutdown during peak ToU tariff periods.

Temperature set point controllers

The cooling load can alternatively be managed with the use of temperature set point or proportional-integral-derivative (PI&D) controllers. PI&D controllers modulate chiller temperature control through the use of control loop feedback systems [79]. This enables the PI&D controllers to control the chiller outlet temperature to the desired temperature set point. The desired outlet temperature set point is achieved by altering the IGVs on the refrigerant compressors. By controlling the inlet guide vanes of the compressors, the swirl pattern of the inlet refrigerant can be altered. Swirl pattern refers to a fast-circular movement. At higher guide vanes, an increased swirl pattern can be realised. By changing the swirl pattern of the inlet refrigerant, the refrigerant delivery capacity can be changed.

During off-peak periods, temperature set points are decreased which implies compressor guide vanes are subsequently increased, therefore, lowering the chiller outlet temperature, resulting in an overall reduction

in the chilled water dam temperature. This, therefore, accommodates for effective peak load reduction, enabling setpoints to be raised during peak periods.

Thermal ice storage

Thermal ice storage systems effectively reduce the cooling load on the chillers. Ice systems increase the cooling capacity of a system by producing and storing ice during off-peak ToU tariff periods. During peak ToU tariff periods the chillers and cooling auxiliaries can be switched off with the required cooling load provided by the stored ice. When required, warm evaporator water is pumped through the ice plant, melting the ice. Ice plants were developed to primarily reduce the energy cost of a refrigeration system by storing cooling capacity during off-peak ToU tariff periods for later usage [80]. In an investigation conducted on a deep mine in South Africa, it was concluded that thermal storage boasts the largest potential for shifting the energy load usage of the chillers [50].

1.5.3 Performance of cost saving strategies on mine refrigeration systems

Cooling system performance

When developing a cost-saving strategy, the performance of cooling system components should also be considered and critically analysed. It would not make sense to implement a cost-saving initiative with system components operating inefficiently, resulting in long-term increases in maintenance and equipment replacement costs. Alongside mine health and safety, the primary objective with regards to any energy or cost saving intervention is to ensure that the existing state and operation of the system is not jeopardised in any way [78]. Specific operational factors that typically need to be considered are as follows:

- Chiller COP
- Individual chiller performance (adverse impact on coolant temperature, gearbox temperatures etc.)
- COP of the entire cooling system
- Cooling tower and BAC performance and efficiencies
- Average electrical energy usage

The operation of an integrated cooling system can be evaluated by the COP of the entire system. The global COP can be determined through application of Equation 1. Equation 1 is useful in evaluating how any load management strategy indirectly impacts the performance of the entire integrated cooling system. An increase in the total average electrical energy usage without proportionally increasing the cooling load will result in a reduced global COP, therefore, implicating reduced system performance capabilities. The total thermal load of the integrated cooling system can be derived from Equation 2.

Equation 1: Global coefficient of performance of entire integrated cooling system [81]

$$COP_{global} = \frac{\dot{Q}_{cooling. system}}{W_{cooling. system}} \quad [-]$$

Where:

COP = coefficient of performance of integrated refrigeration system [-]

$\dot{Q}_{cooling. system}$ = total thermal load of integrated cooling system [kW]

$W_{cooling. system}$ = electrical power usage of all contributing consumers [kW]

Equation 2: Thermal load absorbed by entire cooling system [81]

$$\dot{Q}_{cooling. system} = \dot{m}_{w,daily avg} C_{p,w} (T_{hot dam} - T_{cold dam}) \quad [kW]$$

Where:

$\dot{Q}_{cooling. system}$ = total thermal load of integrated cooling system [kW]

$\dot{m}_{w,daily avg}$ = daily average mass flow rate of water to be cooled [kg/s]

$C_{p,w}$ = specific heat constant [kJ/kg.K]

$T_{hot dam}$ = hot dam water temperature [°C]

$T_{cold dam}$ = chilled dam water temperature [°C]

The development of any load management strategy should continuously take into account the operational performance of the entire system as well as individual components. This will ensure that any cost saving realised will not be nullified by the degrading performance of system components.

Service delivery requirements

To effectively implement a load management strategy, mine service delivery requirements must be identified and adhered to during the strategy development phase. Mine service delivery requirements typically serve as control constraints and assist in analysing the performance of a project during the pre- and post-implementation stages. To ensure the sustainable implementation of load management initiatives within the mining industry, it is imperative that acceptable mine service delivery requirements are maintained throughout the longevity of the project. Although mine service delivery requirements play an integral role in determining the overall performance of load management proposals, project performance

should also consider the actual effects within the system. These factors include electrical energy consumption, productivity and the safety of the mine and mine workers [71].

As discussed previously, mine refrigeration systems are required to supply sufficiently cool chilled water and air to underground end-users [82]. Consequently, chilled water characteristics such as flow rate and temperature as well as the BAC air outlet temperature have been identified as important system requirements. Therefore, it is important that the chilled water temperature, flow rate and chilled dam level be kept within specified limits [78]. By adapting these requirements to a set of acceptable boundary limits, productivity and mine safety will not be compromised but rather enhanced [83]. These limits are typically established during the project commissioning phase.

In general, each individual mine's chilled water and air requirements may differ based on mine depth, vastness of underground network, presence of underground machines, geographical location with regards to VRTs and the extent of underground mining operations. Mine personnel, therefore, formulate suitable chilled water and air requirements, unique to the safe and productive operation of the specific mine. These requirements must align with health and safety regulations and satisfy mining demands. Literature has suggested that chilled water temperatures of less than 6°C will be sufficient to ensure optimal cooling of underground networks [60][84]. Supplying chilled water according to these temperatures will assist in ensuring safe operating conditions of underground working sections. Legislation dictates that underground temperatures should not exceed 27.5°C (WB) [53]. It is crucial that any load management strategy applied to the mine refrigeration system should not adversely impact underground temperatures, ensuring a safe and productive mining environment.

1.5.4 Challenges associated with existing load management initiatives

Deep-level gold mines in South Africa are facing many challenges that pose a threat to the sustainability of current and future mining operations. One major challenge is the increasing depth of mines. As mines dig deeper, underground environmental conditions become increasingly unbearable, jeopardising not only the health and safety of mine workers but has additionally proven to adversely influence productivity. This highlights the importance of a sustainable and reliable refrigeration system to operate efficiently, even under maximum load [78].

Aside from main ventilation fans required to supply sufficient ventilation air to underground, safe underground environmental and mining conditions solely rely on the installed refrigeration system. This has resulted in the refrigeration system becoming the largest safety concern within the deep-level gold mining industry [85]. With this being said, mines are extremely cautious, and in some cases inflexible when any proposed load management or optimisation strategy directly involves the refrigeration system [86]. The

main factors contributing towards this mindset involve both technical and human-related aspects, namely [78][87][88]:

- **The human factor:** Many mine personnel have been involved in the mining industry for the majority of their lives, and as a result, coupled with a lack of educational awareness, refuse to be told how to run their mine. Even when faced with proven practical evidence, they generally believe that no additional improvements can be made.
- **Lack of capital expenditure:** Mines have been known to focus on the initial capital cost of equipment rather than long-term benefits.
- **Uncertainty:** Due to the current instability experienced within the gold mining sector, mines are reluctant to commit resources to long-term projects.
- **Incorrect control and operation:** Load-shifting projects typically require the full attention and cooperation of mine operators. Operators have been known to interfere with automated systems, switching control from automatic to manual for no apparent reason. Inefficient operator control can lead to project deterioration, adversely impacting project performance and cost-saving potential.
- **Lack of capacity:** To enable specific load-shifting projects, refrigeration systems require adequate thermal storage capacity. The performance of the refrigeration cycle is highly dependent on the systems' storage capacity.
- **Equipment lifecycle:** Mine personnel, specifically the mechanical foreman, are particularly reluctant to implement load-shifting projects. Many have experienced the increased maintenance requirements and costs associated with the constant stopping and starting of machines, or the addition of technology promised to realise energy cost savings.
- **Poor project performance:** The underperformance and project deterioration of existing DSM initiatives has only added fuel to the fire, inciting a mines reluctance to implement new initiatives.

In order to convince mines to implement new and innovative load-shifting projects, an in-depth understanding of the mine's current operations is required. Proof of concept through investigation and simulation is imperative to eliminate any concerns regarding productivity as well as mine health and safety. Thorough research is a necessity to identify all risks, system constraints and variables that may negatively influence project performance. Measures on how to mitigate these factors will also be required.

1.5.5 Mine refrigeration system sustainability requirements

Although many load management projects and optimisation strategies have been implemented on mine refrigeration systems, long-term sustainability remains of prime concern [89]. Through literature, it has been suggested that the implementation of an Energy Management System (EMS) is crucial to achieve a sustainable solution [72][90]. Automatic control of the mine refrigeration system has the ability to further improve the performance, reliability and sustainability of current and future load management initiatives

[77]. An additional tactic for improving the long-term sustainability of mine refrigeration optimisation strategies involves key performance indicators (KPIs). KPIs are typically utilised to monitor the performance, behavioural changes and characteristics of a mine refrigeration system and system components [60]. KPIs should be identified during strategy development and included in the monitoring and reporting system. Accurate monitoring and reporting on KPIs result in effective communication between ESCOs and the client, ensuring sustained cost savings [91]. Through effective communication, responsible parties are constantly informed of project performance and possible degradation. This will assist mine personnel and ESCOs alike to immediately attend to the situation and develop a solution or perform a root cause analysis, enabling them to make informed decisions [92]. Due to improved communication and constant feedback, preventable maintenance measures can be implemented, thereby decreasing shutdown times, maintaining component efficiency and increasing operations [93].

Through an investigation conducted by Peach (2016), it was discovered that many load-shifting projects implemented specifically on mine refrigeration systems did not address the issue of sustainability during the initial stages of project development [89]. This led to the systematic degradation of system parameters such as chilled water temperature, therefore, compromising the longevity of the load-shifting project altogether. Peach (2016) suggested that the application of an optimised control strategy will benefit the sustainability of load management initiatives and cost-saving measures. Optimised control strategies typically developed using calibrated simulation models result in low cost and rapid implementation of load management initiatives [89]. Control optimisation also assists in ensuring minimal effect on key operational parameters, therefore, enabling sustainable load-shifting potential. Groenewald (2015) identified that improper maintenance of industrial DSM projects is a large contributing factor leading to project deterioration [87]. Through the application of a performance-centered maintenance (PCM) strategy (including practical maintenance guidelines), Groenewald (2015) hypothesised that a projects' performance could be better sustained. The strategy was based on a plan-do-check-act cycle that focused on continuous improvement, evaluation and monitoring of project performance.

Maintenance procedures and schedules play an integral role in the performance of a mine refrigeration system and the sustainability of implemented load management projects. In a study conducted by Holman (2014), the benefits of an improved maintenance regime on mine refrigeration system components were investigated. After cleaning the evaporator tubes within a chiller, improved heat transfer between the water and refrigerant was noticed [60]. Improved heat transfer yields enhanced cooling capabilities and a reduction in the compressor power usage. Additional advantages include; a slight increase in the water flow rate due to a decrease in the resistance within the chiller tubes and an increase in the consistency of performance. As a result of regular maintenance, significant energy and cost savings were realised. In addition, the COP of individual chillers had increased by between 29% and 42% respectively. Due to the nature of mining operations, it is crucial that maintenance schedules of system components are adhered to

and monitored to maintain and improve operational performance parameters [87]. The deterioration of individual chillers could severely impact the long-term sustainability of load management projects.

For long-term sustainability and to determine the effect any strategy has on the performance of the mine cooling system and individual components, important KPIs and operational parameters should be analysed and compared before and after project implementation. Long-term sustainability is highly dependent on evaluating and reviewing these parameters [94]. Implementation of sustainable load management strategies has not only enhanced service delivery requirements but has additionally ensured maximum cost-saving potential is realised.

1.5.6 Previous load management studies performed on mine refrigeration systems

State-of-the-art studies have proven that the majority of load management strategies implemented on mine refrigeration systems have positively benefited load reduction, and in some cases efficiency and operational performance. To evaluate the impact of load management strategies implemented on mine refrigeration systems, a comprehensive literature review on previous study contributions is required. This section will provide an overview of various applicable study contributions, limitations and constraints encountered throughout the study. Recommendations identified by each author for future study are also reviewed. Table 1 summarises the load shift achieved from the application of various existing load management techniques through case study implementation.

The main findings obtained through literature as depicted in Table 1 can be attributed to the successful load shifting of chillers outside of Eskom's evening peak period, resulting in significant cost savings. The formulation of new, optimised control strategies, utilisation of back-pass and underground water control valves, and the optimal use of available thermal storage capacity, have all assisted in improving a mine's load-shifting potential. It is clear that load management efforts implemented on deep-level gold mines promise strong returns. However, from the percentage of the baseload chiller power consumption shifted, there remains significant potential to implement improved load management solutions. Unless otherwise stated, the load shift results depicted in Table 1 represent load reductions achieved in Eskom's evening peak period.

Table 1: Evaluation of existing load management initiatives on mine refrigeration systems

<i>Author</i>	<i>Focus</i>	<i>Evening peak load shift</i>	<i>Morning peak load shift</i>	<i>Load shift achieved</i>	<i>% Baseload shifted</i>
Calitz (2006) [78]	➤ Developed a new control strategy that could be utilised to provide an improved load shift of the chillers. Focus was based on optimised chiller schedules.	✓	X	➤ 3.6 MW during summer months ➤ 3.1 MW during winter months	➤ 30% during summer months ➤ 53% during winter months
Crawford (2019) [76]	➤ Investigated the implementation of an automated dynamic control strategy that could be utilised to optimise the control and system performance of a mine refrigeration system. ➤ Main focus was to achieve reduced operational costs and improve system sustainability.	✓	X	➤ 2.5 MW during summer months ➤ 2.1 MW during autumn months ➤ 1.0 MW during winter months ➤ 1.8 MW during spring months	➤ On average a 45.7% reduction in peak demand
Engles (2015) [95]	➤ The main focus of the study was to implement an optimised control strategy on a mine refrigeration system that combined both energy efficiency and load-shifting initiatives.	✓	X	➤ 3.5 MW during summer months	➤ 58% during summer months
Schutte (2007) [71]	➤ Developed a new control strategy for implementation on a cascaded mine surface refrigeration system, utilising a real-time energy management system. ➤ Optimised chiller scheduling and cascaded chiller temperature control.	✓	X	➤ 4.2 MW during summer months ➤ 4.2 MW during winter months	➤ 100% during summer months ➤ 100% during winter months
Strydom-Bouwer (2008) [96]	➤ Investigated the possibility of implementing DSM on both surface and underground refrigeration systems incorporating a lead-lag chiller configuration across four mines. ➤ Focused on reducing the chillers load during Eskom's peak periods.	✓	✓	➤ Mine A morning peak: 2.5 MW during winter months and 1.8 MW during summer months ➤ Mine A evening peak: 1.3 MW during winter months and 2.3 MW during summer months	➤ Mine A morning peak: 32% during winter months and 16% during summer months ➤ Mine A evening peak period: 21% during winter months and 23% during summer months
				➤ Mine B: 3.15 MW	➤ Mine B: 34%
				➤ Mine C: 0 MW	➤ Mine C: 0%
				➤ Mine D: 0 MW	➤ Mine D: 0%
van der Bijl (2007) [72]	➤ Focus of the investigation was to develop an optimised real-time control solution that could successfully move chiller operations out of the more expensive Eskom peak period without adversely impacting mine safety or operational constraints. ➤ Application of back-pass valves.	✓	X	➤ Mine A: 3.6 MW during summer months and 1.3 MW during winter months	➤ Mine A: 34% during summer months and 37% during winter months
				➤ Mine B: 4.0 MW during summer months	➤ Mine B: 100% during summer months
Jansen van Rensburg <i>et al.</i> (2017) [97]	➤ Investigated the benefits optimised control strategies, maintenance and reconfiguration had on mine refrigeration systems.	✓	X	➤ 4.6 MW during summer months	➤ 100% during summer months
Peach (2016) [89]	➤ Main focus of the study was attributed towards developing an optimised control strategy to achieve sustainable cost savings.	✓	X	➤ Mine D: 7.28 MW during summer months	➤ Mine D: 100% during summer months
				➤ Mine R: 2.0 MW during summer months	➤ Mine R: 100% during summer months

Limitations and constraints

In an effort to improve profitability, implementation of various load management strategies has assisted numerous mining operations in reducing their overall operational costs. Although the majority of load management initiatives implemented on mine refrigeration systems have been advantageous, various study limitations were identified.

Calitz [78] identified that the biggest problem that could occur during the implementation process was that of an operational fault within the refrigeration system. To mitigate severe knock-on effects, mine constraints such as inlet and outlet water temperatures of the chillers, dam levels, ambient temperature and the temperature of water going underground should constantly be monitored and reported on [78]. Contingency plans should additionally be considered to prevent constraints exceeding their design limitations. Due to various constraints such as chilled water temperature and flow requirements, a full load shift on the chillers could not be implemented.

Crawford's [76] research was aimed towards the implementation of an automated dynamic control strategy on a mine cooling system for optimal operation. Through the dynamic control of cooling system components, significant operational and financial benefits were achieved. However, the control strategy was only implemented and tested on one mine; therefore, the research and corresponding results are only valid for the mine used as a case study. Since no mine cooling system is the same, differing in configuration, system components and constraints, the automated control model may be mine-specific. A generic solution is required that can obtain similar results.

Engles [95] evaluated the feasibility of implementing both individual and combined cost-saving measures on deep-level platinum mines. Although significant cost savings were achieved, it was determined that the load shifting portion of the project was not feasible and was unsustainable from inception [95]. Since all the chiller machines were switched off during the evening peak period, the load shift was routinely interrupted due to underground chilled water requirements. In order to improve load management potential, Engles highlighted the importance of including the underground chilled water demand in the control strategy.

Schutte [71] was able to successfully capitalise on a complete evening peak chiller shutdown, however, as a result, chilled water dam temperatures increased beyond design limitations. During the study, Schutte recognised that thermal storage is an integral component to enable effective load shifts on a mine refrigeration system. Schutte identified the possibility to implement a more sustainable solution such that similar results can be realised without compromising service delivery requirements.

Strydom-Bouwer [96] investigated the feasibility of implementing load management on lead-lag refrigeration machines. With regards to Mine A's refrigeration system, of the two sets of lead-lag refrigeration machines, only the two lagging machines could be switched off. This was due to system constraints including underground chilled water flow requirements and the flooding of the pre-cooling dam. Mine C and D were not capable of implementing a load shift due to dam level control limitations and thermal storage capacity constraints.

Jansen van Rensburg et al. [97] showed that the sustainability of load management initiatives can be improved by replacing old and inefficient equipment, regular maintenance and an optimised control philosophy. Implementation results revealed a significant reduction in the chill dam temperature during peak periods and an improved load shift of 28%.

Peach [89] identified that many load management initiatives implemented on deep-level gold mines across South Africa have deteriorated in terms of project performance and sustainability. From the various load management projects investigated within his study, in terms of sustainability, the project lifetime was on average limited to 13 months. It is clear that a more sustainable solution is required.

As identified through previous studies, load-shifting strategies are severely restricted by service delivery requirements such as the temperature of chilled water sent underground and the chilled water flow demand. Depending on the extent and nature of underground mining operations as well as the available thermal storage capacity, in some cases it may prove impractical to implement a load management strategy on the chillers and refrigeration system without adversely impacting service delivery requirements.

State-of-the-art load management initiatives have been developed to maximise cost-saving potential and sufficiently meet various cooling demands. Many studies encountered in literature have focused on implementing load-shifting strategies during Eskom's evening peak period, with few contemplating Eskom's morning peak period. Since Eskom's evening peak period typically aligns with the off-peak mining period, service delivery requirements such as chilled water temperature and flow are slightly less stringent. However, even then, mines are limited on the number of chillers that they are able to turn off. It has, therefore, become clear that there remains significant scope to implement a solution that would not only enable the mine to turn off more or even all of the remaining chillers during Eskom's evening peak period, but could additionally be utilised to shift chiller load out of Eskom's morning peak period, without compromising business-as-usual (BAU) conditions and service delivery requirements.

Analysis of recommendations for further study from literature

Several authors suggested recommendations for future study that may either mitigate study limitations or introduce alternative, innovative cost-saving measures. Through previous study contributions and

investigations, authors have recognised the cost-saving potential the use of ice for underground cooling possess. In a study conducted by Maré (2017), the use of ice for underground cooling was briefly explored [51]. Although Maré focused on the operation, benefits and limitations of an ice plant conveying either hard ice or a slush solution underground, Maré acknowledged the advantages of ice-associated cooling. It was suggested that further study be conducted to determine the effectiveness of an ice plant with regards to its thermal energy storage and load-shifting capabilities [51]. Proceeding successful DSM implementation on mine surface and underground chillers, Strydom-Bouwter (2008) suggested further investigations should be conducted on the DSM possibility in refrigeration systems consisting of ice coolers [96].

In the study conducted by Calitz (2006), research into the implementation of load management strategies on a mine refrigeration system was conducted. Although implementation results realised significant cost savings, Calitz recognised that there exists bigger load-shifting potential through the utilisation of ice tanks for additional thermal storage [78]. Du Plessis (2015) conducted a study to investigate various strategies and tactics that can be implemented within the mining industry that can be utilised to achieve energy efficiency savings. Du Plessis suggested that the use of ice thermal storage provides the mine with the ability to reduce peak-time power consumption, allowing a significant electrical load to be shifted to off-peak periods [98]. In a similar investigation, Els (2014) concluded that ice banks should be considered and utilised for underground cooling systems.

A study completed by Kamyar *et al.* (2016) outlined current ventilation and mine refrigeration strategies, as well as the latest techniques utilised by mines and experts alike to combat ever-increasing energy costs. In a review of ice cooling strategies, Kamyar recognised the ability of ice to be utilised for purposes other than underground cooling. It was suggested that in countries where power tariffs are levied, ice cooling systems are particularly worth implementing due to their thermal energy storage and load-shifting capabilities [99].

Biffi and Stanton (2008) conducted a comprehensive study to investigate current cooling methods implemented on a mine. In addition, they formulated novel ventilation and cooling strategies, tailor-made to meet the demand for cooling in deepening operations and offset the rise in electrical power utilisation and cost. During the study, it was noted that if the installed capacity of the chillers and thermal storage system (ice dam) is large enough, the chillers can successfully be switched off during Eskom's morning peak period, with the required cooling capacity supplied by the thermal storage system [61]. It has been recommended that although ice thermal storage offers many advantages to a system, such benefits need to be tempered with higher capital costs and lower COP values typically associated with the ice building process [61]. Biffi and Stanton concluded that ice thermal storage is feasible, however, must be selected based on the following factors; individual performance, infrastructural merits and overall capital costs (including initial capital expenditure, operating and maintenance costs) [61].

Since the use of ice does offer significant advantages in terms of cooling water more efficiently, it is noteworthy that ice can be produced for alternative energy and cost-saving initiatives. One such initiative is thermal ice storage. In a country where a variable power tariff structure is imposed, implementation of such a system offers substantial savings due to its load-shifting capabilities [51][99]. The concept of using ice as thermal energy storage to reduce overall operating costs has already been successfully implemented on heating, ventilation and air-conditioning (HVAC) systems in buildings [100][101]. However, the effectiveness of thermal ice storage systems still needs to be fully investigated when implemented on mine refrigeration systems.

From Section 1.1 and 1.2, it is evident that the gold mining industry is under financial strain to reduce operational costs. Although implemented load management projects have realised lucrative cost savings, the profitability and sustainability of deep-level gold mining in South Africa remains under threat. Chillers have been identified as the most energy-intensive component of a mines' refrigeration system. It, therefore, makes sense that load-shifting projects implemented on chillers have been well documented. However, the load shift and subsequent cost-saving potential remains limited according to thermal storage capacity, installed refrigeration capacity, service delivery requirements and complex system configurations. The need to further optimise and implement improved, sustainable cost-saving measures on mine refrigeration systems has become a necessity. Ice thermal storage could be used to make up the shortfall. Based on the various available mine cooling strategies depicted in Figure 9, ice thermal storage becomes increasingly viable at depths greater than 1900 m due to the introduction of chillers.

1.6 Thermal energy storage

1.6.1 Background

Air-conditioning and refrigeration systems are major contributors to the energy consumption in buildings and on mines. These systems are extremely energy-intensive, consuming up to 60% of the total energy consumed in buildings [101] and 24% in mines [51]. As a result, load-shifting control strategies have gained increased attention over the years. One of the most promising strategies currently utilised in industry involves the concept of thermal energy storage.

Generally, the use of thermal energy storage (TES) systems to manage energy demand and benefit from a variable tariff structure have been well documented for use in commercial buildings. These systems assist in reserving energy, typically stored in a thermal reservoir for later use. Energy, in the form of chilled water, ice or eutectic salts, is charged and stored during low-demand, off-peak periods where electricity is cheaper [102]. Thereafter, during peak demand periods, the energy is discharged and used as required. Thermal storage is a tactic used to reduce the power consumption during peak tariff periods by cooling water or creating ice which is stored and made available during peak consumption periods [98]. In addition,

MacCracken (2003) and Tabors Caramanis and Associates (1996), as cited by Rismanchi (2013), revealed that the offset in electricity demand is often accompanied by a reduction in total costs and an improvement in system performance [102].

TES systems should be considered when one of the following factors are present: expansion of the current cooling system, limited availability of electrical energy, the availability of an existing storage facility that can be used for cool storage, a flexible electricity tariff rate structure, incentives for the installation of cool storage, and when maximum cooling load requirements are significantly higher than the average load [102].

Operation strategies of TES systems

There are three different kinds of TES systems, namely full storage systems, partial storage systems and demand limiting systems [98]. When determining the most cost-effective strategy, the electricity tariff rate structure, load profile and costs of equipment and corresponding storage should be considered [102]. Figure 10 illustrates the three different operation strategies of TES systems. Each storage system is briefly explained using the application of ice as an example medium.

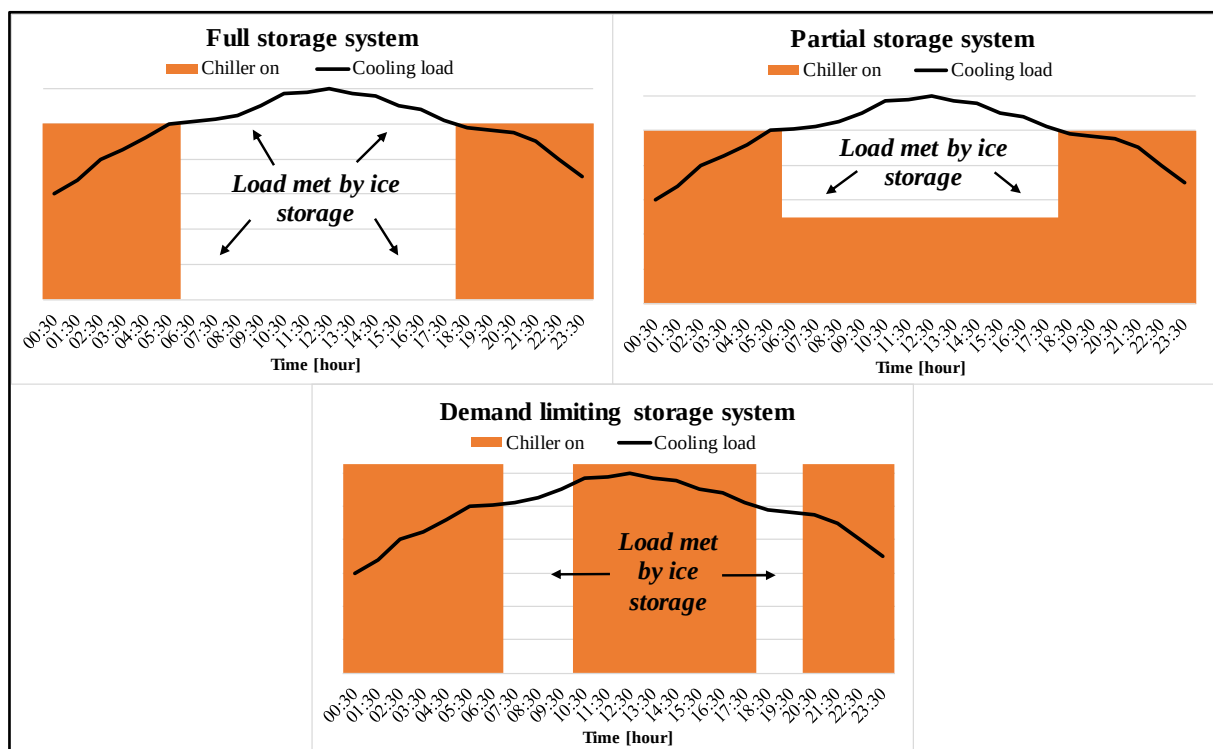


Figure 10: Operation strategies of TES systems (adapted from [69])

Full storage systems are one in which the entire design load is generated and stored during off-peak periods or at night, ready for use during peak periods. This implies that the chillers will be standing during the day when the cooling load is maximum, with the provision of adequate cooling supplied by previously generated and stored ice [98]. The chillers will only operate at maximum capacity at night during periods

of minimal cooling loads, charging the storage tanks at the same time. Full storage systems require larger chillers, in addition to high storage capacities [102]. In partial storage systems, only a portion of the design load is generated and stored during the off-peak period. In this case, the chillers operate continuously throughout the day, with part of the cooling load satisfied by the ice storage system. Generally, the chillers can be operated at a reduced load, possibly providing the ability to run fewer chillers [103]. The last and usually most effective storage system is the demand limiting system [72]. This system turns off the chillers during periods when electricity rates are highest, relying on the stored ice to provide the required cooling load. For the remainder of the day, the chillers alone supply the required design load.

The success of the selected operation strategy is typically based on the imposed electricity tariff rate structure, environmental conditions and thermal storage capacity [70]. However, factors such as production and mine safety should not be ignored when implementing such strategies [73]. Depending on the energy storage medium used, TES systems can be further categorised into three types; chilled water, ice storage and eutectic salt TES systems [104]. Table 2 provides a brief comparison of each storage medium. It may be observed that the main advantage of using ice thermal storage (ITS) systems is based on its high latent heat of fusion, reducing the physical size of storage tanks required when compared to chilled water and eutectic salts. By using ice, a greater portion of the baseload can be stored for later use. However, the COP of ITS systems is generally lower than the other two mediums.

Table 2: Primary features of energy storage mediums (adapted from [102][105])

Parameter	Chilled water	Ice storage (ITS)	Eutectic salt
Specific heat [kJ/kg.K]	4.19	2.04	-
Latent heat of fusion [kJ/kg]	-	334	80 - 250
Chiller type	Standard water cooled	Low temperature secondary coolant	Standard water cooled
Chiller cost per kW [\$]	57 - 85	57 - 142	57 - 85
Tank volume [m ³ /kWh]	0.089 – 0.169	0.019 - 0.023	0.048
Chiller charging efficiency [COP]	5.0 – 6.0	2.7 – 4.0	5.0 – 6.0
Maintenance	High	Medium	Medium
Discharge temperature range [°C]	4 - 7	1 - 3	9 - 10

Over the past few decades, ITS systems have been widely utilised throughout industry, specifically in commercial buildings. Multiple variations, sizes and adaptations have been developed in order to yield the most optimal solution based on end-user requirements. In a statistical study conducted by Potter *et al.* (1995), it was determined that of the 2000 TES units installed in buildings, schools and hospitals across the United States, 80% to 85% of them were ITS systems [106]. In a similar investigation, Hasnain and

Alabbadi (2000) discovered that, of the various types of ITS systems installed in Saudi Arabia, on average, the system had the ability to decrease between 10% and 20% of the peak electrical demand and between 30% and 40% of the peak cooling load demand [107].

Ice was introduced into the gold mining industry in the late 20th century [108]. Although seen as an innovative solution to counteract escalating heat loads experienced at increased mining depths, technical issues as well as monumental capital expenditure costs, has brought with it extensive uncertainty surrounding the success and proposed benefits of ice cooling systems [72]. Ice systems utilised as thermal energy storage is, however, fairly recent technology deployed on mines [109]. In addition, there is limited literature available, therefore, providing the need to quantify the feasibility of implementing ITS systems within the mining industry.

1.6.2 Ice thermal storage techniques

1.6.2.1 Overview

The production of ice can be categorised as either static or dynamic types [110]. Static type systems form ice directly on the chilling surface, whereas in dynamic types, ice is produced and subsequently removed from the cooling surface [110]. Examples of static type systems are ice-mass storage (ice-on-coil) and encapsulated ITS systems. Dynamic type systems include ice-harvesters and ice slurry systems [110]. This section will focus on the various kinds of ITS systems currently available and utilised in industry.

1.6.2.2 Ice-mass storage

Ice-mass thermal storage systems, sometimes referred to as an ice-on-coil system, typically operate by building and storing ice on the exterior surfaces of heat exchange coils submerged in a water dam or tank [105]. Ice is usually made at night and stored for later usage. By operating the chiller at night, lower condensing temperatures are experienced than during the day, therefore, improving the efficiency of the chillers [111]. In the daytime, these chillers can be turned off once enough cooling capacity in the form of ice has been generated. During the charging phase, water freezes on the outside of the tubes by circulating either liquid refrigerant or a glycol solution inside the heat exchange coils. Depending on application, ice thickness varies between 40 mm and 65 mm [105]. Ice-mass storage systems can be categorised as either external melt ice-on-coil or internal melt ice-on-coil storage systems. The way in which discharge occurs defines in which category the system belongs. For external melt ice-on-coil systems, during the discharge procedure warm water is pumped through the ice storage facility, around and over the coils, subsequently cooling the water through direct contact with the ice.

For internal melt ice-on-coil configurations, instead of water melting the ice from the outside in, a warm refrigerant solution is circulated through the centre of the coils, melting the ice from the inside out. Figure 11 provides an illustration of the charging and discharging processes for both external and internal melt ice-on-coil storage facilities. In both scenarios, the heat exchanger (coils) occupy approximately 80% of the tank/container, while the remainder is filled with water.

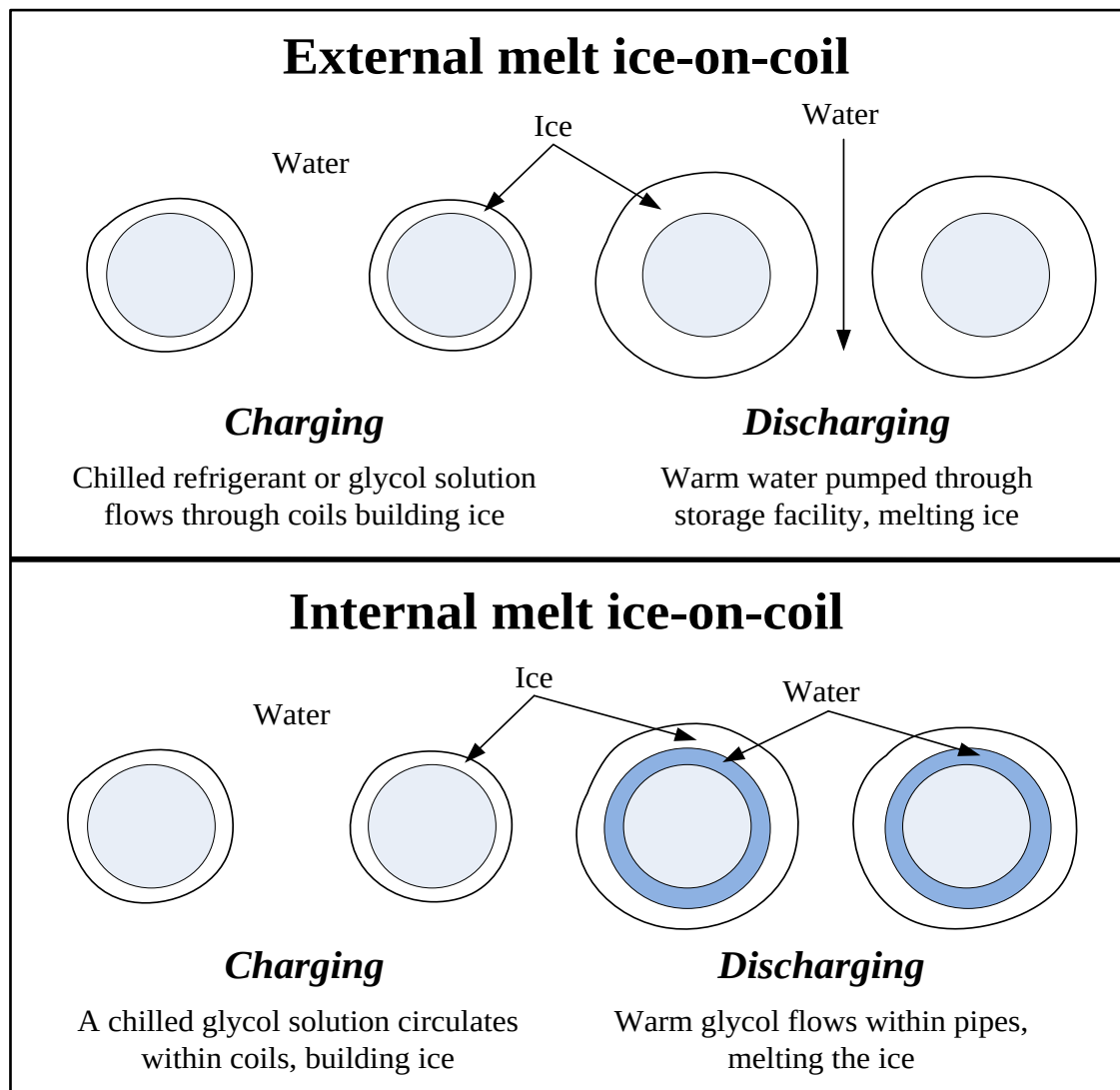


Figure 11: Charging and discharging procedure of ice-mass storage systems (adapted from [105])

To ensure there is no ice remanence (millennium ice) attached to the coils proceeding the ice-melt process, air agitation devices are required for external melt systems [112]. Air agitation is typically required during the first two hours of the ice-building process and whenever cooling is supplied by the ice melt [113]. After two hours, air agitation is no longer necessary as the ice will now be able to build evenly. During the ice formation process, adding turbulence to the water not only ensures that all the water in the storage tank is at 0°C, but additionally prevents the ice water from forming any channels that may cause the flow to bypass some coil areas [113]. During the ice-melt process, air agitation ensures that incoming warm water is evenly

distributed throughout the tank, preventing millennium ice. Internal ice melt systems typically do not require air agitation [113]. Figure 53 illustrated in Appendix A4, displays the general layout of an external melt ice-on-coil system and the placement of individual components including the air agitation device.

Since internal melt ice-on-coil systems have a fairly constant heat transfer area between the coils and ice, the amount of ice formed on each coil is not a limiting factor to the cooling ability as it is for external melt systems. In general, for external melt ice-on-coil systems, the thickness of ice formation and distance between the ice formed on each coil plays a vital role in the heat transfer capability of the ice-plant. If only a thin layer of ice is formed, the ice melt will be short-lived. However, if too much ice is formed on the coils, a solid block of ice will result, therefore, decreasing the overall surface area for heat transfer to take place. If bridging between adjacent coils occurs, not only will the outlet temperature of the water increase but the time taken to completely melt the ice will increase [105]. However, if uniform ice formation is achieved on the coils, external melt systems provide a larger surface area for heat transfer to occur.

External melt systems typically make use of instrumentation to monitor the volume of ice at any one time and to signal the end of the ice-making process. In most scenarios, ice thickness sensors are installed to determine when the required amount of ice has been built [105]. Ice built on bare coils at the beginning of the charging procedure is built at the highest suction temperatures, at the best efficiency and lowest cost. Conversely, toward the end of the charge cycle, ice is built at the lowest suction temperatures, at the lowest efficiency and highest cost. Therefore, to maximise efficiency and minimise costs associated with increased energy consumption, all the ice on the tubes should be melted before the ice-making procedure starts up again. Each charging process should start off with bare tubes [105]. It is imperative that all the ice is melted before recharging occurs. If ice is formed on ice, additional stresses on the coils themselves are induced, thereby damaging the coils and subsequently reducing the lifetime of the coils.

External melt systems can further be divided up into direct and indirect ice builders. Direct, implying refrigerant such as ammonia is used to directly build ice, utilising the coils as an evaporator. Indirect types, however, describe those that build ice with the use of a secondary coolant cooled by a chiller (such as glycol) [105]. In general, a direct refrigeration system is more efficient when compared to the secondary coolant system. This is mainly due to the fact that there is one less step of heat transfer between the evaporative refrigerant and ice building surface [105].

1.6.2.3 Encapsulated ice

An encapsulated ice thermal storage system consists of a number of plastic containers (typically rectangular or spherical in shape) filled with water and submerged in a secondary coolant such as ethylene glycol [105]. During charging, the coolant between -6°C and -3°C is circulated through the storage tank, over and around the submerged containers [105]. The water inside the containers is subsequently cooled and freezes. The

inverse process occurs during discharge, whereby warm coolant carrying heat from the load flows through the tank, melting the encapsulated ice. Thereafter, the chilled coolant is either directly or indirectly utilised to cool the load, in most cases water. Standard chillers incorporating the vapour-compression cycle are typically used to provide required coolant temperatures.

The plastic containers are most commonly made of high-density polyethylene as it is able to withstand the expansion and pressure resulting from the phase change between water and ice [105]. In a study conducted by Saitoh and Hirose (1986), the thermal characteristics of an encapsulated ITS system were investigated. Proceeding the study, it was concluded that the duration of the charging and discharging process is dependent on the following factors; coolant flow rate, coolant temperature and the size and material of the container [114]. Figure 12 illustrates the charging and discharging process of encapsulated ice.

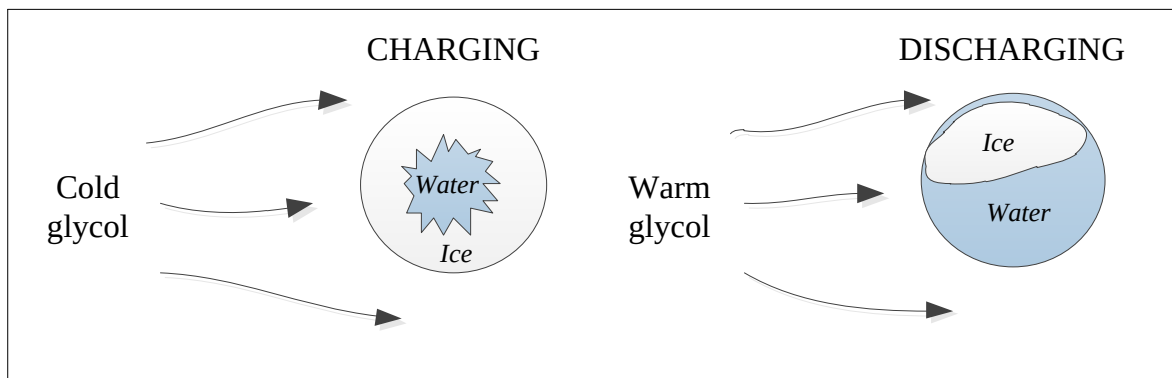


Figure 12: Charging and discharging process of encapsulated ice (adapted from [105])

1.6.2.4 Ice harvesters

Classified as a dynamic type of ITS, ice harvesters typically consist of an insulated storage tank, above which a vertical plate heat exchanger is mounted. During the ice-making or charging phase, ice is formed on the surface of the evaporator. Low pressure liquid refrigerant is fed internally, within the plate heat exchanger, whereby the liquid refrigerant is subsequently vaporized, therefore producing a refrigeration effect. A circulating pump feeds water at a temperature equal to or slightly above 0°C, over the outer surface of the evaporator [105]. The water is subsequently cooled and freezes to form an ice sheet. Depending on the length of the freezing cycle, the thickness of ice sheets may vary between 8 mm and 10 mm [102].

Ice is harvested by reversing the flow of refrigerant, therefore, introducing hot gas to the evaporator. The outer surface of the evaporator subsequently increases in temperature, causing the ice to melt and break-off the heat exchanger, falling into the storage tank below. Due to water stratification, the cooler water with a higher density will “sink” to the bottom of the tank, with the warmer water nearer the surface. During discharge, ice water is pumped from the bottom of the tank and circulated to the end-user. An illustration of an ice harvesting system is depicted in Figure 13.

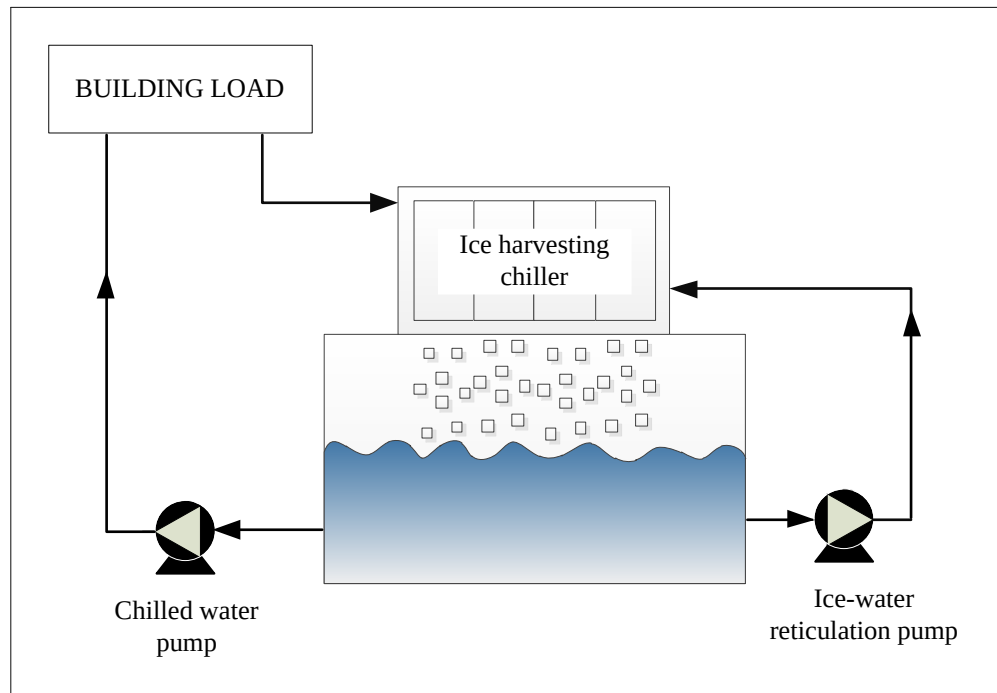


Figure 13: Ice harvesting system (adapted from [105])

1.6.2.5 Ice slurries

Ice slurry systems have gained significant attention over the past few decades. Within industry, ice slurries have been utilised to reduce the load on the chillers. In many circumstances, ice slurry systems have been combined with a storage system such that ice can be stored and used to supply the consumer with chilled water during Eskom's peak ToU periods [115]. In general, an ice slurry system is composed of three independent circuits, namely the refrigeration circuit, an ice slurry circuit and the chilled water circuit which exists between the load and ice [115]. The ice slurry circuit comprises the ice generator, storage tank and heat exchanger. A simplified version of a typical ice slurry system is displayed in Figure 14.

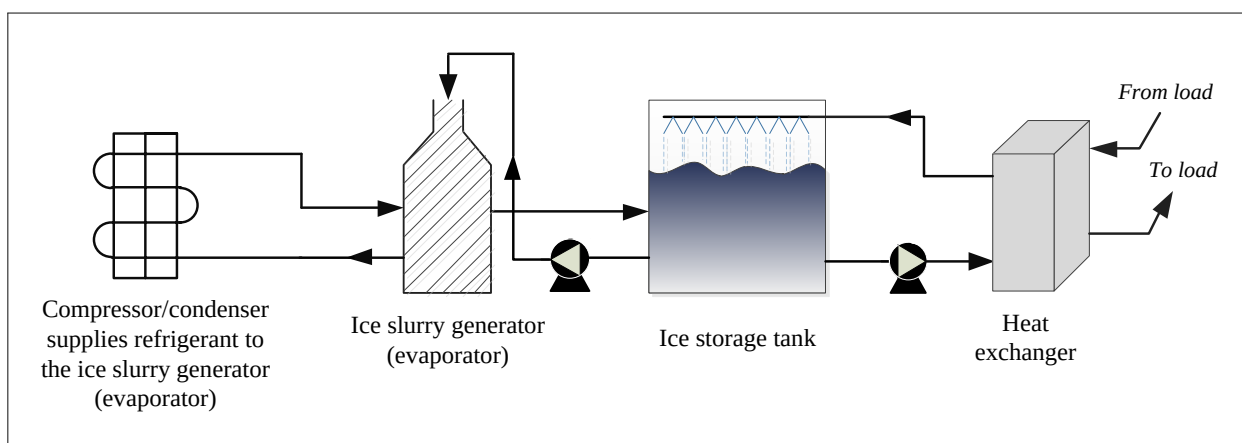


Figure 14: Schematic of an ice slurry system [116]

In this technique, a weak glycol-water solution is circulated through the top of the ice slurry generator, passing through tubes submerged in an evaporating refrigerant [102]. The evaporating refrigerant, typically cooled through a vapour-compression cycle, subsequently cools and freezes the solution, producing ice crystals. The ice slurry leaving the generator is either dropped directly into the storage tank or pumped to a container which may be located remotely from the ice generation system [116]. During discharge, the chilled solution is pumped either from the storage tank directly to the point of use (this could be stored in an underground storage dam) or through a plate heat exchanger, subsequently removing heat from the load.

Since ice slurry systems are classified as dynamic, it does provide the pumpable characteristic advantage when compared to static types [117]. In addition, when compared to static type ITS systems, slurry ice does not suffer insulation effects or bridging between adjacent coils [117].

1.6.3 Previous studies conducted on ice thermal storage systems

1.6.3.1 Preamble

It is worthwhile to consider cost-saving methods on available ITS technologies which have been applied to cooling systems throughout industry. This will assist one to investigate the various viable options that can be implemented on large mine cooling systems. This section will focus on previous case studies and investigations that have been implemented within industry that make use of an ice cooling system as thermal energy storage. The benefits, limitations and recommendations of each study are critically analysed.

In the context of this study, peak and off-peak periods between buildings and mines have a different meaning. Peak periods in building applications (unless otherwise stipulated) typically refer to times of peak occupancy. This will differ depending of the purpose of the building. For mining applications, peak periods refer to Eskom's peak ToU tariff rate structure, discussed in Section 1.1.

1.6.3.2 Application in commercial buildings

A summary of the most important observations derived from each study that may be applicable to application within the mining industry is provided. Additional detail on each study conducted within the commercial building industry is provided in Appendix A5.

Lemort (2006), Commercial building, Belgium [118]:

- Proceeding the investigation, it was determined that the introduction of an ITS system provides significant cost-saving opportunities through optimised load-shifting strategies, however, at the expense of an overall increase in the energy consumption of the cooling system.

- Operational costs were only reduced when the ice storage tanks were fully discharged after being fully charged.
- Lemort concluded that energy savings can only be achieved by decreasing the size of auxiliary components.
- It was found that when an ITS system is integrated into a refrigeration system, the thermal efficiency of the chillers decreases.

Chaichana, Charters and Aye (2001), Commercial and industrial buildings, Thailand [119]:

- Comparing conventional air-conditioning units to that of ITS systems, ITS achieved a 55% energy cost reduction using the full storage technique and a 15% reduction using the partial storage technique.
- Due to lower ambient temperatures typically experienced at night, the full storage technique has the ability to reduce the overall energy consumption by 5%.
- The COP of the refrigeration system was found to be higher at night, during the charging phase. Refrigeration systems consume less energy per unit of cooling at a higher COP [61][119].

Habeebullah (2006), Mosque of Makkah, Saudi Arabia [101]:

- This study investigated the economic feasibility of implementing ITS to supply the required cooling for a religious building, instead of a conventional air-conditioning plant. Results revealed that there is no financial gain in introducing an ice storage system for either full or partial storage systems in a country with a fixed tariff rate. However, based on an incentive time structured rate, by employing ITS significant cost savings could be achieved.

Yau and Lee (2010), Library building, Malaysia [120]:

- In a simulation-based case study, Yau and Lee investigated the effects of employing an ice-slurry cooling storage system in a library building utilising the full storage strategy. It was found that the overall energy consumption increased by as much as 20%. However, due to the variable tariff rate imposed in Malaysia, through application of ITS, the electricity bill could be reduced by approximately 24%.

Hall, Freeland and Nassif, Office building, Orlando [121]:

- In this investigation, research was conducted on the optimal use and design of ITS and its effect on energy cost and consumption. Figure 54 and Figure 55 presented in Appendix A5, illustrates the monthly energy consumption and cost of a system with no ITS, nonoptimal and near optimal ITS design. Results reveal that although an increase in the energy consumption was noticed when

utilising ITS, based on the utility rate structure, a significant reduction in the energy cost was realised.

- Through optimised ice storage design and usage, energy cost savings were 28% higher when compared to nonoptimal ITS designs.
- Results demonstrated that when compared to a system with no ITS, annual energy consumption increased by 11% and the energy cost decreased by 50%. Figure 54 and Figure 55 clearly portray the cost saving benefits the integration of an ITS system has when implemented on a refrigeration system. Further potential can be realised through optimal design and ITS usage.

Erdemir and Altuntop (2018), Hypermarket, Turkey [122]:

- The aim of the study conducted by Erdemir and Altuntop was to determine the effect of various ITS operation strategies on the economic performance of the hypermarket's cooling system. Operation strategies investigated during the study were as follows: full storage, load levelling, partial storage from 10% to 90% and partial storage for peak hours. From the study, it was derived that cooling costs decreased with increasing storage capacity. In addition to this, initial capital investments substantially increase with increasing storage capacity. At the end of a 10-year prediction model, Erdemir and Altuntop concluded that the full storage strategy would yield the highest profit, however, with the longest payback period. The shortest payback period, however, with the lowest profit was seen in the 10% partial storage strategy. To obtain the highest profit from the initial investment made in the ITS system, it is necessary to utilise the stored energy during peak electricity tariff periods. The economic performance of ITS is typically governed by how the stored energy is used. In terms of payback period and profit, the load levelling and partial storage during peak hours constituted the most beneficial utilisation strategies.

Recent research conducted on ITS systems is predominantly applicable to building air-conditioning systems. Extensive cooling in buildings is not required as it is for mines operating around the clock. For building applications, cooling is only required for a limited period of time when the building is occupied [102]. With this being said, although results obtained from research conducted on buildings cannot directly be transferred to mining applications, they will still provide valuable insight that can be used to make informed decisions when implemented within the mining sector.

1.6.3.3 Application in the mining industry

Uys (2014), Deep-level gold mine, South Africa [109]:

An investigation was conducted on a surface mine refrigeration system to determine the feasibility of converting an existing ITS system into a chilled water system. The installed ITS system employed the

external melt technique. The focus of this study was reconfiguring ice storage systems for load management on mine refrigeration systems. Implementation results concluded that converting an ITS system and recommissioning it as a chiller resulted in both energy and cost savings. An annual summer energy efficiency saving of 1.5 MW was realised.

In terms of energy and cost savings, the investigation was deemed successful in converting an existing ITS system into a chiller. However, it is noteworthy to point out that the success of the project was only made possible due to various operational issues encountered with the installed ITS system. Problems identified by the mine personnel are as follows [109]:

- *Inefficient ice plant:*
 - **Problem:** To assist the ice-making process, water from the pre-cooling dam is initially cooled from 13°C to 7°C by virtue of the Hitachi chillers. Thereafter, water is redirected from the chillers to the ice dam where it was further cooled and frozen on the surface of the submerged coils. During Eskom's peak periods, the cooling load of the Hitachi chillers is reduced, with the remainder of the cooling capacity supplied by the ITS system. The main purpose of the ITS installation was to load shift approximately 10 MW out of Eskom's peak periods. However, due to the plant's poor efficiency, baseload chillers were operational 24/7 to make up the required cooling capacity. In short, the ice plant was very wasteful of electrical energy, requiring a large amount of work input to obtain similar cooling outcomes when compared to a chiller.
 - **Reason:** Inefficient ice plant. Proceeding the conversion from an ice plant into a water chiller, it was determined that the COP had increased by 103%.
- *Uneven ice formation:*
 - **Problem:** Multiple dead spots where no ice formation had occurred were identified on the inside of the ice dam. Proceeding the ice melt, it was additionally noticed that there exist various spots whereby ice was still present on the coils.
 - **Reason:** The most probable cause is attributed to poor design, improper maintenance or ineffective air agitation. The flow of water throughout the ice dam was not uniform and inefficient. During the ice build process, the flow of water may bypass some coil areas resulting in dead spots. Incorrect operator control and inexperience may have led to excessive ice build-up, resulting in bridging between coils.
- *Inefficient cooling process:*
 - **Problem:** During ice formation, glycol is cooled to form ice. This process comprises two indirect heat exchanges and one direct heat exchange. The two indirect heat exchanges occur in the shell-and-tube heat exchangers of the condenser and evaporator of the York chiller. R-134a refrigerant is used in the case of the York chiller. In a vapour-compression

process, R-134a is utilised to cool the glycol/water solution which is then used to cool and subsequently freeze water on the surface of the tube structure located in the ice dam (direct heat exchange). During this entire process, a significant amount of cooling is lost to the surroundings, resulting in ineffective cooling [109].

- **Reason:** Since the working fluid utilised in the ice building process is a glycol/water solution, an additional heat exchange process is required. Utilising refrigerant during the charging process is more efficient than a secondary coolant since there is one less heat transfer phase involved. In addition, due to a lack of insulation, especially during summer months, cooling may be lost to the environment.
- *Buoyant tube structure:*
 - **Problem:** On several occasions it was noticed that the tube structure in the ice dam became buoyant in the water when ice formed on the coils. As a result, only the top layer of water was in contact with the ice, therefore, causing the unplanned excessive build-up of ice on the coils. This put severe strain on the tube structure itself.
 - **Reason:** Poor initial design considerations and improper maintenance are the most probable causes for this occurrence.
- *Inconsistent flow of water through the ice dam:*
 - **Problem:** Fluctuations in the demand for chilled water compromised the ice building process. When underground chilled water requirements increased, so the water flow through the ice dam increased, therefore, decreasing the time for water to form ice on the coils. Consequently, there was insufficient ice formation, resulting in either warmer water sent underground, or the duration of the ice melt significantly reduced. Alternatively, if a delay in the continual flow of water through the ice dam occurred, an excessive amount of ice was formed. In some reported cases, a solid block of ice was formed, not only decreasing the overall surface area for heat transfer but additionally blocked the flow of water through the ice dam. As a result, more often than not, neither a morning nor evening load shift could be capitalised on due to problems experienced with regards to inconsistent water flow through the ice dam.
 - **Reason:** The most obvious cause for this is down to fluctuations in the demand for chilled water and insufficient thermal storage capacity. However, further than this, incorrect operator control and experience additionally plays an integral role. If correct dam preparation is achieved, sufficient thermal storage capacity should be available such that a continuous and constant supply of return water can be supplied.
- *Glycol utilised as the working fluid:*
 - **Problem:** Although the mixture ratio of the glycol/water solution was not specifically identified as problematic, it is worthwhile to mention additional concerns the on-site

engineers would have to consider to ensure the optimal operation of the system. To ensure glycol is efficient when utilised as a coolant, the glycol/water solution needs to be mixed according to a certain ratio. If the mixture contains too much water, it will freeze, causing the evaporator side of the chiller to rupture [109]. Alternatively, too much glycol compromises the chiller efficiency.

Although it was ultimately concluded that the installed ITS system was deemed unsuccessful, it is important to note that the issues identified and discussed above could have all been mitigated and avoided. Poor design, incorrect control, improper maintenance and insufficient studies conducted on mine ITS systems all resulted in the poor performance and subsequent decommissioning of the plant. The ITS system was expected to yield a peak demand reduction of up to 10 MW electricity savings. Through correct design, maintenance and implementation, it is evident the cost-saving potential ITS systems possess within the mining industry.

1.6.4 Comparison of available ice thermal storage techniques

Table 3 provides a comparison of the conventional ITS techniques, summarising the primary characteristics of each. Thereafter, a brief comparative overview of the available ITS systems is provided. Comparative results were obtained through literature and various case studies, revealing the strengths and weaknesses of each system. The systems are compared according to the factors mentioned below, with specific reference to the feasibility of implementation within the mining sector.

Before an ITS technique and operational strategy is developed for a specific application, various factors need to be considered in terms of:

- Individual ice plant performance characteristics and installation considerations.
- Actual case study results revealing significant benefits and limitations of the system. This may include significant maintenance requirements or factors that may only arise when integrated with various other refrigeration system components.
- Service delivery requirements that the system must comply with.
- Limitations and constraints present within the industry. This could be a decrease in gold prices, leading to dwindling profit margins and available funds to implement innovative cost saving technologies.

Table 3: Comparative summary of ITS techniques

Characteristics	Chiller type [105]	Chiller cost [\$/ton of ice] [105][111]	Charging temperature [°C] [105][123]	Discharging temperature [°C] [105][113][123]	COP [105][124]	Overall energy / exergy efficiency [%] [102][124]	Energy storage density [kWh/m ³] [105]	Strengths	Weaknesses
Internal melt ice-on-coil	Secondary coolant	Relatively inexpensive: 200 to 500	-6 to -3	1 to 3	2.9 to 4.1	98.5 to 98.92 / 14.05 to 18.0	40 – 50	➤ Highest exergy efficiency ➤ Applicable to both small and large application ➤ Ice inventory control	➤ Discharge temperature extremely dependant on discharge rate ➤ Rate of ice melt limited due to limitations of refrigerant flow caused by pressure drop in coils ➤ Low heat transfer coefficient
External melt ice-on-coil	Standard chiller or secondary coolant	Relatively inexpensive: 200 to 500	-9 to -4	1 to 2	2.9 to 4.1	98.4 to 98.83 / 13.79 to 16.3	40 – 50	➤ Flexibility in length of ice melt ➤ High instantaneous discharge rate ➤ Consistently low discharge temperatures (near 0°C) ➤ Applicable to both small and large application	➤ Bridging between coils ➤ Efficiency penalty in the presence of millennium ice
Ice harvester	Pre-packaged or built up ice-making equipment	Very expensive: 1100 to 1500	-9 to -4	1 to 2	2.7 to 3.7	± 98.3 / -- to 15.9	30 – 50	➤ Quick response to short term cooling requirements ➤ High instantaneous discharge rate ➤ Consistently low discharge temperatures (near 0°C)	➤ Depending on placement, requires overhead clearance above storage tank ➤ Additional loss in efficiency due to defrost cycle ➤ Very expensive
Ice slurry	Secondary coolant	Expensive: ± 1000	-12 to -10	-3	2.4	98.7 to 99.02 / 11.5 to 12.0	30 – 50	➤ Steady discharge temperatures below 0°C achievable ➤ Ability to transport “energy” to point of use ➤ Enhanced heat transfer	➤ Relatively poor system control ➤ Large pipe installations required ➤ May experience problems during transport such as clogging of pipes ➤ High capital expenditure required
Encapsulated ice	Secondary coolant	Relatively inexpensive: 200 to 500	-6 to -3	1 to 3	2.9 to 4.1	98.7 to 98.92 / 13.75 to 14.6	40 – 50	➤ Applicable to both large and small loads ➤ Tank shape may vary	➤ Discharge temperature extremely dependant on discharge rate ➤ Low heat transfer coefficient during (charging/discharging) ➤ May be subjected to supercooling

Since the purpose of this study is focused on load management and maximising the load-shifting potential of mine refrigeration systems through the application of ITS, the system must be able to meet chilled water demand requirements. External melt systems have no restrictions on the ice water flow. The rate of ice melt can vary dependent on cooling requirements. If required it can be as long as 10 hours or as short as 2 hours. For an internal melt system, the rate of ice melt is limited due to constraints in the refrigerant flow rate through the coils, caused by a pressure drop in the ice storage coils [113]. Through previous studies, it was suggested that in terms of COP, energy and exergy efficiencies, the internal melt ice-on-coil system was the most efficient, followed closely by the external melt ice-on-coil and encapsulated ice solutions. However, both internal melt and encapsulated systems are not capable of producing as low discharge temperatures as the external melt ice-on-coil system.

To ensure mine health and safety regulations are met at all times, the temperature requirements of chilled water sent underground are extremely stringent. External melt systems have the ability to supply ice water at 1.1°C or lower for the majority of the melting process [113]. Conversely, for internal melt ice-on-coil and encapsulated ice systems, if a constant discharge temperature is maintained, they have a steadily decreasing discharge rate; however, if a constant discharge rate is desired, they experience a steadily rise in temperature [105][125]. This is as a result of the decrease in ice contact area with the container walls over time. Therefore, the heat transfer characteristics is a limiting factor. Another major disadvantage of the encapsulated ice technology is a phenomenon referred to as supercooling. Supercooling occurs when a substance is rapidly cooled to below its freezing point in the absence of phase change [126]. When this occurs, the capabilities of the sub-zero ice water are significantly compromised in terms of energy storage and release. Heat extraction is less efficient.

The use of ice slurry systems is generally advantageous in that they have the ability to offset high initial installation costs as a result of an overall reduction in return water pumping. However, the system still requires extensive piping installations both on surface and underground. Although this may not be a limitation in building applications, mines typically do not have the space required for such large pipe networks, specifically down the shaft. In terms of discharge temperatures, the ice slurry system provides the most attractive solution, however, in realising these temperatures, the ice slurry system was identified as the least efficient ITS system with regards to COP and exergy efficiency.

Although ice harvesting systems are capable of providing high instantaneous discharge rates and maintaining a consistently low discharge temperature throughout the majority of the ice-melting phase, very high capital expenditure requirements yield an unfavourable solution [105]. In terms of performance, ice harvesters experience an additional loss in efficiency as a result of the defrost cycle. The ice harvester system has a lower energy and exergy efficiency when compared to both ice-on-coil solutions. As discussed previously, both ice-slurry and ice harvester systems represent dynamic systems which are more

complicated compared to static type systems. This implies dynamic systems are more maintenance-intensive, requiring expensive skilled labour [122].

Based on the factors listed above and the comparative summary depicted in Table 3, for application in the mining sector the external melt ice-on-coil technique presents the most attractive system in terms of efficiency, system performance and storage capabilities. The external melt ice-on-coil technique is the most suitable solution for mining applications requiring high discharge rates and consistently low discharge temperatures. Although the study conducted by Uys (2014) concluded that the external melt ice-on-coil system encountered within his study was inefficient and experienced several operational downfalls, system shortcomings were a result of poor installation and design, incorrect control and improper maintenance. Since these issues were not directly caused by the installed ITS system itself, these findings should not adversely impact the decision-making process regarding the most desirable ITS technology for a specific application. Problems identified by Uys (2014) should be utilised as pre- and post-implementation considerations to ensure successful implementation and long-term sustainability.

1.7 Problem statement and study objectives

Over the past decade, the mining industry has been faced with several challenges that have contributed towards dwindling profit margins across many South African deep-level mines. One of the major, if not the most significant contributing factors have been attributed to ever-increasing operating costs, primarily resulting from escalating prices in electricity. Implementation of innovative technologies and strategies is key to reducing operating costs, increasing production and maximising profitability.

Concerns over escalating operational costs prompted by the ever-increasing depth of mines and price of electricity have recently been compounded by the instability in South Africa's national power grid. This is mainly due to Eskom struggling to adequately meet the country's energy demands. During peak periods, Eskom typically operates without adequate reserve margins. As a result, to assist in grid stability, load shedding or load reduction is introduced. Such challenges highlight the importance of load management initiatives within the mining industry.

Refrigeration systems have been identified as one of the largest single energy consumers in the mining sector. With mines digging deeper in search of gold, more complex and energy-intensive refrigeration systems are required. Without sufficient cooling, mines will not only struggle to meet health and safety regulations but will inadvertently compromise gold production. Managing heat loads in a cost-effective manner will alleviate the financial strain currently experienced in the mining industry.

Numerous load management strategies have been implemented on mine refrigeration systems to reduce operating costs and enhance profitability. However, literature has indicated that many of these initiatives

are limited in terms of cost-saving potential due to several governing factors including; service delivery requirements, mine health and safety regulations and thermal storage capacity. Consequently, load management is not possible on many mine refrigeration systems utilising existing strategies outlined in Section 1.5.2.

To remain financially competitive, there is a need to implement more effective load management strategies. There exists significant opportunity to implement an innovative load management initiative that possesses greater load-shifting capabilities, enabling maximum cost-saving potential of mine refrigeration systems. Based on widespread success within the building industry, ice thermal storage has the potential to make up the shortfall. However, research on such systems implemented within the mining industry is limited. Presently few mines across South Africa utilise ITS for underground cooling. There is therefore a need to determine the holistic impact and quantify the feasibility of implementing ice thermal storage as an alternative cost-saving technique on mines. Therefore, extending the knowledge in the field of ice based thermal storage, contributing to the development and possible wider utilisation of such systems in the mining industry.

Study objectives

The aim of the study is to prove whether it is worthwhile to implement ITS on mines as an alternative, more effective cost saving solution. A holistic approach is required to quantify and evaluate both the operational and financial impact. The main study objectives of this research include:

- To develop a generic methodological approach that can be used to evaluate and sustainably implement ITS on deep-level mines.
 - Quantify and assess the feasibility of using ITS on deep-level mines without capital expenditure.
 - Construct improved implementation and operation approaches to assist future ITS installations on mines, focusing on sustainability and maximising cost-saving potential.
- Quantify the holistic impact and benefits gained from the implementation of an ITS system within the mining industry. The holistic approach will incorporate both the operational and financial impact.

1.8 Overview of study

Chapter 1: Literature study - This chapter gives an overview of the need for the implementation of energy and cost-saving initiatives in the mining sector. Various factors contributing to the growing financial instability of the mining sector in South Africa are introduced and discussed. Significant energy consumers on a typical deep-level gold mine are identified.

A comprehensive background of a deep-level gold mines' cooling system is provided. Different cooling strategies and energy-intensive components are evaluated and studied in detail. The potential for the implementation of innovative and sustainable cost-saving initiatives on mine refrigeration systems is critically explored and reviewed. Existing load management strategies implemented on buildings and on mines are investigated with focus on available cost-saving measures and techniques.

Chapter 2: Methodology to evaluate ice thermal storage systems implemented on deep-level mines - A methodology that can be utilised to evaluate and implement ITS as an alternative cost-saving technique on deep-level mines is discussed in detail. This will include developing a simulation model that can be used to quantify the feasibility of ITS installations on mines utilising a holistic approach.

System inefficiencies and shortcomings of previously implemented ice thermal storage systems are discussed and addressed. Improved implementation and operation strategies will be investigated to assist with the sustainability of future installations.

Chapter 3: Strategy implementation through practical application - In this chapter, the methodology developed in Chapter 2 will be implemented and evaluated on an existing mine cooling system. The feasibility of the study with regards to sustainability, cost-saving potential and operational impact including service delivery requirements is discussed. For strategy verification, actual results obtained from the case study are compared to simulated results. Pre- and post-implementation results are analysed to identify shortcomings and areas for improvement. Measures to enhance the sustainability of future ice thermal storage installations are also introduced and discussed.

Chapter 4: Conclusion and recommendations - This chapter provides a summary on the feasibility of implementing ice thermal storage on deep-level gold mines as a cost saving technique. Key findings of the study are discussed. Finally, recommendations are provided on possible improvements to the study and to assist with future research that can be conducted in the field.

CHAPTER 2: METHODOLOGY TO EVALUATE ICE THERMAL STORAGE ON DEEP-LEVEL MINES



5

The development of a methodology that can be utilised to evaluate and quantify the impact of ITS systems on deep-level gold mines is discussed. This section is divided into four steps, each integral to quantify and evaluate the feasibility of implementing ITS systems as an alternative cost-saving technique in the mining industry.

⁵ https://www.evapco.com/search?search_api_fulltext=ice+formation+time

2.1 Introduction

From literature, numerous load management initiatives implemented on mine refrigeration systems were critically analysed and evaluated. Implementation of such contributions have realised significant cost savings. The primary focus for many of these initiatives was to solely reduce the operating costs of a mine, subsequently improving profitability. Further benefits were achieved by reducing the peak electrical energy demand, subsequently assisting Eskom in stabilising the national power grid.

Despite implemented load management projects realising lucrative cost savings, the profitability and sustainability of deep-level gold mining in South Africa remains under threat. Project underperformance and factors leading to restrictions in the load management potential on mine refrigeration systems have prompted the need for the implementation of an improved and sustainable cost-effective solution. Through literature, it became apparent that there remains significant scope and cost-saving potential regarding the load shifting of mine refrigeration system components, specifically chillers.

Air-conditioning and chillers are major contributors to the energy consumption in buildings and on mines. These systems are extremely energy-intensive and, as a result, load-shifting strategies have gained increased attention over the years. One of the most promising strategies currently utilised in industry involves the concept of ice thermal energy storage. Through previous studies conducted within the commercial building sector, ITS has proven to be largely successful, realising significant economic and operational benefits such as; operational cost reduction, reduction in peak electrical demand, allows for flexibility such that technicians can attend to plant breakdowns, and increased cooling capacity for expanding operations. Literature has hypothesised similar results can be attained through application in the mining industry. ITS systems are a relatively new technology utilised on mines and as a result, research is limited. Amongst the available ITS techniques for application in the mining sector, the external melt ice-on-coil technique presents the most attractive solution in terms of efficiency, system performance and storage capabilities. Results obtained from previous studies conducted in the building sector support this hypothesis.

In this chapter, the information gathered in Chapter 1 will be used to develop a methodology that can be utilised to evaluate and implement ITS as an alternative cost-saving technique on deep-level mine refrigeration systems. This will include quantifying the feasibility of ITS installations utilising a holistic approach. Improved implementation strategies and considerations will be investigated to assist with the sustainability of future installations. Figure 15 provides a visual representation of the methodological approach to accomplish the objectives in this study.

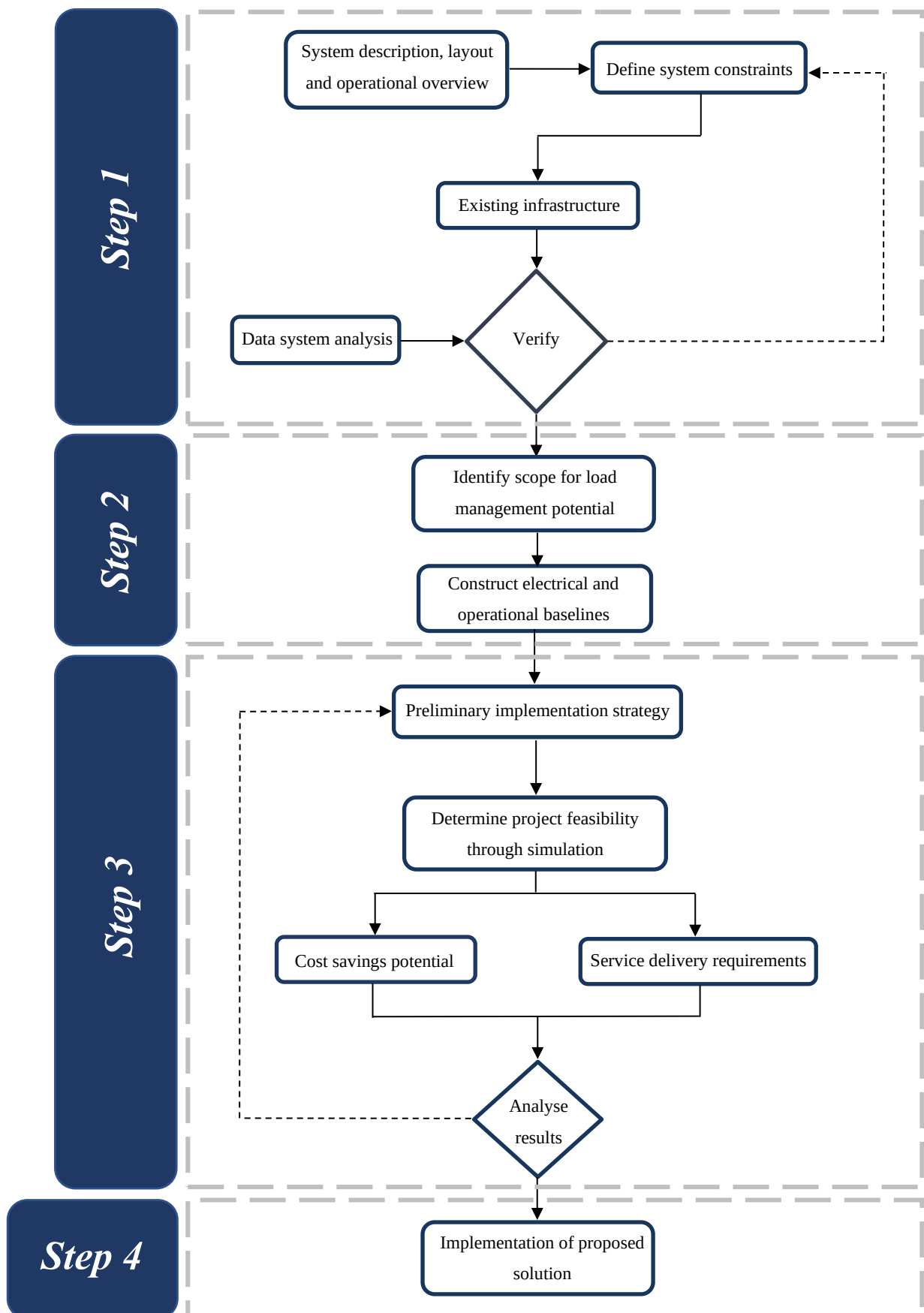


Figure 15: Methodological approach to evaluate and implement ITS on deep-level mines

Steps 1 to 3 provide a methodology that can be utilised to evaluate, assess and quantify the feasibility of implementing ITS as an alternative cost saving technique through effective load management on deep-level gold mines. Step 4 introduces improved implementation strategies and operation approaches focusing on the sustainable implementation of ITS within the mining industry. This will assist in mitigating future ITS systems from experiencing similar inefficiencies in terms of control, utilisation and design as identified in Section 1.6.3.3.

2.2 Step 1: Characterising the system

2.2.1 Preamble

To establish the feasibility of a potential load management initiative, a comprehensive understanding of the existing infrastructure is required. This will enable one to identify system operational parameters, boundary conditions and constraints that may govern the success and sustainability of proposed load management projects. The procedure required to accurately characterise the system is discussed in the following sub-sections. Figure 16 depicts an expanded, high-level breakdown of the general procedure to be followed during the system characterisation phase.

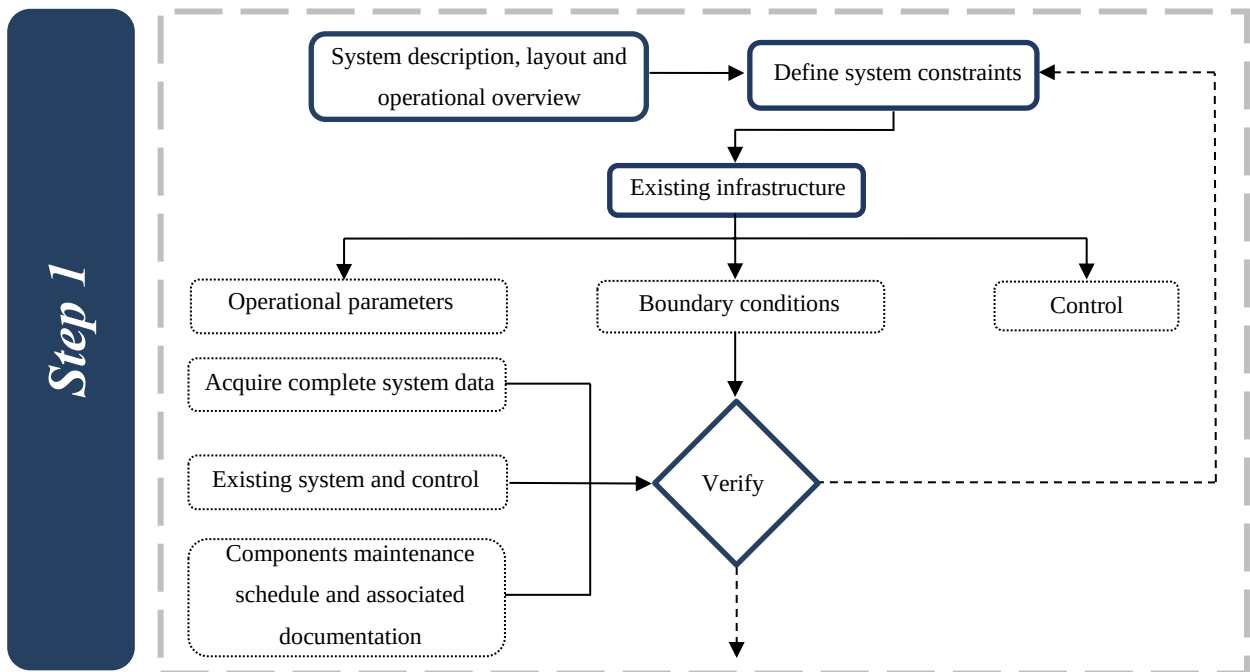


Figure 16: Step 1 - Characterising the system

2.2.2 System description, layout and operational overview

To ensure an accurate representation of the mine's cooling system is constructed, a detailed system analysis must be conducted. Data collated from the installed Supervisory Control and Data Acquisition (SCADA) system, control manuals, component documentation, mine personnel and process flow schematics will

assist in the process. The main objective is to verify the operational parameters, boundary conditions and control limits of the holistic system and individual components. Accurate data collection is important to ensure reliable and quality data is available such that informed decisions can be made during project implementation. Accurate data acquisition will assist to ensure technical system specifications and process variables are measured and logged precisely. This is essential to implement a sustainable solution. Process flow schematics are required to provide further detail regarding the interaction of system components and viability of potential load management strategies.

Figure 17 provides a simplified layout and overview of a typical mine cooling system. It is crucial that the location of the cooling auxiliaries, major storage dams and the water reticulation network are all accurately displayed in the layout. This will aid in determining how the system will react to changes in operation and control. The basis of a detailed investigation into the system layout and functionality will assist in understanding how the system operates, how each individual component is connected and affects one another, and whether the system can be adapted to include a load shift during Eskom's peak periods.

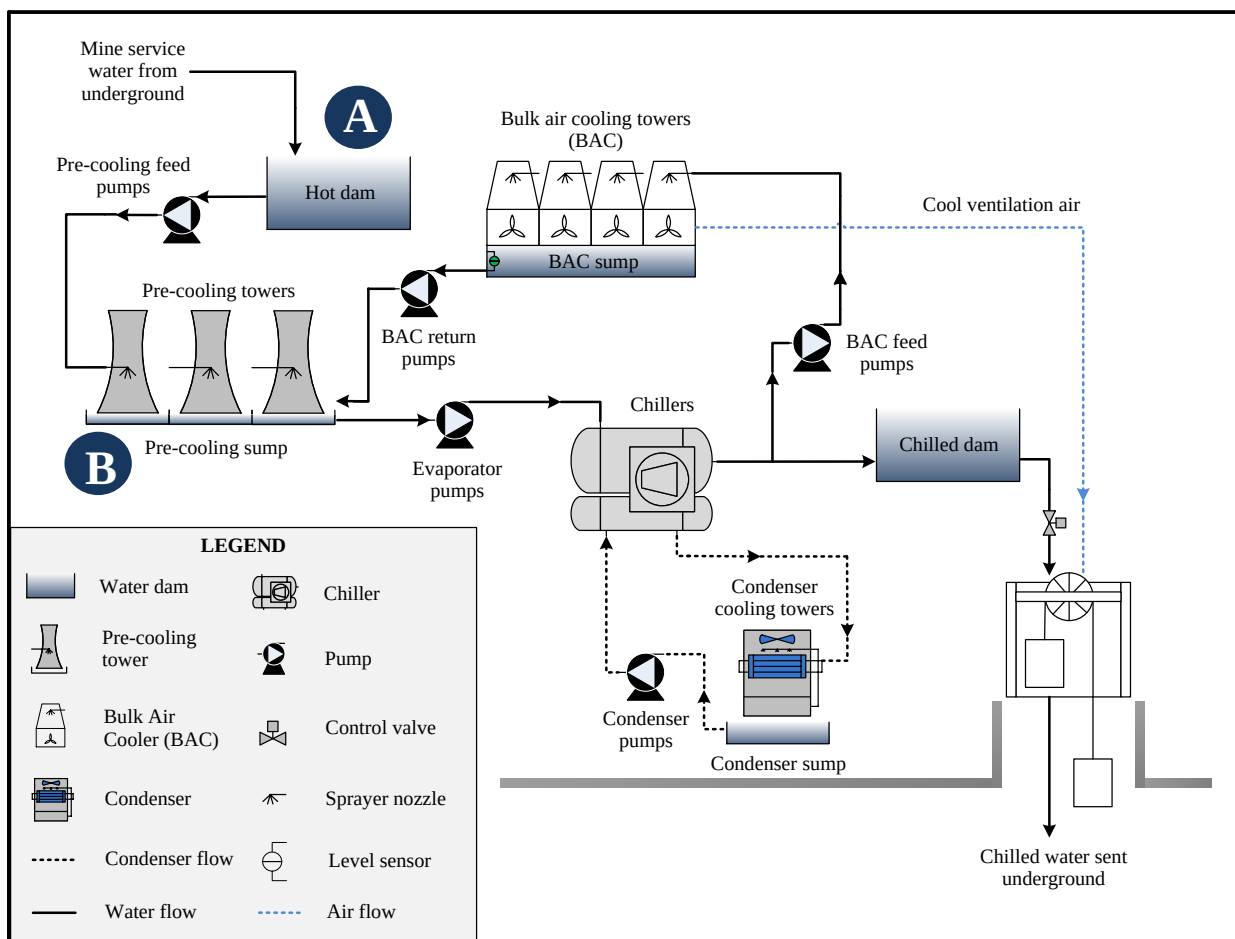


Figure 17: Simplified mine surface cooling system layout

Once the cooling system has been well defined, a summary of the mine's operational stance throughout the year is required. This will involve a consultation with mine personnel to ascertain normal BAU conditions in terms of the operational status of installed refrigeration components throughout the year and corresponding maintenance schedules.

Since mines typically operate all year round, ambient temperatures play an integral role in the operation and performance of chillers. During summer months, ambient WB temperatures are significantly higher than during winter. Due to higher ambient conditions, an increased cooling capacity is required to offset elevated temperatures. Therefore, the majority of the installed chillers and cooling system components will be fully functional. This typically leaves little room for optimisation of the refrigeration system due to stringent end-user requirements. However, as observed in Section 1.6.3, proceeding correct design and utilisation, ITS has the potential to provide significant cost savings with little to no impact on service delivery requirements. During winter, due to cooler ambient temperature conditions, cooling requirements are significantly reduced. In some scenarios, chillers and BAC units are subsequently shutdown without adversely impacting production, service delivery requirements and mine health and safety regulations. This allows mines to conduct maintenance on refrigeration system components.

After the cooling system has been characterised in terms of description, layout and operation, system constraints that may affect the implementation and sustainability of a new load management initiative involving the integration of ITS must be identified.

2.2.3 System constraints

Machines never operate with 100% efficiency. This implies that before a new cost-saving initiative may be executed, each machine involved in the process should be analysed separately to determine possible limitations and constraints that may adversely impact the proposed initiative.

System constraints are characterised as specific factors present in the existing system that may influence the operation of ITS integrated into the system. As discussed in Section 1.5.4, it becomes increasingly important to identify and understand these constraints as they will effectively govern the implementation and success of ITS. Table 4 provides a summary of the possible constraints, restrictions and related risks when determining load management potential through the implementation of ITS. Colour coding red, orange and green indicates the level of risk, with red of highest concern indicating a risk that may severely impact system performance, and green of least concern. A brief description of each constraint in terms of the risk involved is also provided.

Table 4: Identified constraints influencing the implementation of ITS systems on deep-level mines

Constraint	Risk
Cooperation of mine personnel	Incorrect control and operation. The cooperation of mine personnel, specifically operators, play a significant role in the sustainability of load management initiatives.
Condition of installed chillers	Inefficient chiller utilisation and old equipment. Some components may experience problems resulting from the continual stopping and starting of the chiller itself. To improve sustainability, these components should be excluded from the load management strategy. Depending on the ITS operation strategy applied to the system, the operation of inefficient chillers will compromise project sustainability.
Safe underground working conditions	Underground temperatures may exceed limitations during the ice melt/discharge process.
Demand flow requirements	Inefficient flow to underground will adversely impact production, underground environmental temperatures. Inconsistent flow will influence the ice build and discharge processes.
Chill dam storage condition	If the chill dam is not well insulated, a significant amount of heat loss will be experienced. This will require the start-up of chiller units, therefore, resulting in an unsustainable solution.
Thermal storage capacity	Inefficient dam capacity before the ITS facility (typically the pre-cooling storage dam) may result in the flooding of the dam. Since the flow of water through the ice dam is required to be constant throughout the discharge process, along with correct dam preparation, sufficient storage capacity is required. To prevent underground hot water dams from flooding, water is continuously pumped from underground into the pre-cooling storage dam. If the amount of water entering the dam is greater than that leaving the dam, towards the ITS system for a lengthy period of time, flooding of the pre-cooling storage dam will result.

2.2.4 Existing infrastructure

Utilising a similar approach to collect data as discussed in Section 2.2.2, the available control and instrumentation, a list of the installed cooling system components, corresponding installed capacities and technical specifications can be compiled and verified.

Control and instrumentation

Reliable control servers and communication networks are imperative to ensure the sustainable implementation of a cost-saving measure [127]. It is necessary to understand how each cooling system and water reticulation component is controlled, whether it is automated or manually controlled. This will provide additional system considerations and possible restrictions that may need to be accounted for during project implementation. For example, if equipment is controlled manually, mine personnel are required to manually stop and start equipment whilst constantly monitoring process parameters. Therefore, constant human supervision and communication is crucial with manual control intervention.

In general, mines make use of a centralised SCADA system to communicate with programmable logic controllers (PLCs) and field equipment. Utilising the SCADA system, mine operators have the ability to control field equipment and remotely monitor operational parameters of the mine and individual components. To ensure an accurate representation of field measurements is portrayed by the SCADA system, possible measuring points need to be identified such that verification measuring equipment can be installed. This is necessary to not only verify process parameters such as chilled water temperature and flow but will assist in identifying faulty field instrumentation. Accurate monitoring and reporting on process parameters is imperative to ensure sustained cost savings [91].

Technical specifications

To ensure operating conditions of individual components are not compromised, it is crucial to identify technical specifications of each individual component of the installed cooling system. This includes the pre-cooling towers, BACs, chillers, pumps and thermal storage dams. To implement a new cost-saving strategy, pre-implementation component specifications are required.

Technical specifications will assist in identifying and defining important criteria such as process control parameters. Table 5 displays the required specifications of each component present on a typical deep-level gold mine cooling system, necessary to evaluate the feasibility of ITS. To ensure the sustainability and successful integration of an ITS system into a mine's cooling network, identified technical specifications must be adhered to.

Table 5: Required system specifications

System description	Required data
Chillers	• Compressor type [-] • Refrigerant type [-] • Chiller cooling capacity [kW] • Nominal efficiency, COP [-] • Evaporator water outlet temperature [°C] • Evaporator water flow rate [l/s] • Condenser water inlet temperature [°C] • Condenser water flow rate [l/s]
Pre-cooling and condenser towers	• Number of towers [-] • Water inlet and outlet temperature [°C] • Water flow rate [l/s]
Thermal storage dams	• Volume [Ml] • Operating range [%]

BACs	• Number of BACs [-] • Water inlet and outlet temperature [°C] • Water flow rate [l/s] • Air outlet temperature [°C]
Auxiliary pumps	• Number of pumps [-] • Motor rating [kW] • Flow rate [l/s]

Since the implementation of ITS affects the running status of installed chiller plants, additional operational parameters and control limits must be defined to ensure the integrity of the chillers is not compromised. If exceeded, these parameters will cause the plant to trip or lead to the long-term deterioration of affected components. Therefore, control limits need to be monitored post-implementation to ensure that the performance of each individual chiller is not compromised through the implementation of ITS.

Typical parameters and control limits that must be critically analysed to ensure long-term sustainability include, but are not limited to, compressor oil temperature, compressor vibration, gearbox oil temperature, evaporator refrigerant temperature and evaporator refrigerant pressure. Parameters and control limits are typically identified from control manuals and verified by the on-site mechanical foreman. The accuracy of the data gathered in this section is crucial as it will be utilised to simulate and verify the cooling system's operation. Thereafter, the potential impact of ITS on deep-level mines will be simulated and evaluated.

Once all cooling system components have been identified and quantified in terms of layout and system integration, potential scope to implement load management can be determined by evaluating the current operation and control of the system.

2.3 Step 2: Constructing baseline models

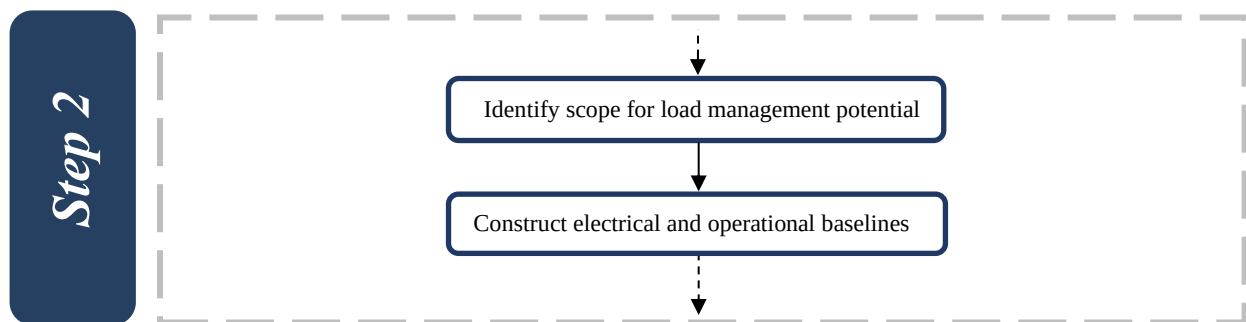


Figure 18: Step 2 - Developing baseline models

2.3.1 Identify scope for load management potential

An important part of the research is to make a case for ITS installations on deep-level mines. To do this, the study herein will assess how effectively ITS can shape peak-tariff demand loads to provide significant cost-saving opportunity. From Section 1.6.1, it was determined that there exist several potential operation strategies associated with ITS systems, namely full storage, partial storage and demand limiting. When determining the most cost-effective operation strategy, the installed refrigeration capacity, cooling load profile, costs of equipment and storage requirements need to be considered.

Although these strategies have proven widely successful in buildings, application in the mining industry is still widely unknown. In a study conducted by Erdemir and Altuntop (2018), the effect of various ITS utilisation strategies were investigated on the economic performance of a hypermarket's cooling system [122]. The study concluded that the full storage system could provide the most significant cost-saving potential, however, consequently resulting in a prolonged payback period. Conversely, the 10% partial storage system resulted in the shortest payback period, however, realising significantly reduced cost savings. In terms of payback period and cost-saving potential, the demand limiting strategy signified the most beneficial solution. Based on both the widespread financial instability of the South African mining industry, the demand limiting storage strategy poses the most realistic solution for deep-level mines. Therefore, focus of this investigation will be to determine the feasibility of implementing the demand limiting strategy. This implies that load reduction potential during Eskom's peak periods will be of primary concern. However, if it has been identified that little scope remains due to already implemented load management strategies, the partial storage strategy should be considered. The generic methodology discussed herein is applicable to either scenario.

The load reduction potential of a mine's refrigeration system can be established in one of two ways. Both of which involve collating the electrical power data of the installed chillers. Either a physical representation of the data can be constructed, whereby it will quickly become apparent whether scope is present. Alternatively, a chiller utilisation ratio can be developed to quantify additional load-shifting potential. The flow diagram depicted in Figure 19, illustrates the general procedure that should be followed when identifying the load reduction potential of a mine refrigeration system. By determining the load reduction potential, not only will the viability of ITS be determined, but the most favourable operation strategy can be established. For clarity purposes, the cooling load calculation will only consist of operational chillers, condenser towers and pumping auxiliaries.

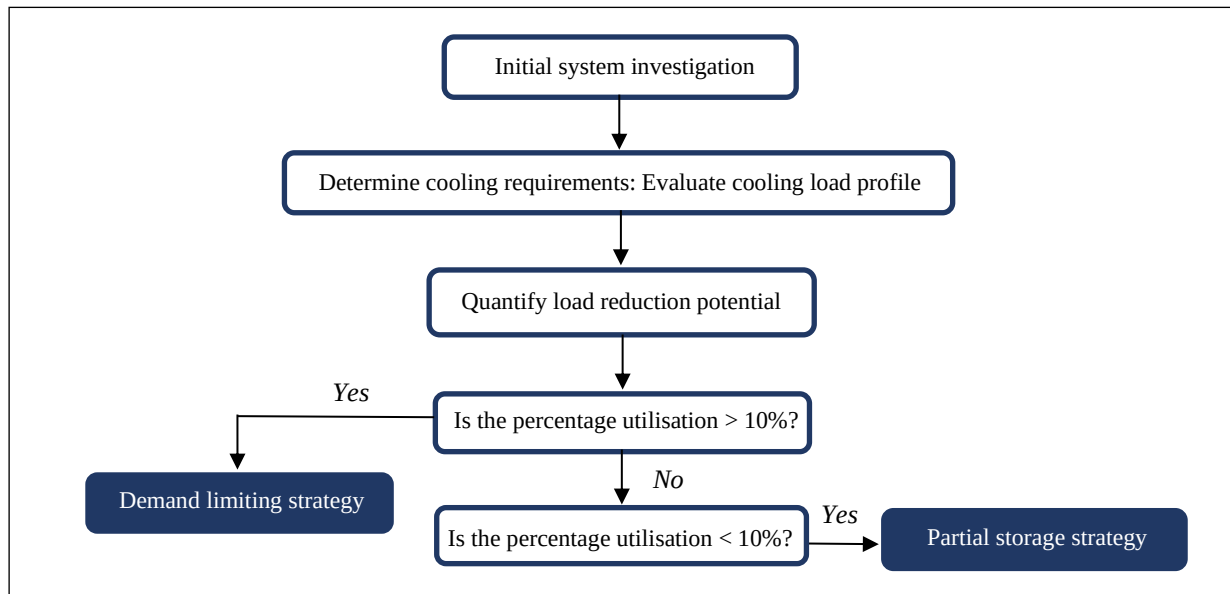


Figure 19: Load reduction and operation strategy identification flow diagram

A consultation with mine personnel will be necessary to determine the potential for load management on the particular refrigeration system. Daily averaged cooling load profiles will provide a useful tool to verify information gathered from mine personnel. It is suggested that both summer and winter cooling load profiles are considered such that minimum and maximum chiller running configurations are determined. Once an accurate representation of the normal BAU cooling load profiles have been generated, the load reduction potential can be quantified. Since gold mines typically operate according to Eskom's Megaflex ToU tariff structure, cost-saving potential relies on a mines ability to shift load out of Eskom's peak periods. Therefore, potential scope can be measured by estimating the potential of reducing the cooling cost (chillers electricity demand) during these periods.

The theoretical load shift is the average power consumption during Eskom's peak periods between 06:00 to 09:00 and 17:00 to 19:00 during winter months (June to August), and between 07:00 to 10:00 and 18:00 to 20:00 for the remainder of the year. Figure 20 depicts an illustrative example of the three plausible refrigeration profiles. Two of the profiles (solid and dotted blue lines) represent systems in which load reduction potential is present, whereas the remaining profile (dotted green line) depicts a system where further load management potential does not exist. Although the profile indicated by the dotted blue line portrays a system whereby an existing load shift is present, there remains significant potential to implement improved load management solutions. ITS has the capability to make up the shortfall. In the scenario that a combined load shift is already capitalised on (dotted green line), additional cost savings can still be realised, however, through the implementation of the partial storage strategy.

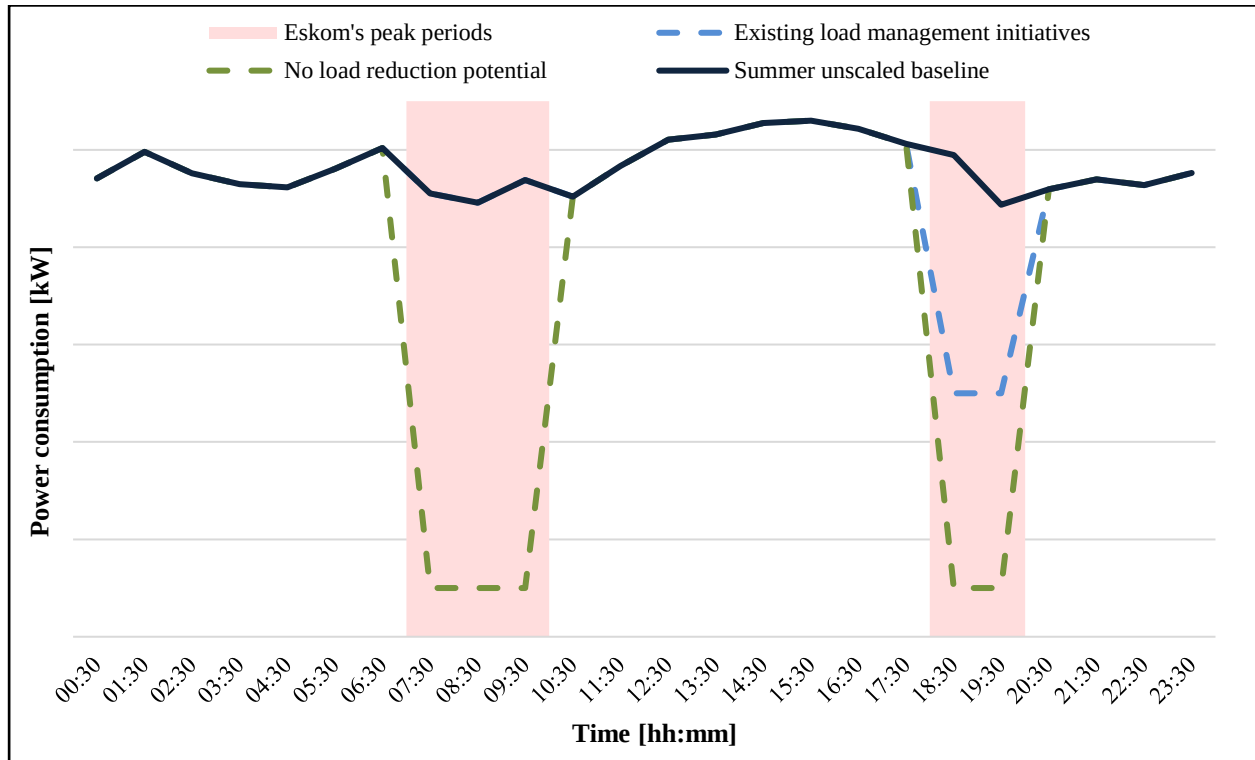


Figure 20: Cooling load profile example

To provide additional support to load reduction estimations made from the cooling load profile, a chiller utilisation ratio can be developed. The utilisation ratio, indicated by Equation 3, represents the average electrical power consumption of the chillers during Eskom's peak periods compared to the installed capacity of the operational chillers during this period. Both measured in kW. This calculation should be conducted separately for both morning and evening peak periods.

Equation 3: Chiller machine utilisation

$$\% \text{ Utilisation} = \left(\frac{\frac{\sum \text{Peak period electrical power usage}}{\text{Duration of peak period}}}{\sum \text{Total installed capacity of operational chillers}} \right) \times 100 \quad [\%]$$

Where:

$\% \text{ Utilisation}$ = utilisation of chillers compared to installed capacity [%]

$\text{Duration of peak period}$ = Number of hours in peak period [–]

The percentage obtained from the calculation will determine the total chiller utilisation during each peak period. A utilisation ratio of 0% indicates a complete chiller shutdown, resulting in no load reduction potential. As the value increases, so too does the systems potential in implementing a load management strategy. According to industry standards, a system utilisation of greater than 10% is deemed acceptable to

start considering the implementation of DSM and load management initiatives [87]. It will therefore be assumed that if the chiller utilisation ratio is greater than 10%, there is sufficient capacity in the system to implement an improved load shift through the use of ITS. In the scenario that both morning and evening peak periods reveal a percentage utilisation of less than 10%, the partial storage system should be considered.

Once the scope for load management has been determined, it will then be required to develop baselines from historical data. Both operational and electrical baselines are required to provide benchmark comparisons such that the future performance and sustainability of ITS can be measured.

2.3.2 Constructing baselines

In order to accurately quantify the feasibility of implementing ITS as an alternative cost-saving technique on deep-level mines, baseline models must be developed. Baseline models represent the performance and current operating conditions of a particular system. In the context of the study herein, it is necessary to develop two types of baseline models, namely electrical power and operational baselines. The electrical power baseline will be used to quantify the power consumption of the system incorporating an ice plant, and the subsequent cost savings realised through effective load management. The operational baselines will be used to determine the impact ITS has on the holistic system, in terms of service delivery requirements and the overall efficiency of the holistic system and individual components. As such, the project's sustainability can be measured.

Electrical power baselines

Before a load management initiative is implemented, the total power demand load (kW) for the mine's chillers and auxiliaries must be quantified. Electrical power data should be collected and analysed such that averaged 24-hour seasonal cooling load profiles can be formulated. It is imperative that accurate cooling load profiles are formulated such that ITS equipment design and sizing is optimal according to the specific application. Undersized ITS systems will result in limited saving opportunities and the inability to meet required performance parameters. Conversely, oversized ITS systems will add an unnecessary expense in terms of increased power consumption and capital expenditure.

Since cooling load requirements are highly dependent on the ambient temperature, there is a seasonal effect on the energy usage of the chillers. From previous studies conducted on mine refrigeration systems, the electrical power baseline representing summer included months from September to May. Baselines were essentially formulated based on "feel". Since daily average ambient temperature conditions range between 11°C and 30°C during this period, the baseline will not accurately capture the month-to-month energy usage of the refrigeration system. Therefore, subsequent energy and cost savings will be quantified with

questionable accuracy. To accurately evaluate the energy and cost-saving potential of any initiative directly affecting the refrigeration system, it is necessary to critically analyse cooling load requirements based on ambient temperatures. Since the feasibility of implementing ITS technologies on deep-level gold mines is largely dependent on its cost-saving potential, accurate baselines through which cost savings are quantified are imperative. To do this, a statistical approach will be adopted.

The first step of the process will require the acquisition of a complete data set of ambient temperatures, outlining localised ambient conditions for a period of one year. Figure 21 illustrates a profile of ambient temperature conditions recorded for Orkney, a region hosting a high-density of deep-level gold mines in South Africa. The maximum, minimum and average daily temperatures are depicted. Since there is a high variance in ambient temperature conditions experienced throughout the year, quartiles were utilised to divide the data into defined intervals of similar temperatures. Quartile intervals are defined based on the value of the data and how it compares to the entire data set. Dividing the data into separate intervals will assist in constructing accurate electrical baselines based on ambient temperatures and corresponding energy usage.

The quartile intervals calculated for the purposes herein, illustrated in Figure 21, are; $Q_1 = 14.43$, $Q_2 = 18.83$, $Q_3 = 22.25$, and $Q_4 = 29.29$. Q_4 represents the maximum value in the sample. Once each quartile interval has been defined, the temperature data range between adjacent quartile intervals can be critically analysed and evaluated. To determine date ranges hosting similar ambient temperature values, a trendline was constructed. A trendline will not only assist to express the general relationship between time of year and ambient temperature experienced but will provide a visual representation of the prevailing direction and behaviour of the data throughout each of the months. Based on the trendline and quartile intervals, date ranges hosting similar ambient temperature values could be derived. Table 6 illustrates the four date range intervals through which corresponding baselines can be constructed.

Based on the temperature data depicted in Figure 21, it is evident that there exists significant variance in the data on a month to month basis. Large variations between August and September can be attributed towards high day-time temperatures and low night-time temperatures, typically associated with the change in season between winter and spring. Since South Africa typically experiences its rainy season between October and February, an increase in humidity, and the resultant decrease in ambient temperatures, will result in large fluctuations in the daily average temperature throughout this period. To evaluate the variance of the temperature data between adjacent quartile intervals, the standard deviation (SD) of each date range was considered. Standard deviation is a useful tool to determine how much variation exists from the mean value of the data set. A low standard deviation indicates a set of values close to the mean, whereas a higher standard deviation represents an increasing variance in the results. To derive boundary conditions with which an acceptable standard deviation can be determined, a normal distribution about the mean was assumed for each interval. This implies that 68% of the data must be within $\pm 1SD$ from the mean, 95% of

the data within $\pm 2SD$ of the mean, and 98% of the data within $\pm 3SD$ of the mean. The equations utilised to derive the quartile ranges and standard deviation of a sample are represented by Equation 17 and Equation 18 found in Appendix A6.

Based on the results depicted in Table 6 to follow, the standard deviation of each date range is acceptable, assuming a normal distribution. As an illustrative example, for baseline period 1, 68% of the data lies within $\pm 1SD$ (14.04 and 9.77) of the mean, 96% of the data lies within $\pm 2SD$ (16.17 and 7.64) of the mean and 100% of the data lies within $\pm 3SD$ (18.31 and 5.50) of the mean. Although baseline 2 recorded only 65% of the data within $\pm 1SD$ from the mean, it will still provide for a valid assumption that the temperature values within the range are close enough to the mean to be grouped in the same baseline. Statisticians involved in quality control programs suggest that the reliability of data is only compromised once the data routinely falls outside of the $\pm 2SD$ range [128]. Therefore, since 99% of the temperature data between 07 November to 10 February falls within the $\pm 2SD$ range, the assumption is valid.

Table 6: Electrical baseline development through the application of statistics

Date range	Baseline	Mean [°C]	$\pm SD 1$ [°C]	$\pm SD 2$ [°C]	$\pm SD 3$ [°C]	Normal distribution [%]		
						68	95	98
13 May to 23 Aug	1	11.90	14.04	16.17	18.31	68	96	100
			9.77	7.64	5.50			
07 Nov to 10 Feb	2	24.34	27.01	29.68	32.35	65	99	100
			21.67	19.00	16.33			
11 Feb to 01 Apr + 28 Sep to 06 Nov	3	20.7	23.29	25.92	28.54	68	95	100
			18.05	15.43	12.81			
02 Apr to 12 May + 24 Aug to 27 Sep	4	16.24	19.19	22.13	25.07	73	96	99
			13.30	10.36	7.41			

Based on the findings documented in this section, electrical baselines will be formulated according to each date range as depicted in Table 6. Date ranges have been constructed and verified based on a low standard deviation of temperatures about the mean. Therefore, since a chillers' energy consumption is heavily dependent on the ambient temperature, energy usage of the installed chillers throughout each date range should remain relatively consistent. This will ensure accurate cost-saving potential of an ITS system implemented on deep-level gold mines is quantified.

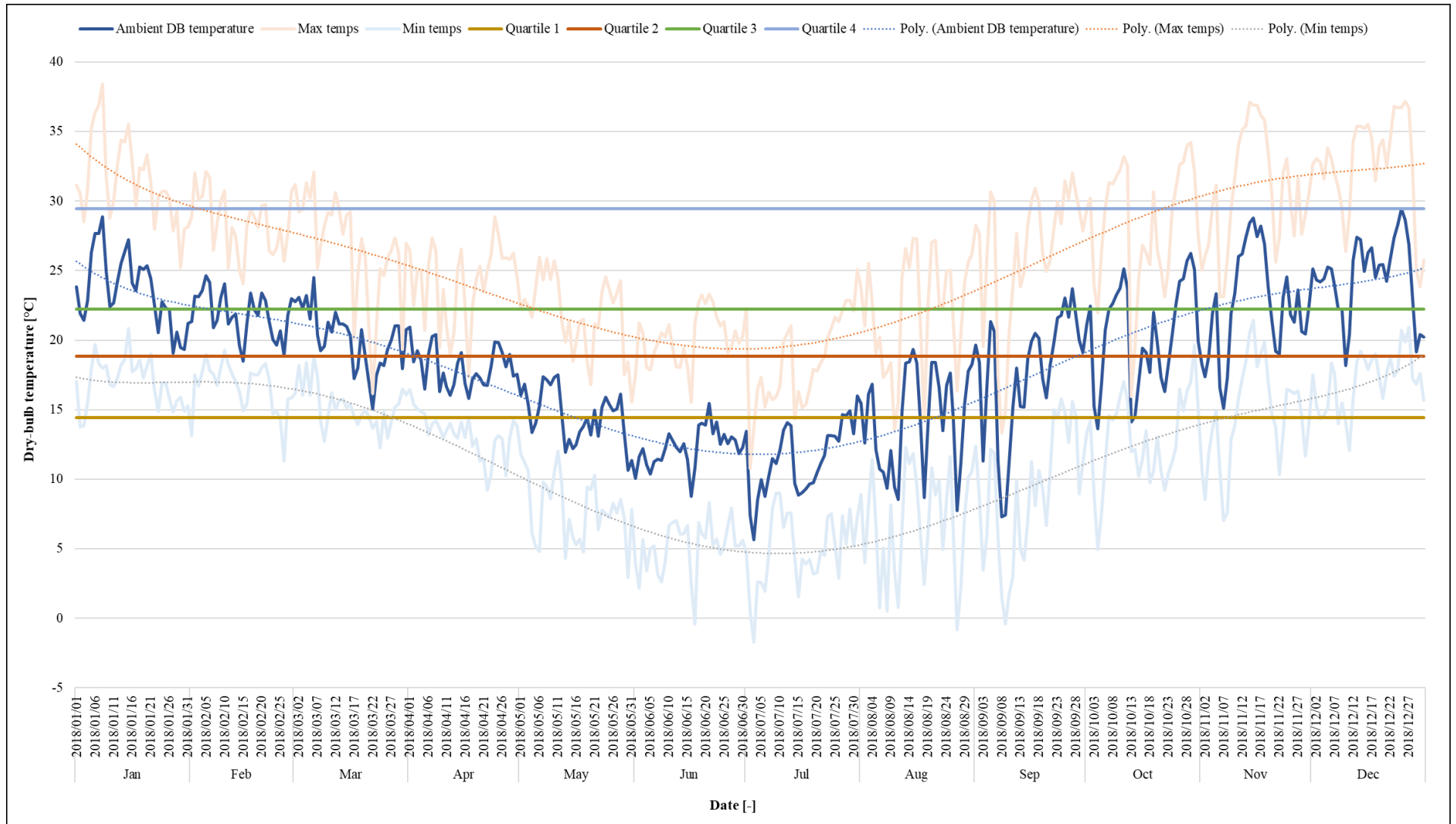


Figure 21: Ambient dry-bulb temperatures for 2018

Due to the dynamic nature of deep-level gold mining operations, a scaling factor, commonly referred to as a service level adjustment⁶ (SLA), is required. The SLA accommodates for significant system disturbances such as operational changes that were not included during baseline development. Through application of an SLA factor, credible cost savings can be determined based on the operational performance of the system for that particular day. The SLA factor can be calculated by applying Equation 4.

Equation 4: Service level adjustment factor

$$SLA_i = \sum_{i=1}^{48} \frac{kWh_{actual_i}}{kWh_{baseline_i}} \quad [-]$$

Where:

$$SLA_i = \text{half} - \text{hourly SLA factor} \quad [-]$$

$$kWh_{actual_i} = \text{half} - \text{hourly actual energy consumption} \quad [kWh]$$

$$kWh_{baseline_i} = \text{half} - \text{hourly unscaled baseline energy consumption} \quad [kWh]$$

Utilising the SLA factor, the corresponding scaled baseline can be determined through application of Equation 5.

Equation 5: Scaled baseline calculation

$$Scaled_{baseline_i} = SLA_i \times Unscaled_{baseline_i} \quad [kW]$$

Where:

$$Scaled_{baseline_i} = \text{half} - \text{hourly adjusted baseline power consumption} \quad [kW]$$

$$Unscaled_{baseline_i} = \text{half} - \text{hourly unscaled baseline power consumption} \quad [kW]$$

For the purposes of the study herein, energy neutral scaling will be adopted. This typically applies to load-shifting projects, whereby part of the operational load is shifted from one period to another [129]. Therefore, to accurately quantify the cost-saving potential of ITS, a fixed unscaled weekly baseline will be utilised, however, adjusted daily using the SLA factor.

⁶ The SLA is representative of the standard M&V procedure to accurately quantify load management savings.

By incorporating an SLA factor, the scaled baseline will be representative of what the energy usage would have been without the implementation of an ITS system. As an illustrative example, Figure 22 depicts the concept of SLA. As a result of external factors such as the load shift, the fixed unscaled baseline is scaled downwards to match the particular day's power consumption.

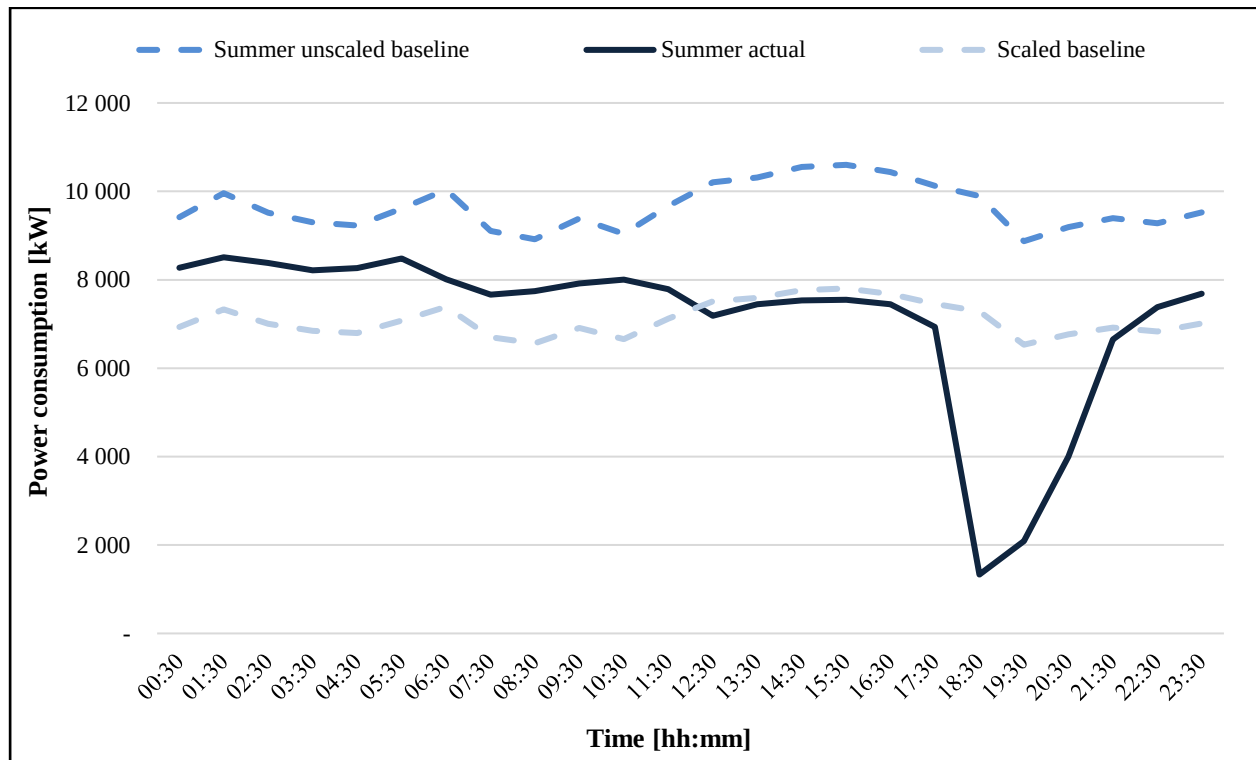


Figure 22: Example application of SLA and scaled baselines

Once electrical baselines have been derived, operational baselines of the overall cooling system and affected system components must be identified.

Operational baselines

Although load reduction potential has already been quantified, process parameters must be determined such that load-shifting potential can be established. A refrigeration system may pose significant opportunity to implement a load-shifting strategy; however, if certain process parameters are compromised, poor sustainability will lead to inevitable project deterioration and eventually, decommissioning of the initiative. To successfully develop and implement an innovative load-shifting strategy employing an ITS system, important process parameters need to be defined. By establishing process parameters, the effect of ITS on the operational performance of the cooling system and service delivery requirements can be determined.

A set of process parameters that will be applicable to monitor the impact of ITS across any deep-level gold mining operation is provided in Table 7. Identified process variables represent system variables that will

either directly affect the performance of an ITS system, or alternatively, be affected by the implementation of ITS. Therefore, for performance monitoring and performance tracking purposes it is important to analyse the trends of identified parameters.

Process parameters highlighted in blue will serve as KPIs. KPIs will be utilised to monitor and compare the impact ITS has on the total operational performance of the mine cooling system and service delivery requirements. To ensure a sustainable daily load shift is attained, KPIs must be monitored to ensure they remain within prescribed limits. Effective monitoring and reporting of KPIs throughout the project's life cycle is imperative to ensure the sustainability of the cost saving measure. Adherence to identified KPIs is tested through simulation and subsequently validated through actual implementation.

Table 7: Cooling system process variables

Allocation	Description	Unit of measure
1	BAC air outlet temperature	[°C]
2	Chilled water temperature sent underground	[°C]
3	Pre-cooling tower sump/dam temperature	[°C]
4	Pre-cooling tower sump/dam capacity	[%]
5	Chill dam capacity	[%]
6	Return water flow from underground	[l/s]
7	Flow of chilled water to underground	[l/s]
8	Chiller outlet water temperature	[°C]
9	Chiller running status	[0/1]
10	WB ambient air temperature	[°C]
11	Chiller COP	[-]
12	Global cooling system COP	[-]
13	Combined system power consumption	[kW]

From the study conducted by Uys (2014), it is clear that the dynamic nature of deep-level gold mining operations pose multiple threats to the operation and efficiency of an ITS system [109]. Therefore, to ensure a sustainable solution is maintained, it is crucial that additional KPIs are derived for the ITS system, such that continual performance monitoring and performance tracking can be conducted to mitigate documented flaws. Additional KPIs will be identified, reviewed and critically analysed.

2.4 Step 3: Developing a cost-saving strategy utilising ice thermal storage

Figure 23 provides the process required to evaluate the feasibility of ITS implementation on deep-level mines. Since limited research has been conducted on the application of ITS systems on deep-level gold mines, predictive modelling is imperative to evaluate the feasibility prior to actual implementation. In order to accurately evaluate and analyse challenges associated with mine cooling, refrigeration systems and new load management initiatives, dynamic simulation models are utilised [50]. Simulation modelling will provide one with the ability to accurately emulate the dynamic operation of a mine cooling system, predicting system behavioural changes, exposing unexpected occurrences and evaluating system performance. Uys (2014) identified that one of the fundamental reasons behind the decommissioning of the ITS system investigated within his study was attributed to poor design and operation. Factors which could have been mitigated through effective simulation modelling. Figure 23 depicts a detailed breakdown of the general procedure to be followed when developing a cost-saving strategy utilising ITS.

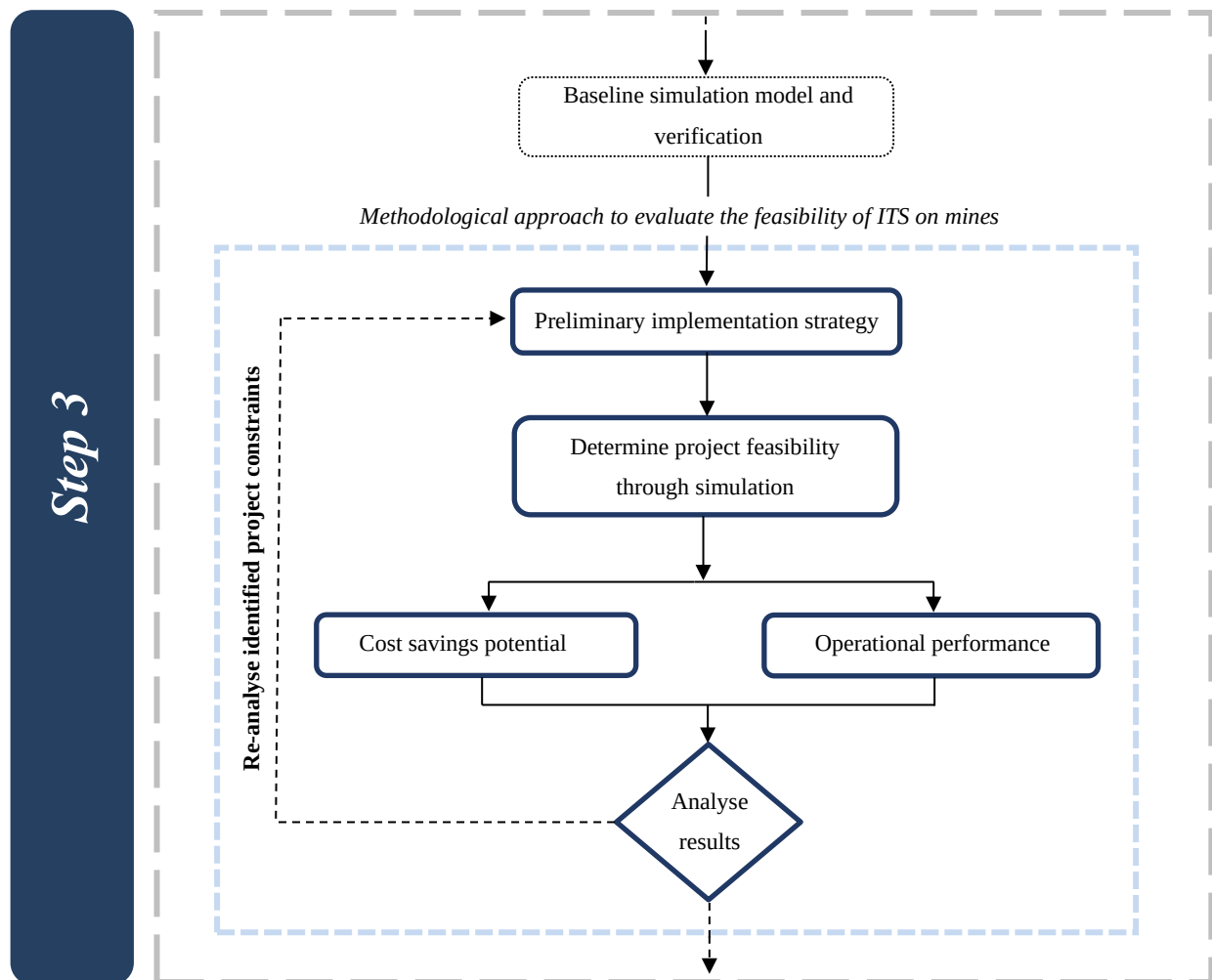


Figure 23: Step 3 - Developing a cost-saving strategy utilising ice thermal storage

By predicting the outcome of a proposed cost-saving initiative by means of simulation, informed decisions can be made to improve the operation and sustainability thereof. Similarly, simulation software has the ability to predict the cost-saving potential of load management initiatives prior to implementation. This becomes particularly advantageous given the current financial stance of gold mining operations across South Africa. Mines cannot afford to waste time, labour and unnecessary capital expenditure on initiatives that may ultimately prove unfeasible, whether it be an unrealistic payback period or adversely impact service delivery requirements to the extent that the project is discontinued or decommissioned.

2.4.1 *Baseline simulation modelling*

According to Peach (2016) there are upwards of 45 available software packages specifically designed to simulate mine cooling systems, each possessing individual benefits and limitations [89]. Based on a comprehensive literature review, multiple authors have identified several software simulation packages that can be utilised for mine cooling system energy studies, namely ENVIRON, Ventilation of Underground Mine Atmospheres (VUMA) and Process Toolbox (PTB) [51][72][76][89]. Each author subsequently reviewed and critically analysed the application of each simulation software package for conducting energy management on mine cooling systems. The review of the above-mentioned software packages was considered based on widely available studies and publications that used the packages for respective applications.

Of the commercially available simulation packages mentioned above, it was concluded that they are all capable of effectively simulating deep-level mine cooling systems [89]. However, to determine the suitability of each software package to fulfil the objectives of this study, the limitations and benefits of each need to be evaluated. Table 33 found in Appendix A7, provides a brief overview of each simulation package, along with the most noteworthy limitations and benefits of each. Based on the benefits and limitations illustrated in Table 33, PTB was identified as the most suitable simulation package to conduct energy management on mine cooling systems and subsequently evaluate the implementation of an ITS system on deep-level gold mines. PTB constitutes a component-based simulation package, incorporating the use of a Graphical User Interface (GUI), allowing the user to drag and drop system components [130]. System components representing that of ITS (specifically that of the external melt ice-on-coil variation), have already been developed in the software package, therefore, eliminating the need to construct each individual component. Pipes and nodes not only form the connection between system components but additionally calculate the thermal hydraulic properties and flow at specified points [130].

PTB simulation software has been utilised in various studies and publications to verify a wide variety of energy and cost saving strategies on mine cooling systems. Peach, Crawford and Maré have all utilised PTB to review, evaluate, analyse and optimise novel control strategies on mine cooling systems [76][89][127]. The accuracy of the simulation package, PTB, was verified by each respective author,

revealing strong correlations to actual conditions with an average percentage accuracy of 97%, 95.6% and 96% respectively. PTB is clearly capable of establishing accurate simulation models that can precisely emulate the dynamic operation of deep-level gold mines.

It is important to note that the mathematical modelling behind the simulation software package, PTB, is not included because developing a simulation package does not form part of the main focus of the study held herein. Arndt, Bouwer, Peach, Maré and van der Bijl all provide further detail on the mathematical models utilised in the simulations constructed in PTB [51][72][75][89][131]. The cooling system components available in PTB will be utilised to construct a new integrated simulation model, used to predict the operation and influence of ITS on mine cooling systems.

Before a solution can be formulated, it is important to construct a baseline simulation model to accurately depict current operating conditions. The baseline simulation model is primarily required to verify the accuracy of the simulation. This will ensure an accurate system response is attained. To evaluate and verify the accuracy of the baseline simulation model, the following procedure should be followed:

- i. Compile a schematic layout of the cooling system
- ii. Collect data of system components to replicate existing cooling system in the simulation package. If measurements are not available, manual measurements should be conducted. This may include flow measurements utilising an ultrasonic flow meter. For complete accuracy, the sizing and location of pipe connections should also be considered and documented. If this is not possible, the pressure drop across a pipe section will suffice.
- iii. Select a normal BAU mine operating day; the simulation model should be constructed to emulate this day. Include ambient temperature conditions (DB and WB temperatures if available, otherwise, DB temperature along with the relative humidity).
- iv. Calibrate and finalise simulation.
- v. To verify the accuracy of the simulation model, compare the simulation results to the actual electrical power data and KPIs identified in Section 2.3.2 for the selected day. Van der Bijl (2007) recommended that a simulation model with an average percentage accuracy of greater than 90% is considered feasible to provide accurate system responses [72]. Therefore, if the error percentage is greater than 10%, the simulation must be recalibrated, and the system adjusted. Repeat the process until a suitable accuracy is obtained. Once results are acceptable, the simulation can be used for further investigations.

A baseline simulation will be required for each baseline period discussed in Section 2.3.2. Before an ITS system is incorporated into the simulation model, it will be worthwhile to analyse pre-existing energy management initiatives already implemented on the mine to determine mine-specific reasoning behind

possible poor performance and project deterioration. This will be necessary to evaluate and compile a mitigation plan that can be incorporated into the ITS implementation strategy to prevent a similar outcome.

Critically analyse pre-existing mine specific initiatives

Through independent studies conducted by Peach (2016) and Groenewald (2015), it was identified that the sustainability of both energy and cost-saving initiatives implemented on large scale operations such as deep-level gold mines is particularly poor [89][87]. Project deterioration may be accredited to a variety of reasons, namely poor condition of plant equipment, mediocre adherence to maintenance schedules, particularly difficult mine personnel unwilling to change, chilled water supply requirements, inability to meet stringent service delivery requirements, poor project maintenance due to a lack of monitoring and reporting procedures, and operator negligence. Investigating pre-existing mine-specific initiatives will assist in identifying the root causes for underperformance such that a mitigation plan can be formulated to prevent factors from influencing the proposed ITS entity. This will not only improve the sustainability of the ITS installation but will ensure acceptable project performance parameters are maintained. Additional site-specific KPIs will provide for the means with which to monitor system performance.

An investigation into pre-existing energy and cost-saving initiatives is imperative for a feasibility analysis to identify risks that may adversely impact the successful implementation of a project. The general process that should be followed when analysing existing initiatives is depicted in Figure 24 and discussed in more detail thereafter.

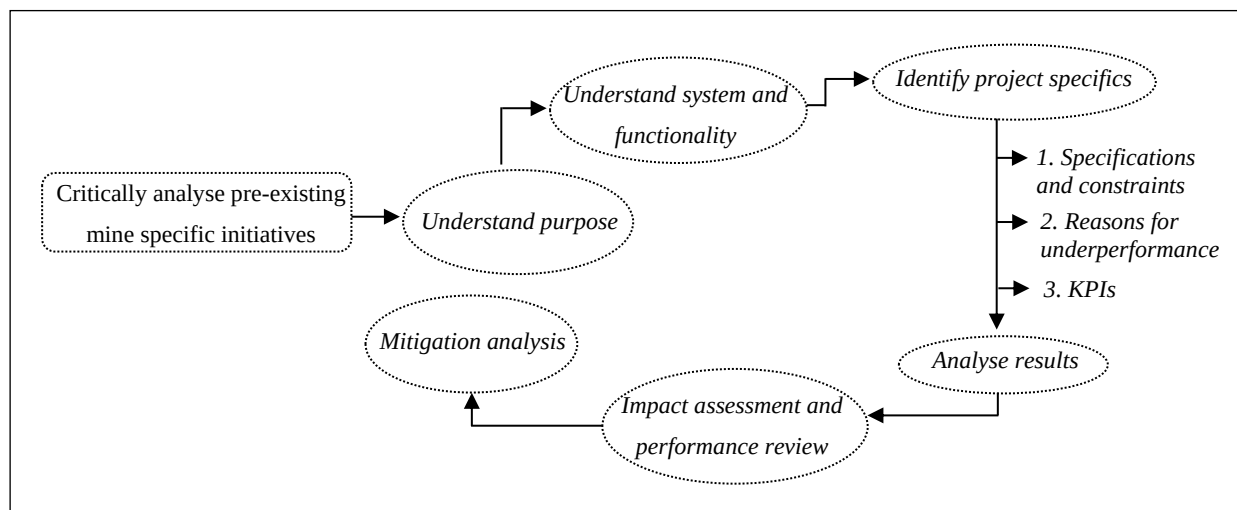


Figure 24: Methodology to analyse pre-existing energy and cost-saving initiatives

Understand the purpose: When analysing and evaluating pre-existing initiatives, it is important to determine why the system, control strategy, mechanical component or system reconfiguration was

implemented. Usually a site visit with mine personnel or contact with the ESCO or contractor that commissioned the initiative is required.

Understand the system and functionality: Once the purpose of the project has been determined, a comprehensive understanding of the initiative and general operation is required. Depending on the nature of the project, it is common that a user manual or handover documentation is available on request. On-site engineers will be able to assist in characterising the initiative.

Identify project specifics: It would be beneficial to conduct a site audit of the installed system/mechanism, along with the on-site mechanical foreman such that operational limitations, constraints and risks can quickly be identified. This will also enable one to determine how the project was integrated into the holistic cooling system and affects both downstream and upstream components. Additional site specific KPIs may be identified in the process.

Analyse the results: Historical trends can be utilised to analyse and verify identified pre-implementation constraints and risks. The baseline simulation model constructed in Section 2.4.1 will provide for an effective method to identify root causes for project underperformance.

Conduct an impact assessment and performance review: The penultimate step of the process will be to determine the overall effectiveness of the existing initiative. In doing so, a decision can be made whether it is more beneficial to integrate the existing initiative into the control philosophy incorporating ITS, or alternatively, discontinue existing control as it may jeopardise the successful implementation of the ITS system, leading to project deterioration and ultimately reduce cost-saving potential.

Mitigation analysis: To prevent project deterioration, comparison studies are conducted. Comparison studies are particularly useful in determining alternative methods that can be applied to reduce existing system constraints which may lead to the subsequent deterioration of ITS installations. Once a mitigation proposal has been formulated, the proposed solution incorporating the use of ITS must be simulated to quantify the operational impact, energy consumption and subsequent cost-saving potential. It is, however, important to note, through the mitigation of existing constraints, new project constraints could be realised. It is, therefore, crucial to re-evaluate and re-analyse mitigation control limits and constraints such as infrastructure, human factors and operational limits.

The primary outcome of this investigation is attributed to determining the constraints and risks that existing mine-specific initiatives may pose to the success and sustainability of an ITS system.

2.4.2 Methodological approach to evaluate the feasibility of ITS on mines

Proceeding baseline simulation modelling, it is then required to utilise the information gathered and mentioned in previous sections to develop a preliminary implementation strategy that can be used to evaluate the feasibility of implementing ITS on deep-level mines. Given the limited availability of research on ITS implemented within the mining industry, simulation models incorporating the use of ITS will provide for a useful tool to quantify initial project feasibility prior to actual implementation. Operational parameters, service delivery requirements and the cost-saving potential will be used to quantify the impact.

2.4.2.1 Preliminary implementation strategy

The optimal design of ITS systems for specific applications have been well documented [105][113][121]. The purpose of this research, therefore, does not cover the specific design of an ITS system, but rather evaluates the feasibility of implementing ITS as an alternative, more effective cost-saving technique for large scale applications such as deep-level gold mines. An important contribution from this research will assess how effectively ITS can shape peak demand loads in South Africa's deep-level mining sector and provide cost savings with a variable ToU tariff structure.

The implementation strategy will focus on establishing a generic step-by-step procedure that can be applied to any deep-level gold mine that will enable the sustainable use of ITS to offset the cost of cooling during Eskom's peak ToU periods. The procedure is divided up into two separate operating periods. The preparation period during which the ice-making process will take place, and the peak period symbolising the ice-melting cycle. A control philosophy was subsequently developed which can be utilised to firstly evaluate the feasibility of ITS implementation through simulation, thereafter, it will provide for a step-by-step procedure for actual implementation purposes. The control philosophy provides further detail on the steps required to ensure a complete peak period load shift is capitalised on.

In order to maximise the cost-saving potential of the ITS system, an important factor that must be considered during both simulation and actual implementation is the effect of ambient temperatures. Amongst several other parameters, the ambient temperature plays an integral role in the ice-making process. As depicted in Figure 21, during winter months the ambient temperature is significantly lower than that experienced during the height of summer. This implies that the possibility of a double ice melt (both the morning and evening peak period) during colder months of the year should be investigated. During months when only one ice melt is feasible, the decision is ultimately up to the mine to decide during which peak period the ice melt should be executed. Intuitively, it would make sense to conduct a morning peak period ice melt to capitalise on an extra hour of peak period tariffs.

From various ITS installations applied to HVAC systems in buildings, it was found that the COP of the refrigeration system during the ice-making phase was higher at night. At higher COP values, refrigeration systems consume less energy per unit of cooling [61][119]. Therefore, to offset lower COP values typically associated with ice systems, night-time operation should be considered. This will not only improve system efficiency but will reduce energy consumption during the ice-making process [132].

Since the use and success of ITS on deep-level gold mines is widely unknown due to the limited availability of associated research, it is worthwhile to provide additional information on the generic setup and integration of ITS into the existing chilled water circuit of a mine cooling system. Depending on the mine cooling system configuration, the ideal location of the ITS system may vary from mine to mine. An ITS system provides for a “side-stream” addition to the existing chilled water circuit, introduced between the hot water confluence dam/pre-cooling towers and the surface chill dam. Hot return water is pumped from underground and received by the hot confluence dam or pre-cooling tower sump. As per normal operation, during the ice-making cycle, water from the hot confluence dam or pre-cooling sump is pumped to the chillers, where after it is stored in the surface chill dam. Conversely, during the ice-melting cycle, instead of water being pumped through the chillers for cooling, water will be redirected through the ice dam, melting the ice, before being sent to the surface chill dam. Therefore, the ice dam will provide the provision for cooling during Eskom’s peak periods, allowing the operational chillers to be turned off. The remaining chilled water circuit equipment such as the BACs and pre-cooling towers will operate as per normal.

Control philosophy incorporating ITS into a mine cooling system

Preparation period:

During the course of the preparation period, the mine cooling system will operate as per normal BAU conditions. The preparation period is governed by the peak period (morning or evening) through which the stored energy will be released. For an evening peak ice melt, the time interval between 20:00 and 18:00* during the low-demand season, and 19:00 and 17:00* during the high-demand season will resemble the preparation period. Whereas, the time interval between 10:00 and 07:00* during the low-demand season and 09:00 and 06:00* during the high-demand season resembles the preparation period corresponding to a morning peak ice melt. According to Eskom’s variable ToU tariff structure depicted in Figure 2, the high-demand season correlates to the winter period, June to August. Consequently, the low-demand season is represented by the remaining months of the year. The control philosophy applicable to the preparation period or ice-making cycle is summarised as follows:

* The ice-making refrigeration machine will operate as needed and switched off once a full ice build has been achieved

- Before the ice-making cycle is initiated, it is imperative to ensure that the initial ice dam water level is within an acceptable range, typically between 70% and 90% respectively. If too little water is present within the ice dam, the tube structure will not be completely submerged, therefore resulting in uneven ice formation. Conversely, if too much water is present, the dam level will slowly rise during the ice formation process, resulting in the flooding of the dam and wastage of stored energy.
- Thereafter, the ice-making refrigeration plant must be started. During the ice-making cycle, although the refrigeration machine is operational, there is no water flow through the dam. Water sent up from underground is firstly received by the pre-cooling towers before being circulated to the chillers, bypassing the ice dam on the way.
- Dependent on the charging temperature of the refrigeration machine, the ice-making cycle will last between 8 – 12 hours [133], until full ice build has been achieved. Thereafter, the refrigeration machine must be stopped to prevent excessive ice formation, resulting in bridging between coils. Automated control will turn off the machine once sufficient ice has formed, whereas manual control requires the plant operator to manually switch off the machine. It is important to note that ITS is a very sensitive operation and if not controlled automatically or according to design specifications, the system may become an unnecessary power consumer that may eventually be decommissioned by the mine. Section 2.5.2 and 2.5.3 provide additional pre- and post-implementation considerations to ensure the day-to-day operation of the ITS system is sustainable and successfully utilised as originally intended.
- Preceding the ice melt, dam preparation may be necessary. However, this is dependent on the chilled water demand specifically during peak periods and implemented load management initiatives on the dewatering system. The dam feeding the ice plant and chillers (either the hot water dam or pre-cooling sump, components A and B illustrated in Figure 17) will require sufficient capacity to melt the ice during the peak period. Therefore, increase the hot water dam capacity such that the dam will not run dry during the peak period. Conversely, if a pumping load shift is not present, the difference in volumetric flow between water entering and leaving the hot water dam will subsequently dictate dam level requirements. Typically, it will be required to decrease the dam/sump level to generate capacity for return water inflow during peak periods. Chill dam preparation is not necessary as the ITS system capabilities should be designed according to peak period chilled water demand requirements. Therefore, no buffer storage capacity is required.

Peak period:

As mentioned previously, during peak periods, the ice-melting cycle will commence. An evening peak ice melt will occur between 18:00 and 20:00 during the low-demand season and between 17:00 and 19:00 during the high-demand season, whereas, a morning peak ice melt will take place between 07:00 and 10:00

during the low-demand season and 06:00 to 09:00 during the high-demand season. The following bullets provide the procedure to be adhered to during the ice-melting cycle.

- During the ice-melting cycle, the ice-making refrigeration machine must be off. Stop all operational chillers according to system constraints. This includes the condenser cooling tower fans, condenser water pumps, evaporative condenser pumps and fans.
- Redirect warm evaporator water from the pre-cooling sump to the ice dam. Depending on system configuration, a series of bypass valves will ensure water flows through the ice dam, instead of the chillers.
- The flow through the ice dam is dependent on supply constraints, the pre-cooling sump level and chilled water demand requirements. Since each mine has varying requirements and constraints, the flow should be controlled accordingly. For example, if the pre-cooling sump level falls below 20%, the ice dam outlet valve must be closed, and ice dam feed pumps stopped. Only once the pre-cooling sump level rises above approximately 40% can the ice dam feed pumps be restarted, and the outlet valve opened. In addition, the ice dam level should remain relatively consistent throughout the melt. Any major deviation in the dam level may indicate a possible blockage or alternatively, a possible leak or ruptured pipe.
- Constant monitoring of system parameters and identified KPIs is imperative throughout the ice-melting cycle. Aside from dam levels, the temperature of water leaving the ice dam poses one of the, if not the biggest constraint to the success and sustainability of the ice system. If at any point the outlet water temperature of the ice dam rises above the temperature setpoint stipulated by mine personnel, remedial action is required. Once a temperature rise is noticed, a delay of approximately five minutes should be considered to allow for temperatures to stabilise. Proceeding the delay, if the outlet temperature continues to impede requirements, the chillers must be started immediately.
- Once the peak period has ended, before the ice dam bypass is closed, it is imperative to ensure there is no ice remanence on the coils. This can be done manually through visual inspection or automated, corresponding to ice thickness sensors present on adjacent coils. Only once all ice has been melted can the ice dam bypass be closed, chillers started, and normal operation continued.
- Proceeding the ice-melting cycle, the preparation period and ice-making cycle will resume.

A mining operation primarily relies on an adequate and reliable cooling system to provide safe and habitable underground working conditions. Any changes to the normal operation of the cooling system may adversely impact underground working conditions, subsequently compromising production. Therefore, it is imperative that a simulation model be developed such that the theoretical impact of the proposed strategy on a practical system can be determined.

2.4.2.2 *Simulating the control philosophy incorporating ITS*

Proceeding the preliminary implementation strategy, project feasibility can be determined through simulation. The performance of the cost-saving measure will be tested and evaluated, outlining the cost-saving potential and ability of the ITS system to comply with service delivery requirements. The simulation will provide for a viable solution to accurately predict system responses, behavioural changes and effects. It is imperative that an integrated simulation model is developed such that the entire cooling system can be analysed as a result of the integration of an ITS system. Thereafter, problematic areas and concerns can be identified, analysed and mitigated proceeding large capital expenditure. Since the baseline simulation model representing current operating conditions has already been calibrated and verified in Section 2.4.1, the proposed load-shift implementation strategy incorporating ITS can be simulated with confidence such that the simulated outcome will accurately emulate actual implementation results. From the simulation model incorporating the use of ITS, the following questions need to be investigated and answered:

- Is it possible to implement both a morning and evening ice melt?
- What size of the load can be shifted without adversely impacting service delivery requirements or mine health and safety?
- The length of time the load can be shifted and at what time of the day?

The considered ITS system in this study falls in the category of static, direct cool thermal storage employing an external melt ice-on-coil approach. Therefore, to accurately emulate system characteristics and behavioural changes of a typical external melt ice-on-coil ITS system, the following model assumptions were made in the simulation software package, PTB [130]:

- No stratification takes place within the ice dam. The water temperature throughout the dam is assumed to be constant, therefore, represents a fully mixed state.
- Ice begins to form on the outside of the ice coils when the dam water temperature is at 0°C.
- The cross-sectional area of the dam remains constant with variations in height.

Throughout literature, there are several mathematical models that have proven particularly useful in determining the exact characteristics of an ITS system [125][134]. These models are applicable for systems that have already been designed and implemented, with variables associated with coil dimensions known. However, since the aim of this research is to cover the physical interaction and impact a proposed ITS installation has on a deep-level mine, various approximations to determine theoretical ITS system characteristics are required to construct an accurate simulation model. These approximations and simplifications are outlined in Table 8 as simulation input variables. Depending on the simulation package utilised, required input variables may vary slightly.

Setting up and calibrating the simulation model incorporating an ITS system will require various iterations before an acceptable simulation is obtained. The input variables listed in Table 8 will provide for initial starting conditions. Thereafter, through several iterations, the input variables will vary according to defined mine cooling system characteristics such as water temperatures, flow and ambient temperature conditions. Input values must subsequently be updated with the value obtained at the end of each iteration. For example, the new ice building water temperature will represent the temperature of the water leaving the ice dam towards the end of the ice-melting cycle.

Through a separate iterative process, the initial ice dam level can be deduced. For example, if one were to start with an initial ice dam level of 90% and during the simulation the dam is noted to flood, it is obvious that the initial dam level must be reduced. The number of iterations will depend on how long the solver takes to tend towards a solution in the form of stabilised variables. The input variables that will be utilised to verify a converging solution are; the initial dam level, the ice-building water temperature, and the ice-melting water temperature. Only once the identified variables have stabilised can it be assumed that the ITS model will provide an accurate representation of the proposed system.

An acceptable solution represents one in which the ice system produces the required outlet water temperature throughout the duration of the given time frame. To achieve this, the ice plant must build a specific amount of ice to provide the required cooling capacity such that a complete load shift is attained.

Table 8: Ice plant model simulation input variables [130]

Input variable	Description	Value
Pressure [kPa]	Ambient pressure at the surface of the dam.	100.0
Initial dam level [%]	The initial level of the dam, preceding the ice-building process. A high dam level is required to ensure coils are submerged.	90.0
Heat transfer coefficient [kW/°C/m ²]	The total combined heat transfer coefficient between the water in the dam and the ambient temperature.	0.0 *
Ambient temperature profile [°C]	The average daily ambient temperature profile according to the baseline periods outlined in Section 2.3.2. A 24-hour profile will be required to represent the change in ambient temperature conditions throughout the day.	-
Initial ice mass in the dam [kg]	The initial mass of ice in the dam. It is assumed that there is no ice present in the system preceding the ice-building process.	0.0
Ice building water temperature [°C]	The dam water temperature at the start of the ice-building phase when there is no ice present on the coils. Since the outlet water temperature associated with external melt ice-on-coil systems will rise toward the end of an ice melt due to ice depletion, a value of 5°C will provide for a good initial approximation.	5.0

Ice building COP [-]	Refrigeration cycle COP for each time step. Through literature it has been identified that the COP typically associated with ITS installations is generally lower than that of chillers. Therefore, a value of 3.0 will provide for a good initial approximation.	3.0
Ice melting rate [kg/hr]	The ice-melting rate at the ice-melting inlet water temperature.	Equation 6
Ice melting ice mass [kg]	The maximum/required ice mass at the end of charging.	Equation 7
Ice building cooling duty [kW]	The refrigeration cycle cooling duty at the ice-building water temperature. This is specified at the start of the ice-building cycle when there is no ice present on the coils.	Equation 8
Dam water volume [m ³]	Maximum capacity of the ice dam.	0.023 m ³ /kWh
Ice building time [hours]	Amount of time it takes to achieve a full ice-build.	10
Ice melting water temperature [°C]	The required dam water outlet temperature. This temperature is based on the chilled water temperature requirement specified by mine personnel.	1.0 - 3.0
Energy tariff [R/kWh]	The electrical energy tariff rate imposed by Eskom.	-

* Heat losses due to convective heat transfer between the dam water and the environment are assumed negligible. This is based on the assumption that the dam is well insulated.

Since the stored energy (in the form of ice) will need to provide the same cooling capacity as chilled water during peak periods, Equation 6 can be utilised to derive the melting rate of the ice according to the dam water inlet temperature and required dam water outlet temperature. Thereafter, through application of Equation 7, the required ice-mass the plant must generate can be determined. It is important to note that the water flow utilised in Equation 6 correlates to flow requirements during peak periods.

Equation 6: Melting rate of stored ice

$$\frac{\dot{Q}_{ice}}{\dot{Q}_w} = \frac{\dot{m}_{ice,m} h_{fg}}{\dot{m}_w C_{p,w} (T_{w,i} - T_{w,o})} \quad [-]$$

$$\Rightarrow MR = \left[\frac{\dot{m}_w C_{p,w} (T_{w,i} - T_{w,o})}{h_{fg}} \right] \times (3600) \quad [kg/hr]$$

Where:

$\dot{Q}_{ice}$ = cooling capacity of ice [kW]

$\dot{Q}_w$ = cooling capacity of water [kW]

$\dot{m}_{ice,m}$ = MR = melting rate of stored ice [kg/hr]

h_{fg} = latent heat of fusion [kJ/kg]

$\dot{m}_w$ = water mass flow rate * [kg/s]

$C_{p,w}$ = specific heat of water [kJ/kg.°C]

$T_{w,i}$ = dam water inlet temperature [°C]

$T_{w,o}$ = dam water outlet temperature [°C]

Equation 7: Required mass of ice

$$m_{ice} = MR \times t_{peak} \quad [kg]$$

Where:

MR = melting rate of stored ice [kg/hr]

m_{ice} = mass of stored ice [kg]

t_{peak} = duration of peak period [hr]

It is suggested that the ITS system be designed according to the duration of Eskom's evening peak period. By doing this, although the system will only be able to capitalise on a two-hour load shift, there exists alternative solutions to extend the ice melt to capitalise on an additional hour of peak tariff rates specifically during the morning peak period. Thermal storage capacity provides one solution. Designing the system according to Eskom's morning peak period will require additional storage capacity, increasing both initial capital expenditure requirements and the charging time required to achieve a full ice build.

Equation 8 can be utilised to determine the ice cooling duty of the refrigeration cycle to create the required amount of ice. It is important that both sensible and latent heat is considered. The sensible portion pertains to the cooling capacity required to lower the initial dam water temperature ($T_{ice-build}$) to the freezing temperature, at 0°C. Thereafter, the latent heat percentage will refer to the phase change between water and ice (the ice-formation process).

Equation 8: Ice building cooling duty

$$\dot{Q}_{ice-build} = [\dot{m}_{ice}[C_{p,w}(T_{ice-build} - 0) + h_{fg}] \quad [kW]$$

Where:

$$\dot{Q}_{ice-build} = \text{refrigeration cycle cooling duty} \quad [kW]$$

$$\dot{m}_{ice,b} = \text{required ice building rate} \quad [kg/s]$$

$$C_{p,w} = \text{specific heat of water} \quad [kJ/kg \cdot ^\circ C]$$

$$T_{ice-build} = \text{ice building water temperature} \quad [^\circ C]$$

$$h_{fg} = \text{latent heat of fusion} \quad [kJ/kg]$$

To determine the ice cooling duty of the plant in Equation 8, the required ice-building rate must first be derived. The required ice-building rate is a function of the charging time and required mass of stored ice. Equation 9 depicts the calculation that can be utilised to determine the required ice building rate.

Equation 9: Required ice building rate

$$\dot{m}_{ice,b} = \frac{m_{ice}}{(t_{ice-build} \times 3600)} \quad [kg/s]$$

Where:

$$\dot{m}_{ice,b} = \text{required ice building rate} \quad [kg/s]$$

$$m_{ice} = \text{mass of stored ice} \quad [kg]$$

$$t_{ice-build} = \text{duration required to build required amount of ice} \quad [hr]$$

It is generally very difficult to determine the exact time required to achieve a full ice build. As mentioned previously, if the ice plant is stopped prematurely, the amount of ice on the coils will be lower than expected. Conversely, if the ice plant is run for too long, overcharging will occur. Overcharging will result in bridging between adjacent coils, eventually forming a solid block of ice. Extensive bridging between coils will not

only restrict water flow through the dam but will prevent uniform ice melting. This will result in elevated water outlet temperatures and may inflict damage on system components such as the coils.

Although the affect associated with bridging between coils will not be apparent during the simulation process, it is still important to determine how long the ice plant should run to create the required amount of ice such that simulation results will most closely emulate actual conditions of the system, thereby, adding credibility to the study. To do this, additional iterations will be necessary. For simulation purposes and as a first approximation, to determine how long the plant should run for, the charging temperature of the refrigerant in the ice plant will be considered. Although charging temperatures remain unknown at this stage, as an initial approximation, the worst-case scenario will be considered. In this case, the worst-case scenario represents a plant supplying relatively “high” charging temperatures. Therefore, for charging temperatures greater than $-4.0\text{ }^{\circ}\text{C}$, a build time of approximately 12 hours is required [135]. Proceeding the first iteration, the total amount of ice created should be compared to the required amount of ice derived from Equation 7. Thereafter, the operational time of the ice plant should either be increased or decreased until the simulated amount of ice mass present in the system is equal to that derived from Equation 7. The ice building cooling duty can also be varied to achieve the desired amount of ice, however, will directly influence capital expenditure requirements. Therefore, should remain as a last resort. It is important to remember that every time the charging time is changed during the simulation, both the ice building rate ($\dot{m}_{ice,b}$) and the required ice building cooling duty ($\dot{Q}_{ice-build}$) must be updated.

Intuitively, the dam volume is especially important to ensure all the coils remain submerged. Therefore, since the actual dam size is an unknown variable, an educated assumption is imperative. Through literature, several authors have formulated a ratio which can be utilised to derive the required tank/dam volume to store a given cooling capacity. Specifically, for the external melt ice-on-coil technique, the minimum required dam volume can be derived from the following ratio [105]:

- $0.023\text{ m}^3/\text{kWh}$

Equation 10 provides the calculation which can be utilised to determine the amount of stored energy in kWh. It is however noteworthy to mention, the larger the dam volume, the higher the possibility of the water bypassing the tube structure during the ice-melting period, therefore, increasing the outlet water temperature.

Equation 10: Amount of stored energy in the form of ice

$$Q_{ice} = \frac{(m_{ice} h_{fg})}{3600} \quad [kWh]$$

Where:

Q_{ice} = amount of stored energy in the form of ice [kWh]

m_{ice} = mass of stored ice [kg]

h_{fg} = latent heat of fusion [kJ/kg]

Once the simulation has converged to a solution, the performance of the ITS system and the holistic cooling system can be critically analysed and evaluated. Simulating the KPIs identified in Table 7 and ensuring that they remain within prescribed limits will confirm the sustainability of the ITS installation. To ensure that the proposed ITS system remains sustainable for an extended period of time, the simulated values must adhere to system constraints identified in Section 2.2.3. Table 34 found in Appendix B depicts the simulation output variables that need to be monitored and evaluated throughout the simulation phase. Monitoring and reviewing these parameters will provide valuable insight into system performance and efficiency, and the impact on the holistic cooling system and individual components.

To quantify the impact of the ITS installation throughout the year, the simulation must be repeated to represent varying operational parameters and temperatures associated with each baseline period derived in Section 2.3.2. Based on the power consumption of the refrigeration system incorporating ITS, by applying the applicable Megaflex tariff structure, the cost-saving potential of ITS can be quantified. At this stage, an economic analysis will be required to evaluate if an ITS system is economically feasible. One way to do this would be to estimate the payback period. The payback period can be quantified through application of Equation 11.

Equation 11: Payback period

$$PB = \frac{CAPEX}{\text{Annual savings according to imposed tariffs}} \quad [\text{years}]$$

Where:

PB = payback period [years]

$CAPEX$ = capital expenditure [Rand]

The capital expenditure represents the capital costs of the entire ITS system including the required refrigeration machine (chiller). To prevent large capital expenditure typically associated with the storage dam and chiller, it will be worthwhile to consider existing mine refrigeration system components to form part of the installation. By retrofitting an existing chiller to supply sufficiently low charging temperatures, significant capital expenditure can be averted. Likewise, based on availability and redundancy, the conversion of an existing thermal storage dam into an ice dam (storage medium for the ice coils), should be considered.

Since the total required capital investment is unknown, a formal quote from an external party (contractor) will be required. For ice-coil selection and sizing, a list of the required information that should be provided to the supplier is provided. Additional information may, however, be required on request.

- Dimensions of the storage dam [L x W x H]
- Melting rate [kg/hr]
- Ice build time [hours]
- System type [External melt ice-on-coil]
- Ice dam water inlet temperature [°C, based on the water received from the pre-cooling towers]
- Required supply temperature [°C]
- The required ice mass [kg]

By analysing the outcome of the simulation model in terms of identified KPIs listed in Table 7, the overall power consumption of the system, the cost-saving potential and payback period of the ITS installation, a project proposal can be drafted to inform the client of the theoretical financial and operational impact. Thereafter, an informed decision can be made by the site engineer on the feasibility of installing an ITS system on the specific mine.

2.5 Step 4: Implementation of proposed solution

2.5.1 Preamble

Once the installation of an ITS system for a specific mine has been proven feasible, the next step of the process involves actual implementation. Figure 25 illustrates the generic implementation methodology developed to ensure the long-term sustainability of ITS installations within the mining industry. This will ensure measures are taken to prevent project deterioration and encourage sustainability, to ensure the proposed ITS system operates according to design specifications, mitigate inefficiencies such as incorrect control and utilisation, and to make certain that the system capitalises on maximum cost-saving potential.

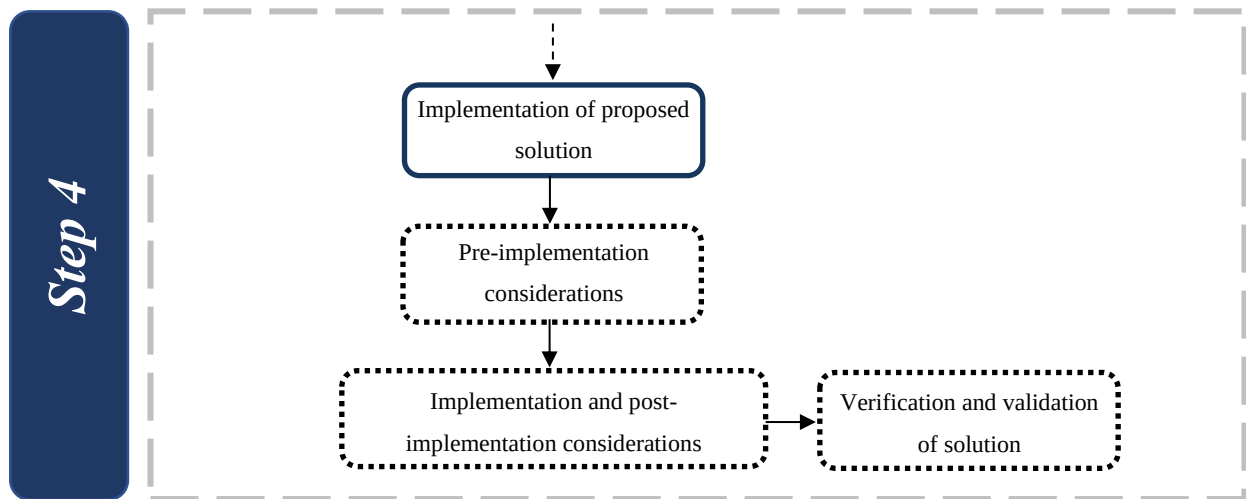


Figure 25: Step 4 – Implementation of proposed solution

Implementation will involve the procurement of an ITS system, optimally designed according to system specifications and service delivery requirements the installation must meet. Implementation and utilisation of the ITS system will require the cooling system to operate according to the control philosophy discussed in Section 2.4.2.1. In this section, improved implementation strategies and operation approaches will be discussed to ensure a sustainable solution is realised. Possible system improvements and optimisation strategies will also be mentioned and reviewed such that maximum cost-saving potential is achieved, with minimal impact on service delivery requirements.

2.5.2 Pre-implementation considerations

One of the most important phases for enabling the successful implementation of a new initiative or project on any system involves pre-implementation considerations. This becomes increasingly important for large-scale applications, specifically deep-level gold mines, which bring into play the overall efficiency of the system, underground working conditions and gold production. The establishment and sustainability of the ITS system will require careful planning to ensure that the implementation of the project proceeds in a comprehensive, cost-effective and timely manner. Before an ITS system is installed on a deep-level mine cooling system, there are several factors that need to be considered. Planning and addressing these factors will avoid project underperformance and deterioration as a result of operational issues. The pre-implementation considerations relating to the installation and operation of an ITS system are provided.

Risk assessment

A risk assessment is important to create awareness of possible risks and hazards associated with the implementation of a new project or initiative. Since implementation of an ITS system has the ability to

directly influence the cooling system, mine health and safety, and day-to-day mine operating conditions, a risk management plan is imperative.

Considerations based on previous studies

Based on various problems experienced in previous studies, a list of pre-implementation considerations can be constructed such that similar issues can be successfully mitigated from future installations. In the study conducted by Uys (2014), an existing ITS system implemented on a deep-level gold mine in South Africa experienced several operational issues, subsequently resulting in the decommissioning of the plant [109]. The problems identified from mine personnel have been reviewed and critically analysed in Section 1.6.3.3. Poor design, incorrect control, improper maintenance and insufficient studies conducted on mine ITS systems all resulted in the poor performance and subsequent decommissioning of the plant.

Preventative measures that can be applied to eliminate such factors from adversely impacting future installations yielding a similar result are provided. Adherence is crucial to ensure the ITS system is successfully implemented and sustainably maintained.

- Preventative measures:
 - Ensure proper design of ice plant, coil arrangement and dam geometry. The layout of the coils in the dam should be arranged in such a manner to ensure uniform flow of water through the coil structure and dam. In addition, correct sizing of pumps large enough to overcome the pressure drop between the water inlet and outlet of the dam is imperative. This will ensure a constant flow of water through the dam, preventing water from stagnating, leading to uneven ice melting. Typically, it is most beneficial for the storage tank, in this case a dam, to be circular in design. A circular storage dam promotes 100% mixing with no corners to prompt the possibility of water stagnating, leading to water stratification. If not designed correctly, the ice storage system will not provide the expected load shift or performance parameters. It is, therefore, important that optimal design of the system is achieved to prevent the deterioration of plant performance. Through optimised ice storage design and use, electricity cost-saving potential is significantly higher when compared to nonoptimal ITS designs [121].
 - Operator training. Plant operators are required for plant performance monitoring (alarm and trip recognition), as well as plant stopping and starting. Depending on the ITS installation and control, if plant operators are not trained, plant performance and sustainability will be compromised. Incorrect operator control and inexperience may lead to excessive ice build-up, resulting in bridging between coils. Bridging between coils will result in a reduction in the surface area for heat transfer to take place, therefore, compromising the water outlet temperature.

- Once a week, preferably on the weekend when cooling requirements are reduced due to no mining activity, the ice-making cycle should be delayed for an extended period of time. During this period, warm water should be circulated through the ice dam, thereby melting any residual ice that may be building up in areas that do not melt during daily cycles.
- Temperature sensors placed at strategic locations on the inside of the dam will provide constant monitoring on the temperature of water throughout the dam. Maintaining a constant temperature of water throughout the dam will promote even melt-rates in all parts of the dam and coils. In addition, ice thickness sensors provide for the means with which to monitor ice formation, ensuring the required amount of ice is created. No more, no less.
- The use of a secondary coolant such as glycol introduces unnecessary concerns and inefficiencies. The use of glycol requires constant monitoring to ensure the ratio of glycol to water is precise. If the ratio is incorrect, the operator will run the risk of insufficient heat transfer, therefore, compromising ice formation. In this scenario, as identified in the study conducted by Uys (2014), a chiller was required to pre-cool water before entering the ice dam during the ice-making process. This is necessary to ensure the available cooling capacity is sufficient to achieve a full ice-build. Therefore, refrigerant or ammonia should be considered, as it is more efficient due to a direct heat exchange process. This will prevent the need for a chiller to pre-cool water, subsequently making the cooling process more efficient.
- To allow for even ice formation, the ice storage system should represent a side-stream addition to the refrigeration system. This implies that when the ice-making process is initiated, warm water will bypass the ice dam and flow directly to the chillers. By doing this, chilled water demand requirements will not impact ice formation. Conversely, during the ice-melting process, warm water will flow directly through the ice dam, melting the ice.
- Insulation should be considered to prevent heat loss to the surroundings.

Pre-cooling tower optimisation

One of the underlying factors governing the length of an ice melt and, therefore, subsequent cost-saving potential, is the inlet water temperature. The lower the inlet water temperature, the lower the rate of ice melt (providing volumetric flow is kept constant). This implies that stored energy in the form of ice will last longer, subsequently increasing the cost-saving potential of the system. Therefore, specifically for mining applications, since water from the pre-cooling towers will be redirected to melt the ice, it will be in the mines best interest to ensure the pre-cooling towers are optimised such that the lowest water inlet temperature to the ice dam is achieved. Maré (2015) investigated the control and operation of pre-cooling towers, outlining ways in which the performance could be improved [127]. Identified factors would

essentially ensure optimal heat transfer between ambient air and return water from underground, therefore, resulting in a lower outlet water temperature. Additional detail on these factors and ways in which to improve the performance of a mine's pre-cooling towers is summarised in Appendix A2.

Depending on the underground chilled water flow demand, as an alternative technique to lower the pre-cooling tower sump temperature, and hence the water inlet temperature to the ice dam, the application of a back-pass valve system will be beneficial. As discussed in Section 1.5.2, by implementing back-pass valve control between the chiller outlet and pre-cooling sump, a portion of the chilled water leaving the chiller mixes with the warm water in the pre-cooling sump, therefore, decreasing the overall sump temperature.

Performance monitoring and tracking

It is essential that the mine implements performance monitoring and reporting practices from project inception. As mentioned in Section 1.5.5, the application of such practices is integral for maintaining the performance of the ITS system and corresponding cost-saving potential. Through effective monitoring and reporting, operational inefficiencies are easily identified.

2.5.3 Implementation and post-implementation considerations

The basis of this section will be to evaluate and critically analyse how the system will react to the integration of an ITS system. The sustainability of ITS depends on the impact the ice-making and ice-melting cycles have on the overall cooling system performance and KPIs. Although the simulation model developed in Section 2.4.3 may indicate that KPIs remain unaffected throughout the ice melting cycle, monitoring and reporting on system KPIs during and after project implementation is imperative to ensure service delivery requirements are continuously met.

To ensure the ITS system is continuously up to date with system and behavioural changes, identified KPIs should continuously be reviewed, re-evaluated and updated accordingly. Since the operation of an ITS system affects normal chiller operational parameters, it is imperative to additionally review and evaluate identified control limits. Control limits need to be monitored to ensure the performance of each chiller is not compromised due to the implementation of the ITS system. Typically, system limitations and constraints are identified during the initial stages of the project investigation. However, it is impossible to identify all system limitations. Problematic areas and concerns can be identified, analysed and mitigated by gaining extensive knowledge on the operation of the ITS system and how it interacts with the mine cooling system. Process data should be extensively analysed throughout project implementation to ensure the ITS system functions as expected. If cooling system parameters change, the operation of the ITS system should be revisited such that system sustainability is not compromised.

A comprehensive maintenance schedule must be developed and adhered to. Since ITS systems are typically far more complicated than non-storage systems, it is important to note that extra time and skilled personnel will be required to ensure the plant is sustainably maintained and operating according to the intended design [111]. Holman (2014) confirmed that the application of a thorough maintenance regime is integral to maintain operational performance parameters of a system [60]. The goal of preventative maintenance procedures is to establish consistent practices that will ensure the ITS system is sustainably maintained, preventing inevitable deterioration in system performance. Moreover, planned maintenance improves the life cycle of system components and avoids costly unplanned maintenance activities. The cooperation of mine personnel is imperative to ensure a successful maintenance program is achieved.

Quantifying improvements

By comparing pre- and post-implementation power data, based on the applicable Eskom tariff structure, daily cost savings can be quantified. Possible energy savings can be quantified in a similar manner. Comparing pre-implementation KPIs and process parameters to that obtained proceeding ITS implementation, the operational impact on the holistic mine cooling system, limitations and benefits gained can be determined.

Another useful way to quantify the impact of an ITS system is to compare the energy expenditure and cost to cool one litre of water before and after implementation. Equation 12 and Equation 13 provide the general equations that can be utilised to derive the cost and energy required to cool one litre of water. The daily energy consumption and cost to cool water incorporates the chillers, condenser towers, ITS plant and pumping auxiliaries. Other cooling system components such as the BACs and pre-cooling towers are not included. By comparing the cost and energy to cool one megalitre of water of a conventional refrigeration system to that incorporating the use of ITS, additional insight on how ITS impacts the holistic refrigeration system performance is attained.

Equation 12: Energy consumption required to cool daily water volumes

$\text{Cooling ratio}_{\text{energy}} = \frac{E_{\text{cooling}}}{V_{\text{sys}}} \quad [\text{kWh/l}]$
Where:
$E_{\text{cooling}} = \text{daily energy consumption due to cooling} \quad [\text{kWh}]$
$V_{\text{sys}} = \text{total volume of water cooled per day} \quad [\text{l}]$

Equation 13: Total cost to cool daily water volumes

$\text{Cooling ratio}_{cost} = \frac{C_{cooling}}{V_{sys}} \quad [R/l]$
Where:
$C_{cooling} = \text{daily cost of cooling} \quad [R]$
$V_{sys} = \text{total volume of water cooled per day} \quad [l]$

2.5.4 Verification and validation of solution

In general, once a new control strategy or load management initiative has been simulated, the next step of the process would be to physically test the strategy on an existing system. However, since one of the primary goals of this research is to determine the feasibility of ITS on deep-level gold mines, testing the solution is not plausible prior to actual implementation. Therefore, to assist other mining operations in determining mine-specific ITS feasibility, it is worthwhile to verify that the proposed methodology and analytical approach in setting up a simulation model discussed in Table 8 is valid in accurately emulating actual implementation results. This will be conducted on an actual case study mine employing the use of ITS for effective load management. In addition, to add credibility to the developed solution, it is necessary to validate the results obtained from the simulation.

To validate the simulation model, the following parameters must be monitored proceeding implementation and compared to the results obtained from the simulation.

- Temperature of water leaving the ice dam
- Ice building time
- Duration of the ice melt
- Chilled water temperature sent underground
- Pre-cooling sump water temperature
- Power consumption of combined system including the chillers, condenser towers, ITS plant and associated pumping auxiliaries

Accurate verification and validation results will afford other similar mining operations the ability to apply a similar approach in determining mine-specific project feasibility without capital expenditure. Considering the financial instability currently experienced throughout the mining industry, along with large capital investment requirements typically associated with ice systems, this will prove invaluable to mines seeking innovative cost-saving measures.

2.6 Conclusion

Previous studies have indicated that mine refrigeration systems are ideal for implementing load management initiatives. Although there exist several load management strategies that have already been implemented on mine refrigeration systems, the subsequent load-shifting capability and cost-saving potential remains limited. Factors such as thermal storage capability, installed refrigeration capacity, service delivery requirements and complex system configurations contribute to restrictions in load management potential and project underperformance. From extensive application and success in the building industry, ITS systems have been identified as an alternative cost-saving technique that can be applied to mine refrigeration systems.

This chapter provides the methodological approach that can be utilised to evaluate, assess and implement ITS on deep-level mines. The methodology focuses on characterising the system, identifying potential load management scope, developing a simulation model to quantify the theoretical impact and evaluate project feasibility without capital expenditure, and finally, the sustainable implementation of ITS on a practical system. Moreover, it provides a generic approach that can be used to quantify the cost-saving potential and benefits gained from the implementation of ITS systems in the mining industry.

The methodological approach developed herein adheres to the objectives stated in the previous chapter, which is to evaluate and quantify the feasibility of using ITS on deep-level mines. Application of ITS systems on deep-level mines have the ability to not only maximise the cost-saving potential of mine refrigeration systems through effective and sustainable load management but will also increase Eskom's reserve margin in peak periods, further stabilising the national power grid. The next section will focus on implementing the proposed methodology on an actual deep-level mine as a case study.

CHAPTER 3: STRATEGY IMPLEMENTATION THROUGH PRACTICAL APPLICATION



7

This chapter discusses case study results, quantifying the feasibility of implementing ice thermal storage on deep-level gold mines. Simulation and actual implementation results are discussed to prove the feasibility of utilising ice thermal storage technologies as an alternative cost-saving strategy through effective load management. Post-implementation results serve as a performance assessment tool on ice thermal storage implemented within the mining industry.

⁷ <https://www.planetkb.co.za/cmsAdmin/uploads/mine-headgear-surface-infrastructure-sunset.jpg>

3.1 Introduction

The benefits of an ITS installation implemented on a deep-level mine cooling system will be quantified through actual case study implementation. The mine in which the research was conducted, hereafter referred to as Mine P was selected as a suitable case study, hosting one of the only ITS installations within the mining industry in South Africa. During the course of the 2018/2019 financial year, Mine P's ITS system experienced its fair share of operational issues. Poor control and utilisation ultimately lead to extensive downtime due to unplanned maintenance. This, therefore, provides the ideal scenario to conduct a feasibility analysis and critically evaluate the holistic impact ITS has when implemented on a deep-level gold mine.

The aim of this chapter is to add relevant research to literature on the potential of utilising ITS as an alternative cost-saving measure within the mining industry. This chapter will follow the methodology outlined in Chapter 2 by initially analysing Mine P's cooling system during the extended periods of time in which the ITS system was not operational. From this, results will be used to validate the developed methodology and simulation strategy such that other deep-level mining operations will be able to utilise a similar approach in determining mine-specific feasibility. Thereafter, actual implementation results with and without the use of ITS will be compared, quantifying the financial impact and benefits gained by incorporating ITS on a mine cooling system. This will provide valuable insight into the use of ITS within the mining industry, outlining how the system will impact service delivery requirements, normal BAU conditions and the operational performance of the holistic cooling system and individual components. Improved implementation strategies and operation approaches Mine P adopted to prevent project deterioration will also be discussed to improve the sustainability and cost-saving potential of future ITS installations.

3.2 Step 1: Characterising the system

3.2.1 System description, layout and operational overview

As mentioned above, to validate the methodology and simulation approach developed in Chapter 2, Sections 3.2 to 3.4 will exclude Mine P's ITS installation, utilising actual system parameters and conditions derived from the intermittent periods in which the ice plant was not in operation.

Mine P reaches depths of up to 3 100 m below surface in search of gold rich ore deposits. The surface cooling system utilised at Mine P is solely utilised for mine cooling and ventilation purposes. A substantial combined system cooling capacity is available to offset large heat loads typically experienced at these depths. Figure 26 displays a simplified layout of Mine P's surface cooling system excluding the ITS installation. The location of the cooling auxiliaries and major surface storage dams are depicted in the

layout. The process starts with hot return water pumped from underground to three pre-cooling towers located on surface. The long-term daily average water flow rate from underground is 450 l/s at a temperature ranging between 12 °C and 22 °C depending on the season. The pre-cooling towers utilise ambient air to cool the water to within approximately 3 °C of the ambient WB temperature. Thereafter, the water is stored in the pre-cooling sump, before entering the evaporator circuit.

From the pre-cooling sump, the water is supplied to five Hitachi chillers arranged in parallel. The water passes through the Hitachi machines for a first stage of cooling down to 6 °C, where after the water is temporarily stored in the intermediate dam. Each chiller has the ability to operate between 200 to 320 l/s by virtue of variable speed drives (VSDs) installed on the evaporator pumps of each Hitachi chiller. Depending on the chilled water demand, the evaporator pumps are controlled according to high, medium or low water flow rates. The pumping regime is operator-controlled, based on dam levels and time of the day. Chilled water demand is reflected by the level of the surface chill dam, as well as underground cold-water dams.

From the intermediate dam, the water is pumped to six ammonia plants, also arranged in parallel, for a second stage of cooling to approximately 1.5 °C at a flow rate of up to 180 l/s per plant. Thereafter, the chilled water is stored in the surface chill dam before being sent underground. The purpose of the chill dam is to provide buffer capacity between supply and fluctuating demand requirements. From the chill dam, a percentage of the chilled water is circulated to three BACs through the provision of BAC feed pumps at a rate of approximately 220 l/s, dependent on the season. Utilising BAC return pumps, water is supplied from the BAC sump to the pre-cooling sump at about 12 °C (also dependent on the season) and mixed with the pre-cooled water.

Chilled water from surface is supplied underground through the use of a three chamber pipe feeder system (3CPFS), split into east and west chambers at between 1 °C to 4 °C. Surface booster pumps supply the 3CPFS with chilled water at a flow rate of about 220 l/s per chamber, where after the water is stored in the 1200L* cold-water dam. Similar to the Hitachi evaporator pumps, the booster pumps are fitted with VSDs. Depending on the chilled water demand, the pumps are operated according to high, medium or low water flow rates. Once the water has circulated through the underground system, it is returned to the 1200L hot confluence dam before returning to surface through the use of the 3CPFS. Dewatering pumps are utilised when necessary to supplement the 3CPFS to overcome losses due to friction in the chambers. The entire process is then subsequently repeated. A detailed layout and operational overview of a 3CPFS is available in Appendix A2.

* Contrary to conventional mining terminology, for the case study mine investigated herein, 1200L represents 0.36 km underground.

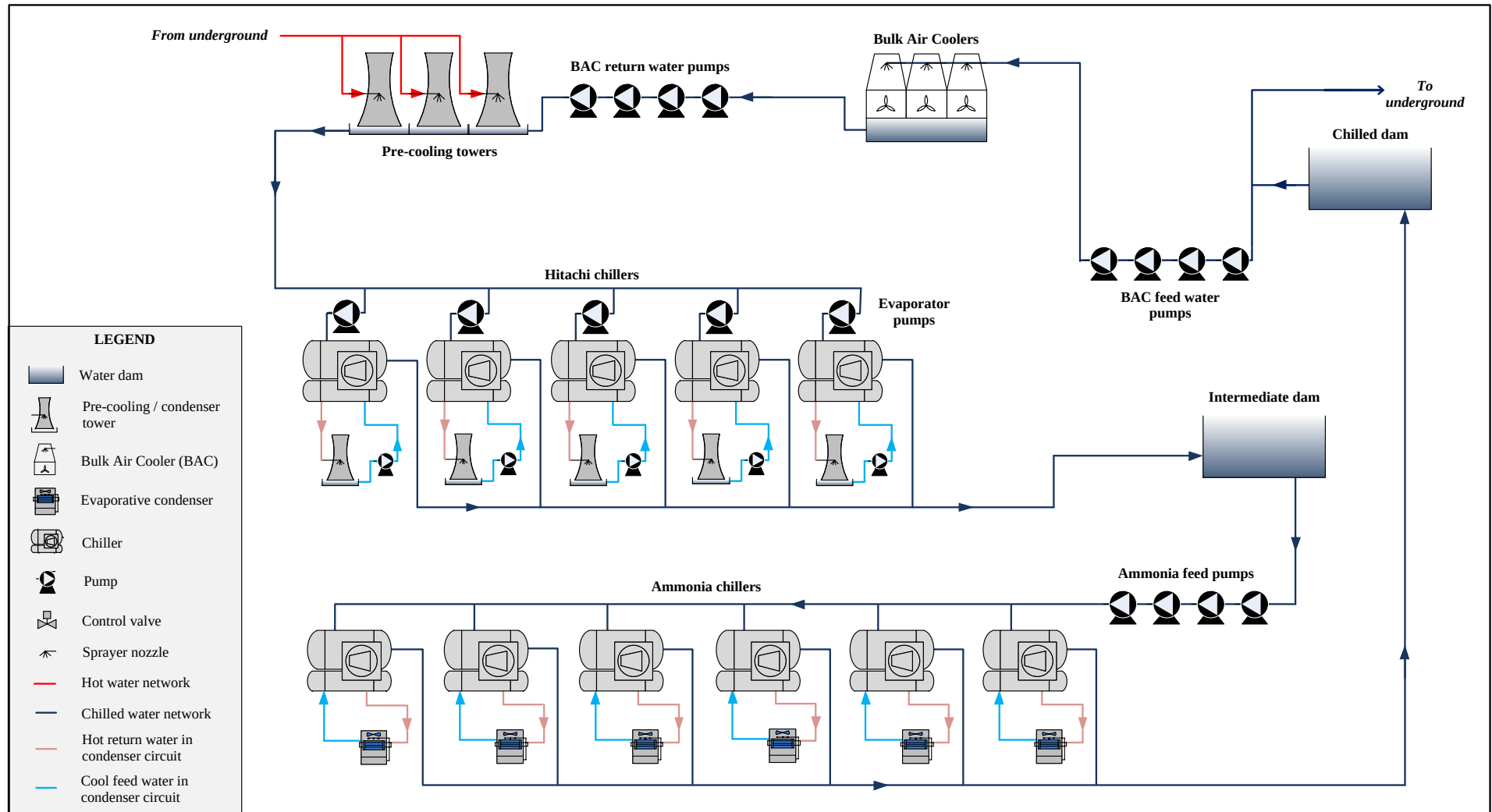


Figure 26: Surface cooling system process flow diagram - Mine P

Normal system operation

During hot summer months the majority of the mine cooling system is operational due to a significant increase in the demand for chilled water and cooled air. This implies all available BACs and a total of eight chillers are in operation. During peak winter months, a significant reduction in ambient WB temperature is experienced. Due to significantly low ambient WB temperatures resulting in sufficiently cool and dry air, a reduction in the demand for cooled air and chilled water allows for several chillers and BAC fans to be stopped without adversely impacting productivity and mine health and safety regulations. For the remaining months of the year, cooling system components are started based on cooling load requirements. Table 9 provides further detail on the operational status of Mine P's cooling system throughout the year.

Table 9: Operational status of Mine P's cooling system components throughout the year

Component	Baseline 1: 13 May to 23 Aug	Baseline 2: 07 Nov to 10 Feb	Baseline 3: 11 Feb to 01 Apr + 28 Sep to 06 Nov	Baseline 4: 02 Apr to 12 May + 24 Aug to 27 Sep
Pre-cooling towers	3	2	2	2
BAC fans	0	3	2	2
BAC return pumps	0	3	2	2
BAC feed pumps	0	3	2	2
Hitachi chillers	2	4	3	2
Condenser towers	2	4	3	2
Evaporator pumps	2	4	3	2
Ammonia chillers	2	4	3	3
Ammonia feed pumps	2	4	3	3
3CPFS (east and west)	2	2	2	2

Due to the dynamic nature of Mine P's cooling system and daily changes in the operational performance of the system, the operational status of installed chillers is not necessarily constant throughout each period. It is not uncommon that an extra chiller be started depending on underground temperatures and/or downstream chilled water dam levels.

3.2.2 System constraints

System constraints were identified based on existing areas of concern, and system limitations that may adversely impact ITS performance and operation. Identified constraints include cooperation of mine personnel, safe underground working conditions, demand flow requirements, evaporator pump control, pre-cooling sump capacity and the operation of pre-cooling towers throughout the year. Table 10 outlines the

risks associated with identified constraints. A mitigation plan corresponding to each constraint is additionally provided. Colour coding red, orange and green indicates the level of risk. Red indicates severe concern suggesting that the risk may influence project performance and success, and green of least concern.

Table 10: System constraints - Mine P

Constraint	Risk	Mitigation
Cooperation of mine personnel	Incorrect control and operation. Due to the lack of training and operator cooperation, several previously implemented load management initiatives on Mine P were unsustainable and subsequently decommissioned.	To mitigate a similar outcome regarding new initiatives, operator training will be required. Operators must be proficient in the steps to be taken during both ice charging and discharging cycles.
Safe underground working conditions	Underground temperatures may exceed limitations during the ice-melting process.	It is required to constantly monitor chilled water temperatures leaving the ice dam. If temperatures exceed prescribed limitations, additional chillers should be started immediately.
Demand flow requirements	Inefficient flow to underground will adversely impact production, underground environmental temperatures.	The flow of water through the ice dam must match that sent underground specifically during peak periods. This will require strategic dam preparation.
Evaporator pump control	When the evaporator pumps are started, the Hitachi plants automatically start in unison.	To prevent this from happening during the ice-melt sequence, additional programming in the evaporator pump control is necessary. Pumps can be placed on a “maintenance setting”, allowing the pumps to run for an extended period without the chiller machine starting.
Pre-cooling sump capacity	Due to the presence of a 3CPFS, water is continuously sent to surface throughout the day.	To prevent the flooding of the pre-cooling sump during peak periods, dam preparation is necessary.
Operation of pre-cooling towers throughout the year	As depicted in Table 9, at least two pre-cooling towers are operational throughout the year. Since pre-cooling towers utilise ambient air to cool return water from underground, during peak summer months, the reverse may occur. As soon as the ambient air WB temperature exceeds that of the return water temperature, the ambient air will in fact heat up the water.	To maximise the length of the ice melt and subsequent cost savings, it will be beneficial to operate the pre-cooling towers based on ambient WB temperatures. This will ensure that the water pumped through the ice dam during the ice-melting process is of lowest temperature possible.

3.2.3 Existing infrastructure

Control and instrumentation

At Mine P, equipment is controlled from a centralised control room. Mine P makes use of a Citect™ SCADA system to communicate with field instrumentation and PLCs. Mimic operators utilise Citect™ to

remotely and automatically control mine cooling system equipment through respective PLCs. The PLCs interacts with the SCADA and corresponding field instrumentation using open platform communication (OPC). With read and write capabilities, OPC tags have been created to record and monitor critical process parameters. OPC tags subsequently convey specified process parameters to the SCADA whereby mimic operators can monitor the performance of the cooling system in real-time and take immediate remedial action when necessary. Field instrumentation fitted strategically along Mine P's cooling system in terms of dam level sensors, temperature sensors and flow meters report necessary process parameters.

Mine P's technical specifications

The technical specifications for Mine P's cooling system components are presented in Table 35 found in Appendix C1. Technical specifications are crucial to identify the operating parameters and conditions of installed components.

To ensure the integrity of installed chillers are not compromised as a result of the implementation of ITS, additional control limits must be identified and adhered to throughout project implementation. Table 36 and Table 37 found in Appendix C2 illustrate the existing control limits for the ammonia and Hitachi chillers installed at Mine P. To ensure the long-term sustainability of ITS, constant monitoring and reporting is imperative to ensure operating conditions of individual chillers do not exceed these control limits.

3.3 Step 2: Constructing baseline models

3.3.1 Identify scope for load management potential

Due to the presence of a 3CPFS on Mine P, load-shifting initiatives corresponding to the chillers have not been feasible. The pre-cooling sump and surface chill dam do not have the required thermal storage capacity to turn off the chillers during Eskom's peak ToU periods. A continuous flow of chilled water must be supplied to the surface chill dam throughout the day.

Figure 27 illustrates the daily average cooling load profiles for Mine P during peak summer and winter months. Cooling load profiles represent normal operating conditions of Mine P's refrigeration system when the ITS system is not in use. For the initial investigation, only summer and winter profiles were considered such that minimum and maximum chiller running configurations could be determined. In general, the power consumption of installed chillers remains relatively consistent throughout the day during summer. However, during winter months, in the absence of ITS, Mine P implements an evening peak clip on one of the operational chillers. Proceeding the evening peak period, ending at 19:00, the plant is restarted, and normal chiller operation is resumed.

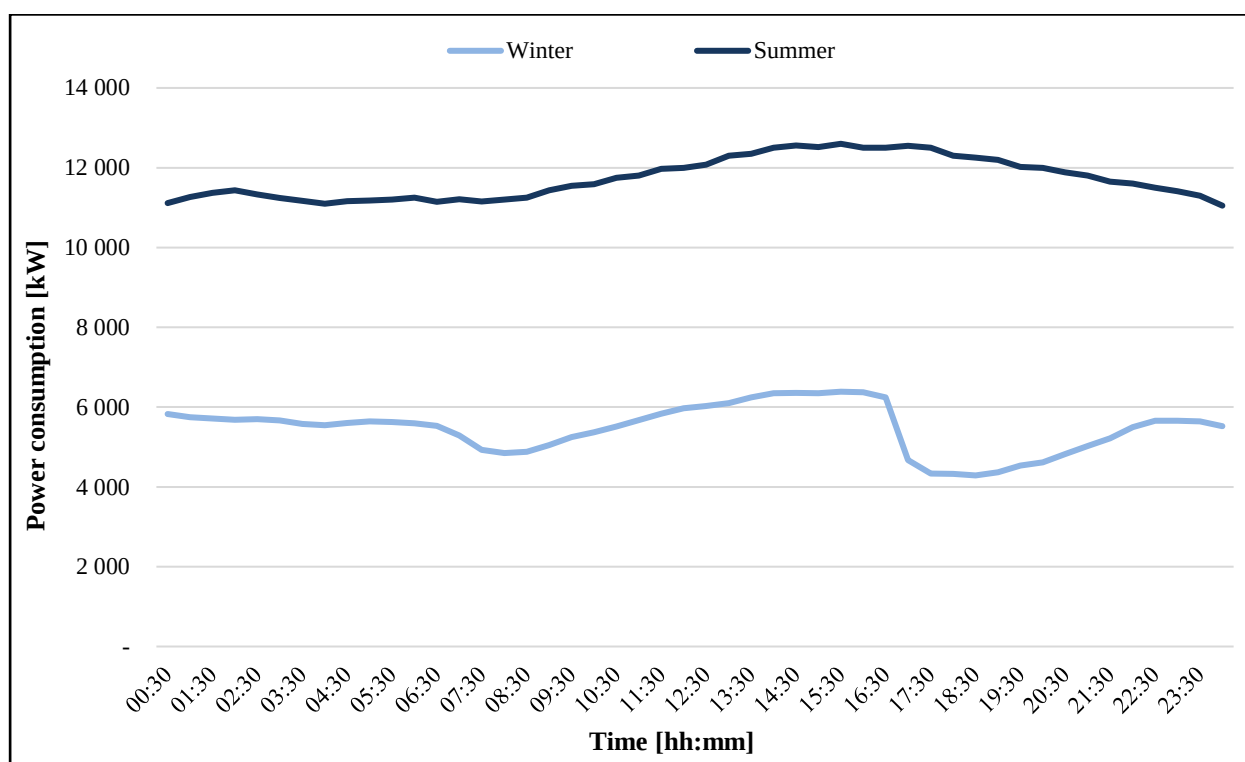


Figure 27: Electrical power baselines - Mine P

It is evident from the daily average power consumption profiles illustrated in Figure 27 that significant scope is present for a load shift of the installed chillers on Mine P. The chiller utilisation ratio for both morning and evening Eskom peak ToU periods support these findings, as tabulated in Table 11. To ensure there is sufficient capacity in the system to justify ITS implementation, it was required that the chiller utilisation percentages are greater than 10%. Since both summer and winter profiles indicate significant load reduction potential with the chiller utilisation percentages far greater than 10%, the demand limiting strategy is applicable.

Table 11: Chiller utilisation percentages - Mine P

Eskom peak period	Chiller Utilisation [%]	Is percentage > 10%?
Summer – morning	83.7	YES
Summer – evening	85.6	YES
Winter – morning	79.4	YES
Winter – evening	66.7	YES

As an illustrative example, through application of Equation 3, the percentage chiller utilisation for the morning peak period corresponding to the winter profile has been calculated below in Table 12. A chiller utilisation percentage of 79.4% was obtained.

Table 12: Application of Equation 6

Equation 3: Chiller machine utilisation	
$\sum$ Peak period electrical power usage	(5 474 + 4 888 + 4 884) kW
Duration of peak period	3 hours
$\sum$ Total installed capacity of operational chillers	6 400 kW
% Utilisation	79.4%

3.3.2 Constructing baselines

Electrical power baselines

To accurately quantify the theoretical cost-saving potential of ITS on Mine P, electrical power baselines were formulated according to the date ranges outlined in Table 6 of Section 2.3.2. Electrical power baselines are representative of the extended periods of time through which the ice plant was not in operation during the course of 2018/2019. Figure 28 illustrates the daily average electrical power baselines generated for Mine P.

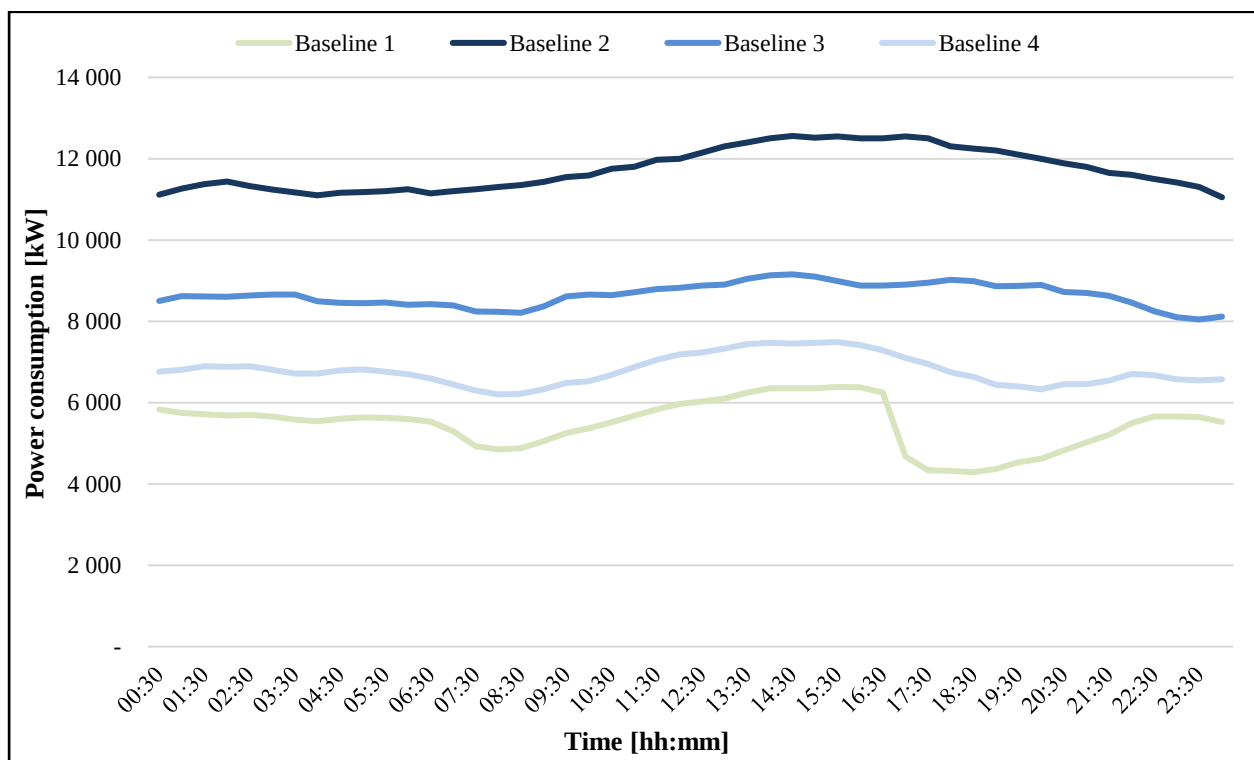


Figure 28: Electrical power baselines - Mine P

Due to the dynamic nature of Mine P's refrigeration system and operational status of installed chillers, SLA will be conducted. This will account for large, unforeseen system disturbances that have not been included

during the development of the baselines above. SLA will ensure the cost-saving potential of the ITS installation on Mine P is accurately quantified.

Operational baselines

Utilising the specifications listed in Table 35, important process variables specific to Mine P were identified. Table 13 illustrates the process variables required to monitor the performance of ITS on Mine P.

Process variables highlighted in blue and green will serve KPIs and energy performance indicators (EPIs) respectively. KPIs and EPIs will be utilised to holistically quantify the impact ITS has on the total operational performance of Mine P's cooling system and service delivery requirements. Adherence to identified KPIs will be tested through simulation, thereafter, subsequently validated through actual implementation. KPIs will essentially monitor the performance of the ITS system with regards to its impact on service delivery requirements. Conversely, EPIs will monitor the hourly power consumption of the refrigeration system, incorporating the ice plant, such that the cost-saving potential of ITS can be quantified based on Eskom's variable ToU tariff structure. The limits identified for KPIs depicted in Table 13 remain constant throughout the year.

Table 13: Process variables - Mine P

Allocation	Description	Condition	
		Minimum	Maximum
1	BAC air outlet WB / DB temperature [°C]	N/A	12.0 / 14.0
2	Chilled water temperature sent underground [°C]	N/A	4.0
3	Pre-cooling tower sump temperature [°C]	-	-
4	Pre-cooling tower sump operating range [%]	40	95
5	Chill dam operating range [%]	35	90
6	Flow of chilled water to surface chill dam [l/s]	-	-
7	Hitachi chillers outlet water temperature [°C]	1.5	9.5
8	Chiller running status [-]	-	-
9	WB ambient air temperature [°C]	-	-
10	Hitachi chillers COP [-]	-	-
11	Ammonia chillers COP [-]	-	-
12	Global cooling system COP [-]	-	-
13	Combined system power consumption [kW]	-	-

Process variables indicated in Table 13 without prescribed limits imply that there are no specific limits/requirements that must be adhered to. However, these variables will still be included and compared in the

investigation. This will provide an indication on how the ITS installation impacts the holistic cooling system and individual components. The flow of chilled water to the surface chill dam generally has no specific limitations. Dependent on the surface chill dam level and the flow of water to the BACs and underground, the flow of water to the surface chill dam can differ by as much as 400 l/s during normal operation. Therefore, it is important to include the flow of chilled water to the surface chill dam as a process variable to ensure the ITS system has the ability to implement a successful load shift in any scenario.

Since the ITS system may inadvertently impact the pre-cooling sump temperature, it must be included in the list of process variables. Any changes in the pre-cooling sump temperature will subsequently influence the performance of the Hitachi chillers. The combined system power consumption represents the following system components: Hitachi chillers, ammonia chillers, evaporator pumps, ammonia feed pumps and condenser towers including auxiliary pumps.

3.4 Step 3: Developing a cost-saving strategy utilising ice thermal storage

3.4.1 Baseline simulation

Once the system has been characterised and defined, baseline simulation models can be developed. As discussed in Chapter 2, PTB was deemed as a feasible simulation package to emulate real-time conditions at Mine P. Baseline simulations were constructed using the approach discussed in Section 2.4.1. Mine P's cooling system, including pumping and water reticulation network, was constructed and simulated. The baseline simulations were compiled to represent the four date ranges derived in Table 6. Temperature data was obtained from Mine P's SCADA for a period of one year, such that average ambient temperature conditions could be derived for each baseline period. Average ambient temperature conditions were used as input data for all climate components in PTB. The component statuses of all relevant equipment in operation during each baseline period was matched with simulation inputs.

To ensure the simulation was calibrated according to normal BAU mining conditions, only weekday operating conditions were considered. Baseline simulations were calibrated based on mass flows, operating schedules, actual power, average ambient temperature conditions and equipment specifications.

The calibrated simulation model utilised to emulate Mine P's integrated cooling system is illustrated in Figure 56 in Appendix D1. To ensure the accuracy of the baseline simulation models, the simulation results were verified against actual electrical power data. Figure 57 to Figure 60 in Appendix D2 illustrates the actual and simulated baseline power profiles for each baseline period evaluated in this study. The simulation models representing baseline periods 2, 3 and 4, revealed an average error of approximately 3.3% between simulated and actual power profiles. However, for baseline period 1, an average error of 8.0% was obtained. Discrepancies between the simulated and actual power profile between 10:00 to 23:00 were attributed

towards warmer ambient temperature conditions present during the assessment period, as well as the mine conducting an evening peak period load shift. The load shift was not included in the simulation.

Although comparative power profiles reveal a strong correlation between the simulated and actual conditions, it is also necessary to evaluate the accuracy of various service delivery requirements. This is required to evaluate that the simulation model and ensure approaches utilised within the simulation accurately capture and predict the operational response of the holistic system and individual components. Dam temperatures, the BAC outlet air temperature and dam levels were considered. For illustrative purposes, operational parameters corresponding to baseline 2 were analysed in detail. However, baselines 1, 3 and 4 were analysed using a similar approach. Figure 61 to Figure 63 in Appendix D2 illustrates the comparative service delivery profiles for baseline period 2.

The temperature of the surface chill dam plays a significant role in system performance, therefore, can be considered the system driving temperature. If chilled water temperature requirements are exceeded, safe underground environmental conditions and subsequent productivity will be compromised. It is imperative that the simulation has the ability to accurately capture changes in the system that may influence the chilled water supply temperature and flow. Analysing the surface chill dam level will ensure that the dam level remains within specified boundaries. The major concern of the surface chill dam is the lower limit, if the dam level reduces to below 35%, service delivery requirements will be compromised. This will directly impact flow requirements to underground and the BACs. A reduction in the flow rate to the BACs will adversely impact heat transfer capabilities, resulting in an increase in the BAC air outlet temperature supplied underground. Therefore, it is crucial to analyse the capacity of the surface chill dam. In Figure 61, the surface chill dam temperature and corresponding dam level is compared to that obtained from the simulation. It is evident that there is a strong correlation between the actual and simulated chill dam temperatures and capacities, revealing an average simulated percentage accuracy of 96% and 98% respectively.

In Figure 62, the simulated BAC air outlet WB temperature is compared and analysed. As expected, there is a strong correlation between the chilled water temperature depicted in Figure 61, to that of the BAC air outlet temperature in Figure 62. Although the profiles illustrated in Figure 62 compare favourably, slight discrepancies were noticed. Discrepancies are largely accredited to the operation of the BAC feed pumps. Control room operators stop and start additional pumps according to ambient air WB temperatures and the BAC air outlet temperature. Nonetheless, comparing the accuracy of the simulated BAC air outlet temperature to that of actual conditions, an average percentage accuracy of 94% was obtained.

Finally, the simulated pre-cooling sump temperature and sump level is evaluated in Figure 63. As mentioned previously, along with ambient temperature conditions, the temperature of water leaving the pre-cooling sump governs the performance of downstream refrigeration units. Elevated water temperatures

require an increased cooling capacity to offset larger heat loads. Since the pre-cooling sump temperature will directly influence the performance of the proposed ITS system, specifically during the ice-melting cycle, it is important that the simulation model accurately matches actual conditions. Additionally, the pre-cooling sump capacity is just as important to monitor.

Thermal capacity in the pre-cooling sump will be required to supply the ice dam with a constant flow of water during the ice-melting process. However, if the flow of return water from underground exceeds the flow of water leaving the pre-cooling sump, depending on the remaining sump capacity, flooding is a real possibility. Flooding of the pre-cooling sump will inevitably compromise the sustainability of the ITS system. An increase of warm water flow through the ice dam will limit the systems load-shifting capability and subsequent cost-saving potential. From Figure 63 it is clear that the simulation model reciprocates actual conditions corresponding to pre-cooling sump temperatures. Conversely, the pre-cooling sump level profile differs slightly. However, it will be sufficient to identify any system changes and determine the effect thereof. The average percentage accuracy of the simulation model to emulate actual conditions associated with the pre-cooling sump temperature and sump level profile is 99% and 96% respectively.

A summary of the simulation verification results is illustrated in Table 14 below. The calibrated simulation model had an overall accuracy of 97% when compared to actual operating conditions. Mentioned in Section 2.4.1, an average percentage accuracy of at least 90% is considered feasible to provide accurate system responses. Therefore, based on the power and process variable comparisons, it is evident that PTB is sufficient to precisely emulate the dynamic operation of Mine P's cooling system throughout the year.

Table 14: Process parameters simulated versus actual comparison – baseline period 2

Allocation	Description	Actual	Simulation	Accuracy [%]
1	BAC air outlet WB temperature [°C]	10.0	9.9	94
2	Chilled water temperature sent underground [°C]	2.7	2.6	96
3	Pre-cooling tower sump temperature [°C]	15.9	16.1	99
4	Pre-cooling sump level [%]	48	46	96
5	Chill dam level [%]	68	67	98
Average accuracy of simulation				97

Before incorporating ITS into the simulation model, pre-existing mine-specific energy and cost-saving initiatives must be reviewed and critically analysed to identify root causes for underperformance. By doing this, additional risks are identified that may impact the performance and sustainability of ITS. To mitigate these risks from impacting the ITS installation, additional KPIs and control considerations are included. This will ensure a thorough feasibility analysis is conducted.

Critically analyse pre-existing initiatives***Load shift of underground dewatering pumps***

As mentioned previously, Mine P hosts an energy recovery device in the form of a 3CPFS system. The technology eliminates the need for high-pressure pumping from underground to surface with the only pumping power being that required to overcome friction losses of the water in the pipes. As a result of this, a substantial reduction in the overall power consumption of the water reticulation system is realised. Implementation of the 3CPFS has enabled the mine to execute a significant load shift on the dewatering pumping system. The aim of this is to shift a surplus of 6 MW out of the Eskom peak periods to other times of the day where the electricity costs are lower. Since operating conditions can vary significantly during normal operation, a successful load shift is not always possible. Other factors contributing to an unsuccessful load shift include unavailability of the 3CPFS due to maintenance downtime, inexperienced control room operators and unforeseen imbalances in the water reticulation system itself.

In order to optimise the dewatering system and ensure a sustainable load shift during Eskom peak periods, the pumps were automated to eliminate poor operator control and implement a more effective load shift. However, due to the complexity of Mine P's water reticulation network, poor execution and automated control of the pumps led to immediate project deterioration and subsequent decommissioning. Proceeding project decommissioning, control returned to the operators to manually load shift the pumps through effective dam preparation. Even so, operator negligence and inconsistent pumping regimes implemented by each operator compromises the load shift. Therefore, to prevent operator negligence leading to the deterioration of ITS, it is clear that effective reporting systems are required. In doing so, the daily performance of the ITS system in terms of cost savings achieved and operation can be monitored. Once any discrepancies are noticed, revaluation of system control and utilisation must be considered as per Figure 23.

3.4.2 Methodological approach to evaluate the feasibility of ITS on mines***ITS integration on Mine P***

Due to the configuration of Mine P's cooling system, and location of cooling and pumping auxiliaries, the ITS system is introduced between the pre-cooling towers and evaporator pumps. During the ice-making cycle, normal system operation will commence as discussed in Section 3.2.1. The ITS system represents a closed-circuit system during the ice-making cycle, whereby water from the pre-cooling sump bypasses the ice plant before being received by the Hitachi chillers. During the ice-melting cycle, all operational chillers and feed pumps are stopped, excluding the evaporator pumps. Ice plant feed pumps are used to pump water from the pre-cooling sump through the ice dam, subsequently melting the ice in the dam. To prevent

additional pumping costs, it makes sense to bypass the intermediate dam, therefore, supplying hot water directly from the pre-cooling sump through the ice dam to the surface chill dam before being sent underground. The evaporator pumps will provide for the means with which to pump water from the ice dam to the surface chill dam.

Refrigeration equipment and the associated control philosophy of the system is unaffected by the integration of an ice storage facility during the ice-making cycle, except during the ice-melting cycle whereby the chillers and condenser towers will be switched off. The remaining chilled water circuit equipment such as the BACs, pre-cooling towers and evaporator pumps will operate as per normal.

Simulating the control philosophy incorporating ITS

The electrical power consumption and various KPIs compared in Section 3.4.1 illustrated that Mine P's integrated cooling system can be simulated accurately. Therefore, the simulation model developed in PTB will provide for a viable solution to accurately predict system responses and behavioural changes brought about by the integration of ITS on Mine P. Before the physical interaction and impact of ITS on Mine P is simulated, the ITS component must be set up to emulate the theoretical response. For illustrative purposes, the process will be discussed in detail for baseline period 1. The results for baseline periods 2, 3 and 4 were obtained using a similar approach.

Since PTB represents a component-based simulation package, the physical operation of an ITS system has already been modelled. To ensure the simulation approach developed in Section 2.4.2.2 is valid in accurately setting up and emulating the actual response and impact an ITS system will have on a mine cooling system, the analytical approach must be verified. Validating simulation results by comparing them to actual implementation results will also be required. The process of verifying and validating developed methodologies and analytical approaches will afford other similar mining operations the ability to accurately evaluate the theoretical impact of ITS, and the feasibility for implementation. Therefore, instead of calibrating the simulation according to Mine P's current ITS installation, to verify and validate the developed procedures, the simulation model incorporating ITS will be theoretical, based on the strategy developed in Section 2.4.2.2.

As a first approximation, the various starting conditions were derived from Table 8, in Section 2.4.2.2. Through application of Equation 6 to Equation 9, starting conditions for the ice plant model were determined. Calculations for baseline period 1 are presented in Table 15.

- $\dot{m}_w$ – represents the maximum average flow of water sent to the surface chill dam during peak periods. Since the ITS system is required to store energy during off-peak periods for use during peak periods, flow profiles during peak periods are utilised as design parameters for the simulation.

- $T_{w,i}$ – represents the average inlet water temperature received from the pre-cooling sump.
- $T_{w,o}$ – representing the ideal outlet water temperature from the ice dam.
- $t_{ice-build}$ – an ice building time of 8 hours was used as an initial approximation.

Table 15: Application of analytical approach for simulation model - baseline period 1

Equation 6: Melting rate of stored ice		
$\dot{m}_w$	480 l/s	
$C_{p,w}$	4.187 kg/kJ. °C	
h_{fg}	334 kJ/kg	
$T_{w,i}$	13 °C	
$T_{w,o}$	2 °C	
MR	$MR = \left[\frac{\dot{m}_w C_{p,w} (T_{w,i} - T_{w,o})}{h_{fg}} \right] \times (3600)$	238 283 kg/hr
Equation 7: Required mass of ice		
MR	238 283 kg/hr	
t_{peak}	2 hours	
m_{ice}	$m_{ice} = MR \times t_{peak}$	476 566 kg
Equation 8: Ice building cooling duty		
$\dot{m}_{ice,b}$	Equation 14	
$C_{p,w}$	4.187 kg/kJ. °C	
$T_{ice-build}$	5 °C	
h_{fg}	334 kJ/kg	
Peak period duration	2 hours	
$\dot{Q}_{ice-build}$	$\dot{Q}_{ice-build} = \dot{m}_{ice,b} [C_{p,w} (T_{ice-build} - 0) + h_{fg}]$	5 874 kW
Equation 9: Required ice building rate		
m_{ice}	476 566 kg	
$t_{ice-build}$	8 hours	
$\dot{m}_{ice,b}$	$\dot{m}_{ice,b} = \frac{m_{ice}}{(t_{ice-build} \times 3600)}$	16.55 kg/s
Equation 10: Amount of stored energy in the form of ice		
m_{ice}	476 566 kg	

h_{fg}	334 kJ/kg	
Q_{ice}	$Q_{ice} = \frac{(m_{ice}h_{fg})}{3600}$	44 215 kWh
Minimum required dam size	$(0.023 \text{ m}^3/\text{kWh}) * Q_{ice}$	1 017 m³

It is important to emphasise that PTB was purely utilised as a predictive tool to outline the operational impact ITS has on Mine P's installed cooling system. The integrated simulation model incorporating the ITS system is depicted in Figure 64 found in Appendix E1. As a first approximation, the required ice dam capacity was derived based on the minimum volume required to store a given cooling capacity ($0.023 \text{ m}^3/\text{kWh}$). From Table 15, according to the ice mass required to provide an outlet water temperature of 2°C for a load shift duration of two hours, the required stored energy in the form of ice is 44 215 kWh. Therefore, from Equation 10, the minimum required ice dam volume is $1\,017 \text{ m}^3$. Consequently, following the first iteration, the ice dam flooded. Therefore, to allow for the sudden rise in dam level due to the inflow of water during an ice melt, the dam size was increased until an acceptable volume was reached. The minimum required dam volume was obtained as $4\,500 \text{ m}^3$. Proceeding numerous iterations, the initial dam level and the ice building water temperature stabilised to within 5% of the previous iteration. This implies that the ice plant model had converged to a solution. Thereafter, Equation 8 was updated accordingly, yielding an ice building cooling duty of approximately 6.0 MW. Finally, the proposed implementation strategy discussed in Section 2.4.2.1 was simulated.

Table 16 illustrates the initial starting conditions compared to that obtained from the final iteration. The final iteration values represent the theoretical system characteristics of the ice plant component for baseline period 1. Final iterated values characterise an acceptable solution.

Table 16: Simulation input variables for ITS system calibration: baseline period 1

Input variable	Baseline 1: 13 May to 23 August		
	Initial input value	Final iteration: Morning ice melt	Final iteration: Evening ice melt
Pressure [kPa]	100.0	100.0	100.0
Initial dam level [%]	90.0	83.1	83.0
Heat transfer coefficient [$\text{kW}/^\circ\text{C}/\text{m}^2$] *	0.0	0.0	0.0
Ambient temperature profile [$^\circ\text{C}$]	Average ambient temperature profile obtained between 13 May and 23 August		
Initial ice mass in the dam [kg]	0.0	0.0	0.0
Ice building water temperature [$^\circ\text{C}$]	5.0	6.9	7.0
Ice building COP [-]	3.0	3.0	3.0
Ice melting rate [kg/hr]	238 283	238 283	238 283

Ice melting ice mass [kg]	476 566	476 566	476 566
Ice building cooling duty [kW]	5 874	6 005	6 012
Dam water volume [m ³]	1 017	4 500	4 500
Ice building time [hh:mm]	08:00	08:30	08:10
Ice melting water temperature [°C]	2.0	2.0	2.0

* As mentioned previously, for simulation purposes, it was assumed that the ice system is fully insulated such that there is no heat loss to the surroundings. Realistically, there will be heat loss between the ice dam and ambient temperature; however, compared to the amount of stored energy in the dam, it is minimal, therefore, neglected.

Figure 29 illustrates the ice dam outlet temperature for the final iterated values illustrated in Table 16. A running status of 0 implies the ice plant is off, with a value of 1 suggesting the system is operational. Since the volume of the ice dam is large, a temperature field exists during the early stages of the ice-melting process. This implies that the temperature of water received from the pre-cooling sump does not fall rapidly, but instead takes time to cool. After approximately 20 minutes, the temperature of the water leaving the ice dam reaches its minimum, approximately 2.4°C during the morning ice melt and 2.5°C during the evening ice melt.



Figure 29: Ice dam outlet temperature simulation results - baseline 1

During the course of the ice melt, the surface area of the ice decreases as the ice is consumed. As the surface area of the ice around the coils decrease, so the rate of thermal energy transferred from the ice to the water in the dam is reduced. Illustrated in Figure 29, as the ice in the dam is melted, the ice dam water outlet temperature increases. As expected, the temperature of the water increases exponentially towards the end of the melt, reaching 4.9°C during the morning peak period and 5.1°C during the evening peak period. To ensure no ice remanence was left on the coils proceeding either ice melt, water from the pre-cooling sump was pumped through the ice dam for an additional 10 - 20 minutes. This increased the outlet water temperature to 6.9°C and 7.0°C respectively.

Based on the same inlet conditions and starting parameters, if lower water outlet temperatures are required for an extended period of time, a larger mass of ice will be necessary. Consequently, this will require a larger dam volume, longer charging times and/or increased cooling capacities of the ice plant refrigeration machine. All of which will either result in elevated capital expenditure or increased energy consumption. Therefore, although the outlet water temperatures depicted in Figure 29 seem excessively high, as long as the temperature of the chilled water in the surface chill dam remains below the specified limit of 4°C, the solution is feasible. Evaluating the simulated surface chill dam water temperature illustrated in Figure 30, it is clear that the surface chill dam temperature remains within specified limitations throughout the day. However, there is a clear deterioration in service delivery due to the implemented ice melts. The surface chill dam temperature rises to approximately 3.2°C and 3.5°C during peak periods.

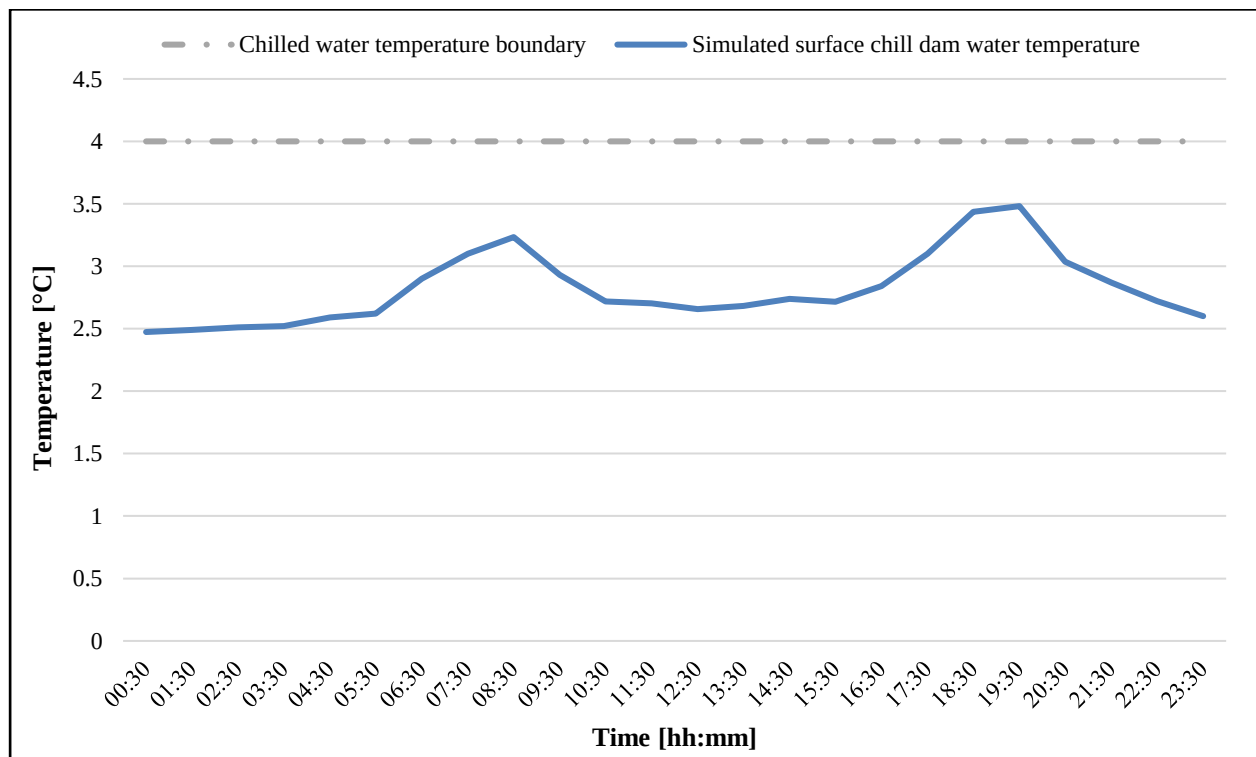


Figure 30: Simulated surface chill dam water temperature - baseline 1

Simulation results reveal that by performing a morning and evening ice melt, an average chill dam water temperature of 2.8°C is anticipated. Although the average temperature increased, it was considered negligible. Figure 31 illustrates the simulated power consumption of Mine P's refrigeration system, incorporating an ITS system. The simulation model suggests that a load shift of 5.0 MW and 4.0 MW is achievable through the implementation of ITS. As expected, there is an increase in the refrigeration systems power consumption due to the ice-building process.

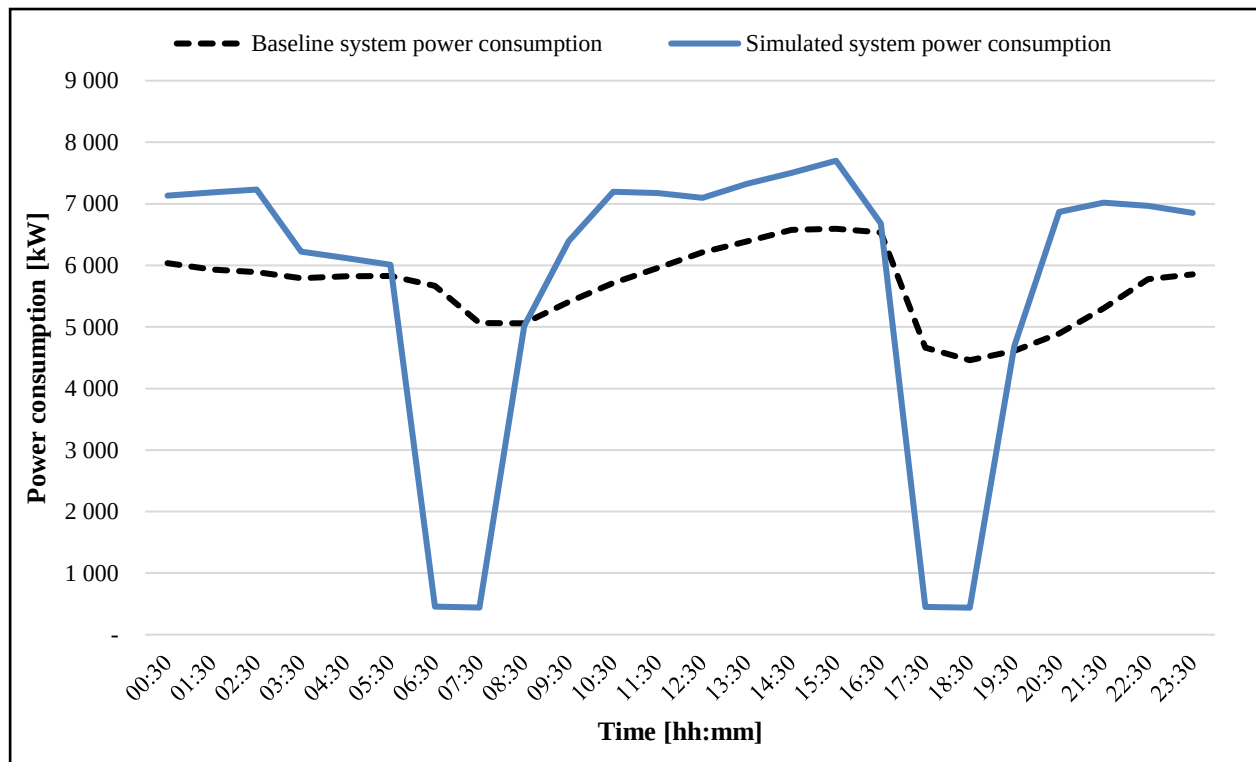


Figure 31: Simulated system power consumption - baseline 1

Table 17 presents a summary of the system and operational characteristics of Mine P's cooling system incorporating ITS. Baseline results represent normal BAU operating conditions. A period of one week was deemed long enough to deduce BAU system parameters for baseline 1. Based on these conditions, the simulated impact of utilising ITS as an alternative load-shifting strategy could be measured and quantified. To holistically characterise the impact of ITS, 12 facets were compared.

Table 17: Summary of simulated ITS implementation results – baseline 1

Description	Baseline	Simulated	Percentage impact [%]
Average system power [kW]	5 473	5 695	-4.1
Hitachi chillers utilisation [-]	2	2	0
Ammonia chillers utilisation [-]	2	2	0
Surface chill dam temperature [°C]	2.4	2.8	-16.7

Surface chill dam level [%]	40.2	79.2	-97.0
Pre-cooling sump temperature [°C]	11.4	11.6	-1.8
Pre-cooling sump level [%]	43.0	50.2	-16.7
BAC air outlet WB temperature [°C]	3.2	4.7	-46.9
Combined Hitachi chillers COP [-]	4.7	4.8	-2.1
Combined ammonia chillers COP [-]	3.7	3.7	0
Total daily volume of water received by the surface chill dam [ML]	31.08	31.2	-0.4
Global system COP [-]	2.7	2.1	22.2

Analysing the results presented in Table 17, it is apparent that the largest impact resulting from ITS implementation was that of the surface chill dam level. The surface dam level was purposely controlled to a higher capacity in anticipation of a similar control to be implemented on Mine P. Since an ITS system is more complex than conventional chillers, by controlling the surface chill dam to a higher level, sufficient thermal storage capacity is available in case of system failure. In addition to this, with a larger volume of chilled water stored in the surface chill dam, cost-saving potential can be maximised through implementation of an extended ice melt without severely compromising the temperature of the water in the dam. Since the volume of water stored in the dam is far greater than that pumped into it from the ice dam, the chill dam temperature will not rise above the specified limitation of 4.0°C. Obviously dependent on the duration of the extended ice melt. In simple terms, an extended ice melt refers to a prolonged ice-melting process. Water is continually pumped through the ice dam proceeding the two-hour load shift, ensuring all the ice on the coils has been melted. Additional detail on this process is provided in Section 3.5.2.

Results presented in Table 17 suggest that the simulated temperature difference between the pre-cooling sump and surface chill dam remain almost the same when compared to baseline conditions. With a similar volume of water cooled and an increase in the systems power consumption outside of peak periods, results indicate a decrease in the systems global COP proceeding ITS installation. In terms of service delivery requirements such as the surface chill dam temperature, BAC air outlet temperature and total daily volume of water received by the surface chill dam, an overall deterioration of 21.3% was revealed, the largest contributor being that of the BAC air outlet temperature. The BAC installation at Mine P represents an enclosed multi-stage horizontal forced draft BAC. A general overview of the operation of a multi-stage forced draft BAC is discussed in Appendix A2, in Figure 49. A bleed off supply from the surface chill dam supplies the BAC towers with approximately 3 l/s throughout the day. During winter months with the BAC fans standing, the convection of air through the BACs and down the shaft is resultant due to the pressure difference created by the main ventilation fans. Intuitively, when air passes through the BACs, heat transfer between ambient air and the chilled water stored in the BAC sump takes place. Therefore, the air temperature passing through the duct over the temperature sensor is significantly lower compared to the

ambient temperature. This phenomenon is not accounted for in the simulation; therefore, the BAC outlet air temperature represents that of the ambient WB temperature.

The remaining baseline periods outlined in Table 6 were analysed utilising a similar approach. To maximise the cost-saving potential and minimise the impact on service delivery requirements, several scenarios were simulated and critically analysed. The final iterated simulated control philosophy for each baseline is depicted in Table 38 in Appendix E2. Ice plant charging times required to build a certain mass of ice to achieve acceptable ice dam outlet water temperatures are also included. Figure 65 to Figure 67 depicted in Appendix E3 provides the simulated power profiles for baselines 2, 3 and 4, incorporating the use of ITS.

Due to ambient temperature conditions experienced during baseline periods 1, 3 and 4, slightly lower water temperatures and a reduction in the time required with which to achieve a full ice build, a double ice melt was achieved. Intuitively, the length of the ice melt achieved decreased with increasing ambient temperatures. Due to elevated temperatures experienced during peak summer months, represented by baseline period 2, a double ice melt was not achievable. Higher day-time water temperatures, a decrease in the plants cooling capacity due to higher ambient temperatures reducing the condensers efficiency, and an increase in the amount of time required to achieve a full ice build, restricted the number of ice melts per day to just one. It is worthwhile to mention that a double ice melt was attempted, however, not enough ice could be formed in the allocated time to make an evening load shift feasible. When compared to the cost to run the ice plant, the achievable cost savings for an evening peak load shift just shy of one hour was not economically feasible.

Based on simulation results, Table 18 presents the load shift savings anticipated through the installation of ITS on Mine P's refrigeration system. Intuitively, increasing ambient temperatures require higher cooling capacities to offset accompanying heat loads. This implies, a refrigeration systems' power consumption and thus cost to provide adequate cooling also increases. During peak summer months (baseline period 2) the simulation model reveals an average hourly morning peak period load shift of 10.8 MW, whereas, compared to winter months (baseline period 1), an average morning load shift of 5.0 MW is anticipated. This is attributed to the extensive use of refrigeration system components during summer months.

Based on the results presented in Table 18, the annual cost-saving potential of an ITS system implemented on Mine P was quantified. To calculate the electricity cost savings anticipated from the implementation of ITS on Mine P, Eskom's 2018/2019 MegaFlex tariff structure illustrated in Table 40 and Table 41 of Appendix F was applied. To quantify accurate cost-saving potential, cost savings were calculated based on SLA factoring. It is important to note that if baselines are formulated according to the date ranges illustrated in Table 6, the correct Eskom tariff rate structure must be applied. According to the Megaflex tariff rate structure applicable to the mining industry, summer tariff rates apply for months between September and May. Conversely, winter tariff rates are applied for the months of June, July and August respectively.

The estimated annual electricity cost savings are tabulated in Table 18. Through the implementation of ITS on Mine P, a total annual cost saving of R 4 774 829 is anticipated.

Table 18: Summary of simulated hourly load shifts

Baseline	Peak demand load shift [MW]		Combined electricity cost savings [R]
	Morning peak period	Evening peak period	
1	5.0	4.0	R 2 419 708
2	10.8	-	R 732 211
3	7.8	7.6	R 891 630
4	5.8	5.7	R 731 281
Total annual cost-saving potential			R 4 774 829

With the annual return on investment now established, the proposed payback period can be calculated and evaluated. In general, the project payback period is calculated by comparing the initial capital investment against the electricity cost-saving potential. Since the initial capital investment will be unknown at this stage, a formal quote will be required. As mentioned in Section 2.4.2.2, for the external contractor to design/select the optimal tube structure and coil design according to the required amount of stored energy in the form of ice, basic system requirements must be supplied.

To ensure the ITS system has the capability to create and store enough ice to successfully implement a full two-hour load shift, the worst-case scenario is utilised as design parameters. Based on simulation results, Table 19 illustrates the requirements of an ITS system implemented on Mine P to achieve the proposed cost-saving potential presented in Table 18. Parameters were based on the results obtained from the simulation model emulating baseline period 2, representing peak summer months. By doing this, a full build of ice will ensure a complete two-hour load shift is realised during summer months. Thereafter, the duration of the charging period, initial ice building water temperature and ambient temperature conditions associated with each remaining baseline period will subsequently determine the amount of ice required. Final iterated ice plant system characteristics attained through the application of the analytical and simulated approaches derived for baseline period 2 are depicted in Table 39 found in Appendix E4.

Table 19: ITS system requirements

Description	ITS system requirements
Required dam capacity [m^3]	> 4 500
Melting rate [kg/hr]	324 931
Ice build time [hours]	12
System type [-]	External melt ice-on-coil
Ice dam water inlet temperature [°C]	17.0

Required supply temperature [°C]	< 2.0 (ideal)
Required ice mass [kg]	649 863
Ice building cooling duty [kW]	≈ 6 012

It is important to point out that the ice building cooling duty illustrated in Table 19 portrays that derived from baseline period 1 (peak winter months). Intuitively, one would expect cooling duty requirements to be highest for peak summer months. However, based on the required ice mass to deliver acceptable outlet water temperatures for a duration of two hours (649 863 kg), and a charging time of 12 hours required to achieve a full ice build, an ice building cooling duty of only 5 514 kW was derived for baseline period 2.

Table 20 provides a basic outline of the major equipment installations and requirements of the current ITS implementation on Mine P. To save significant capital expenditure, a secondary pre-cooling sump that was no longer in use was subsequently converted into the required ice dam. The secondary pre-cooling sump has a volume of 6 500 m³, well above minimal dam size requirements stipulated in Table 19. The total capital investment of the ITS system implemented on Mine P was approximately R 30 million. Based on the potential cost savings displayed in Table 18, a payback period of 76 months (6.3 years) was derived.

Table 20: Basic overview of equipment requirements for Mine P's ITS system

Description	Quantity
Ammonia refrigeration machine and compressor. Cooling capacity of 6 MW at -8°C	1
Feed pumps each capable of supplying the ice dam with 475 l/s	2
Aeration blower	1
Ice coils with a nominal storage capacity of 900 tons of ice	56
Evaporative condensers, each with a cooling capacity of 2.48 MW	3
Conversion of pre-cooling sump into the ice dam	1
Polyurethane insulation panels, 80 mm thick	-
PLC equipment, communications, temperature sensors, thickness sensors and pH sensors	-
Total capital expenditure:	<u>R 30 million</u>

At this stage of the feasibility study, the results must be reviewed and approved by mine personnel before hard commissioning commences. Based on the payback period attained for Mine P's ITS system, ITS employed to achieve effective load management on deep-level gold mines remains seemingly unrealistic. With many deep-level gold mines facing dwindling profit margins, ITS is not feasible. Feasibility will be dependent on the current financial status of the mining operation as well as the expected life of mine.

The following section will provide further insight on the feasibility of installing ITS systems on deep-level mine cooling systems through actual case study implementation. Implementation considerations and operation approaches are also provided and discussed.

3.5 Step 4: Case study implementation

Existing ITS system on Mine P

During the ice-making cycle (Eskom's off-peak and standard periods), normal system operation commences. The ITS system represents a closed-circuit system during the ice-making cycle, whereby water from the pre-cooling sump bypasses the ice plant before it is received by the Hitachi chillers. To incorporate the ice plant into Mine P's cooling system, a series of bypass valves were installed. Figure 68 found in Appendix G illustrates the operation of Mine P's surface cooling system during the ice-making cycle. Control valves highlighted in green and red indicate the current position of the valve, either open or closed. During the ice-making cycle, hot return water is pumped from underground and received by the pre-cooling towers located on surface. The pumping regime is operator-controlled, based on dam levels and time of the day. Via the ice dam bypass valve, water from the pre-cooling sump is pumped to the Hitachi chillers utilising the evaporator pumps. Thereafter, the water is stored in the intermediate dam before being pumped to the ammonia chillers for a second stage of cooling through provision of ammonia feed pumps. Chilled water is subsequently stored in the surface chill dam before it is distributed to the BACs and underground.

Conversely, the ice-melting cycle is represented by Figure 69 of Appendix G. During Eskom's peak periods, chilled water is supplied by the Howden ice plant (HIP) to the surface chill dam before being sent underground to 1200L chill dam. Due to the configuration of Mine P's cooling system, and location of cooling and pumping auxiliaries, the ITS system was introduced between the pre-cooling towers and evaporator pumps. The ice dam bypass valve is now closed, with water from the pre-cooling sump pumped through the ice dam utilising ice plant feed pumps. Thereafter, chilled water from the ice dam at between 300 l/s – 520 l/s, is pumped to the surface chill dam utilising the evaporator pumps of the Hitachi chillers.

The intermediate dam bypass valve and ammonia bypass valves are subsequently open to provide the means through which chilled water can be directly supplied to the surface chill dam. Refrigeration equipment and the associated control philosophy of the system is unaffected by the integration of an ice storage facility during the ice-making cycle, except during the ice-melting cycle whereby the chillers and condenser towers will be switched off. The remaining chilled water circuit equipment such as the BACs, pre-cooling towers and evaporator pumps will operate as per normal.

The ITS installation on Mine P utilises liquid ammonia to provide the means through which ice is created. Liquid ammonia is subsequently pumped from the ice plant machine into the coils placed inside the ice

dam. The coils inside the dam act as the evaporator heat exchangers whereby the liquid ammonia evaporates inside the coils causing ice to form on the surface of the coils.

3.5.1 Pre-implementation considerations

Risk assessment

The significant hazards that were identified which may pose a significant risk to the installation of ITS on Mine P is depicted in Table 43 found in Appendix H. Identified hazards are; health and safety, impact on service delivery requirements and production, and overhead costs. Hazards have been ranked in order to determine which risk poses the biggest threat to normal operating conditions on Mine P. The risk associated with each hazard is briefly discussed:

- Health and safety: since the proposed ITS system will make use of an existing chiller making use of ammonia as the refrigerant, chemical exposure to both the environment and employees is a major risk.
- Service delivery requirements: as a result of uneven ice formation and melting, as well as bridging between adjacent coils, service delivery requirements may be compromised.
- Production: any changes to the normal operation of the cooling system and service delivery requirements may adversely impact underground working conditions, subsequently compromising production.
- Cost: additional overhead costs in terms of extensive maintenance requirements.

Based on the results illustrated in Table 43, the highest risk is associated with production. Mine P operates as one of South Africa's most efficient gold mines in terms of energy usage per ton of rock hoisted. Mine P would sooner chase production targets than implement a load management initiative that may adversely impact gold production. Therefore, any load management initiative, control strategy or project that compromises production will immediately be decommissioned or discontinued. Although environmental health and safety poses the highest hazard severity, resulting in immediate danger in the case of a leak, this aspect has the least risk amongst the others. The reason for this is largely due to the likelihood of chemical exposure and prominence in contingency plans in the case of a leakage or contamination.

The last step of the risk analysis includes possible ways to either eliminate the hazard or control the risk in circumstances that the hazard cannot be removed. Each aspect can either be eliminated or mitigated as follows:

- Health and safety impact: in the event of a leakage, several contingency plans are in place to prevent contamination and harm to the surrounding environment. pH sensors placed at the outlet of the ice dam will detect a change in pH of the outlet water caused by ammonia leaks from the coils. A

change in pH will trigger a water valve located at the outlet of the ice dam to shut, preventing downstream contamination. Alternatively, if ammonia leaks from the external system via the compressor or surge drum, ammonia detecting sensors will be installed to immediately alert the on-site engineer.

- Service delivery requirements and production: through constant monitoring and reporting of system KPIs, service delivery requirements are constantly reviewed and evaluated. Once system operational parameters and service delivery requirements are compromised, immediate notification and remedial action can be taken. This includes the isolation of the ice dam and subsequent starting-up of installed chillers.
- Cost: by implementing regular scheduled maintenance, unforeseen overhead costs can be mitigated, and equipment downtime minimised due to component failure.

Considerations in line with previous studies

In an attempt to eliminate similar factors outlined in Section 1.6.3.3 from adversely impacting the ITS installation on Mine P, the following preventative measures were implemented.

Design considerations

Mine P's ice dam overview is illustrated in Figure 32. To prevent uneven ice-formation and ice melting, the ice dam was divided up into three separate sections, each containing its own set of coils. Each section is further divided in half by a plate just shorter than the width of the dam. By doing this, warm water from the pre-cooling sump enters the left-hand side of each section, circulating through the coils, subsequently melting the ice. Water is then drawn into the right-hand section due to a pressure difference, before exiting to the surface chill dam. Dividing each section into two halves creates a pressure difference. A pressure difference is created as a result of water being pumped into the left-hand side via the ice plant feed pumps and extracted from the right-hand side utilising the evaporator pumps, thereby ensuring a constant and uniform flow of water through each section. If each section was not divided into two, water would either stagnate in the dam, or alternatively, only melt the ice at the dam inlet before immediately exiting the dam, both resulting in uneven ice melting and an increase in the outlet water temperature. Due to the sheer magnitude of ice mass requirements to provide adequate cooling during Eskom's peak periods, careful consideration was required to ensure uniform ice formation and melting. Intuitively, the liquid ammonia will rise in temperature as it flows through the ice coils, therefore, forming thicker ice near the refrigerant inlet and thinner ice toward the outlet. Consequently, by dividing the dam up into three separate sections, the above-mentioned problem is minimised. The liquid refrigerant in each section will be required to travel a shorter distance through each coil section, therefore, exposed to the water in the dam for a shorter period of time. A more uniform build of ice throughout each section is subsequently achieved.

Another advantage in splitting the dam into separate sections is portrayed in its ability to easily and quickly isolate an ammonia leak. Separating the dam into sections will allow an ammonia leak in the coils to be effectively contained and repaired while the rest of the ITS system continues operating. This means that the water and ammonia circuits of each section can be isolated independently while the other sections operate as per normal.

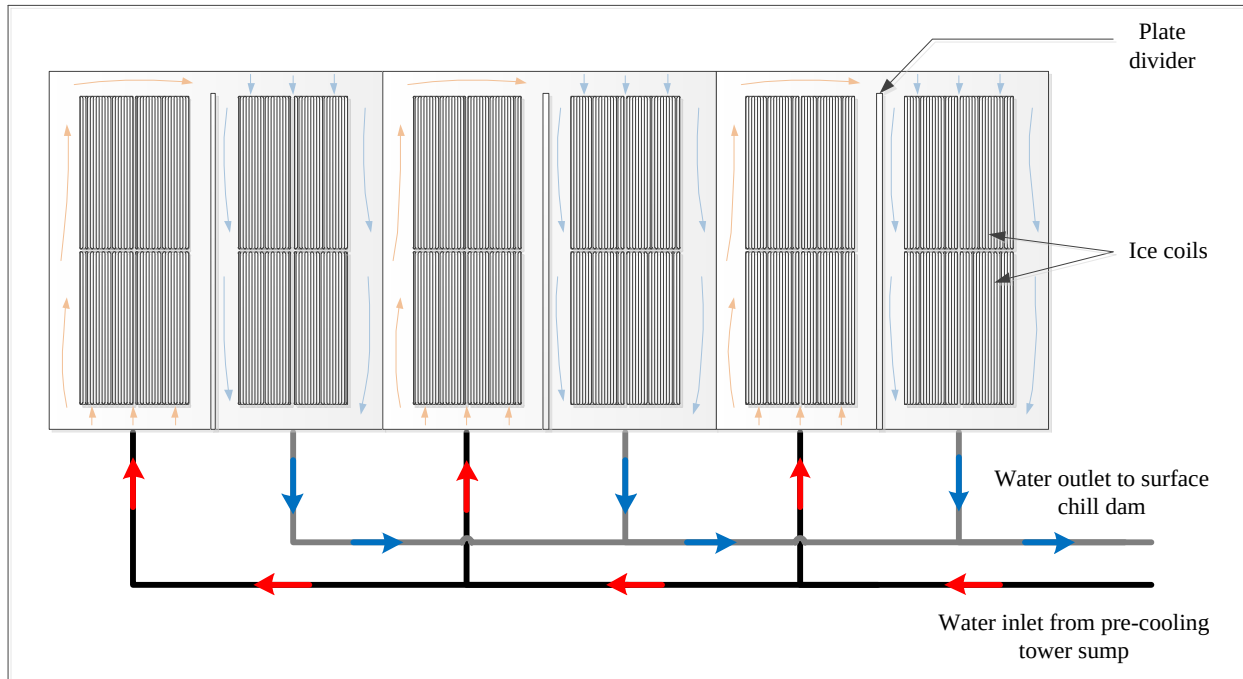


Figure 32: Ice dam overview - Mine P

To prevent bridging between adjacent coils caused by parallel flow circuits, Mine P utilises counter-current flow circuits. An illustrative example of each concept is portrayed in Figure 33.

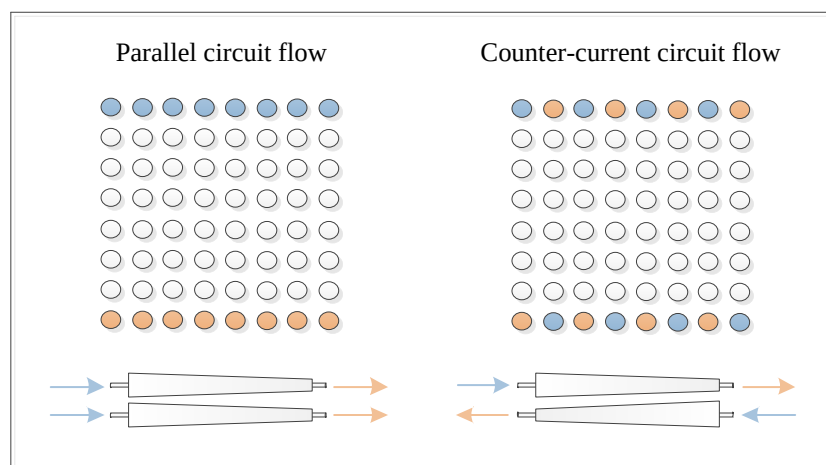


Figure 33: Ice coil circuiting

This implies that instead of liquid ammonia entering the top of each adjacent coil, it enters through the top of one coil and the bottom of the next. Parallel circuit flow can be seen to cause bridging between coils at the refrigerant inlet, whereas counter-current circuit flow results in the tapering of ice on the coil in opposing directions, therefore, maximising the ice volume potential. Parallel flow circuits can result in a reduction of up to 20% in the total storage capabilities of a coil [136].

Ice thickness sensors

To prevent issues with the ice plant being run too long, resulting in bridging between adjacent coils subsequently forming a solid block of ice, ice thickness sensors are located strategically throughout the ice coil banks. These sensors monitor the ice build on the coils. Once the maximum amount of ice has been built, the solenoid valves on the specific pack of coils is closed, therefore, preventing any more liquid ammonia from flowing through the coils. The ice build is thus stopped, protecting that specific set of coils from over-build.

Ice thickness sensors are primarily installed to deactivate the refrigeration process at a full build of ice. The ice building process is then reinitiated by the operator proceeding the ice-melting process.

Insulation and refrigerant utilised

Since the ice dam represents an open tank, to further improve the efficiency of the ice-building process and prevent unnecessary heat loss to the surroundings, insulation has been installed. It is, however, important to note that although the application of insulation reduces the loss of heat to the surrounding environment, realistically, heat losses to the surroundings will still be present.

Due to the unnecessary complications of glycol, and the addition of an indirect heat exchange process, liquid ammonia is utilised.

Performance monitoring and tracking

To ensure the ice plant operates according to design specifications, the control limits of each system component is closely monitored. A line of sight monitoring system was installed to provide effective real-time component monitoring and measurement. Alarms and trip limits based on parameters listed in Table 36 and Table 37 were generated to ensure the integrity of installed chillers is not compromised due to the implementation of the ITS system. Trip alarms sent out via sms or email immediately notify mine personnel once a components' operational integrity is compromised. Immediate action can then be taken. By doing this, not only are machine components kept within design limits, prolonging their operational lifecycle, but operational inefficiencies can be identified and mitigated at an early stage before a mechanical breakdown or component failure occurs, thereby preventing the costly replacement of equipment and

lengthy downtime periods. It is important to note that the line of sight monitoring system was not incorporated in the capital expenditure listed in Table 20. Mine P already had the existing infrastructure and communication platforms in place to set up a performance monitoring and tracking system.

3.5.2 ITS implementation results

To quantify and evaluate the impact the ITS installation has on Mine P's cooling system and normal operating conditions, two comparable periods were required. As mentioned previously, Mine P's ITS installation has suffered from intermittent downtime during the course of the 2018/2019 financial year, thereby providing a good opportunity to establish baseline operating conditions in the absence of ITS. Representing post-implementation results incorporating the use of ITS, a suitable assessment period was derived for each baseline period.

To effectively analyse system parameters, all necessary process variables and power data was logged and captured for each baseline period. To precisely compare the impact of ITS on the performance of Mine P's cooling system, comparable boundary conditions were considered and established. Identified system boundary conditions are as follows: ambient air DB and WB temperatures. Ambient temperature conditions were considered as boundary conditions since a cooling systems' performance and the operational status of refrigeration equipment is largely dependent on the ambient temperature.

Mine P hosts numerous uncontrolled variables that have the potential to skew results and conceal the operational influence of an ITS system. To effectively analyse the ITS system, it was required that uncontrolled variables remain consistent when comparing baseline conditions to that of the assessment period. Uncontrolled variables specific to Mine P are provided.

- Inconsistent control. Control room operators at Mine P are well-known to make use of slightly different control philosophies such as dam level control.
- The operational status of refrigeration system components. When compared to normal operating conditions, it is imperative that the same number of chillers and exact same chiller units are utilised during the assessment period. This is important, as changes in the number of operational chillers influence service delivery requirements. Additionally, each chiller plant has a different cooling capacity when compared to the next. Therefore, to quantify the impact on the performance of individual chillers, the same running configuration during the assessment period were utilised.

An assessment period of one week was attained in which uncontrollable variables and comparable boundary conditions were consistent to conduct an accurate comparative study. Since all four baseline periods account for vast changes in ambient temperature, comparing one week's data was deemed long enough to accurately capture and quantify the impact of ITS on Mine P.

To analyse the impact and operational trends induced by the installation of the ITS system on Mine P's cooling system, results pertaining to baseline periods 1 and 2 representing peak winter and summer months are reviewed and critically discussed. The results obtained for the remaining baseline periods have been summarised in Appendix I. The comparable boundary conditions pertaining to baseline period 1 and associated assessment period is presented in Figure 34. Analysing Figure 34, the average difference in the ambient air DB and WB temperatures is 0.3°C and 0.2°C respectively. This implies an overall percentage error of approximately 3.3%. Differences in ambient air temperatures between the two periods were considered small enough, suggesting the assessment period is viable for comparisons.

In addition to the ambient temperature, uncontrolled variables listed above were also considered such that accurate and valid results could be obtained and subsequently compared.

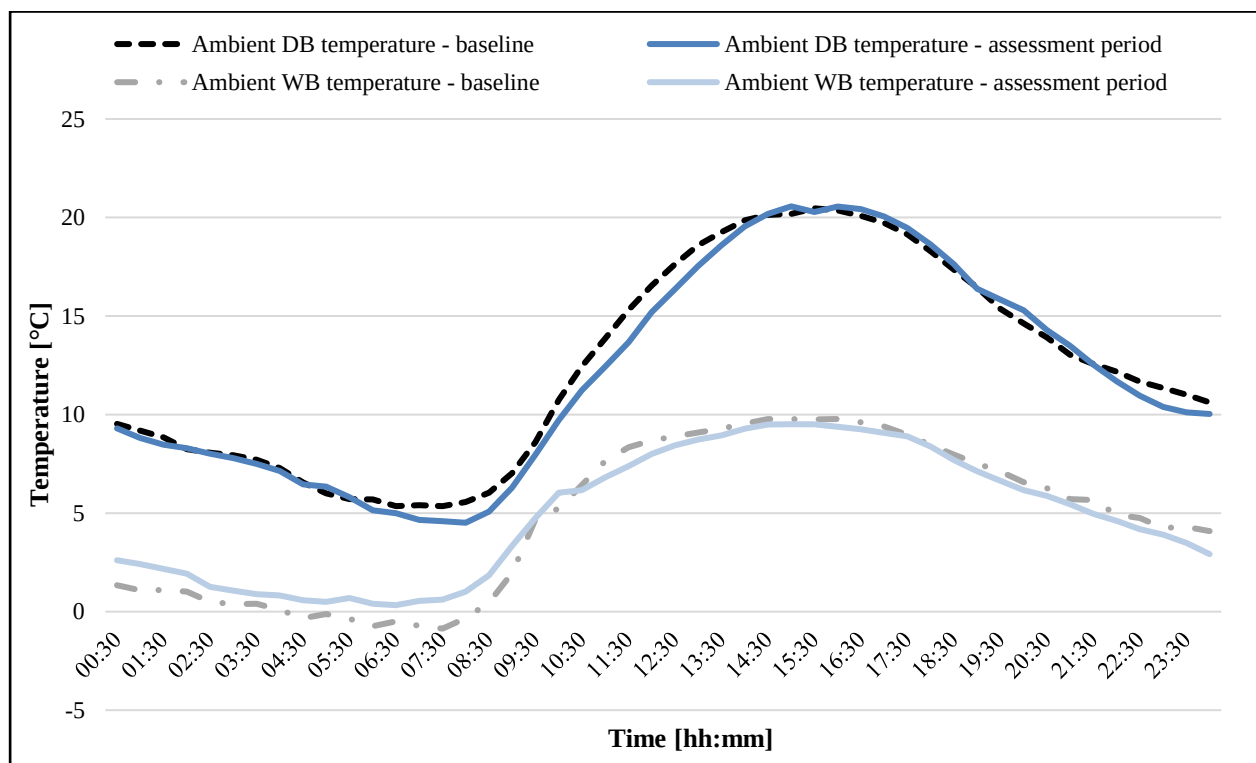


Figure 34: Comparable boundary conditions - baseline period 1

Once comparable boundary conditions have been considered feasible for comparisons, cooling system performance characteristics and behavioural changes brought about by the implementation of ITS can be compared and critically analysed.

Implementation results – Baseline period 1

An assessment period hosting similar ambient temperature conditions, operator system control and chiller operational configurations was identified. Comparative results between baseline and assessment period

conditions for baseline period 1 representing peak winter months is critically evaluated and discussed in this section.

To accurately quantify the impact of ITS implementation, the holistic systems performance is compared. Figure 35 illustrates a comparison of Mine P's refrigeration system power consumption for the two periods. Analysing the refrigeration systems' power profile, it is clear that a double ice melt was successfully capitalised on for the duration of the assessment period. The ITS system attained an average hourly morning and evening peak load shift of 4.9 MW and 3.9 MW respectively. As expected, an increase in the systems' power consumption was noticed throughout the remainder of the day due to the ice-making process. Since the energy utilised outside of peak periods to charge the ice dam is greater than that shifted during peak ToU periods, the scaled baseline depicted in Figure 35 shifts upwards accordingly. The scaled baseline represents the baseline through which cost savings will be quantified.

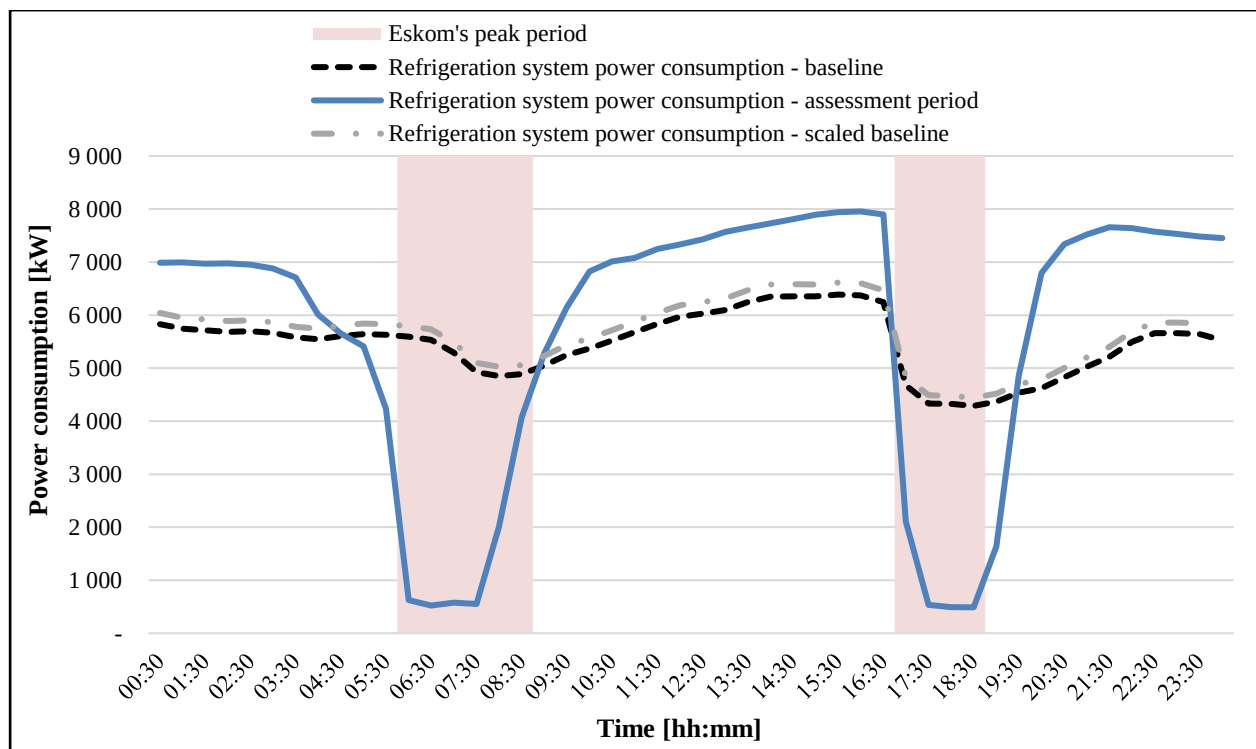


Figure 35: Refrigeration system power consumption - Mine P, baseline period 1

Figure 36 reveals the operational status of installed chillers for the two periods. Two Hitachi chillers and two ammonia chillers were operational. Comparing the two periods, the total number of operational chillers remain unchanged. Baseline period operation revealed zero chiller starts and stops. However, for the assessment period, the daily number of chiller-starts and stops increased by four per plant. This increase is purely attributed to the load-shifting control strategy incorporating ITS. Therefore, the long-term impact of ITS implemented for effective load management on the maintenance costs of chillers requires further investigation.

The running status of the ice plant during the ice-making process is also depicted in Figure 36. In preparation for the morning and evening ice melts, the ice plant was operated for approximately 8 hours 04 minutes and 7 hours 32 minutes respectively. The morning ice melt lasted on average 2 hours 20 minutes, whilst the evening melt managed 2 hours 05 minutes. Due to night-time operation resulting in increased cooling capacities and lower refrigerant temperatures, a full ice build is achieved in preparation for the morning ice melt. Conversely, due to day-time operation and a reduction in the ice plants cooling capacity, a full two-hour evening ice melt is not always achievable.

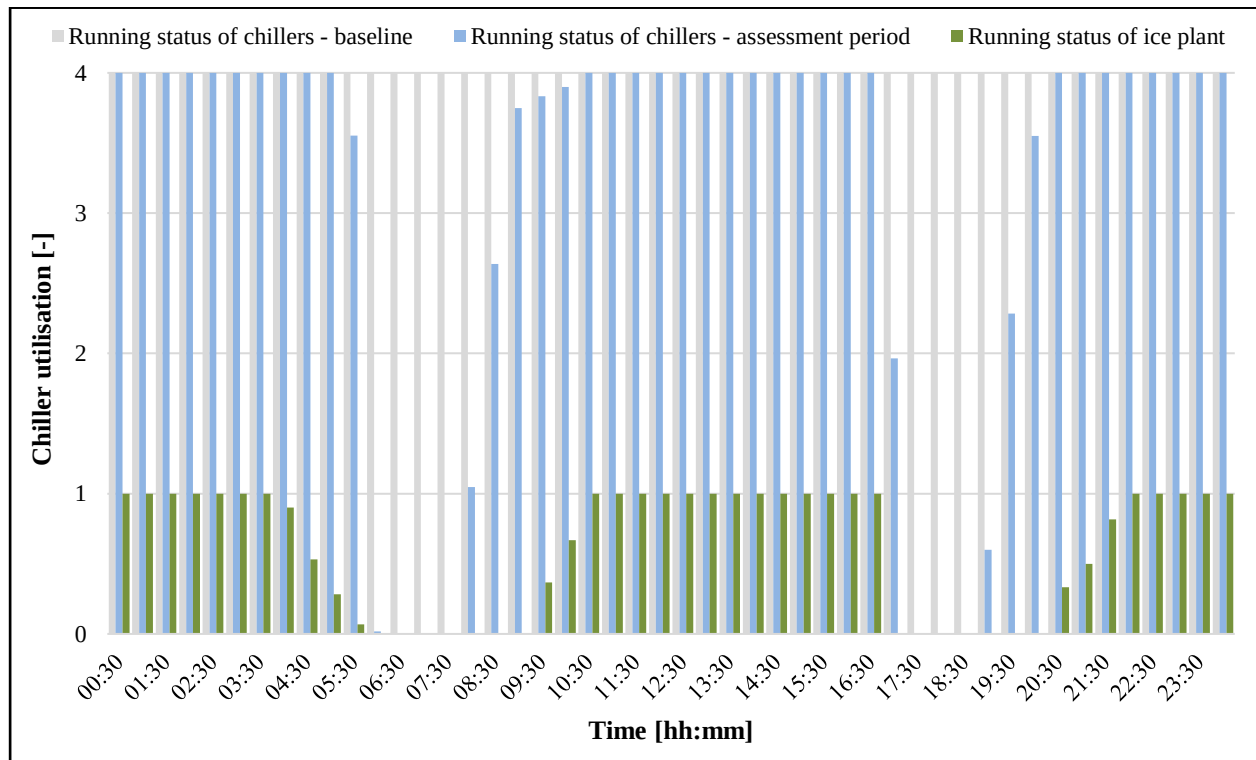


Figure 36: Running status of installed chillers - Mine P, baseline period 1

Figure 37 and Figure 38 illustrate the ice dam outlet water temperature during both morning and evening peak periods. Due to a longer charging period and a lower ice dam inlet water temperature, the morning ice melt lasts longer than the evening ice melt. First analysing the performance of the morning ice melt in Figure 37, it may be observed that a minimum ice dam outlet temperature of 0.98 °C was achieved. Within one hour, the water temperature leaving the ice dam reaches 2.0 °C. Thereafter, the system suffers from an exponentially increasing discharge temperature due to the depletion of ice in the dam. Once the discharge temperature reaches between 8.0 °C and 9.0 °C, an extended ice melt is conducted. This may be observed at 09:00 in Figure 37.

An extended ice melt is necessary to ensure all ice remanence on the coils is melted before the ice-making process is reinitiated. During an extended ice melt, two ammonia chillers are started. Water from the pre-cooling sump receives the first stage of cooling through the ice dam, melting what little ice is left.

Thereafter, it is pumped to the recently started ammonia chillers for a second stage of cooling before being stored in the surface chill dam. By doing this, not only is millennium ice prevented, but Mine P is able to capitalise on an extra hour of reduced energy consumption, specifically during Eskom's morning peak ToU tariff period. Therefore, subsequently improving the cost-saving potential of the ice system.

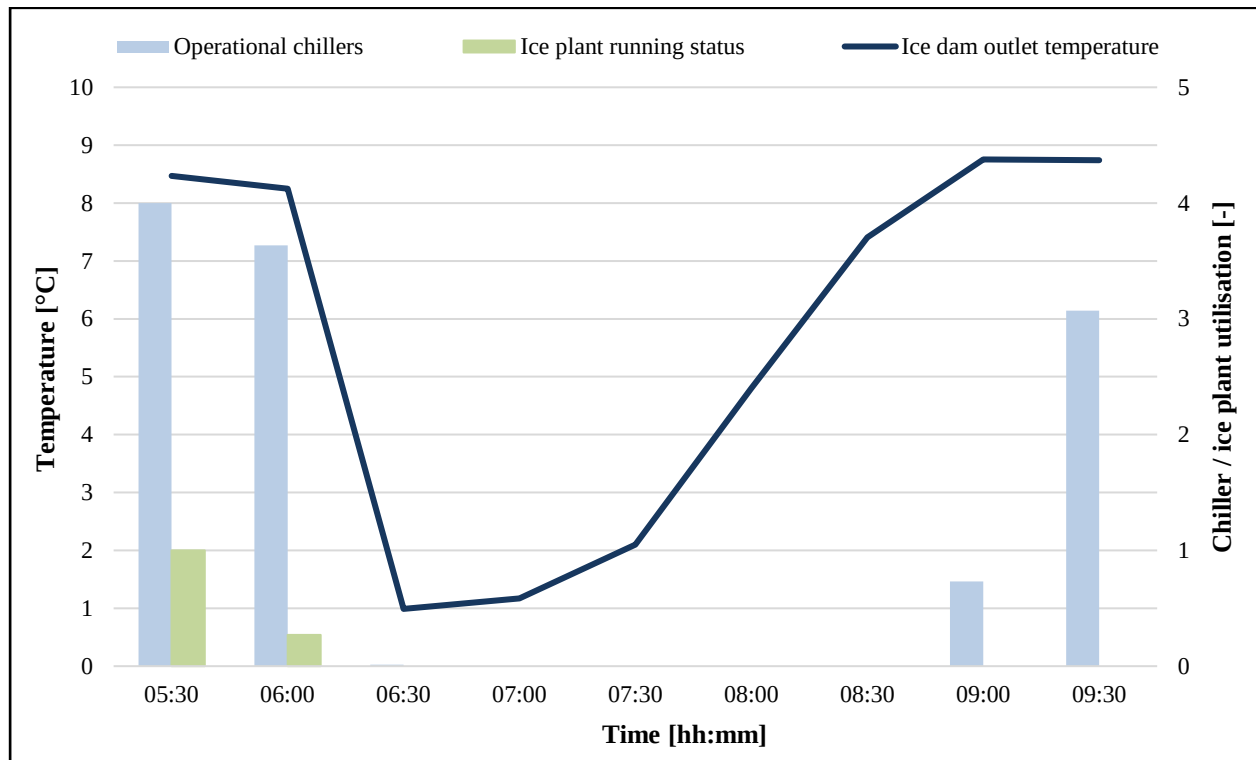


Figure 37: Ice dam outlet temperature during morning ice melt - Mine P, baseline period 1

Analysing the performance of the evening ice melt in Figure 38, a similar trend is noticed. The ice melt achieves a minimum temperature of 1.39°C, however, reaching 5.2°C within one hour. In general, the evening ice melt is short-lived when compared to the morning melt. Due to night-time operation and a longer available charging period, the ice mass present in the ice dam preceding the morning ice melt is greater than that present in preparation for the evening ice melt. In addition, depicted in Figure 39 illustrating the pre-cooling sump temperature, a lower inlet water temperature is experienced during the course of the morning ice melt compared to the evening ice melt. These contributing factors result in the morning ice melt lasting longer, with consistently lower ice dam water outlet temperatures. The extended ice melt for the evening period was initiated when the ice dam outlet water temperature reached approximately 8.7°C.

Portrayed in both Figure 37 and Figure 38, the initial temperature of the water leaving the ice dam represents that of the water in the dam. It takes anything up to 30 minutes into the ice-melting process before the ice dam water outlet temperature reaches its minimum. A similar trend was derived from the simulation results depicted in Figure 29.

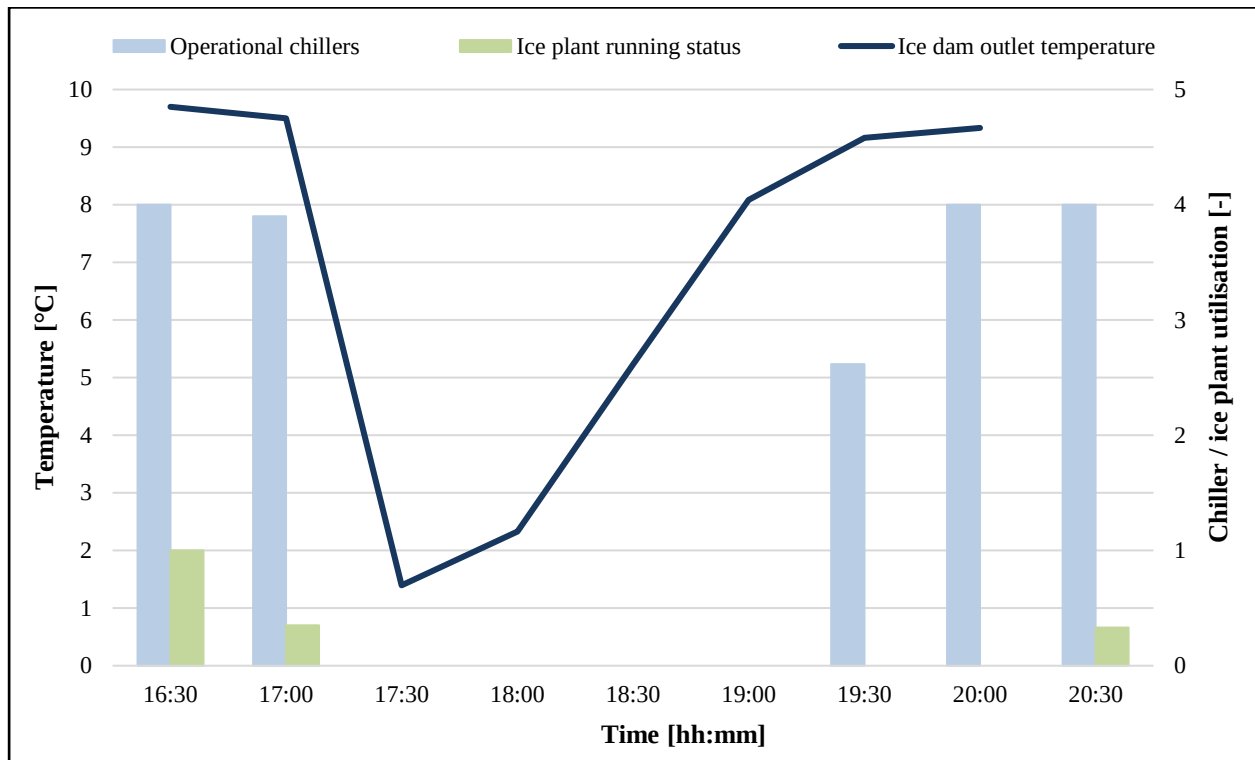


Figure 38: Ice dam outlet temperature during evening ice melt - Mine P, baseline period 1

Figure 39 illustrates the comparative profiles of the surface chill dam and pre-cooling sump temperatures for the two periods. Analysing Figure 39, it is apparent that the average chilled water temperature stored in the surface chill dam is higher proceeding ITS implementation. On average, the chilled water temperature stored in the surface chill dam is 0.5 °C higher for the assessment period when compared to the baseline (system without ITS). There are several reasons as to why this occurs, of which all relate to the ice plant. Once the ice-melting process is started, hot water from the pre-cooling sump is redirected through the ice dam to be cooled. Initially, the outlet temperature of water leaving the ice dam is relatively high, representing a mixture of the water initially in the dam and water received from the pre-cooling sump, typically between 8.0 °C and 10.0 °C. It takes approximately 20 – 30 minutes for the temperature of the water in the ice dam to drop to just below 1.0 °C. The time taken to reduce the temperature of water in the ice dam is, however, long enough to increase the temperature of the water stored in the surface chill dam by between 15% - 18% respectively. Conversely, during the ice-melting process, it may be observed that water in the surface chill dam during both morning and evening peak periods drops below normal baseline conditions. This results in an average chill dam temperature improvement of 14% and 34% purely during peak periods.

Although the mine is able to capitalise on an extended load shift, chilled water temperatures are compromised. As mentioned above, an extended ice melt is only initiated once the discharge temperature from the ice dam exceeds approximately 8.0 °C – 9.0 °C, therefore, in the meantime the surface chill dam is supplied with water of up to 9.0 °C, compromising the temperature of the water in the chill dam.

Fortunately, due to the initial volume of water in the chill dam, although the average temperature does increase, the extended ice melt does not occur for long enough to exceed chilled water temperature limits. Operators must, however, be careful to ensure that the inlet water temperature to the ammonia chillers remains below 9.5 °C during the extended ice melt. The installed ammonia chillers on Mine P have several conditions that must be met before the plants slide valve angle increases, therefore, increasing the cooling performance of the plant. One of these conditions that must be met is that the inlet water temperature may not exceed 9.5 °C. Once this condition is met, the slide valves will remain in their current position, therefore, unable to cool the water sufficiently. In this circumstance, once the water temperature from the ice dam reaches 9.0 °C, water is redirected through the Hitachi chillers before entering the ammonia plants.

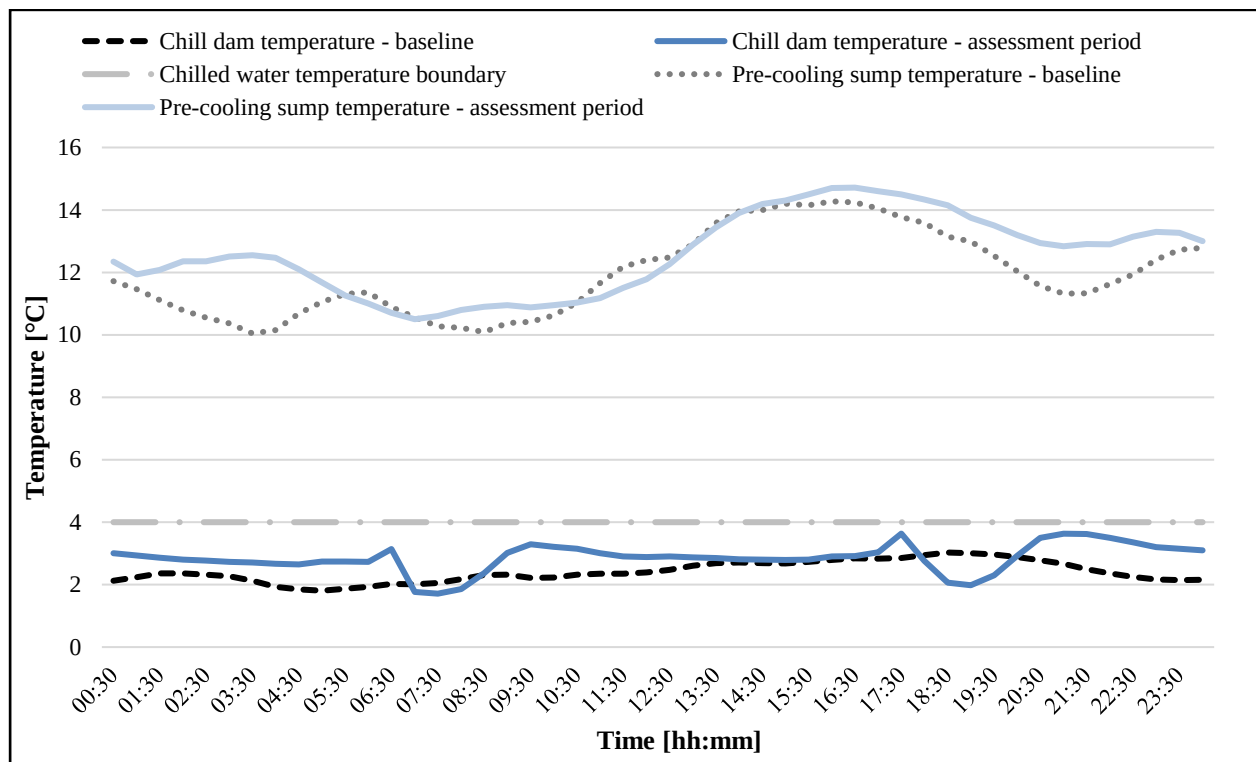


Figure 39: Surface chill dam temperature - Mine P, baseline period 1

Comparing the pre-cooling sump temperatures depicted in Figure 39, the most notable differences occur in the morning from 01:00 to 05:00 and in the evening between 15:00 and 23:00 respectively. An increase of 10.5% in the pre-cooling sump temperature was revealed. Increases in the return water temperature and subsequent pre-cooling sump temperature is attributed to the increase in chill water temperature circulating the system caused by the ice system. Depending on the extent of underground mining operations, water typically takes an extended period of time to circulate underground networks before returning to surface. According to the pre-cooling sump temperature recorded during the assessment period, the increase in chilled water temperature proceeding the evening ice melt is only realised the following day after 15:00 in the afternoon. Pre-cooling sump temperatures then stabilise and match that of the baseline between 05:30 and 07:30 as a result of the previous days morning ice melt. Thereafter, a slight increase in the pre-cooling

sump temperature is realised due to increased chilled water temperatures proceeding the morning ice melt. Temperatures then stabilise as a result of the evening ice melt, before increasing again, repeating the process.

Although increases in chilled water temperatures influence the temperature of return water from underground, additional unmeasurable factors underground play an integral role in the temperature of return water. Therefore, it cannot conclusively be said whether an increase in pre-cooling sump temperature is purely as a result of the increase in the initial chilled water temperature circulating the system. However, temperature trends depicted in Figure 39 do indicate a strong correlation to this hypothesis. An additional investigation will be required to determine the impact and to what extent underground heat loads and day-to-day mining operations have on the temperature of water circulating the system.

Since the surface chill dam directly supplies the surface BACs with chilled water to cool ambient air before being sent underground, increases in the chill dam water temperature will adversely impact the temperature of cool ventilated air supplied underground. Therefore, the BAC air outlet temperature must be critically analysed and evaluated. However, during peak winter months, BAC fans and feed pumps are switched off due to significantly low ambient air temperatures. Therefore, the BAC outlet air temperature is unaffected by the installation of the ITS system. To outline the performance of the chillers throughout the assessment period, the plants COP was compared and analysed. The combined COP of the Hitachi and ammonia chillers is illustrated in Figure 40.

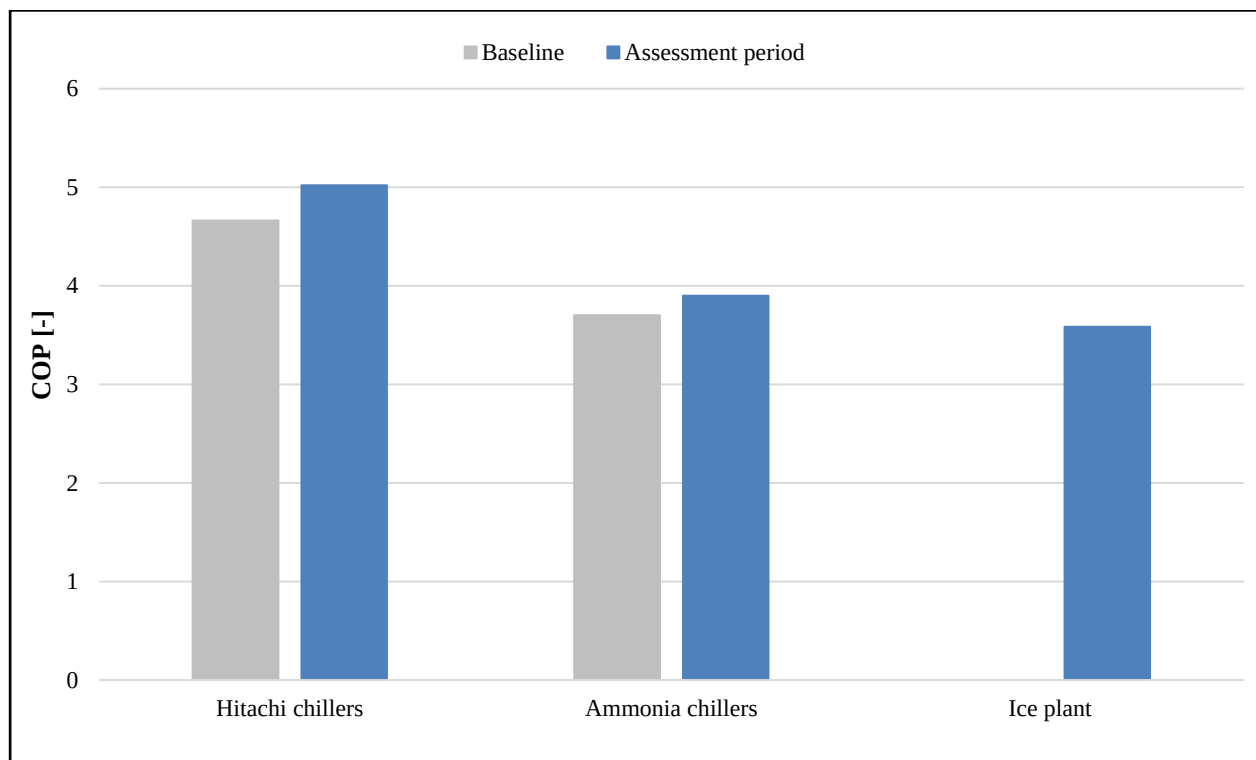


Figure 40: Combined COP of installed chillers - Mine P, baseline period 1

Proceeding ITS implementation, the average delta evaporator temperature increased from 6.3°C to 6.5°C respectively. This represents a 3.2% temperature difference improvement. With an increase in the temperature difference across the evaporator, improved heat transfer and, therefore, higher plant COPs result. This implies that as a result of the ITS implementation on Mine P, the Hitachi chillers efficiency improved. Comparing the baseline COPs to that derived for the assessment period, an average increase of 4.2% was realised. Since the COP additionally relies on the flow rate of water through the plant, it is worthwhile to mention that compared to baseline conditions, the average flow per plant increased by 21 l/s for the assessment period. Each operational Hitachi plant processing a higher volume of water at an increased inlet water temperature subsequently improved the plants' performance, operating closer to design conditions.

Analysing the performance of the ammonia chillers, a similar result was attained. Normal BAU operating conditions constitute an average ammonia plant COP of 3.7. The average delta temperature across the evaporators increased on average by 0.4°C proceeding ITS implementation. This resulted in improved chiller performance, revealing an increase in COP of 5.4%, to 3.9. Although water temperatures in the system increased, an increase in chiller COP has resulted in operational efficiency improvements as a result of the ITS installation. It is worthy to mention that ammonia plants are typically more efficient in terms of cooling capacity per unit energy expenditure than conventional chillers such as the Hitachi machines. However, Mine P operates installed ammonia chillers inefficiently. As a result of the low inlet water temperature received from the intermediate dam, the delta temperature across the evaporators is on average 3.8°C. This implies that the slide valves controlling the cooling capacity of the plant remain partially open at approximately 62%. Therefore, since the power consumption of the compressor is not directly proportional to the slide valve angle, the plants power consumption remains relatively high for low slide valve angles. This in turn results in a lower COP.

In addition to the chillers COP, Figure 40 additionally provides the average daily ice plant COP. The ice plant COP depicted in Figure 40 represents the refrigeration cycle COP during the ice-building phase. As expected, the COP of the ice plant during the ice-building phase is lower than conventional chillers. A value of 3.58 was obtained. As suggested in Section 1.6.2.2, night-time operation of the ice plant increases system performance as a result of lower condensing temperatures due to a reduction in the ambient temperature [101]. This was confirmed during the assessment period, where the ice plant COP dropped from 3.7 to 3.4 at midday.

It is important to note that the purpose of this study is to identify the shift in performance of the holistic cooling system and individual system components as a result of the implementation of ITS. The chillers COPs are indicative of this. However, the methodology utilised within calculates the COP assuming 100% guide vane angle. Although Mine P's chillers rarely reach 100% guide vane angle, the methodology remains valid to derive the general relationship and trends induced from the integration of ITS.

To account for the ITS installation on Mine P, dam preparation was required. Operators were required to ensure the pre-cooling sump level was low enough to allow for the inflow of hot return water from underground during Eskom's peak periods. Since the 3CPFS located on 1200L supplies the pre-cooling sump with between 220 l/s and 260 l/s per chamber, if the flow of water through the ice dam is consistently lower, the mine will run the risk of flooding the pre-cooling sump. In addition, to prevent the surface chill dam from running dry during the ice-melting process, it was required that the chill dam contain sufficient capacity during peak ToU periods. Again, this is dependent on the setting of the 3CPFS.

Figure 41 illustrates the flow balance control employed during the assessment period between the pre-cooling sump and surface chill dam. The pre-cooling sump was controlled to a much higher level when compared to baseline conditions. On average, proceeding ITS implementation, the pre-cooling sump level was approximately 25.4% higher. Preceding the morning and evening ice melts, the pre-cooling sump was controlled to a level of 68% and 62% respectively. By doing this, sufficient water capacity is available in the scenario that the 3CPFS is unavailable or not operational due to maintenance downtime. The level is low enough to allow for the inflow of water from underground, however, high enough to ensure the ice dam receives a constant flow of water during the ice-melting phase without risk of running the pre-cooling sump dry. During the morning and evening peak ToU tariff periods, the pre-cooling sump level subsequently rose to 88.6% and 82.8% respectively.

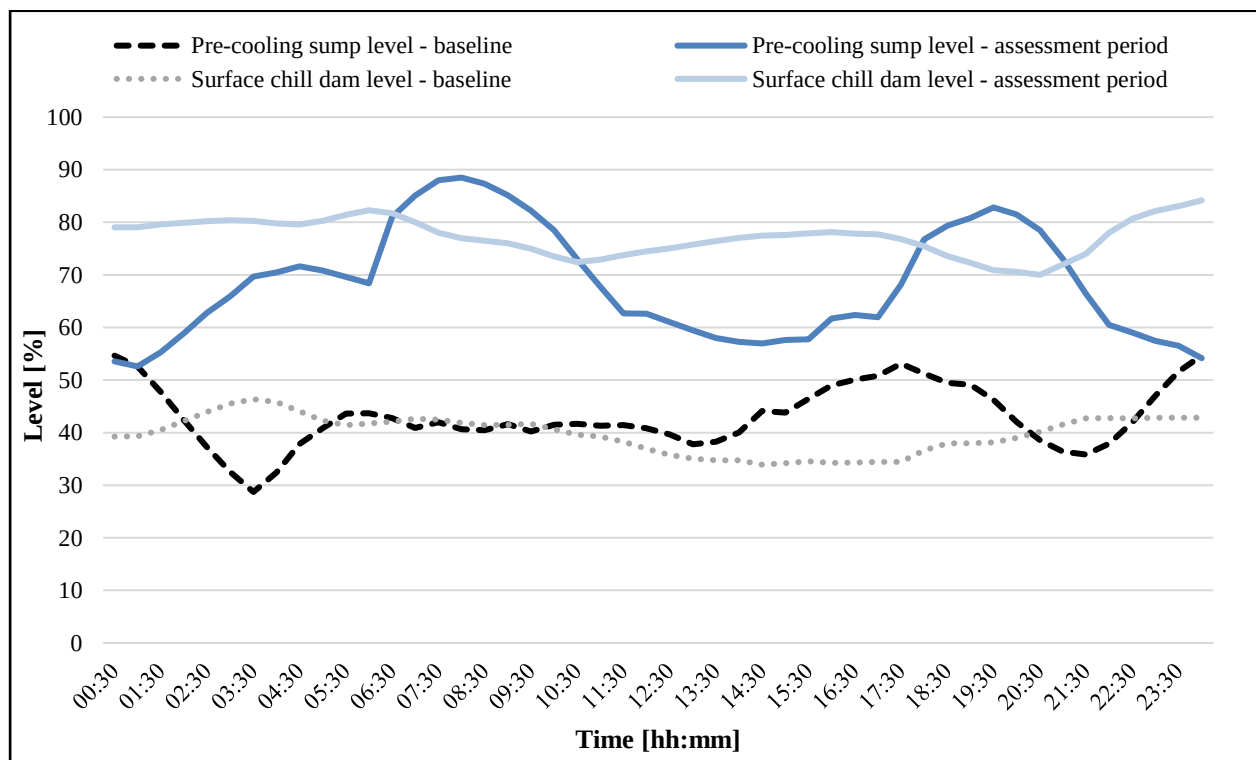


Figure 41: Pre-cooling sump and chill dam levels - Mine P, baseline period 1

Compared to the pre-cooling sump level, a similar yet opposite trend is noticed for the surface chill dam level during the course of the assessment period. Depicted in Figure 41, the surface chill dam level decreases in peak periods due to underground chilled water requirements and the operational status and setting of the 3CPFS. The 3CPFS was operated in high during both morning and evening peak periods. With an average flow of 475 l/s (morning ice melt) and 425 l/s (evening ice melt) flowing through the ice dam into the surface chill dam, the surface chill dam level was expected to decrease. Since the surface chill dam has double the capacity when compared to the pre-cooling sump, the surface dam level does not vary as much as the pre-cooling sump does.

Proceeding the implementation of an ITS system, it is clear that chill dam preparation is necessary. When compared to baseline conditions, the surface chill dam level was on average 36.5% higher proceeding ITS implementation. Due to the implementation of a more complex ITS system and the addition of various bypass valves, in the scenario that any one of these components fail, the chill dam should have enough capacity to continue supplying end-users with sufficient chilled water during periods of extended downtime. The surface chill dam should have enough capacity to allow for a significant difference between the inflow and outflow of water during peak periods. In addition, by controlling the surface dam level to a higher level during peak periods, this affords the mine with the luxury of implementing an extended ice melt without chilled water temperatures surpassing the limits set by mine personnel. If the dam capacity was significantly less, an extended ice melt would not be feasible without breaching service delivery requirements.

Finally, to quantify the operational performance of the holistic cooling system incorporating the use of ITS, the COP of the entire system is evaluated. Figure 42 illustrates the system COP versus the total power consumption of the cooling system for the two periods. Analysing Figure 42, proceeding ITS implementation, the overall performance of Mine P's cooling system deteriorates. Comparing the required power consumption to supply a specific cooling load at any one time, the COP of the system decreases by 18.5% from 2.7 to 2.2. By adding an additional energy consuming component operating for the majority of the day to attain a similar temperature difference, a reduction in the performance of the holistic cooling system was expected.

It is worthwhile to mention that Mine P's cooling system, both excluding and including ITS is relatively inefficient. It is expected that global system COPs should be between 4.0 and 5.0. However, since Mine P operates installed chillers extremely inefficiently throughout the year, an increase in the total average electrical power consumption without proportionally increasing the cooling load results in a reduced system COP. Although global system COPs are generally low, the study herein is interested in the shift in performance.

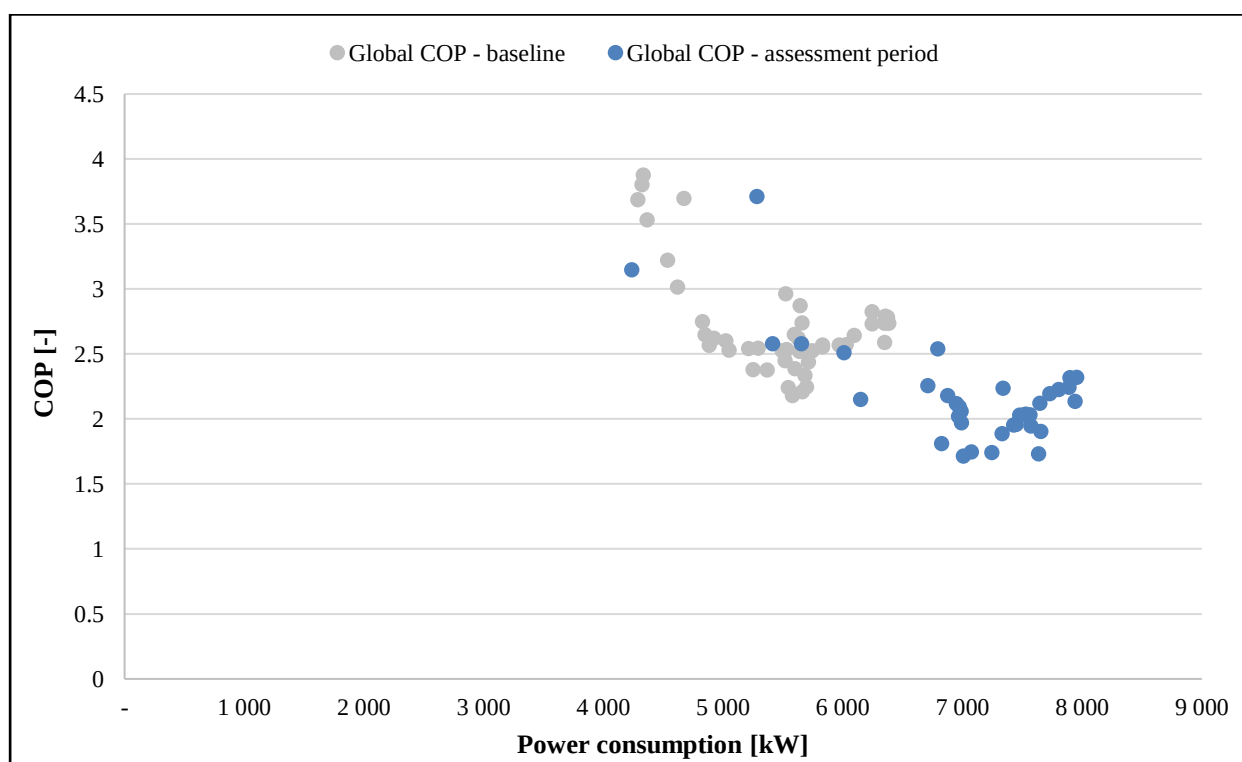


Figure 42: Global system COP - Mine P, baseline period 1

A summary of the implementation results for baseline period 1 is presented in Table 21. The percentage error provided is determined based on the averaged results between the baseline and assessment period. In terms of BAC air outlet temperature, the temperature of the water and volume of water sent underground, results indicate a 7.7% deterioration in service delivery requirements when compared to baseline conditions. Table 21 indicates that the total refrigeration systems power consumption on average increased from 5473 kW to 5667 kW. Comparing the daily average energy consumption of the holistic refrigeration system, proceeding ITS implementation, the total energy usage increased by 3.5% from 131.4 MWh to 136.0 MWh. An increase in the total energy consumption was revealed since the energy required to operate the ice plant exceeded that of the total reduction during Eskom's peak periods. Therefore, in terms of the financial impact for peak winter months, ITS offers only cost-saving potential through effective load management and a variable electricity tariff rate structure. ITS system characteristics attained for baseline period 1 are summarised in Table 22 to follow.

Table 21: Summary of baseline period 1 implementation results - baseline and assessment period

Description	Baseline period 1				Percentage error [%]
	Minimum	Maximum	Average		
			Baseline	Assessment	
Average system power [kW]	488	7 954.1	5 473	5 667	-3.5
Average daily energy consumption [MWh]	-	-	131.4	136.0	-3.5

DB Ambient air temperature [°C]	4.51	20.6	12.4	12.1	2.4
WB Ambient air temperature [°C]	0.3	9.5	4.7	4.9	-4.2
Hitachi chillers utilisation [-]	2	2	2	2	0
Ammonia chillers utilisation [-]	2	2	2	2	0
Surface chill dam temperature [°C]	1.7	3.6	2.4	2.9	-20.8
Surface chill dam level [%]	70.8	81.0	40.2	76.7	-90.8
Pre-cooling sump temperature [°C]	10.8	14.8	11.4	12.6	-10.5
Pre-cooling sump level [%]	52.6	88.5	43.0	68.4	-59.0
BAC air outlet DB temperature [°C] *	2.1	9.9	5.9	6.0	-1.7
Combined Hitachi chillers COP [-]	1.1	5.5	4.7	4.9	-4.2
Combined ammonia chillers COP [-]	2.2	4.4	3.7	3.9	-5.4
Total daily volume of water received by the surface chill dam [Ml]	-	-	31.08	32.01	-3.0
Global system COP [-]	2.0	3.5	2.7	2.2	18.5

* During the assessment period of baseline 1, the humidity sensor utilised to determine the BAC air outlet WB temperature was faulty. Therefore, for comparative purposes the DB temperature was utilised.

Table 22: ITS system characteristics - baseline period 1

Description	Baseline period 1			
	Morning ice melt	Extended melt	Evening ice melt	Extended melt
Charging time [hh:mm]	08:04	-	07:32	-
Duration of ice melt [hh:mm]	02:20	00:30	02:05	00:25
Ice plant COP during ice building process [-]	3.7	-	3.5	-
Flow of water through the ice dam [l/s]	475		425	
Ice dam outlet temperature [°C]	Minimum = 0.98	Maximum = 8.7	Minimum = 1.4	Maximum = 9.2
	Average = 4.6		Average = 5.1	

Implementation results – Baseline period 2

For peak summer months represented by baseline period 2, only an evening peak ice melt was achieved. Figure 43 illustrates the power consumption profile incorporating the use of ITS, an average hourly evening peak load shift of 11.0 MW was attained.

Due to significantly high ambient temperatures experienced during peak summer months, the cooling capacity of the ice plant is reduced as a result of less efficient evaporative condensers. Ultimately this implies that refrigerant charging temperatures are higher, therefore, requiring the ice plant to be operational

for a longer period of time to create a full build of ice. Since the ice plant is run for approximately 12 hours to achieve a full ice build, there is not enough time in the day to create enough ice to make it worthwhile to implement a second ice melt. Comparing actual implementation results to that derived through simulation, Mine P opted to implement an evening ice melt during peak summer months instead of a morning ice melt. This decision was entirely down to the on-site engineering manager. There is no technical or operational constraint preventing a morning ice melt from being conducted.

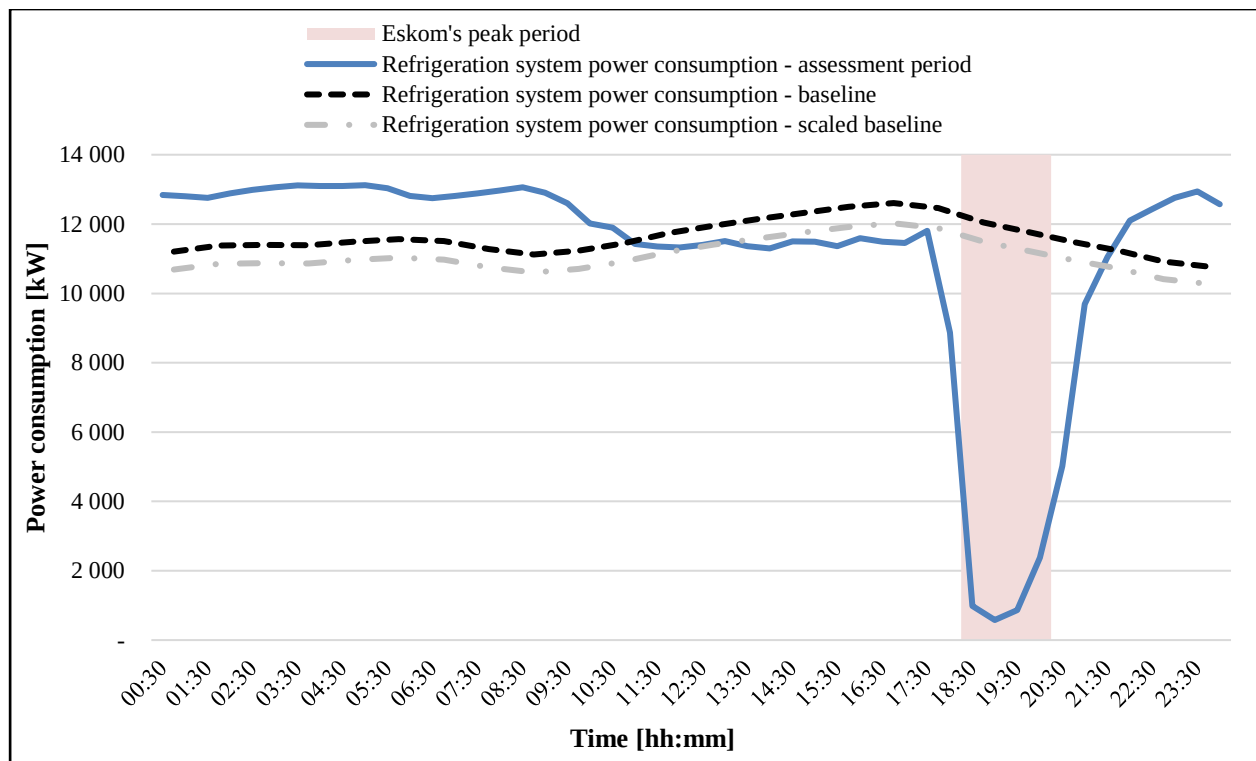


Figure 43: Refrigeration system power consumption - Mine P, baseline period 2

A summary of the implementation results and ITS system characteristics derived for baseline period 2 are presented in Table 23 and Table 24 respectively. From the ambient temperature comparisons presented in Table 23, based on an average percentage error of 4.8% and 0.4%, the selected assessment period was deemed viable for comparisons. Analysing the results presented in Table 23, due to ITS implementation, the power consumption reduced on average by approximately 616 kW. In addition, the daily average energy consumption of the refrigeration system reduced by 5.2% from 280.8 MWh to 266.1 MWh. This implies that the reduction in energy usage during Eskom's evening peak period was greater than the total energy required to charge the ice dam for 12 hours. In terms of service delivery requirements (BAC air outlet temperature, the temperature and volume of water sent underground), an overall deterioration of 2.4% was revealed. However, upon closer inspection, chilled water temperature requirements stipulated by mine personnel were breached.

Although the surface chill dam temperature increased on average by approximately 0.1°C, a maximum chill dam temperature of 4.1°C was recorded proceeding the evening ice melt. To prevent this from becoming a common occurrence, the extended ice melt should be started sooner. Toward the end of the ice melt, ice dam outlet temperatures increase exponentially due to the depletion of ice in the dam. This implies that, by leaving the chiller machines off for an extended period of time, the surface chill dam is supplied with water of between 7°C and 9°C. Therefore, by initiating an earlier extended ice melt, a second stage of cooling through the ammonia chillers will ensure the temperature of water stored in the surface chill dam remains within required limitations.

Table 23: Summary of baseline period 2 implementation results - baseline and assessment period

Description	Baseline period 2				Percentage error [%]
	Minimum	Maximum	Average		
			Baseline	Assessment	
Overall system power [kW]	579.4	13 165	11 702	11 086	5.2
Average daily energy consumption [MWh]	-	-	280.8	266.1	5.2
DB Ambient air temperature [°C]	16.9	34.6	26.3	26.4	-0.4
WB Ambient air temperature [°C]	13.6	18.6	16.8	16.0	4.8
Hitachi chillers utilisation [-]	4	4	4	4	0
Ammonia chillers utilisation [-]	4	4	4	4	0
Surface chill dam temperature [°C]	2.0	4.1	2.6	2.7	-3.8
Surface chill dam level [%]	53.5	74.8	61.0	62.8	-2.9
Pre-cooling sump temperature [°C]	13.9	16.9	15.6	15.5	0.6
Pre-cooling sump level [%]	43.2	72.0	46.6	59.5	-27.7
BAC air outlet WB temperature [°C]	6.5	13.8	9.4	9.2	2.1
Combined Hitachi chillers COP [-]	2.2	5.5	4.7	5.1	-8.5
Combined ammonia chillers COP [-]	2.5	5.0	3.1	3.2	-3.2
Total daily volume of water received by the surface chill dam [MI]	-	-	52.96	52.34	1.2
Global system COP [-]	2.3	4.4	2.9	2.7	6.9

Comparing the BAC air outlet WB temperature between baseline conditions to that attained during the assessment period, on average, a 2.1% improvement in the WB air temperature introduced underground was realised. Although a slight improvement was realised, a maximum BAC air outlet WB temperature of 13.8°C was recorded during Eskom's evening peak period. Although this breaches the maximum allowable temperature of 12°C (WB), since the BAC fans and pumping auxiliaries are switched off during this period, this warmer air is not introduced underground. In addition, the BAC air outlet temperature recovers within

one hour proceeding the load shift. The general relationship and trends of the BAC air outlet WB temperature for the two periods is depicted in Figure 44.

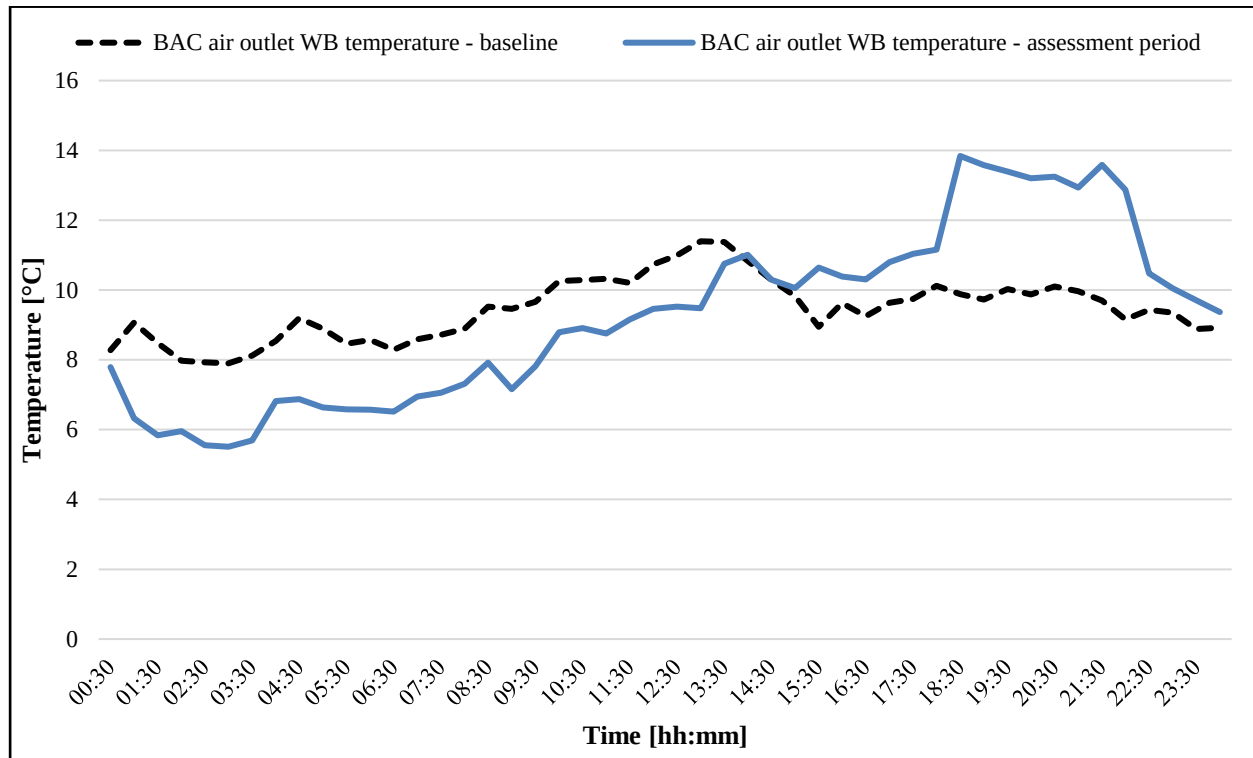


Figure 44: BAC air outlet WB temperature comparison - Mine P, baseline period 2

In general, when analysing the COP of the Hitachi and ammonia chillers, one would expect the resultant COP to be less for baseline period 2 (peak summer) than baseline period 1 (peak winter). This is largely attributed to increased ambient temperature conditions adversely impacting the performance of the condenser towers, subsequently reducing the cooling capacity of the chiller units. However, since installed chillers on Mine P rarely reach 100% guide vane / slide valve angle, this relationship is not clear. Therefore, since the approach temperatures are higher during summer, the chillers operate more efficiently, closer to its design. Improved cooling parameters are attained at higher inlet evaporator temperatures, therefore, improving the performance (COP) of the chiller.

Comparing the performance of the chillers proceeding ITS implementation for baseline period 2, an average COP improvement of 8.5% and 3.2% was realised for the Hitachi and ammonia chillers respectively. Improvements were attributed to an increase in the average water flow processed by each operational Hitachi chiller, whilst maintaining a similar temperature difference across the evaporator compared to baseline conditions. The increase in the ammonia plant COPs is largely attributed towards the significant temperature difference across the evaporator experienced during the extended ice melt. Similar to baseline period 1, the global system COP attained for baseline period 2 decreased as a result of ITS implementation. Although the decrease in the holistic systems' performance is not as significant as it was for baseline 1, an

increase in the energy consumption of the system outside of peak periods resulted in a decrease in the global systems COP.

Table 24 summarises the performance of the ITS system during the assessment period. As expected, due to an increase in ambient temperatures, the cooling capacity of the ice plant is reduced due to a reduction in the performance of the evaporative condensers. This implies that, when compared to peak winter months (baseline period 1), the ice plant building COP attained for peak summer months is lower. A reduction in the ice plants COP of 11% was derived for summer when compared to winter. Due to the ice plant charging for just over 12 hours, a combined ice melt and extended melt of 2 hours 38 minutes was achieved. A minimum ice dam outlet temperature of 0.9°C was recorded. The maximum temperature leaving the ice dam was 9.2°C, experienced toward the end of the extended ice melt. Fortunately, due to the volume of water in the surface chill dam, although the average temperature does increase, the extended ice melt does not occur for long enough to exceed chilled water temperature limits.

The flow rate of water sent through the dam is determined by the pre-cooling sump level, surface chill dam level and the setting of the 3CPFS.

Table 24: ITS system characteristics - baseline period 2

Description	Baseline period 2			
	Morning ice melt	Extended melt	Evening ice melt	Extended melt
Charging time [hh:mm]	-	-	12:01	-
Duration of ice melt [hh:mm]	-	-	01:58	00:40
Ice plant COP during ice building process [-]	-	-	3.2	-
Flow of water through the ice dam [l/s]	-		300	
Ice dam outlet temperature [°C]	-	-	Minimum = 0.9	Maximum = 9.2
			Average = 4.5	

Summary of implementation results

The purpose of this subsection will be to summarise the benefits, improvements and drawbacks associated with the implementation of ITS on deep-level gold mines. General system observations are also provided.

- Across all four baseline periods, the surface chill dam was controlled to a higher level proceeding ITS implementation. On average, an overall average increase of 22.9% dam level control was revealed. Reasons attributing to this are as follows:
 - The 3CPFS is generally operated in high to enable a successful load shift of underground dewatering pumps during peak periods. This implies that, to prevent an excessive amount

- of water being pumped through the ice dam, subsequently limiting the length of the ice melt, sufficient thermal storage capacity is required.
- Controlling the surface chill dam to a higher level allows the mine to implement an extended ice melt without compromising chilled water temperature requirements sent underground. Although an extended ice melt implies water of temperature between 7°C and 9°C is sent to the chill dam, the extended ice melt does not occur for long enough to exceed chilled water temperature limits. Therefore, an extended load shift is capitalised on.
 - Due to the addition of a more complex refrigeration system component in the form of an ice plant, as well as a series of bypass valves, by controlling the surface chill dam to a higher level, sufficient thermal storage capacity is available to mitigate component failures from adversely impacting downstream mining operations.
- The pre-cooling sump was controlled to higher levels proceeding ITS implementation. The main reasoning behind this is regarding the 3CPFS. Although extremely advantageous in reducing the usage of energy intensive dewatering pumps, the installed 3CPFS on Mine P is extremely problematic and maintenance intensive. Therefore, in the scenario the 3CPFS is unavailable during the course of an ice melt, the pre-cooling sump will have sufficient capacity to supply the ice dam with a constant flow of water without running dry.
 - The ITS system resulted in an overall increase in the average chill dam water temperature. During peak summer months (baseline period 2), the chilled water temperature limitation of 4.0°C was breached on several occasions; however, only by 0.1°C. Across all four baseline periods, the chill dam water temperature increased by an average of 0.3°C.
 - The ITS system did not perform as expected. During the course of peak summer months, the ice dam outlet temperature achieved a minimum of 0.9°C. However, within 30 minutes of initiating the ice melt, the ice dam outlet temperature was already reaching 2.5°C. Conversely, for peak winter months, a minimum temperature of 0.98°C was recorded, reaching 2.0°C within one hour of the start of the morning ice melt. For the evening peak period, a minimum temperature of 1.39°C was recorded, reaching 5.2°C within one hour.
 - In general, since the surface chill dam increased slightly in temperature due to the ITS installation, intuitively, so too did the BAC air outlet temperature. On average, the BAC air outlet temperature remained within specified limitations. However, on several occasions, specifically during Eskom's evening peak period, the maximum allowable BAC air outlet temperature was breached. However, since the BAC fans and pumping auxiliaries were intentionally switched off, none of this air was introduced underground.
 - Since the chilled water temperature is the driving temperature circulating the system, increases in temperature should theoretically result in an increase in downstream temperatures, including the pre-cooling sump temperature. However, since the water temperature and flow received from

underground and the BACs dictate the temperature of water in the pre-cooling sump, results may be skewed. The most reliable results are, therefore, obtained from baseline period 1, whereby, the BAC return pumps are not operational. This implies that the pre-cooling sump temperature is solely dependent on water received from underground. Therefore, for baseline period 1 (peak winter months), an increase in return water temperature, and subsequent pre-cooling sump temperatures was noticed. However, it may be said that chilled water circulating underground networks may be exposed to several uncontrolled variables that may influence the temperature of return water sent to surface. Invariably this is true, however, chill dam temperature and pre-cooling sump temperature trends illustrated in Figure 39 support the notion in that the ITS system has increased system temperatures.

- Since the Hitachi chiller COPs are largely influenced by the pre-cooling sump temperature, inefficient and inconsistent control of the BAC return pumps supplying the pre-cooling sump with chilled water has resulted in unreliable COP values obtained for baseline periods 2, 3 and 4. Therefore, to analyse the influence of the ITS system on the performance of the Hitachi chillers, results obtained for baseline period 1 are valid. Due to the implementation of an ITS system on Mine P, approach temperatures to the Hitachi chillers are higher, therefore, increasing the temperature difference across the evaporators, subsequently improving chiller performance.
- Ammonia chillers experienced a slight improvement in operational efficiency across all baseline periods.
- In terms of global system COP, across all four baseline periods, a decrease in the overall system performance was derived. This is largely attributed to the addition of an energy consuming component (ITS system) operating for the majority of the day to attain a similar temperature difference. Therefore, resulting in a reduction in the performance of the holistic cooling system.
- Baseline periods 1, 3 and 4 were all able to capitalise on both morning and evening peak load shifts, whereas baseline period 2 only managed an evening peak load shift. Baseline period 2 only realised a single ice melt due to ambient temperature conditions. A summary of the average hourly load shift attained for each period is provided.
 - Baseline period 1: Morning and evening load shift of 4.9 MW and 3.9 MW respectively.
 - Baseline period 2: Evening load shift – 11.0 MW.
 - Baseline period 3: Morning and evening load shift of 7.6 MW and 7.7 MW respectively.
 - Baseline period 4: Morning and evening load shift of 5.6 MW and 5.8 MW respectively.
- In terms of total system energy usage, baseline periods 2, 3 and 4 revealed a reduction in the energy consumption as a result of the ITS system. Whereas, baseline period 1 recorded an increase in energy consumption. A reduction in the energy usage of the system, even with the added energy consumption of the ITS system during the charging process, is largely dependent on the magnitude and extent of the load shift/s achieved. For baseline periods 2, 3 and 4, the energy consumption

shifted outside of Eskom's peak periods was greater than that required to build a sufficient amount of ice to make the load shift possible.

Although real-time ITS implementation results reveal an overall deterioration of service delivery requirements when compared to baseline conditions, the influence on KPIs and the operational performance of cooling system components is minimal. Service delivery requirements remained within specified limits as stipulated by mine personnel. To further quantify the feasibility of ITS implemented on deep-level gold mines, cost and power savings need to be quantified.

Cost-benefit analysis

To quantify the financial impact associated with ITS implementation on deep-level mines, a cost-benefit analysis is required. By conducting a cost-benefit analysis, the economic performance of ITS is evaluated in terms of cost-saving potential and payback period. All capital outlays must be considered to accurately quantify the realistic year-on-year cost-saving potential of ITS.

To calculate the electricity cost savings achieved from the implementation of ITS on Mine P, Eskom's 2018/2019 MegaFlex tariff structure illustrated in Table 40 and Table 41 of Appendix F was applied. Table 25 illustrates the weekday cost-benefit analysis applicable to baseline period 1. Analysing implementation results presented in Table 25, it is evident the significant cost-saving potential mine refrigeration systems host. Through implementation of an effective and sustainable load management strategy, the excessive electricity cost to provide cooling during Eskom's peak periods can be averted. During winter months, electricity costs during peak periods are approximately six times more when compared to off-peak periods.

Table 25: Summary of weekday electricity cost savings - baseline period 1

Time [hour]	Imposed electricity tariff [c/kWh]	Scaled baseline power [kW]	Project power [kW]	Baseline electricity cost [R]	Project electricity cost [R]	Cost saving [R]
0	47.43	6 038	6 989	2 863.71	3 315.02	-451.31
1	47.43	5 934	6 981	2 814.47	3 311.16	-496.70
2	47.43	5 893	6 961	2 794.84	3 301.54	-506.70
3	47.43	5 794	6 532	2 748.07	3 098.29	-350.22
4	47.43	5 821	5 535	2 760.73	2 625.08	135.64
5	47.43	5 828	4 237	2 764.38	2 009.70	754.68
6	288.29	5 668	575	16 341.30	1 658.97	14 682.33
7	288.29	5 061	1 281	14 591.26	3 692.47	10 898.79
8	288.29	5 057	4 070	14 579.19	11 734.12	2 845.07
9	87.34	5 409	6 086	4 724.16	5 315.64	-591.48

10	87.34	5 713	7 009	4 989.89	6 121.59	-1 131.70
11	87.34	5 958	7 161	5 204.06	6 254.57	-1 050.51
12	87.34	6 213	7 379	5 426.35	6 445.15	-1 018.80
13	87.34	6 390	7 606	5 581.21	6 643.43	-1 062.22
14	87.34	6 578	7 768	5 744.80	6 784.77	-1 039.97
15	87.34	6 595	7 917	5 759.67	6 914.44	-1 154.77
16	87.34	6 534	7 926	5 706.64	6 922.72	-1 216.08
17	288.29	4 663	1 322	13 443.98	3 810.63	9 633.35
18	288.29	4 459	491	12 854.15	1 414.36	11 439.78
19	87.34	4 609	3 249	4 025.84	2 837.78	1 188.06
20	87.34	4 891	7 067	4 271.92	6 172.66	-1 900.73
21	87.34	5 301	7 588	4 629.76	6 627.05	-1 997.29
22	47.43	5 775	7 606	2 738.85	3 607.41	-868.56
23	47.43	5 852	7 505	2 775.86	3 559.78	-783.92
Average weekday cost saving						<u>R 35 957</u>

According to SLA factoring, the scaled baseline developed in Figure 35 was utilised to quantify cost savings for baseline period 1. Implementation results revealed an average hourly morning and evening peak period load shift of 4.9 MW and 3.9 MW respectively. This translates to a weekday cost saving of approximately R 35 957. To derive the holistic cost-saving potential of ITS for the entirety of baseline period 1, electricity cost savings for Saturdays were quantified in a similar manner. Since Saturdays do not incorporate peak tariff periods, cost savings are significantly less when compared to weekdays. Sundays were omitted as they incorporate a fixed tariff rate throughout the day. As confirmed by Section 1.6.3.2, when a fixed tariff rate is imposed, no financial gain is realised [101]. According to the MegaFlex tariff structure illustrated in Table 40, an electricity cost saving of R 2 378 is achieved for Saturdays.

The electricity cost savings applicable to baseline periods 2, 3 and 4 were calculated in a similar manner. The estimated annual electricity cost savings are tabulated in Table 26. Due to the implementation of ITS on Mine P, a total annual cost saving of R 4 455 080 was expected for the 2018/2019 financial year.

Table 26: Summary of annual electricity cost savings - Mine P

Baseline	Peak demand load shift [MW]		Combined electricity cost savings [R]
	Morning peak period	Evening peak period	
1	4.9	3.9	2 241 313
2	-	11.0	664 309
3	7.6	7.7	837 468

4	5.6	5.8	711 990
Total annual cost-saving potential			R 4 455 080

It is important to remember that the annual cost-saving potential derived above represents the expected financial impact of the ITS installation on Mine P. However, recently during the course of the 2018/2019 financial year, ITS system performance has been particularly poor, experiencing several operational issues. As a result, the actual cost saving achieved for the 2018/2019 financial year (FY) was approximately R 2 592 880, an overall reduction of 42%. Table 27 provides a summary of the expected annual cost-saving potential versus that achieved as a result of operational inefficiencies.

Table 27: Cost saving comparison

Baseline	Expected annual cost-saving potential [R]	Cost savings achieved 2018/2019 FY [R]	Percentage reduction [%]
1	2 241 313	1 455 009	35.1
2	664 309	376 977	43.2
3	837 468	346 745	58.6
4	711 990	414 149	41.8
Total	R 4 455 080	R 2 592 880	42%

Estimated return on investment of Mine P's ITS system

The project payback period or return on investment is calculated by comparing the initial capital investment incurred against the electricity cost-saving potential of the ITS system. Since the exact cost savings achieved by Mine P's ITS system to-date is unknown, assuming similar performance parameters in terms of average hourly load shifts achieved, the potential cost savings to-date can be quantified. To derive the potential payback period of the ITS system installed on Mine P, the imposed electricity tariff structure since project inception was considered. The ITS system was commissioned midway through 2009 at the start of Eskom's 2009/2010 financial year. Table 42 found in Appendix F, illustrates the electricity tariffs applicable to the mining industry since the 2009/2010 financial year. Consequently, Table 28 illustrates the annual cost-saving potential from the implementation of ITS on Mine P since inception. Incorporating the unplanned maintenance discussed above, to-date, Mine P's ITS system had the ability to achieve a potential cost saving of R 31 016 867 through effective load management.

Table 28: Approximate cost savings achieved to-date

Baseline	Baseline 1 cost savings [R]	Baseline 2 cost savings [R]	Baseline 3 cost savings [R]	Baseline 4 cost savings [R]	Total cost savings [R]
2009/2010	940 431	220 190	301 135	270 335	1 732 092

2010/2011	1 161 426	271 879	371 847	333 834	2 138 986
2011/2012	1 491 395	349 075	477 402	428 621	2 746 493
2012/2013	1 716 776	401 884	549 537	493 370	3 161 566
2013/2014	1 565 804	468 033	591 445	501 126	3 126 408
2014/2015	1 690 553	501 115	631 805	537 113	3 360 587
2015/2016	1 904 839	563 328	709 452	603 714	3 781 332
2016/2017	2 084 059	617 768	778 822	662 103	4 142 751
2017/2018	2 129 911	631 304	795 908	676 649	4 233 772
2018/2019	1 455 009	376 977	346 745	414 149	2 592 880
Total cost savings to date					<u>R 31 016 867</u>

To ensure a thorough return on investment evaluation is conducted, other considerations such as operational and maintenance costs also need to be incorporated. Although ITS systems are typically described as maintenance-intensive, annual maintenance-related costs are relatively low. Large capital expenditure becomes apparent when ice plant components such as the compressor or set of coils need to be replaced or refurbished. The most notable recurring annual maintenance and operational expenses involve replacing the motor oil, strainers and ammonia refrigerant. Replacement costs are: motor oil and strainers – R 100 000 annually, and ammonia refrigerant – R 130 000 annually (@ R17.00 per kilogram)⁸. Therefore, subtracting these additional annual expenses from the total potential cost savings realised to date, a new cost saving total of R 28 716 867 is attained. Based on the initial capital investment of R 30 million, Mine P's stakeholders may only achieve a return on investment during the course of the 2019/2020 financial year.

To determine the estimated project payback period, the projected cost savings for the 2019/2020 financial year will need to be determined. Based on the 2019/2020 tariff structure depicted in Appendix F, the expected annual cost saving of the ITS system for the financial year 2019/2020 is R 5 072 809. However, incorporating maintenance and operational expenses, a cost-saving potential of R 4 842 809 is derived. Assuming no additional maintenance downtime, come the end of the 2019/2020 financial year, Mine P's ITS system could achieve a potential cost saving of approximately R 33 559 676 since inception. Therefore, when compared to the initial capital investment of R 30 million, a payback period or return on investment of approximately 123 months (10.3 years) is feasible for Mine P's ITS system.

⁸ Moore, H (2019), "Ice plant operating costs", Personal Communication, Mechanical Foreman, Mine P, South Africa

To further quantify the impact of ITS on deep-level gold mines, ratios outlining the energy expenditure and cost to cool one megalitre of water have been developed. Table 29 summarises the energy consumption and volume of water cooled on a daily basis under normal BAU conditions. Each baseline period is analysed to quantify the holistic impact. The volume of water cooled by the refrigeration system is determined by the amount of water received by the surface chill dam throughout the day. Results illustrated in Table 29 represented by a conventional system, depict operating conditions when the ice plant was not in use.

Table 29: Cost and energy comparisons to cool water

Baseline	System type	Daily energy consumption [kWh]	Water cooled per day [ML]	Daily cost to cool water [R]	Cooling <i>ratio_{energy}</i> [kWh/ML]	Cooling <i>ratio_{cost}</i> [R/ML]
1	Conventional	131 351	32.01	165 100	4 103	5 158
	Including ITS	136 012	31.08	130 013	4 376	4 183
2	Conventional	280 841	52.96	200 489	5 303	3 786
	Including ITS	266 051	52.34	181 498	5 083	3 468
3	Conventional	207 305	41.65	148 970	4 977	3 577
	Including ITS	199 394	41.86	128 956	4 763	3 081
4	Conventional	163 134	46.14	115 753	3 536	2 509
	Including ITS	162 239	45.95	105 196	3 531	2 289
Average annual impact				Conventional	4 480	3 757
				Including ITS	4 438	3 255

Analysing the average annual impact, it is clear that the energy expenditure per megalitre of water cooled remains relatively the same comparing a conventional system to that incorporating ITS. As a first approximation, it would be expected that the energy expenditure proceeding ITS installation would be higher. However, specifically for baselines 2, 3 and 4, the energy shifted outside of peak periods is greater than that required to charge the ice system for that specific period. An average decrease of 42 kWh per megalitre of water cooled was revealed. As expected, all baseline periods realise a reduction in the cost to cool a megalitre of water when compared to a conventional system. This is attributed to shifting peak time cooling loads outside of Eskom's peak ToU tariff periods when electricity is most expensive, thereby significantly reducing the cost to cool water. Through the implementation of ITS utilised for effective load management, a reduction of R 502 per megalitre of water cooled is achievable.

With the gold mining industry facing financial uncertainty, capital investment requirements and predicted project payback periods are seemingly unfavourable. Nonetheless, to ensure the long-term sustainability of any future mine ITS installations, post-implementation considerations are provided.

Post-implementation considerations

Project deterioration is measured by the ability of the ITS system to maintain service delivery requirements and meet cost saving targets. To mitigate and ultimately prevent project deterioration, it is imperative that system control and utilisation practices are re-evaluated to ensure the system is operated as originally intended. To promote sustainable practices, a reporting system in the form of a daily report was established to prevent project deterioration. Not only does the daily report monitor system performance, but it assists in identifying system changes that may impact the ice plant performance and operation. The daily report recipient list includes on-site engineers, the chief technician, mechanical foreman and control room operators. The report was set up to include the following elements; operational KPIs including the chillers COP, chill dam temperature, pre-cooling sump temperature, respective dam levels, length of the ice melt and ice-building processes, energy usage and cost savings achieved.

Operational issues experienced with Mine P's ITS system

Issues surfaced proceeding the ice-melting process when the ice-building process had to be restarted. Control room operators subsequently started the ice-building process too soon when ice remanence was still present on the coils. Repeating this process on several occasions inherently led to the damage of several ice coils, subsequently inducing ammonia leaks. As a result, not only have ice coils been damaged in the process but ice thickness sensors have been left either broken or faulty. This then generally implies that the ice-building process and ice-melting process is completely dependent on operator competence, control and system understanding. Too much ice formation resulting in a solid block of ice, insufficient ice formation and extended periods of unplanned maintenance subsequently minimised the annual cost-saving potential of the ITS system. For future ITS installations, periodic operator training is imperative. This will ensure the ITS system performs as per design specifications, capitalising on maximum cost-saving potential.

Maintenance considerations

Although an in-detail maintenance schedule is generally discussed and agreed upon with the supplier of a component, a brief overview of the general maintenance activities that are required to be conducted to ensure the installed ITS system is sustainably maintained, is provided.

- To ensure the long-term sustainability of the ice plant in maintaining significantly low charging temperatures, it is recommended that the compressor be refurbished every five years. Proceeding the second refurbishment, the compressor unit itself should be replaced.⁹

⁹ Moore, H (2019), "Ice plant maintenance requirements", Personal Communication, Mechanical Foreman, Mine P, South Africa

- Approximately once every six months the ice dam must be checked for leaks and cleaned [111]. Although much of the water passes through settlers to facilitate sedimentation before returning to surface, not all of the contaminants are successfully removed. It is not uncommon to find the build-up of sediments in surface thermal storage dams over a long period of time. Therefore, it is important that the ice dam is cleaned under the tube structure to prevent the build-up of sediments interfering with system components.
- Once a week, the ice-making cycle should be delayed for up to five hours with warm water circulating through the ice dam. This will ensure that no remanence of ice remains on the coils. It is required as a preventive measure to melt any residual ice that may not melt during the daily ice-melting cycle, which over time may damage the coils.
- Control and instrumentation should be recalibrated every three months to ensure no faulty instrumentation [127].
- Refrigerant levels should be checked periodically. Any decrease in the refrigerant level is a clear sign of a system leak.
- To check that there are no blockages in the aeration blower, a visual inspection should be conducted every six months. If excessive ice build-up is a common occurrence, more frequent inspections will be required. Another way to determine the effectiveness of the aeration blower would be to install temperature sensors around the dam. Since the aeration blower is required to ensure uniform ice melting and ice formation, any significant changes in temperature at varying points in the dam would indicate a problem requiring immediate attention.

3.5.3 Verification and validation of solution

Verification of methodology and analytical approach

To ensure an accurate feasibility analysis can be conducted by other similar mining operations through application of the methodology and analytical approach developed in Chapter 2, verification is necessary. Verification will ensure that the approaches utilised in constructing a simulation model incorporating the use of a theoretical ITS system is accurate in emulating actual implementation results. To do this, various ITS system characteristics derived from the analytical approach and simulation model are compared to that of the actual ITS installation present on Mine P. Table 30 provides a summary of comparable ITS system characteristics. ITS system characteristics depicted in Table 30 represent the theoretical design requirements of an ITS installation on Mine P. Characteristics represent system requirements, based on current operating conditions to implement a successful load shift of Mine P's refrigeration system.

Table 30: Comparison of theoretical and actual ITS system requirements – Mine P

Description	Theoretical ITS requirements	Mine P's actual ITS system characteristics	Percentage error [%]
Required dam capacity [m^3]	> 4 500	6 500	44.4
The mass of ice required [kg]	649 863	900 000	38.5
Ice building cooling duty [kW]	$\approx$ 6 012	6 000	0.2
Overall percentage error			27.7

From Table 30, it is evident that the methodology and analytical approach developed in Chapter 2 was accurate in predicting ITS system requirements. The theoretical ice-building cooling duty almost exactly matches that of the actual ice plant installation with a percentage error of 0.2%. Although the required dam capacity reveals a relatively high percentage error of 44.4%, this is of little concern as the required ice dam volume was greater than the minimum requirement of 4 500 m^3 . Lastly, the ice storage coils installed on Mine P have the capability of storing up to 900 tons of ice. Therefore, yielding a percentage error of 38.5% when compared to the theoretical requirements. Mine P's ITS installation was designed according to the operating conditions present in 2009. It was required to accommodate a mass flow rate of up to 950 l/s, therefore, requiring an approximate ice storage capacity of 900 tons. Since then, operating parameters have changed, justifying the high percentage error between theoretical and actual storage capacities.

To conclusively verify the developed methodology herein, the approach was reapplied utilising operating parameters present in 2009. In doing so, a theoretical ice storage capacity of 875 tons (874 607 kg) was derived, yielding a percentage error of just 3%. From this, and results depicted in Table 30, it can be concluded that the developed methodology and analytical approach in Chapter 2 is valid in accurately quantifying and predicting the feasibility of implementing ITS on mines.

Validating the simulation model

Table 31 illustrates the comparative results of the simulation and actual implementation data for baseline 1. The facets used to evaluate the accuracy of the ITS simulation model are: average system power consumption, load shift achieved, surface chill dam temperature, ice dam outlet temperature, ice building time and the duration of the ice melt. Identified facets compared in Table 31 were deemed sufficient to quantify the accuracy of the ice plant model between theoretical and actual implementation.

Ideally, more than a week's data is required for effective validation of the PTB simulation model, however, due to uncontrolled variables as mentioned in Section 3.5.2 and the inconsistency of comparable boundary conditions, a period of one week was deemed long enough to accurately validate the simulation model utilised to conduct this investigation.

Table 31: ITS simulation validation – operational impact of baseline 1

Description	Simulated			Actual implementation			Percentage error [%]
	Morning melt	Evening melt	Average	Morning melt	Evening melt	Average	
Average system power [kW]		5 695			5 667		0.5
Load shift [kW]	5.0	4.0	4.5	4.9	3.9	4.4	2.2
Chill dam temperature [°C]	3.2	3.5	2.8	2.3	2.6	2.9	3.5
Ice dam outlet temperature [°C]	3.9	4.1	4.0	4.6	5.1	4.9	22.5
Ice building time [hh:mm]	08:30	08:10	08:20	08:04	07:32	07:48	6.4
Duration of ice melt (including extended melt) [hh:mm]	02:30	02:10	02:20	02:50	02:30	02:40	14.3
Average percentage error							8.4

Based on average results, the simulation and actual implementation results attained an average error percent of approximately 8.4%. Discrepancies are largely attributed to assumptions made in the mathematical modelling of the ice plant model within PTB, and the control of the ice plant by mimic operators. The largest difference between results was attained for the ice dam outlet temperature, with an average temperature difference of 0.9 °C. Typically, ITS systems are installed with ice thickness sensors fitted on the coils such that the thickness of ice can be measured throughout the ice building and ice-melting processes. However, due to operator negligence and poor control and utilisation, the ice thickness sensors on Mine P's installation are no longer operational. Therefore, operators are required to conduct an extended ice melt for longer than typically required to ensure all ice remanence has been removed from the coils before restarting the ice-making process. This, in turn, increases the average water temperature leaving the ice dam. The ice building water temperature for the morning and evening ice melts between simulated and actual results revealed a difference of 2.4 °C and 1.7 °C respectively. Elevated ice dam water temperatures were experienced for the actual implementation results due to prolonged extended ice melts.

Since the duration of the extended ice melts were on average 15 – 20 minutes longer during actual implementation, the average surface chill dam temperature was also noted to be higher when compared to simulated results. An average discrepancy of 3.5% was recorded. Figure 45 illustrates a 24-hour profile of the simulated and actual surface chill dam temperatures.

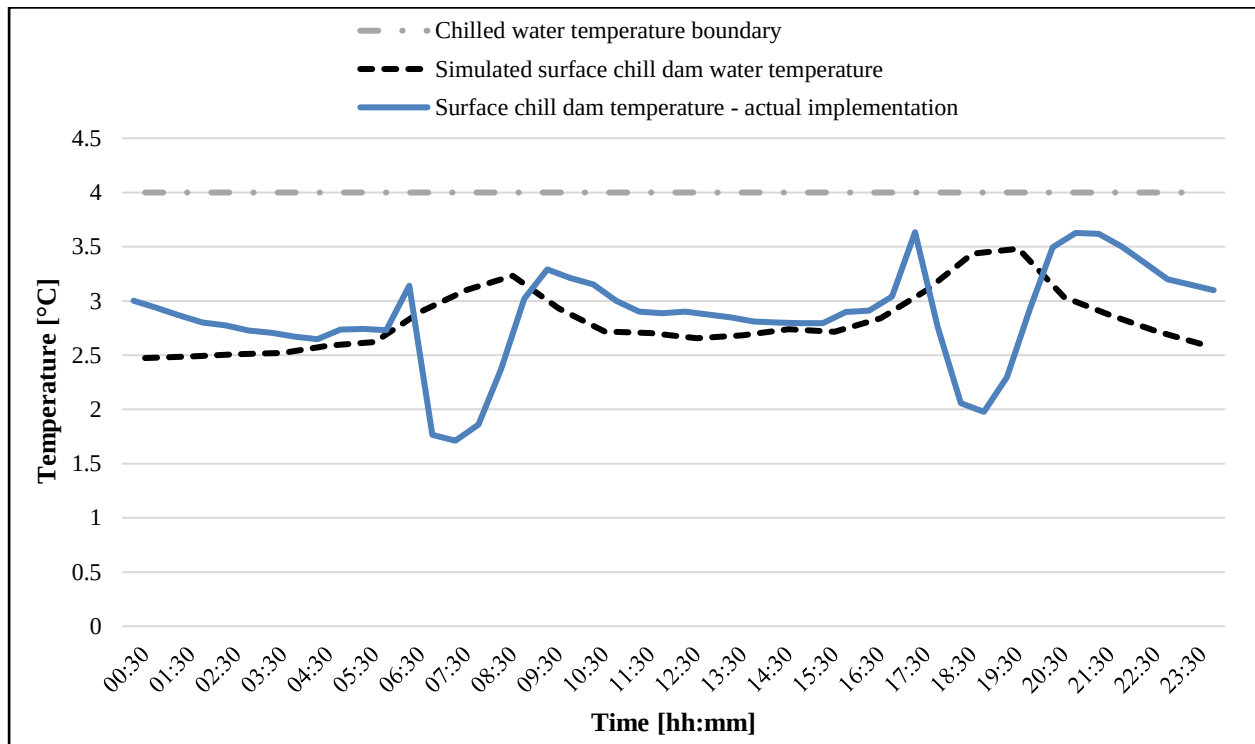


Figure 45: Surface chill dam temperature comparison

Upon initial observation of Figure 45, it is clear that there exists an inverse trend during both morning and evening ice melts. The simulated chill dam temperature increases during the ice-melting period, whereas actual implementation results reveal a decrease in chill dam temperatures. The reason for this is based on the simulation model assumption that 100% mixing occurs with no stratification between the warm inlet water from the pre-cooling sump and cold ice dam water. Based on this assumption, the simulation model attained a minimum ice dam outlet water temperature of 2.2 °C and 2.3 °C for the morning and evening ice melts. However, when compared to actual implementation results, a minimum outlet water temperature of 1.0 °C and 1.4 °C was realised. This implies that 100% mixing does not occur for Mine P's thermal storage installation. Reasons for this may be inadequate agitation resulting in stratification between cold ice dam water and incoming warm water from the pre-cooling sump.

A further discrepancy between the simulated and actual results is observed as the average temperature difference of the surface chill dam outside of peak periods. This is largely attributed to prolonged extended ice melts recorded during actual implementation, therefore, increasing the average temperature of the surface chill dam. In addition to this, the simulation model assumes 100% efficiency of chiller machines, whereas in practice, no chiller is 100% efficient. Cooling capacities are typically reduced based on the age and physical state of chiller components. Therefore, simulated outlet temperatures of chiller machines were lower than that during actual implementation. Based on system power consumption, simulation and actual results attained an average difference of 28 kW. PTB was, therefore, able to accurately simulate the power

response profile of Mine P's refrigeration system incorporating the ITS system with an error of 0.5%. The simulated and actual system's power consumption is compared and presented in Figure 46.

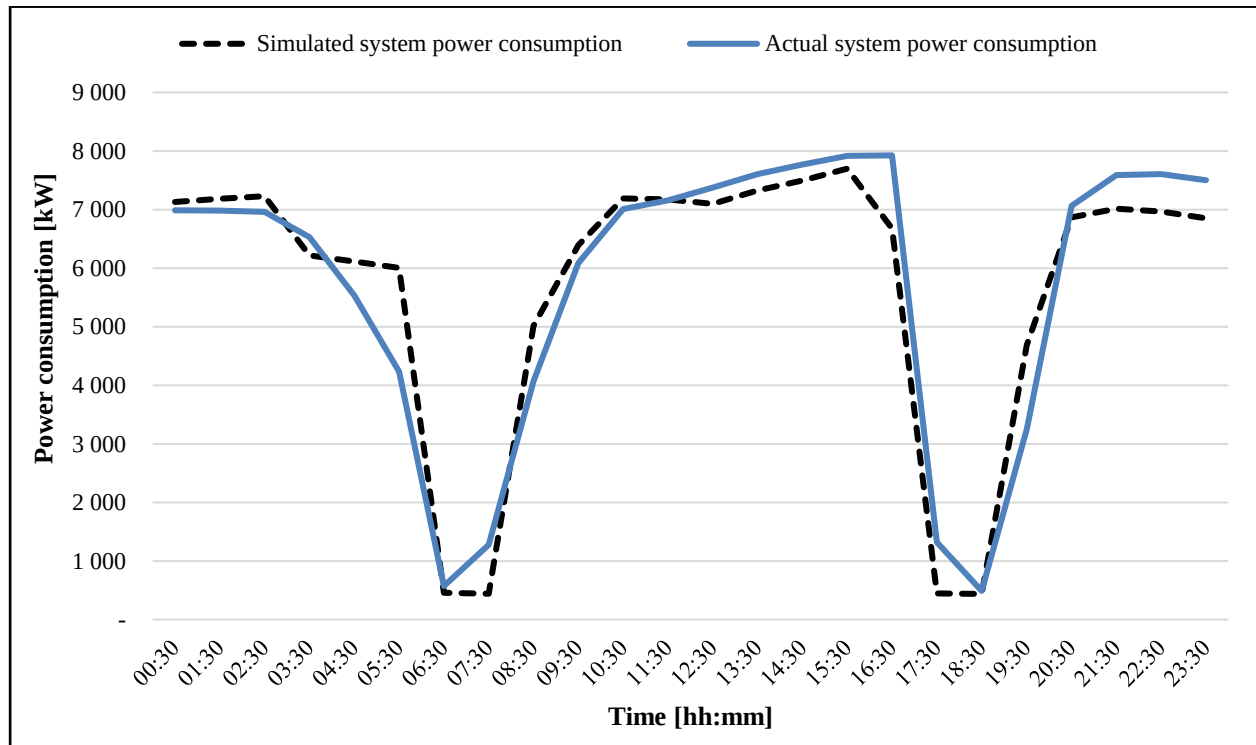


Figure 46: Overall system power consumption comparison

Comparing the ice building times between the simulation and actual implementation results, an average difference of 32 minutes was obtained. Through an iterative process, the simulated version of the ice plant was operated for longer until an acceptable outcome in terms of ice dam outlet water temperature was derived.

The most notable differences between the simulated and actual implementation results were attributed towards the assumptions utilised in the mathematical modelling of the ice plant model and inefficiencies in the actual ITS system, including operator control. Assumptions utilised in the simulation were based on a thermal storage system operating according to original design, therefore, remain valid. With an average percentage error of 8.4% between simulated and actual implementation results, the simulation model is valid in accurately emulating actual implementation conditions. To provide additional validation of the simulation model, the predicted load shift savings and annual cost-saving potential is compared to actual results. Table 32 provides a summary of simulated and actual implementation results. A total average percentage error of 4.5% was attained. Based on the holistic cost-saving potential, actual results reveal a percentage error of 6.7%, or R 319 749 less than that predicted from the simulation. Comparing simulated and actual implementation results for baseline period 2, it is clear Mine P opted for an evening ice melt rather than a morning melt. Although the simulation attained a 0.2 MW reduction in the average hourly

load shift, predicted cost savings were R 67 901 more than that achieved through actual implementation results. Therefore, in terms of maximising cost-saving potential, morning ice melts should be prioritised.

Table 32: ITS simulation validation - economic evaluation

Baseline	Comparative characteristics	Simulated	Actual implementation	Error [%]
1	Morning load shift [MW]	5.0	4.9	2.0
	Evening load shift [MW]	4.0	3.9	2.5
	Cost saving [R]	R 2 419 708	R 2 241 313	7.4
2	Morning load shift [MW]	10.8	-	1.9
	Evening load shift [MW]	-	11.0	
	Cost saving [R]	R 732 211	R 664 309	9.3
3	Morning load shift [MW]	7.8	7.6	2.6
	Evening load shift [MW]	7.6	7.7	1.3
	Cost saving [R]	R 891 630	R 837 468	6.1
4	Morning load shift [MW]	5.8	5.6	3.4
	Evening load shift [MW]	5.7	5.8	1.8
	Cost saving [R]	R 731 281	R 711 990	2.6
Holistic impact	Annual cost saving [R]	R 4 774 829	R 4 455 080	6.7
Total percentage error				4.5

The average percentage errors presented in Table 31 and Table 32 are both less than 10%, within the threshold limit of 90% and greater. Between the operational and economic evaluation, an overall average percentage error of 6.5% was attained. This implies that the simulation model developed in PTB, along with the methodology and analytical approach presented in Chapter 2 is considered feasible for accurately emulating the theoretical impact of ITS on deep-level gold mines.

3.6 Conclusion

The methodological approach developed in Chapter 2 was applied, tested and critically analysed through actual case study implementation. Improved implementation strategies and operation approaches were also introduced and discussed. The simulation software package, PTB, verified and validated the analytical approaches developed in setting up an accurate simulation model to predict the theoretical impact ITS has on a mine's cooling system. The actual and simulated profiles were compared, realising an overall average error of 6.5%. PTB accurately predicted the theoretical impact ITS has when implemented on a mine cooling system.

The performance results of ITS implemented as an alternative cost-saving strategy was critically analysed and evaluated through actual case study implementation. The results reveal lucrative cost-saving potential through the sustainable implementation and application of ITS.

Across the evaluated assessment periods, an average weekday morning and evening peak load-shift of 6.0 MW and 7.1 MW was attained. This equates to an accumulative electricity cost saving of approximately R 4.5 million per annum, providing the system is operated as per design. Through effective load management, the cost-saving potential of Mine P's ITS system was investigated to-date. In doing so, a realistic payback period of ITS implemented on deep-level mines could be derived. Since inception, an estimated cost-saving potential to-date of R 31 million was attained. Comparing estimated cost savings with the initial capital investment, a return on investment of 123 months (10.3 years) is feasible. The operational impact of ITS revealed an overall deterioration in service delivery requirements. Proceeding ITS installation, the holistic cooling systems performance, measured in terms of global COP, reduced by an average of 14.3%.

It was found that although ITS offers lucrative cost-saving potential, ice systems remain financially impractical for many deep-level gold mines in South Africa. Nonetheless, the successful operation and long-term sustainability of ITS within the mining industry ultimately relies on several governing factors.

- Mine personnel cooperation to ensure scheduled maintenance is conducted on a regular basis.
- Operator control, utilisation and system understanding. Operator competence plays an integral role in the operation, performance and sustainability of ITS.
- Constant monitoring of KPIs and process parameters to ensure service delivery requirements and the integrity of system components are not compromised.
- Optimised system design. It is imperative that the ITS system is optimally designed according to mine cooling system requirements and specifications. Systems with a poor design will result in the inability to achieve expected cost-saving potential, compromise service delivery requirements beyond specified limitations and experience periodic operational issues and flaws, leading to project deterioration and ultimate decommissioning.

Considering the challenges faced by the South African mining industry and resultant decrease in profit margins, ITS does not pose a realistic solution for mining operations with a life of mine less than 10 years. However, future ITS installations in South Africa may prove to be more feasible, depending on the following external factors:

- Further hikes in peak electricity tariff rates as imposed by Eskom.
- Reintroduction of the DSM model.
- ITS equipment becomes more affordable over time.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS



10

This chapter summarises the findings of the study held herein. Recommendations and limitations of this research are additionally provided to assist with future studies on the use of ice as a form of thermal storage within the mining sector.

¹⁰ <https://www.planetkb.co.za/cmsAdmin/uploads/twin-boom-drill-underground-trackless-mining-machinery.jpg>

4.1 Conclusion

In recent years, the mining industry has been faced with several challenges that have contributed towards dwindling profit margins across many South African mines. One of the most significant contributing factors has been attributed to ever-increasing operating costs, primarily resulting from escalating prices in electricity. The impact of ever-increasing electricity tariffs has geared up for the development of innovative technologies and strategies capable of reducing a mine's operating costs, increase production and maximise profitability. Mine refrigeration systems have been recognised as one of the most energy-intensive consumers on a deep-level gold mine, accounting for approximately 24% of the total electrical energy consumption. Therefore, host significant cost-saving potential.

Implementation of load management initiatives on mine refrigeration systems have been well documented. These initiatives have reduced operating costs through peak time-of-use electrical demand reductions, however, with varying success. Factors such as thermal storage capacity, installed refrigeration capacity, service delivery requirements and complex system configurations contribute to restrictions in load management potential and project underperformance. Despite the widespread utilisation and implementation of load management strategies, the profitability and sustainability of deep-level gold mining in South Africa remains under threat. To alleviate financial strain prompted by ever-increasing electricity tariff rates, a need was identified to implement more effective load management strategies and techniques, capable of maximising cost-saving potential. ITS has the potential to make up the shortfall. ITS systems represent a relatively new technology utilised on mines and as a result, studies are limited.

In buildings, recent research suggests ITS systems have proven hugely instrumental in successfully achieving lucrative cost savings. Considering mine refrigeration systems are generally extremely energy-intensive, ITS possesses the capability to reap similar benefits. Therefore, the aim of this research is to extend the knowledge in the field of ice based thermal storage, contributing to the development and wider utilisation of such systems in the mining industry. By virtue of the first study objective, this was achieved by developing a generic methodology that can be utilised to evaluate and sustainably implement ITS as an alternative cost-saving technique within the mining industry through effective load management. The methodological approach was divided into four separate, step-by-step sections. Steps 1 to 3 provide a systematic approach that can be utilised to evaluate, assess and quantify the holistic impact of ITS on deep-level mines. Through application of a simulation strategy incorporating analytical approaches, an initial feasibility analysis was incorporated to predict system behaviour and determine project feasibility without capital expenditure. Step 4 introduces improved implementation strategies and operation approaches focusing on the sustainable implementation of ITS within the mining industry. This will assist in mitigating future ITS systems from experiencing similar inefficiencies in terms of control, utilisation and design as identified in previous studies. In the absence of optimal system control, utilisation and design, the ITS

system will not operate as initially intended, compromising the long-term sustainability and cost-saving potential of the system.

To quantify ITS implementation within the mining industry, Mine P, one of the only mines in South Africa employing ITS, was identified as a suitable case study. Due to extended periods of downtime throughout the 2018/2019 financial year, Mine P's ITS system afforded a unique opportunity for this study to analyse the operational and financial impact of the holistic cooling system, with and without the use of ITS. Through case study implementation, the analytical approaches in constructing an accurate predictive simulation model on the use of ITS on mines was verified and validated. Verification and validation by virtue of case study implementation affords other mining operations the opportunity to apply a similar approach to predict mine specific feasibility without capital expenditure. Validation results revealed an average percentage error of 6.5%.

Actual implementation results with and without the use of ITS were critically analysed and evaluated to determine both the operational and economic impact ITS has on Mine P's cooling system. A holistic approach was adopted to accurately quantify the financial impact and benefits gained by incorporating ITS on a mine cooling system. Implementation results achieved an average weekday morning and evening peak load shift of 6.0 MW and 7.1 MW respectively. This equates to an annual electricity cost saving of R 4.5 million. Comparing expected cost savings realised since inception to that of the initial capital investment, a return on investment of 123 months or 10.3 years was approximated for Mine P's ITS system. A reduction of R 502 per megalitre of water cooled was revealed when comparing a conventional refrigeration system to that incorporating the use of ITS. In addition, an average decrease of 42 kWh per megalitre of water cooled was realised. These findings suggest that, in addition to lucrative cost-saving potential, ITS revealed a reduction in the daily energy usage of Mine P's refrigeration system. This implies the energy shifted outside of peak periods was greater than that required to charge the ice dam.

To quantify the holistic operational impact, various performance related KPIs were monitored and evaluated. During peak periods, compared to normal operating conditions, an improvement in chilled water temperatures was realised. However, based on the overall average impact, due to the control and operation of the system, service delivery requirements were consequently compromised, with an overall deterioration of 7.1% across the evaluated assessment periods. Analysing the performance of the holistic cooling system represented by the global systems coefficient of performance, a reduction of 14.3% was revealed.

Based on the results obtained throughout this study, it is clear that ITS systems implemented within the mining industry are expensive with an unfavourable payback period. Since the majority of deep-level gold mines across South Africa are suffering with dwindling profit margins, ITS does not pose as a feasible cost-saving strategy for many mining operations. Be that as it may, ITS systems should still be considered for implementation on profitable mines with a life of mine greater than approximately 10

years. Not only does ITS offer significant cost-saving potential, the successful implementation of ITS within the mining industry has the ability to reduce mine operating costs, improve profit margins, contribute to a stable reserve margin in the power supply and, allow for expansion with an increase in the overall cooling capacity of the refrigeration system. By quantifying the holistic impact and analysing the benefits gained from the implementation of ITS systems within the mining industry, the second study objective was achieved.

Innovation is key to the future of deep-level mining operations across South Africa. New ways to improve the profitability of deep-level mines are vital to ensure the long-term sustainability of the mining industry and indeed the economy in South Africa. ITS has the potential to make up the shortfall. However, if not designed, implemented or operated correctly, ITS may not provide expected load shifts or cost savings.

4.2 Recommendations for future work

Although there exists significant research on the use of thermal energy storage systems in the building industry, limited research is available for application within the mining industry. By conducting additional investigations within the mining industry, further understanding on the feasibility, overall success and general applicability can be derived. To add to the field of research on the use of ITS on deep-level mines, recommendations for future work are provided.

- Based on Mine P's ITS installation, monitoring and control of system performance seems to be particularly problematic. It presents a significant issue in the successful use and application of the system. To exploit the full potential of ice utilised as the storage medium in thermal energy storage systems, an adequate solution is required.
- Optimisation of dam geometry and design to maximise the efficiency of both the ice-building and ice-melting processes. In addition, the flow of water through the dam plays an integral role in the thermodynamic performance of the system. To ensure uniform heat transfer throughout the charging and discharging processes, flow patterns should also be considered and investigated.
- With the ever-increasing prices of electricity in South Africa, further investigations will be required on the applicability of ITS systems utilised as partial storage. By charging the system during the less expensive, off-peak ToU tariff periods, stored energy can be released slowly over a longer period of time during peak and standard rate tariff periods. Since partial storage systems are significantly cheaper than that required for demand limiting, partial storage systems, designed to meet only a portion of the load may prove to be more applicable and beneficial for application in the mining industry. Cost-saving potential vs return on investment will need to be investigated and compared. Erdemir and Altuntop (2017) investigated the effect ITS has on the cost of cooling in a hypermarket [122]. It was concluded that 10% partial storage attained the lowest profit at the end

of a 10-year period, however, resulted in the shortest return on investment. Due to dwindling profit margins of deep-level gold mines, partial storage systems may prove the most viable.

- Through literature, based on typical operational requirements of deep-level gold mines, it was determined that encapsulated ice and external melt ice-on-coil systems were the most applicable for successful application in the mining industry. An investigation into the possibility of using encapsulated ice as an alternative, possibly more effective solution should be explored.
- To add to the field of research on the use and applicability of ITS within the mining industry, additional investigations should be conducted through underground installations. Through underground installation, various additional benefits may be realised, one of which is in the fact that it will be closer to the point of use. However, as with underground chiller installations, heat rejection capabilities of the condensers will be limited.
- The load on the ITS system can be reduced by turning off the BAC fans and associated pumping auxiliaries during the ice-melting process. By turning off the BACs, water flow requirements through the ice dam are reduced, subsequently increasing the length of the ice melt. An additional investigation should be conducted to determine the feasibility of turning off the BACs solely during the ice melting process with regards to service delivery requirements, improved cost-saving potential, additional maintenance considerations and control requirements.
- ITS is most definitely a technology that should be investigated on other deep-level mines around the world. With Australian mines looking to dig deeper in the near future, they have made a point to using lessons learned in South African deep-level mines to investigate appropriate cooling strategies and methods [29]. Therefore, dependent on the imposed electricity tariff rate structure in Australia, ITS remains an innovative technology and concept that could be utilised to keep monthly cooling costs to a minimum. Additional investigations will, however, be required to determine the economic feasibility and quantify the operational impact on installed system components and service delivery requirements.
- With platinum mines hosting similar operations to that of gold mines, it is worthwhile to investigate the cost-saving potential and feasibility of ITS systems on platinum mine cooling systems.
- The study conducted herein focuses on the feasibility of implementing ITS within the mining industry based on case study results. The feasibility study on Mine P calculates the payback period of the ITS system taking into account cost-savings achieved since project inception in 2009. Therefore, it will be worthwhile to investigate current capital expenditure requirements, considering that over time ITS equipment may have become more affordable.
- Based on the substantial savings capabilities and benefits of ITS implemented within the mining industry, it would be worthwhile to investigate alternative technologies that can deliver similar results as ITS, yielding a cheaper and more sustainable solution.

- An additional area of study would be to investigate the number of mines across South Africa (both gold and platinum) that realistically qualify for the installation of ITS systems. As mentioned within this dissertation, realistic case studies are represented by the following categories; mining operations with a life of mine greater than 10 years, deep and vast underground mining networks and, the extensive use of energy intensive chillers for underground cooling.

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APPENDICES

Appendix A: Additional literature

A1: Eskom's energy availability

Figure 47 illustrates Eskom's energy availability between 2016 to 2018, including the first 12 weeks of 2019. The energy availability factor is a measure of the plant availability incorporating energy losses. The factor represents a ratio of the available energy generation to the reference energy generation.

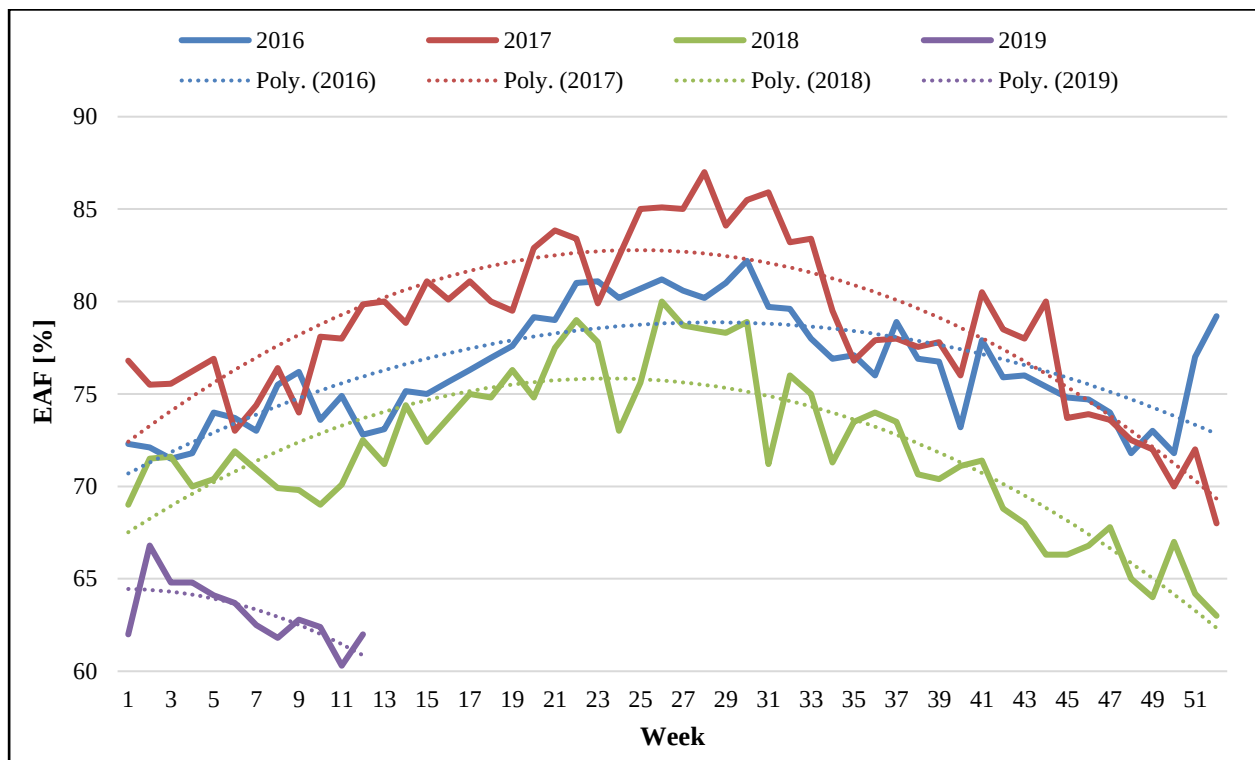


Figure 47: Eskom's week-on-week energy availability [137]

A2: Background on mine cooling systems

Heat rejection systems

Heat rejection systems are used extensively in mining operations to provide artificial cooling. They are particularly advantageous in that, not only do they provide additional low-cost cooling capacity, but they reduce the required capacity and operational costs of energy-intensive chillers.

Within mine cooling systems, there exists two common applications in which heat rejection systems are utilised: pre-cooling towers, used to cool water received from underground before entering the evaporator

flow circuit to the chillers, and condenser towers used to cool water circulated through the condensers. Thermal energy in the form of heat is transferred from the water to the ambient air by a combination of convection and evaporation [138]. According to ASHRAE (1997), as cited by Uys (2014), heat rejection systems have the ability to cool the water to within 3°C and 6°C of the WB ambient air temperature [109].

Figure 48 illustrates the most common variety of cooling tower utilised for mining applications, a vertical counter-flow forced draught cooling tower. In a direct heat exchange process, hot water is dispersed into the cooling tower via spray nozzles. The descending water droplets move in a counter-flow direction to the ascending, cooler ambient airstream. The airstream is forced upwards by a mechanically driven axial fan located at the summit of the cooling tower. The water and air subsequently mix over the packing material which will see to maximise both the time and area of contact, therefore, resulting in a higher thermal performance [139]. Thereafter, the cooled water is temporarily stored in the cooling tower sump before being pumped to the evaporator or condenser flow circuit. Figure 48 illustrates an example of a vertical counter-flow forced draught cooling tower most commonly found in mining applications.

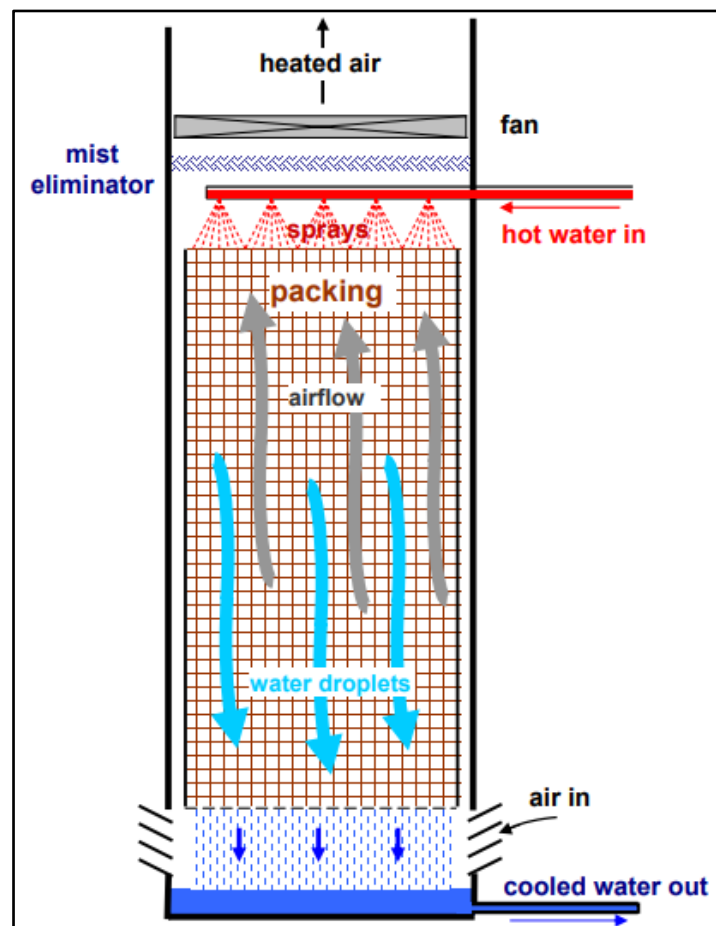


Figure 48: Vertical forced draught cooling tower [138]

When operating efficiently, cooling towers are capable of high COP values of approximately 30 [60]. An efficient cooling tower is one in which there is a very small difference between the inlet air temperature

and outlet water temperature. Regular maintenance on cooling towers is imperative to ensure optimal heat transfer performance. To prevent scaling caused by the build-up in the concentration of dissolved solids and impurities, the water quality should be monitored regularly and replaced by clean water if required [138]. In addition to scaling, cooling towers are also susceptible to fouling by dust or contamination build-up [140]. The effectiveness and thermal capability of cooling towers is dependent on the following factors: difference between the inlet water temperature and ambient air wet-bulb temperature, air mass flow rate, water mass flow rate, psychometric condition of the inlet air and the contact time between the air and water [138][141]. The design of the heat exchanger will determine the latter.

Factors that have an influence on the contact time is the relative velocity between water and air droplets, and the size and concentration of water droplets. The concentration and size of water droplets is governed by the arrangement of spray nozzles, delivery pressure and flow rate of water supply as well as the presence of packing [138]. The higher the concentration and larger the size of water droplets ultimately results in increased heat transfer due to an increase in the overall surface area through which heat transfer can take place.

To improve the performance of pre-cooling towers, the following techniques should be considered [127]:

- Conduct frequent maintenance on the fill and spray nozzles as well as the fans. Measure the air flow through the fans to ensure maximum heat transfer capabilities are realised.
- Ensure the towers are supplied with an adequate amount of water flow at all times to prevent sediment build-up within the towers.
- If VSDs are installed on the pre-cooling pumps to control the flow of water, ensure the operation of the pumps is not compromised and that the original control philosophy is still valid. Ensure ample connection between SCADA and VSDs.
- Since faulty field instrumentation is not an uncommon occurrence on mines, ensure all sensors still display accurate information and are recalibrated regularly.

Ensure the flow through the tower is evenly distributed throughout the tower to prevent scaling and fouling of the tower fill. Due to insufficient flow, solid particles have been known to attach to the tower structure and surface of the fill, therefore, subsequently penalising the overall effectiveness of the system

Bulk Air coolers

The cooling of underground mining networks is primarily performed by centralised BAC units, also known as heat absorption systems or chilled water spray chambers [28]. As with cooling towers, BACs are categorised as direct heat exchangers. Although BACs operate in a similar fashion to cooling towers, heat transfer occurs in the opposite direction. This implies that instead of using ambient air to cool hot water,

chilled water (typically supplied by chillers) is used to cool ambient air to a lower WB temperature. Heat transfer is induced by a combination of convection and condensation [138]. Using mechanically driven axial fans ambient air is drawn in and dispersed within the BAC unit. Spray nozzles supplying chilled water from the chiller provides the medium for heat transfer. Once the air has been cooled it passes through a mist eliminator filter to remove water droplets, therefore, resulting in cool dehumidified air being sent underground. Downward pressure energy (inadvertently created by main ventilation fans extracting warm return air from underground) directs the cool air mixture into shaft ducting, transporting it throughout underground mining networks. Horizontal BAC units are usually preferred for underground applications. This is largely due to convenience, as existing haulages will not require additional excavation. An example of a horizontal draft BAC unit is illustrated in Figure 49. To ensure more efficient cooling, horizontal BAC units typically consist of more than one cooling stage [138]. In multistage BACs, chilled water supplied in the first stage is recycled in the next, and so on.

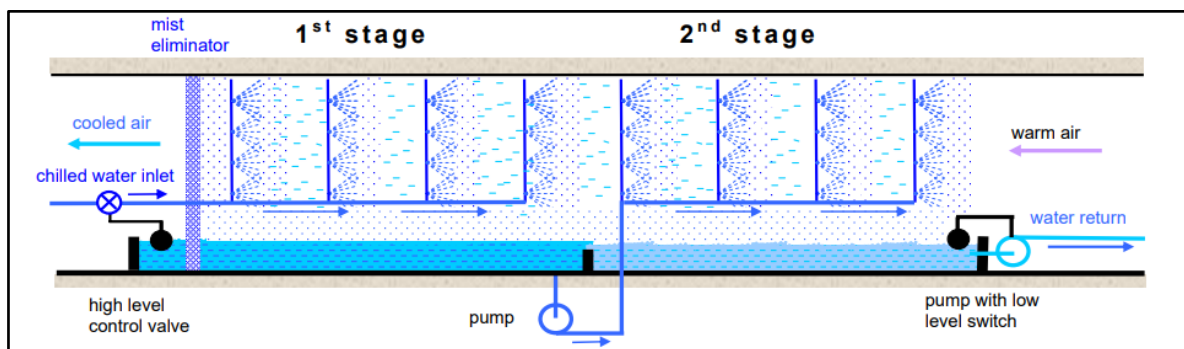


Figure 49: Multi-stage horizontal forced draft BAC [138]

Horizontal draft BACs operate according to the same principle as vertical designs. Ambient air is drawn in and subsequently dispersed within the BAC unit. Thereafter, the air passes through each cooling stage before entering the mist eliminator filter, resulting in dehumidified air. Spray nozzles may be located against oncoming airflow or alternatively across, perpendicular to the airflow. To ensure optimal performance, it is imperative that both the water spray and airflow is uniformly distributed across the cross-section [138]. Water used in the BAC collects in the BAC sumps before being transported elsewhere by return water pumps. As with cooling towers, internal packing is usually installed to increase the efficiency of horizontal sprat chambers.

BAC units can either be installed on surface and/or underground. Underground BAC installations are generally required when surface BAC units can no longer cool haulage and/or rock faces to within acceptable parameters [142]. In general, chilled water supplied to the BACs should be as low as possible, but not higher than 12°C [138]. This ensures the difference in temperature between ambient air and chilled water is as large as possible, therefore, significantly increasing the coefficient of performance (COP) of the cooling system [139]. Regular maintenance is required in order to prevent ineffective and inefficient BAC

performance. Scheduled maintenance typically takes place during winter months when BACs are not required due to a significant drop in ambient air temperatures [60]. Inefficient BACs and cooling towers possess the ability to increase the water circulation temperature throughout the system, therefore affecting the cooling range of the chillers.

Chillers

To ensure the provision of acceptable underground working conditions refrigeration plants or chillers are a necessity. Depending on the specific requirements of the mine, chillers are used to provide chilled water between 1.5°C and 6°C to underground end-users [30]. Mines make use of both surface and underground chillers to cool mine service water and provide cold air to working sections.

Due to the presence of significant thermal loads at increased mining depths, mine cooling systems typically consist of more than one chiller. As illustrated in Figure 50, chillers may be arranged in three different configurations depending on the required outlet water temperature and flow requirements. The three configuration types are as follows: a parallel configuration which is used for varying flow requirements, a series configuration, used for variations in temperature, and a series-parallel configuration or cascaded configuration which can be utilised for both variable flow and temperature requirements [143].

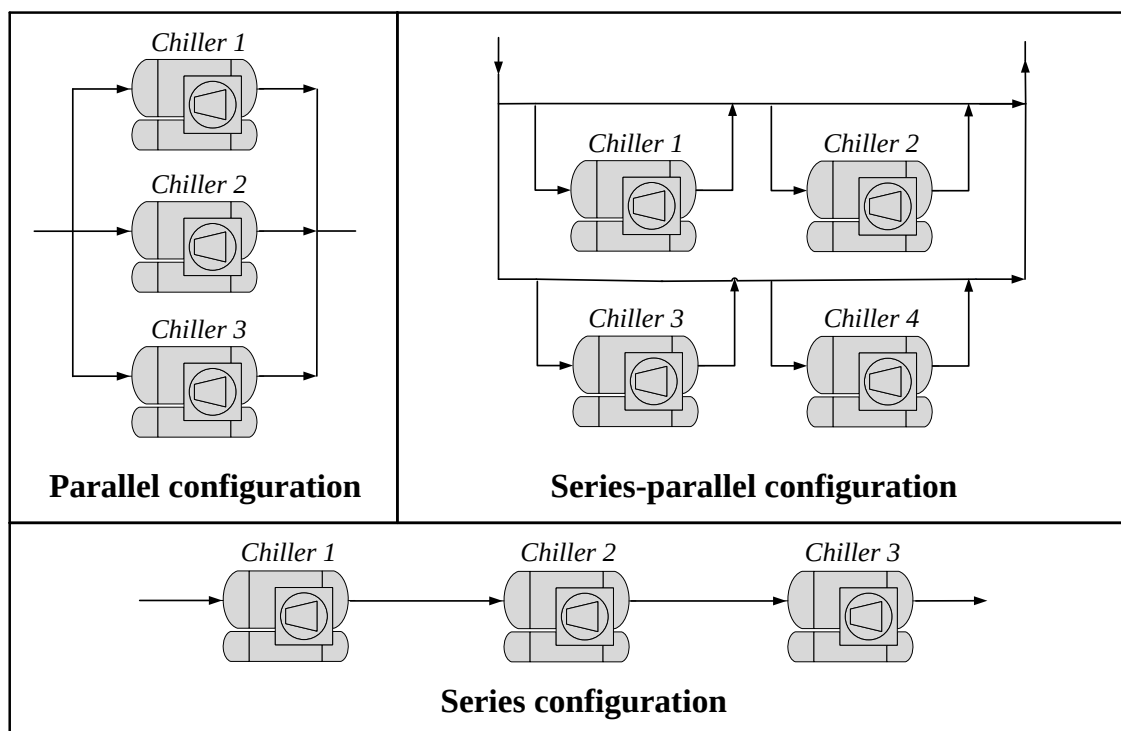


Figure 50: Various chiller configurations used in industry (adapted from [28])

Mine chillers typically make use of shell-and-tube, or plate heat exchangers in conjunction with centrifugal or screw compressors. The most common refrigeration cycles used in industry are the ammonia-absorption

and the vapour-compression cycles. Within the mining industry, the majority of mine chillers make use of the vapour-compression cycle [138]. Vapour-compression cycles offer simplicity, low operational costs and low maintenance considerations. Unlike the ammonia-absorption cycle, vapour-compression cycles are often preferred because the working fluid is not toxic and does not pose significant dangers to the environment and human health in the event of a spillage or leakage [71]. However, with this being said, due to ammonia vaporisation properties, ammonia has the ability to absorb a substantial amount of heat from the surroundings.

To regulate the refrigerant flow rate and subsequent cooling load, guide vanes or slide valves are utilised [144]. The temperature of the evaporator liquid generally governs the position of the guide vanes or slide valves, therefore, varying the cooling load. As the temperature of the evaporator liquid increases, the angles of the guide vanes or slide valves increase (between 0° and 90°), therefore, increasing the refrigerant flow rate and head pressure through the compressor. As the flow rate of the refrigerant increases around the chiller, the ability of the evaporator to absorb more heat increases. Conversely, if the evaporator liquid temperature decreases, the angle of the guide vanes or slide valves will reduce, therefore, decreasing the refrigerant flow and head pressure through the compressor. With a reduction in refrigerant, the evaporator cannot absorb as much heat, therefore, increasing the outlet water or air temperature.

The COP provides for a measurable parameter that can be utilised to quantify the efficiency of a chiller. The COP of a chiller represents the ratio between the electrical energy input and thermal energy output. This implies that cooling load variations and compressor power consumption directly affect a chillers' COP. The COP of vapour-compression and ammonia-absorption refrigeration units can be calculated using Equation 14 and Equation 2. To determine the thermal energy absorbed by the evaporator, Equation 16 is applied.

Equation 14: Coefficient of performance of vapour-compression refrigeration cycles [81]

$COP = \frac{\dot{Q}_{evaporator}}{W_c}$	[–]
Where:	
$COP = \text{coefficient of performance of chiller}$	[–]
$\dot{Q}_{evaporator} = \text{thermal load absorbed in the evaporator}$	[kW]
$W_c = \text{compressor electrical power}$	[kW]

Equation 15: Coefficient of performance of ammonia-absorption refrigeration cycles [81][145]

$$COP = \frac{\dot{Q}_{evaporator}}{W_{in}} = \frac{\dot{Q}_{evaporator}}{W_p + \dot{Q}_g} \quad [-]$$

Where:

W_{in} = total electrical power consumed by pump and generator [kW]

W_p = pump electrical power [kW]

$\dot{Q}_g$ = thermal load supplied by the generator [kW]

Equation 16: Thermal energy absorbed in the evaporator

$$\dot{Q}_{evaporator} = \dot{m}_w C_p (T_{w,o} - T_{w,i}) \quad [kW]$$

Where:

$\dot{Q}_{evaporator}$ = thermal load absorbed in the evaporator [kW]

$\dot{m}$ = mass flow rate of water [kg/s]

$C_{p,w}$ = specific heat constant [kJ/kg.K]

$T_{w,i}$ = inlet water temperature to evaporator [K]

$T_{w,o}$ = Outlet water temperature from evaporator [K]

From Equation 14, Equation 2 and Equation 16 it is clear that changes in evaporator temperature and flow rate will affect the cooling load and subsequently the COP of the chiller. The COP of a chiller increases as a result of lower evaporator flow rates and decreases at lower condenser flow rates [146]. Therefore, lower evaporator flow rates are preferred. A COP value of between 6 and 6.5 indicates an energy-efficient chiller, whereas a chiller with a COP of less than 3 is deemed inefficient [81]. The COP of a chiller can be optimised by reducing the power input whilst maintaining the desired cooling effect. Guide vanes or slide valves used to regulate the refrigerant flow through the compressor provide scope through which the compressor power consumption can be optimised and reduced.

Pumps

In deep-level mining operations, pumps are widely utilised and form an integral part of a mine's water reticulation network. A mine's water reticulation system typically involves two integrated processes; mine cooling and dewatering. Pumps involved in the cooling process, termed auxiliary pumps, supply various

system components such as cooling towers, BACs, condensers and evaporators with service water. Depending on delivery requirements, these pumps generally range between 15 kW and 250 kW respectively [94]. Although auxiliary pumps are directly involved in the mine cooling system, they are controlled independently and operate separately to that of the chillers [60].

Compared to pumps utilised on surface, dewatering pumps typically located underground are extremely energy-intensive, consuming anything up to 4 MW of electricity, dependant on dewatering and pumping head requirements [94]. The control and utilisation of these dewatering pumps vary depending on the thermal storage capacity and the required cooling demand. Control philosophies are often implemented to ensure sufficient thermal storage for daily load shifts.

When considering the implementation of new optimisation strategies on a mine cooling system, several factors concerning the mine's water reticulation and dewatering systems must be considered. These factors are as follows [147]:

- Required water volumes to be sent underground for various mining operations
- Dam capacities including limitations and constraints
- Number of pumps and location
- Amount of water to be pumped

Thermal storage dams

Hot and cold water dams are required in mine cooling systems to provide thermal storage capacity for chilled water on surface and underground, as well as for return water, dewatered from underground [138]. Additional storage capacity provides the mine with flexibility to cope with variations in chilled water usage and return water pumped from underground to surface. The success of load-shifting initiatives rely heavily on the overall water storage capacity of a mine.

Fluctuations in the demand for chilled water not only occurs on a daily basis but will also occur based on seasonal effects. This in turn dictates the number of chillers required to provide sufficient cooling [82]. To ensure service delivery requirements are met, the chillers are required to supply and maintain set chilled dam water temperatures throughout the day [49]. The volatility in the demand for chilled water makes it challenging to meet such requirements.

Once the chilled water storage dam level approaches maximum capacity, pumps are required to reticulate excess water directly to the pre-cooling dam or alternatively increase the flow of water through the BACs (if possible). In some scenarios, mines have been known to throttle valves based on specified chilled water dam levels to prevent unnecessary cooling. This process is, however, very inefficient [148]. Variable flow control strategies would provide for a more favourable solution [149].

Energy recovery devices

Figure 51 illustrates the full working of a 3CPFS. The 3CPFS uses the cold water sent down the mine from the higher storage dam (illustrated in blue) to “pump” the hot water (illustrated in red) out of the mine. The first step of the process is filling the chamber with the hot water that needs to be pumped. This can be seen in the bottom chamber C in Figure 51.

The pressure is then equalised using a smaller cold-water feed pipe with a control valve, as can be seen in chamber B in Figure 51. This step is included to avoid water hammering. Lastly the hot water is driven out by cold water using the pressure built up in the water column as illustrated in chamber A. By alternating this process between the three chambers, a constant flow of hot water out of the mine can be achieved.

Precise valve control and timing is required to ensure the 3CPFS operates as it should. The control of the valves is done by PLCs provided by the manufacturer of the system. In addition to the valves, auxiliary pumps (booster and filler pumps) are required to drive the 3CPFS. These pumps typically have VSDs installed to ensure that a constant flow can be delivered when system variables such as downstream pipe pressure and dam levels vary. The functions of the 3CPFS booster and filler pumps will now be explained.

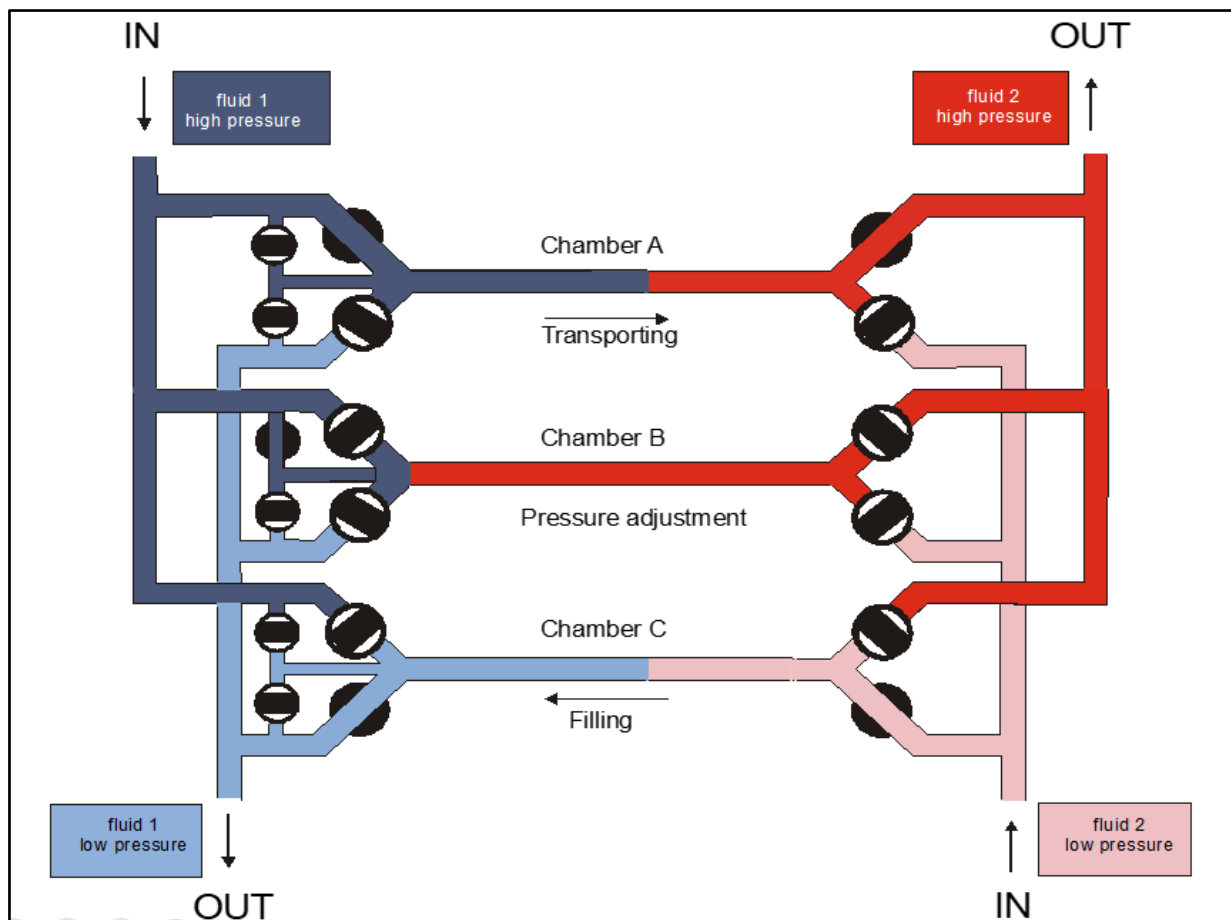


Figure 51: Schematic of a 3CPFS [150]

3CPFS Booster pumps

Booster pumps installed on surface feed chilled water to the 3CPFS underground. The chilled water forces warm water out of the 3CPFS chambers into a hot water column which conveys the water to surface. On surface the hot water is discharged into pre-cooling towers. The booster pumps are required to produce a constant flow with sufficient pressure to overcome system resistances and conditions resulting from pipe friction, pressure losses through the 3CPFS and a change in the water level in the suction dam [150]. The pumps all deliver into a common manifold and supply two operating 3CPFS units. The flow through the units must remain constant at the selected flow set-point for each unit.

3CPFS Filler pumps

These pumps are installed to fill the 3CPFS with warm water and in doing so, to discharge chilled water into the cold-water dam. The pumps are supplied with warm water from a water storage dam. The warm water forces cold water already in the 3CPFS out of the unit and into the cold-water storage dam.

The operation of the 3CPFS results in a steady flow through the piping system by directing flow through each of the three legs in turn. The filling pumps are required to produce a constant flow with sufficient pressure to overcome system resistances and conditions resulting from pipe friction, pressure losses through the 3CPFS and a change in the water level in the suction dam. As with the booster pumps, the filler pumps also deliver into a common manifold. The flow through the units must remain constant at the selected flow set-point for each unit. As with the valve control, the control of the auxiliary pumps is executed by the PLCs that were provided by the manufacturer.

The focus of implementing such technology is to reduce the average load of the dewatering pumping system during the day by improving the efficiency of the pumping system with the 3CPFS. In a study conducted to determine the overall effectiveness of a 3CPFS, calculations revealed that a 3CPFS consumed as little as 12% of the energy consumed by conventional pumping methods per litre of water pumped [150].

A3: Load management strategies: Back-pass valves

Figure 52 displays the typical layout and operation of an existing load management strategy implementing a back-pass valve to enable the provision of peak ToU load shifts.

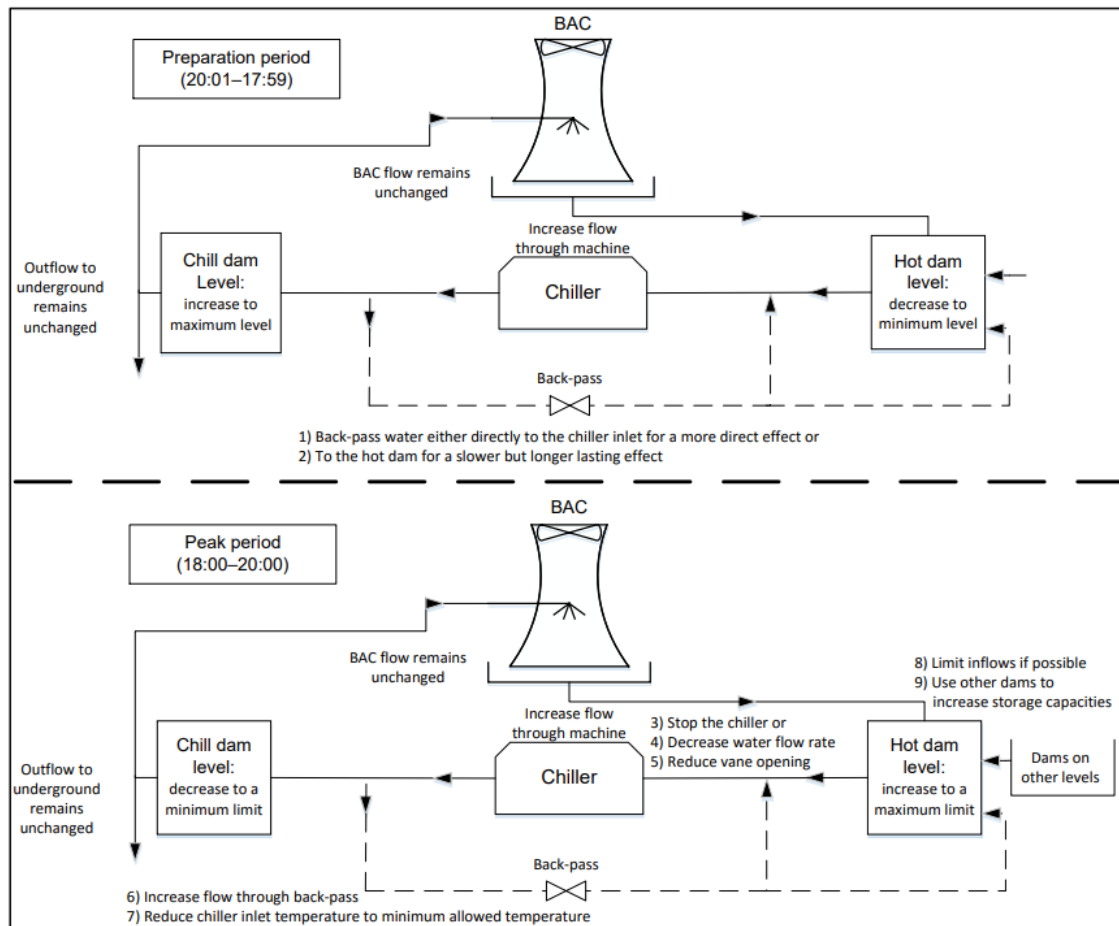


Figure 52: Schematic overview of a back-pass valve control [72][77]

A4: Ice thermal storage: External melt ice-on-coil

Figure 53 displays the general layout of the external melt ice-on-coil system components. The numerical annotations depicted in Figure 53 represent the following components and particulars [135]:

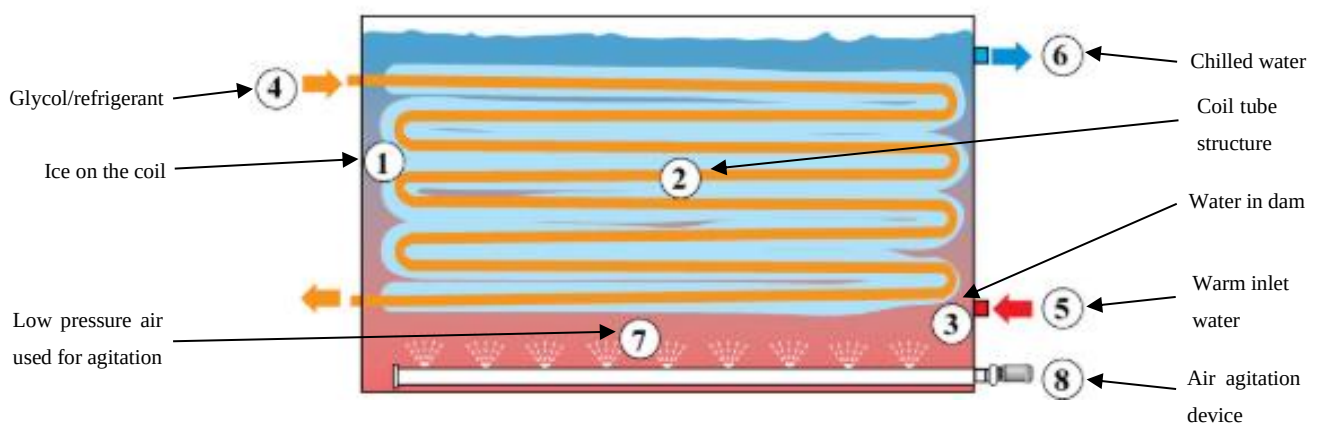


Figure 53: External melt ice-on-coil operation [135]

A5: Previous studies conducted on ice thermal storage systems on buildings

Lemort (2006), Commercial building, Belgium [118]:

An investigation was conducted on an ice storage installation consisting of four horizontal encapsulated ice storage tanks, organised in a parallel-series configuration. The success of three different charging-discharging control strategies applied to the existing ice storage system was analysed. Operational costs and the energy consumption of each strategy was compared. The three different control strategies formulated during the study are as follows:

- Chiller-priority control: This strategy ensured the chillers operated at maximum capacity during peak hours, with additional cooling requirements supplied by the ice storage tank. The control proved to be advantageous in that the chillers operate at constant capacity, eliminating constant ramping up and down of the guide vanes, adding additional stress on the compressor motor [118]. However, proceeding the peak period it was identified that there was still ice present within the storage tank. This implies that the control is not optimal.
- Constant-proportion control: This strategy dictates that during peak hours, a constant proportion of the buildings cooling load is supplied by the ice storage system. A limitation of this control was however premature depletion of the stored ice.
- Load-limiting control: In the final strategy, the aim was to limit the chiller load with the remaining cooling load supplied by the ice storage tanks.

Proceeding the investigation, it was determined that the introduction of an ice storage system provides significant cost-saving opportunities through optimised load-shifting strategies. However, in all scenarios, an overall increase in the energy consumption of the setup was noticed. Operational costs were only reduced when the ice storage tanks were fully discharged after being fully charged. Lemort concluded that energy savings can only be achieved by decreasing the size of auxiliary components. It was found that when an ITS system is integrated into a refrigeration system, the thermal efficiency of the chillers decrease [118].

Chaichana, Charters and Aye (2001), Commercial and industrial buildings, Thailand [119]:

Due to high ambient temperatures experienced in countries such as Thailand, air conditioning plants have been installed in the majority of commercial and industrial buildings. Although conventional air conditioning units are already installed, ice thermal storage systems have become an attractive financial proposition in large scale buildings [119].

The investigation conducted by Chaichana, Charters and Aye (2001) made use of a simulation model to compare the energy usage of conventional air conditioning units to that of ice storage systems. Full storage and partial storage conditions were analysed based on an ice-on-coil thermal storage setup. Due to variable

electricity tariff rates imposed in Thailand, both full storage and partial storage techniques realised financial savings. A 55% energy cost reduction using the full storage technique and 15% reduction using the partial storage technique was achieved. In addition, as a result of lower ambient temperatures typically experienced at night, the full storage technique has the ability to reduce the overall energy consumption by 5% [119]. Furthermore, the COP of the refrigeration system was found to be higher at night during the charging phase. Refrigeration systems consume less energy per unit of cooling at a higher COP [61][119].

Crane and Dunlop (1994), Department store, London [151]:

An external melt ice-on-coil storage system has been installed in a department store in London, supplying roughly half the required building cooling load during the day. Three chillers are used to charge the ice storage tank in approximately ten hours. During the discharging cycle between 09:00 and 17:00, the stored ice provides as much of the cooling load as possible, with the remaining cooling load supplemented by the chillers. For normal BAU conditions, the total required load was approximately 17 MWt whereby the ice would provide 9.2 MWt and the remainder of 8.2 MWt supplied by the chillers [151]. Results revealed that the application of an ITS system yielded significant cost savings by shifting a significant fraction of the demand electricity from peak hours (09:00 to 17:00) to off-peak hours.

Yau and Lee (2010), Library building, Malaysia [120]:

In a simulation-based case study, Yau and Lee (2010), investigated the effects of employing an ice-slurry cooling storage system in a library building utilising the full storage strategy. It was found that the total energy consumption increased by as much as 20%, largely due to longer water pump usage when compared to the baseline design and increased chiller energy consumption. However, due to the variable tariff rate imposed in Malaysia, by making use of an ITS system, the electricity bill could be reduced by approximately 24%.

Hall, Freeland and Nassif, Office building, Orlando [121]:

In this investigation, research was conducted on the optimal use and design of ITS and its effect on energy cost and consumption. An energy simulation model (eQUEST) was developed and utilised as an optimisation tool to emulate real-life circumstances and yield the optimal design of ice storage. The case study cooling system comprises of one large chiller along with six ice thermal storages. The full strategy was considered for the simulation. The peak period, whereby the highest tariff rates were imposed was from 12:00 to 17:00.

Obtained from the case study investigation conducted by Hall, Freeland and Nassif (2016), Figure 54 and Figure 55 display the monthly energy consumption and cost of a system with no ITS, nonoptimal and near optimal ITS design. Results revealed that although an increase in the energy consumption was noticed when

utilising ITS, based on the utility rate structure, a significant reduction in the energy cost was realised. Through optimised ice storage design and usage, energy cost savings were 28% higher when compared to nonoptimal ITS designs. In addition, results demonstrated that when compared to a system with no ITS, annual energy consumption increased by 11% and the energy cost decreased by 50%. Figure 54 and Figure 55 clearly portray the cost saving benefits the integration of an ITS system has when implemented on a refrigeration system. Further potential can be realised through optimal design and ITS usage.

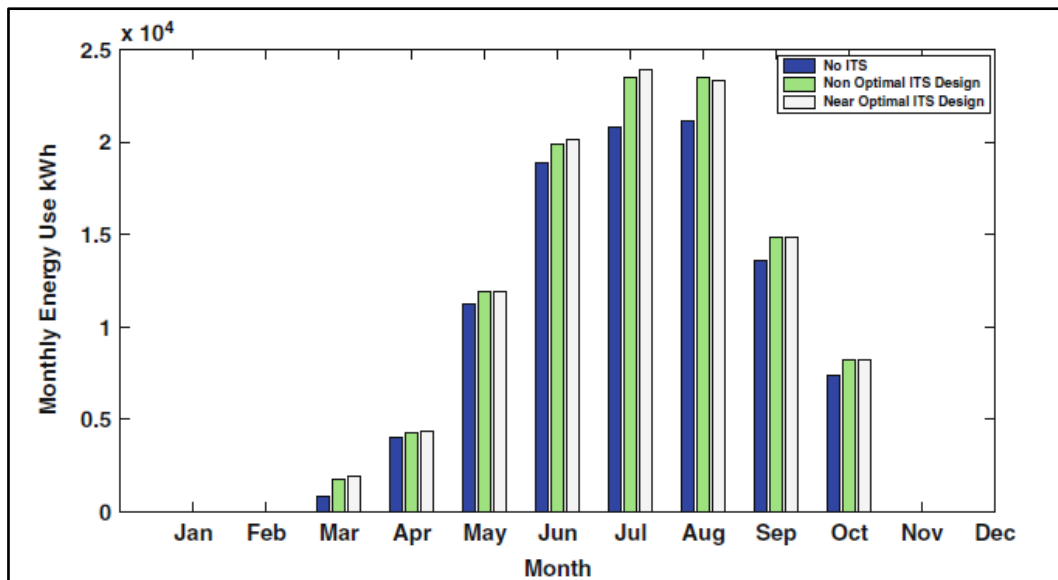


Figure 54: Monthly energy consumption with and without ITS [121]

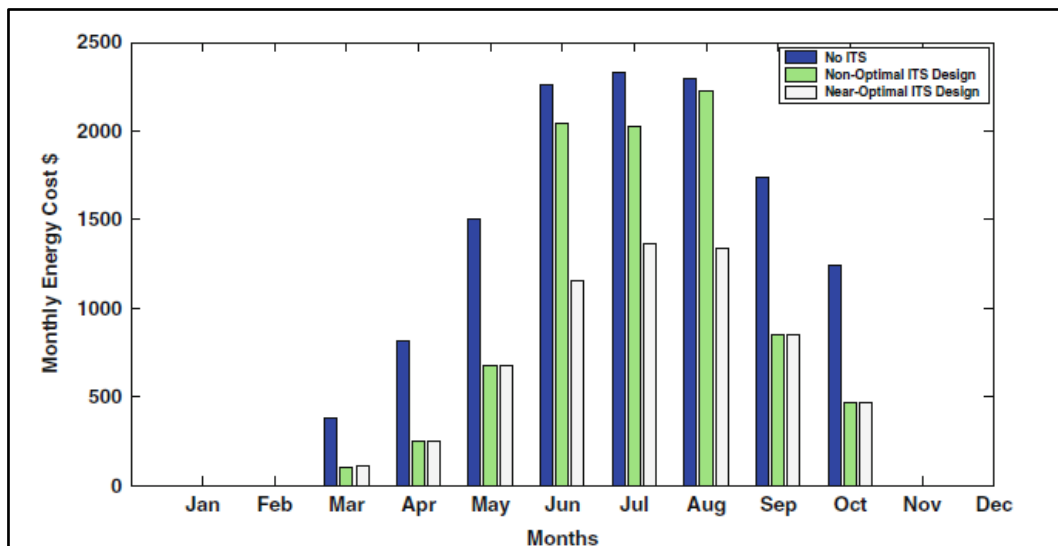


Figure 55: Monthly energy cost with and without ITS [121]

Rismanchi (2013), Office buildings, Malaysia [102]:

This study was conducted to determine the impact the application of ITS systems have when implemented in office buildings. Five different ITS techniques were investigated and critically analysed through multiple

viewpoints from economic assessment, environmental impact and thermodynamic evaluation. The five ITS techniques considered in the study were internal and external melt ice-on-coil, ice slurry, encapsulated ice and ice harvesting. In order to evaluate and predict system behaviour, a computer simulation was formulated. Results revealed that through the application of ITS incorporating the full storage and load levelling strategies, the annual cost of the air conditioning system was reduced by as much as 35% and 8% respectively.

Through the study, Rismanchi identified that an energy and exergy analysis based on the laws of thermodynamics is a powerful tool that could be used to evaluate the performance of TES systems. The energy analysis would focus on the energy efficiency of each ITS technique, whereas the exergy analysis would give an indication on the maximum useful work a system can provide. An exergy analysis is useful to determine and quantify exergy destruction sources such that improved efficiency can be obtained. Irreversibilities such as heat leakages and entropy generation contribute to exergy destruction, leading to the wastage of useful energy. Through the thermodynamic analysis, it was determined that ITS systems are generally highly efficient in terms of energy evaluation. It was determined that ice harvesting had the lowest energy efficiency, whereas the highest belongs to encapsulated ice at 98% [102]. From literature, it has been suggested that the exergetic evaluation provides a more realistic outcome regarding the efficiency, losses and performance of ITS systems [102][152]. In terms of exergy efficiency, Rismanchi found that the technique with the highest total exergy efficiency was the internal melt ice-on-coil system at 18% [102]. In addition, it was determined that the number of storing hours is paralleled by the total exergy destruction. This implies that as the number of storing hours increase, so the total exergy destruction in the system increases, therefore resulting in a decrease in exergy efficiency [102].

MacPhee and Dincer (2009), Office buildings, Canada [124]:

In a similar study conducted by MacPhee and Dincer, the system performance of four ITS techniques utilised for space cooling were investigated. The ice storage techniques considered in the study were ice slurry, ice-on-coil (internal and external) and encapsulated ice. Based on a thermodynamic assessment of each system, the following conclusions were drawn [124]:

- Full storage technique:
 - The energy efficiency of all the systems were extremely high, around 99%. The highest being the ice slurry technique.
 - In terms of total exergy efficiency, the internal melt technique was determined to be most desirable with an overall efficiency of approximately 14.05%.

- Partial storage technique:
 - Performance values were similar to that obtained for the full storage technique; however, efficiencies were determined to be slightly lower. This is attributed to a greater impact of irreversibilities such as heat leakages.

Erdemir and Altuntop (2018), Hypermarket, Turkey [122]:

The aim of the study conducted by Erdemir and Altuntop was to determine the effect of various ITS operation strategies on the economic performance of the hypermarkets' cooling system. Operation strategies investigated during the study were as follows:

- Full storage
- Load levelling
- Partial storage from 10% to 90%, and
- Partial storage for peak hours.

Load levelling is an alternative form of the partial storage strategy whereby the chillers operate at full capacity throughout the day. When the chiller capacity exceeds the cooling load, the excessive cooling is subsequently stored and utilised when the cooling load exceeds the chiller capacity [69].

As a result of the study, it was derived that cooling costs decreased with increasing storage capacity. In addition to this, initial capital investments substantially increase with increasing storage capacity. At the end of a 10-year prediction model, Erdemir and Altuntop concluded that the full storage strategy would yield the highest profit, however, with the longest payback period. The shortest payback period, however, with the lowest profit was seen in the 10% partial storage strategy. To obtain the highest profit from the initial investment made in the ITS system, it is necessary to utilise the stored energy during peak electricity tariff periods. The economic performance of ITS is typically governed by how the stored energy is used. In terms of payback period and profit, the load levelling and partial storage during peak hours constituted the most beneficial utilisation strategies.

A6: Application of statistics

Equation 17 illustrates the general formula that can be utilised to determine four quartile ranges.

Equation 17: Quartile formulas

$Q_1 = \frac{1}{4}(n + 1)th \text{ term}$	[–]
$Q_2 = \frac{2}{4}(n + 1)th \text{ term}$	[–]
$Q_3 = \frac{3}{4}(n + 1)th \text{ term}$	[–]
Where:	
$Q_1 = \text{lower quartile}$	[–]
$Q_2 = \text{median}$	[–]
$Q_3 = \text{upper quartile}$	[–]
$n = \text{number of terms in sample}$	[–]

The standard deviation of a sample can be calculated through the application of Equation 18.

Equation 18: Standard deviation of a sample

$\sigma = \sqrt{\frac{\sum(X_i - \bar{X})^2}{n - 1}}$	[–]
Where:	
$\sigma = \text{standard deviation of a sample}$	[–]
$X_i = \text{each value in the sample}$	[–]
$\bar{X} = \text{mean of the sample set}$	[–]
$n = \text{number of data points in sample}$	[–]

A7: Evaluation of available simulation software packages

Table 33 provides a brief overview of each commercially available simulation package, along with the most noteworthy limitations and benefits of each.

Table 33: Commercially available simulation packages

Simulation package	Description	Benefits	Limitations
<i>ENVIRON</i> [72][153]	Consists of two modules, VENTFLOW and HEATFLOW. Combined, the simulation software is able to model the entire mine in terms of air flow distribution and determining all existing heat loads.	Has the ability to accurately determine cooling capacity requirements to offset underground heat loads.	- Inability to include ToU tariff structure. - Inability to control system components dynamically.
<i>VUMA</i> [51][154][155]	Hosts a user-friendly interface, allowing the simultaneous modelling of air flow, the thermodynamic behaviour of air, as well as providing an accurate simulation of the distribution of heat and gas emissions underground. Primarily utilised to model and optimise complex mine ventilation and water-cooling systems.	- Has the ability to optimise mine ventilation and water-cooling systems. - Has been utilised in life-of-mine planning studies.	- To achieve successful results, trained and experienced personnel are required. - Simulation setup and calibration requires excessive amounts of input data.
<i>PTB</i> [130]	Represents a dynamic thermal hydraulic simulation software package with the ability to accurately simulate a mine's compressed air, dewatering and refrigeration system. Its primary function is to analyse and optimise the performance of mine cooling systems.	- Incorporates the use of a ToU tariff structure, therefore, able to quantify the cost-saving potential of load management initiatives. - Able to ascertain the optimal operation of system components. - Cooling system components already developed.	Requires a significant amount of input data for each component.

Appendix B: Simulation output variables

Table 34 depicts the simulation model output variables that need to be monitored and critically evaluated throughout the simulation phase. This will ultimately assist in determining project feasibility.

Table 34: Simulation model output variables [130]

Output variable	Description
Ice dam level [%]	The level of the dam at the end of each time interval
Ice dam water temperature [°C]	The water temperature of the ice dam at the end of each time interval
Ice mass [kg]	The total ice mass accumulated within the system at the end of each time interval

Power of combined system [kW]	The instantaneous power consumption of the combined system at the end of each time interval. The combined system will comprise of solely the installed chillers, condenser towers and pumping auxiliaries and the ITS system
BAC air outlet temperature [°C]	Since the mine will still require cool, dehumidified ventilated air, it is therefore imperative that the BAC air outlet temperature consistently remain within prescribed limits
Chilled water temperature sent underground [°C]	To ensure safe underground working conditions are maintained, it is imperative that the chilled water temperature sent underground meets stringent service delivery requirements
Pre-cooling tower sump temperature [°C]	Analysing the pre-cooling tower sump temperature will quantify whether the integration of ITS into a mine cooling system has any impact on the energy and therefore the temperature of the water circulating the mine
Pre-cooling tower sump level [°C]	It is essential to evaluate the pre-cooling tower sump level at the end of each time interval to ensure the dam does not run dry or flood at any stage during the simulation
Chill dam level [°C]	It will be worthwhile to analyse the chill dam level. Although the ITS system will be designed to match flow requirements, it makes sense to ensure dam level constraints are not compromised
Individual chiller COP [-]	To evaluate the impact the ITS installation has on the performance and efficiency of system chillers, the COP of each individual chiller should be compared before and after the ITS implementation
Ice plant COP [-]	As a measure of system performance and efficiency, it will be worthwhile to evaluate the ice plants COP
Global system COP [-]	To evaluate the impact the ITS installation has on the performance of the holistic cooling system, the global system COP must be determined

Appendix C: Mine P's system specifications

C1: Technical specifications

Table 35: Technical specifications of Mine P

System description	Specification	Winter (Jun-Aug)	Summer (Dec-Mar)	Autumn (Apr-May)	Spring (Sep-Nov)
Hitachi chillers	Compressor type [-]	centrifugal			
	Refrigerant type [-]	R-134a			
	Chiller cooling capacity [kW]	10 100			
	Nominal efficiency, COP [-]	6			
	Evaporator water outlet temperature [°C]	5 - 7			

	Evaporator water flow rate [l/s]	200 -320
	Condenser water inlet temperature [°C]	25
	Condenser water flow rate [l/s]	560
Ammonia chillers	Compressor type [-]	screw
	Refrigerant type [-]	ammonia
	Chiller cooling capacity [kW]	4 675
	Nominal efficiency, COP [-]	5.8
	Evaporator water outlet temperature [°C]	1.0 – 2.1
	Evaporator water flow rate [l/s]	160 - 180
	Condenser water inlet temperature [°C]	25
	Condenser water flow rate [l/s]	450
Pre-cooling towers	Number of towers [-]	3
	Water inlet temperature [°C]	12 - 22
	Water outlet temperature [°C]	16
	Water flow rate [l/s]	440 - 660
BACs	Number of BAC fans [-]	3
	Water inlet temperature [°C]	1.5 - 4
	Water outlet temperature [°C]	12
	Water flow rate [l/s]	340
	Air outlet WB temperature [°C]	< 12
Auxiliary pumps	Evaporator pump motor rating [kW]	350
	Number of evaporator pumps [-]	5
	Condenser pump motor rating [kW]	185
	Number of condenser pumps [-]	4
	BAC feed pump motor rating [kW]	135
	Number of BAC feed pumps [-]	4
	BAC return pump motor rating [kW]	110
	Number of BAC return pumps [-]	4
	Ammonia feed pump motor rating [kW]	225
	Number of ammonia feed pumps [-]	4
3CPFS	East chamber [l/s]	Low = 220, medium = 240, high = 260
	West chamber [l/s]	Low = 220, medium = 240, high = 260
Thermal storage dams	Pre-cooling sump volume [ML]	2.5
	• Operating range [%]	Minimum = 40, maximum = 95
	BAC sump volume [ML]	1.5
	• Operating range [%]	Minimum = 30, maximum = 50
	Intermediate dam volume [ML]	5.0
	• Operating range [%]	Minimum = 35, maximum = 90
	Chill dam volume [ML]	5.0
	• Operating range [%]	Minimum = 35, maximum = 90

C2: Chiller control limits**Table 36: Operating control limits - Ammonia chillers**

Description	High trip	High alarm	Low alarm	Low trip
Compressor discharge temperature [°C]	95	90	-	-
Compressor discharge pressure [bar]	14.6	14	-	-
Compressor suction temperature [°C]	-	-	-6.5	-7
Compressor suction pressure [bar]	-	-	2.6	2.4
Compressor vibration [mm/s]	11.5	9.9	-	-
Compressor oil temperature [°C]	55	50	-	-
Surge drum level [%]	97	90	-	-
Economiser level [%]	-	60	-	-
Motor DE bearing temperature [°C]	90	80	-	-
Motor NDE bearing temperature [°C]	90	80	-	-
Motor U phase temperature [°C]	100	90	-	-
Motor V phase temperature [°C]	100	90	-	-
Motor W phase temperature [°C]	100	90	-	-
Motor amps [A]	150	150	-	-
Gearbox bearing temperature No.1 [°C]	75	65	-	-
Gearbox bearing temperature No.2 [°C]	75	65	-	-
Gearbox bearing temperature No.3 [°C]	75	65	-	-
Gearbox bearing temperature No.4 [°C]	75	65	-	-
Gearbox oil temperature [°C]	60	57	-	-
Gearbox oil pressure [bar]	-	-	0.84	0.84
Evaporator refrigerant temperature [°C]	-	-	-5	-7
Evaporator refrigerant pressure [bar]	-	-	2.5	2
Evaporator water inlet temperature [°C]	-	-	-1	-1
Evaporator water outlet temperature [°C]	-	-	0.4	0.1
Evaporator water flow rate [<i>l/s</i>]	-	185	115	100
Condenser pressure [bar]	14.5	14	-	-
Condenser temperature [°C]	95	90	-	-

Table 37: Operating control limits - Hitachi chillers

Description	High trip	High alarm	Low alarm	Low trip
Motor winding temperature 1 [°C]	110	100	-	-
Motor winding temperature 2 [°C]	110	100	-	-
Motor winding temperature 3 [°C]	110	100	-	-
Motor DE bearing temperature [°C]	80	70	-	-
Motor NDE bearing temperature [°C]	80	70	-	-
Motor amps [A]	206	195	-	-
Economiser level [%]	-	60	-	-
Compressor discharge temperature [°C]	80	70	-	-
Compressor discharge pressure [bar]	9.5	9.0	-	-
Compressor suction temperature [°C]			1.5	1.0
Compressor suction pressure [bar]	-	-	2.2	2.0
Compressor vibration [mm/s]	6.0	3.0		
Compressor oil temperature [°C]	60	55	-	-
Gearbox bearing temperature No.1 [°C]	80	70	-	-
Gearbox bearing temperature No.2 [°C]	80	70	-	-
Gearbox bearing temperature No.3 [°C]	80	70	-	-
Gearbox bearing temperature No.4 [°C]	80	70	-	-
Gearbox oil temperature [°C]	70	60	35	30
Gearbox oil pressure [bar]	-	-	5	4.6
Evaporator refrigerant temperature [°C]	-	-	1.5	1.0
Evaporator refrigerant pressure [bar]	-	-	2.1	2.1
Evaporator water inlet temperature [°C]	-	-	-1	6.6
Evaporator water outlet temperature [°C]	-	-	3.0	2.5
Evaporator water flow rate [<i>l/s</i>]	-	400	185	170
Condenser pressure [bar]	8.8	8.4	-	-
Condenser temperature [°C]	85	80	-	-

Appendix D: Baseline modelling

D1: Baseline simulation model of Mine P

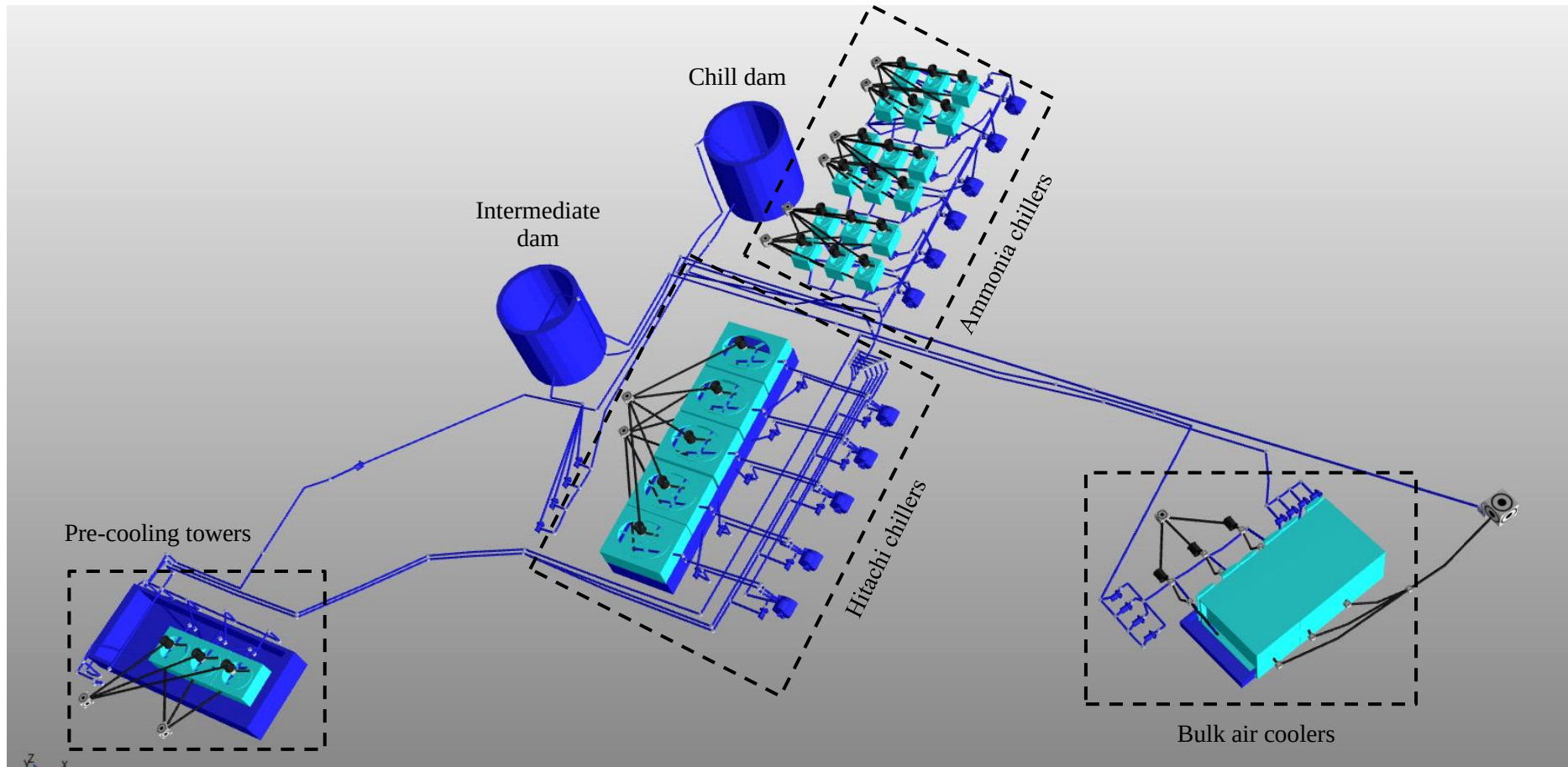
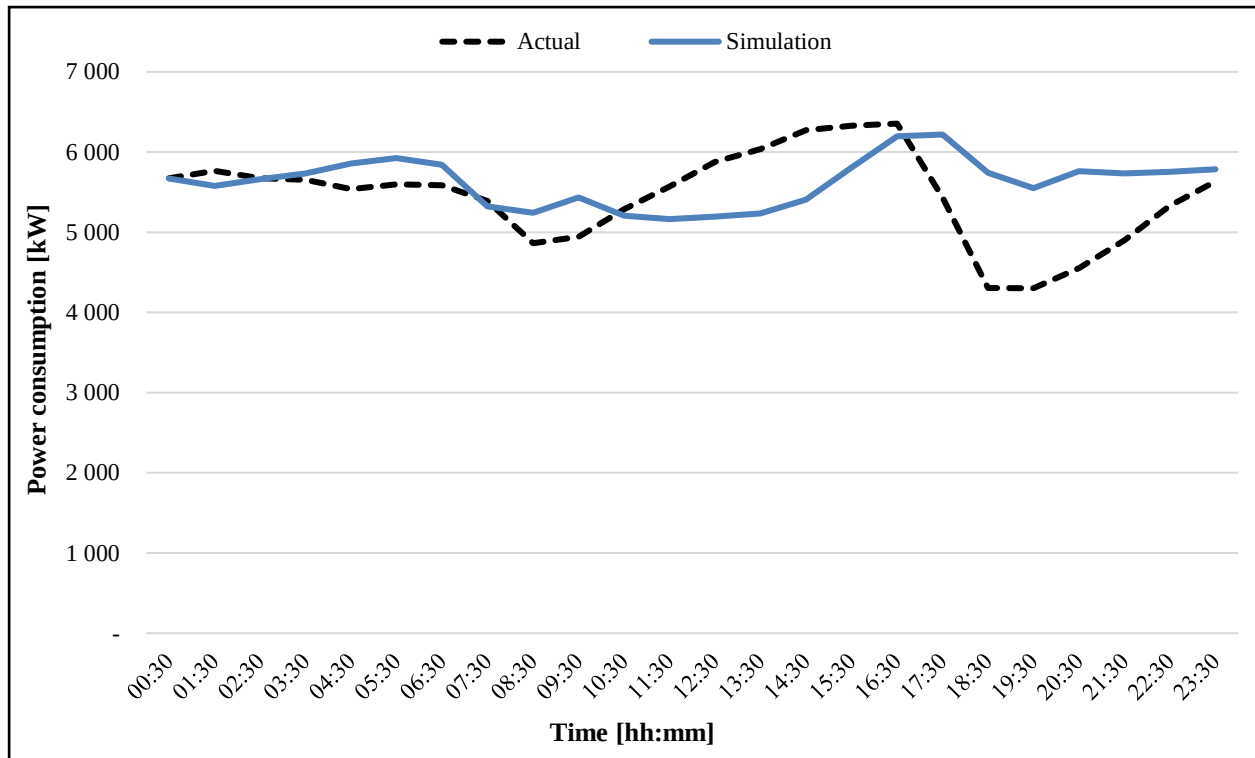
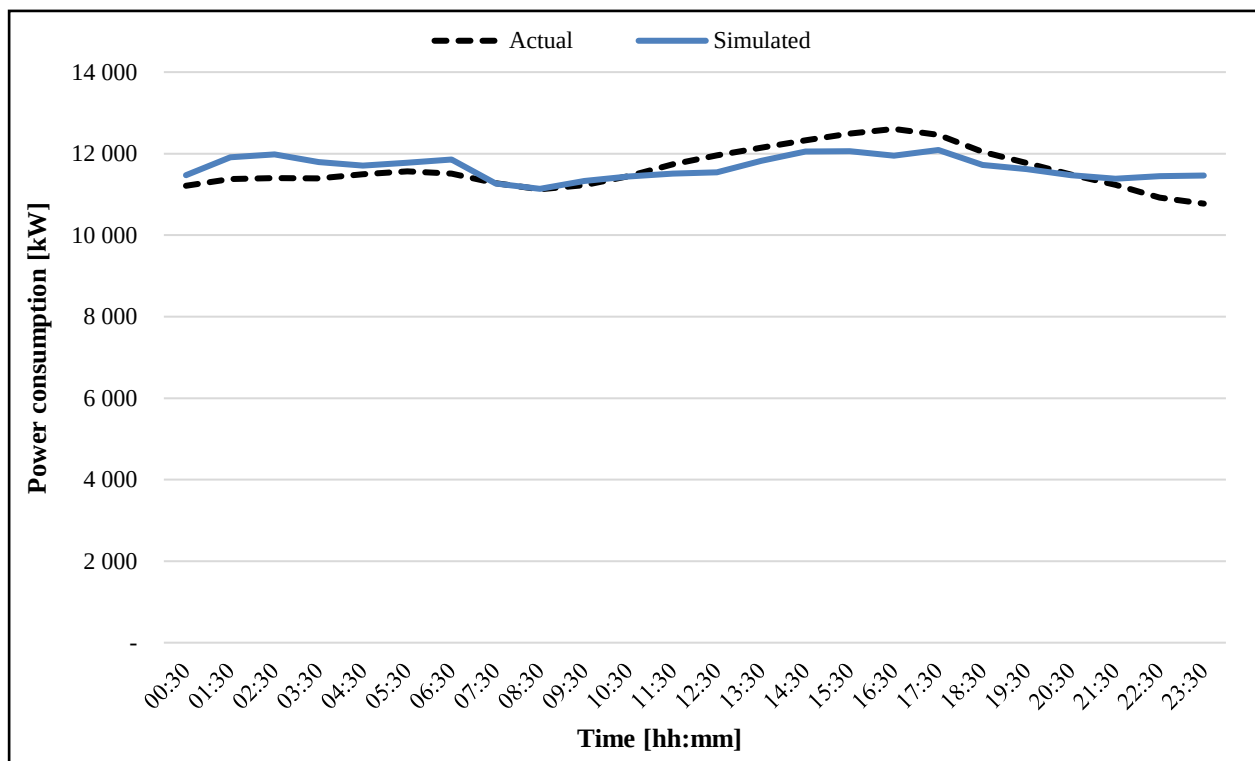


Figure 56: Integrated simulation model - Mine P's surface cooling system

D2: Baseline simulation results**Figure 57: Power profile verification – baseline 1****Figure 58: Power profile verification – baseline 2**

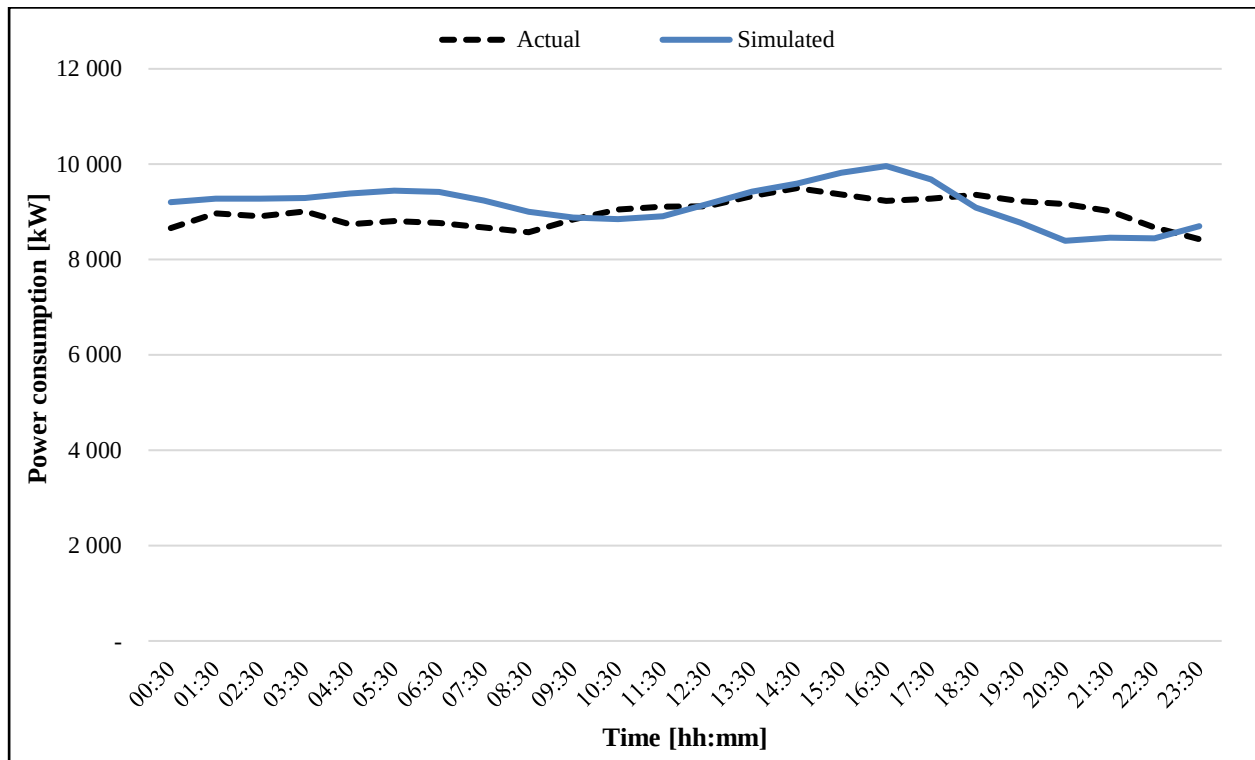


Figure 59: Power profile verification – baseline 3

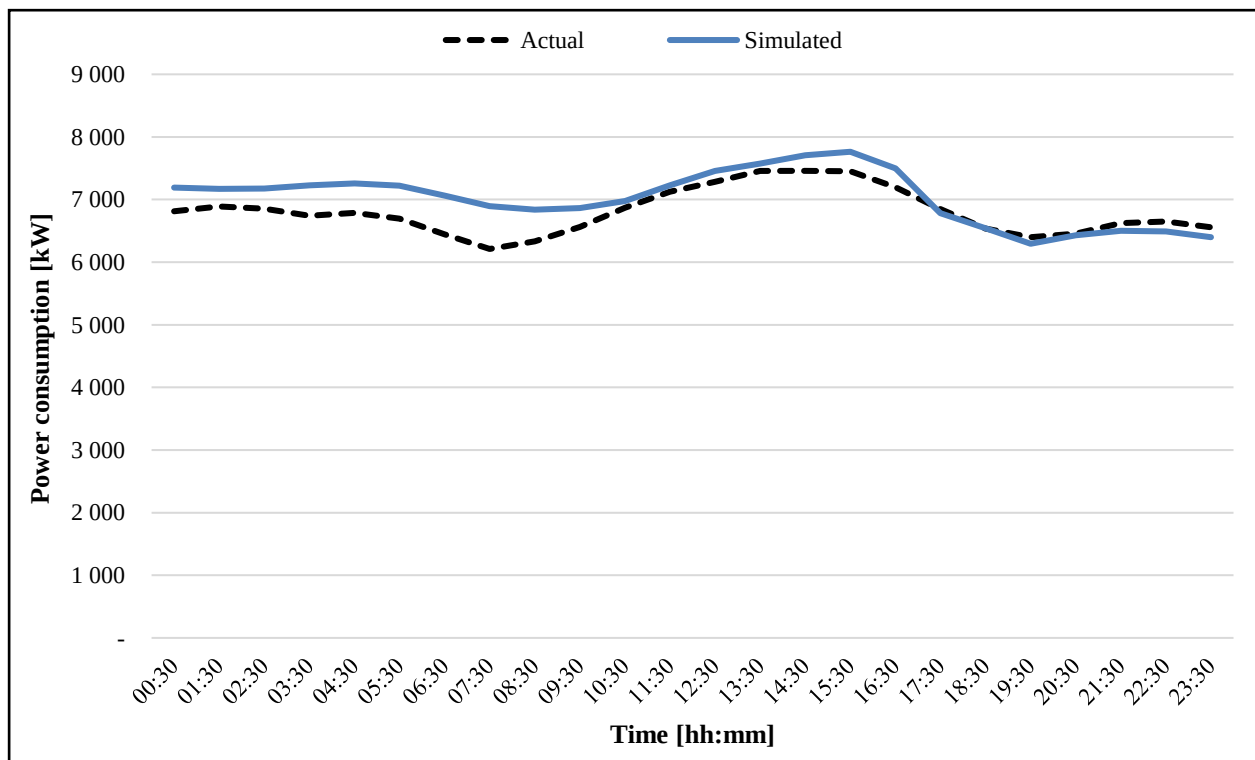


Figure 60: Power profile verification – baseline 4

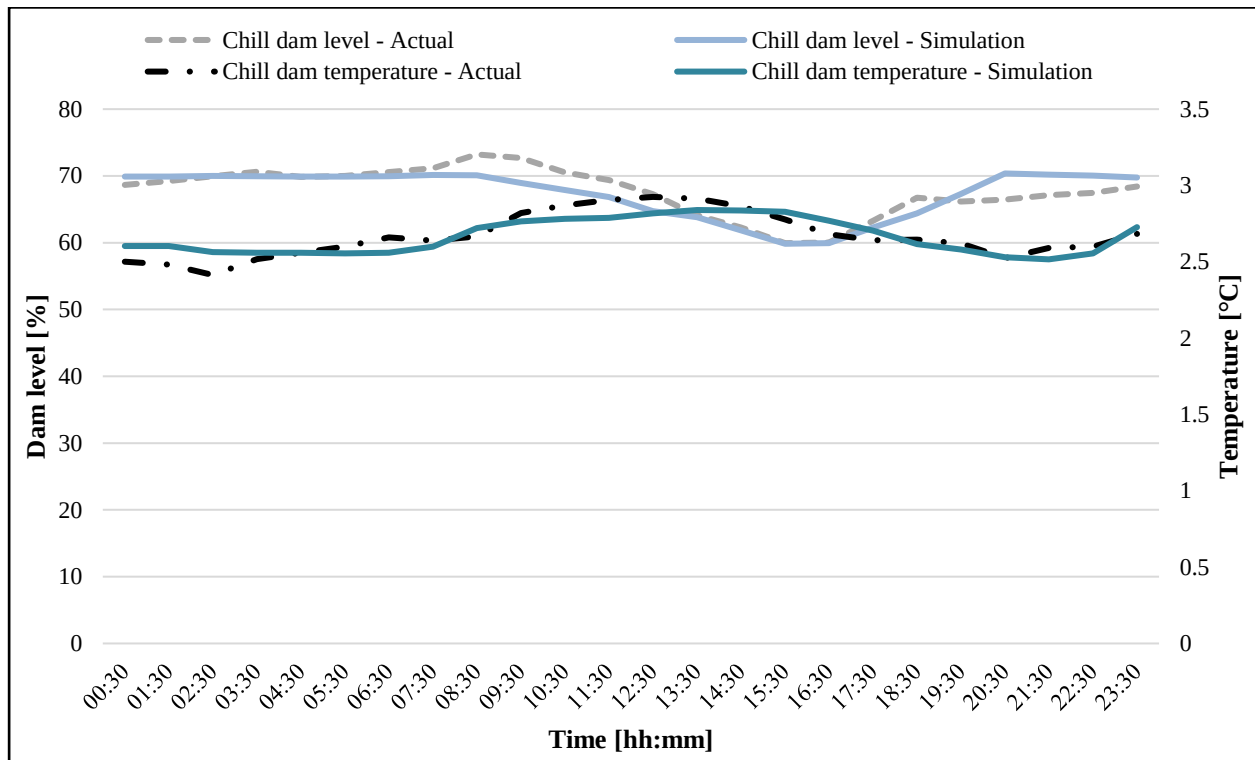


Figure 61: Surface chill dam verification - baseline period 2

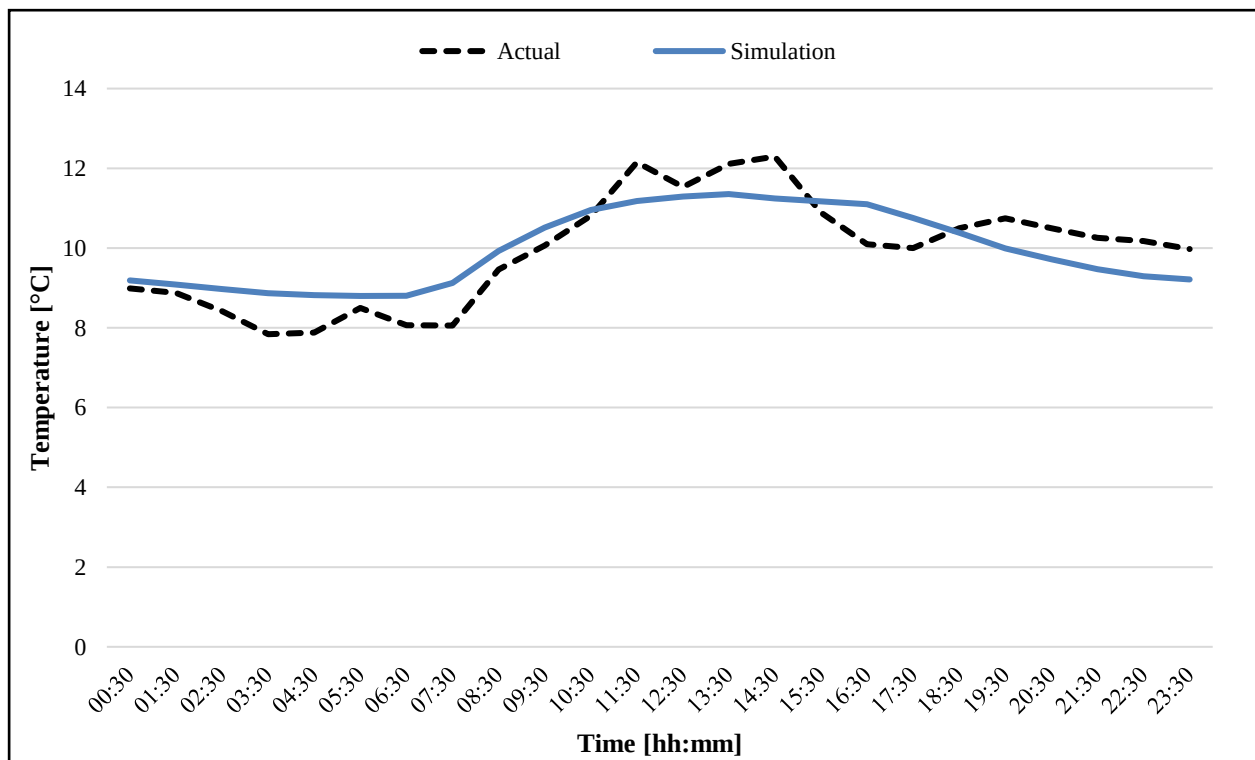


Figure 62: BAC air outlet temperature verification - baseline period 2

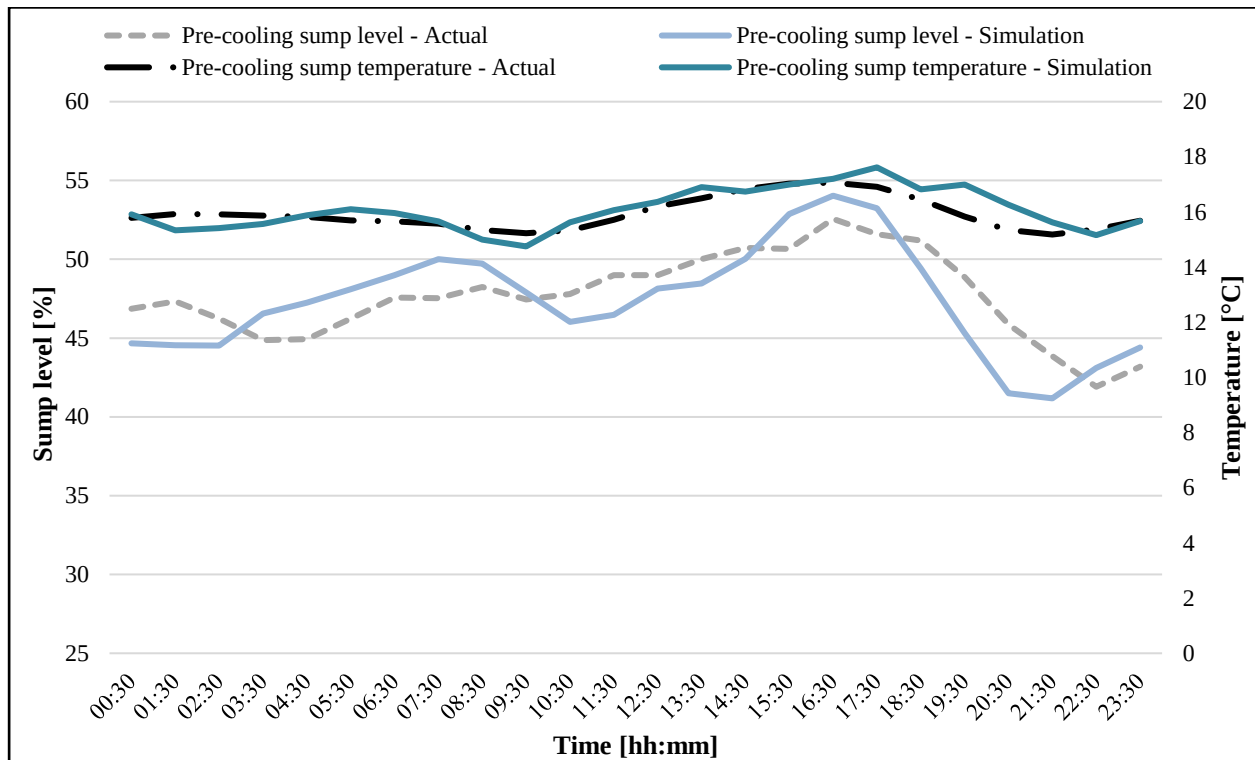


Figure 63: Pre-cooling towers verification - baseline period 2

Appendix E: Theoretical ice plant simulation modelling

E1: Simulation model incorporating ITS – Mine P

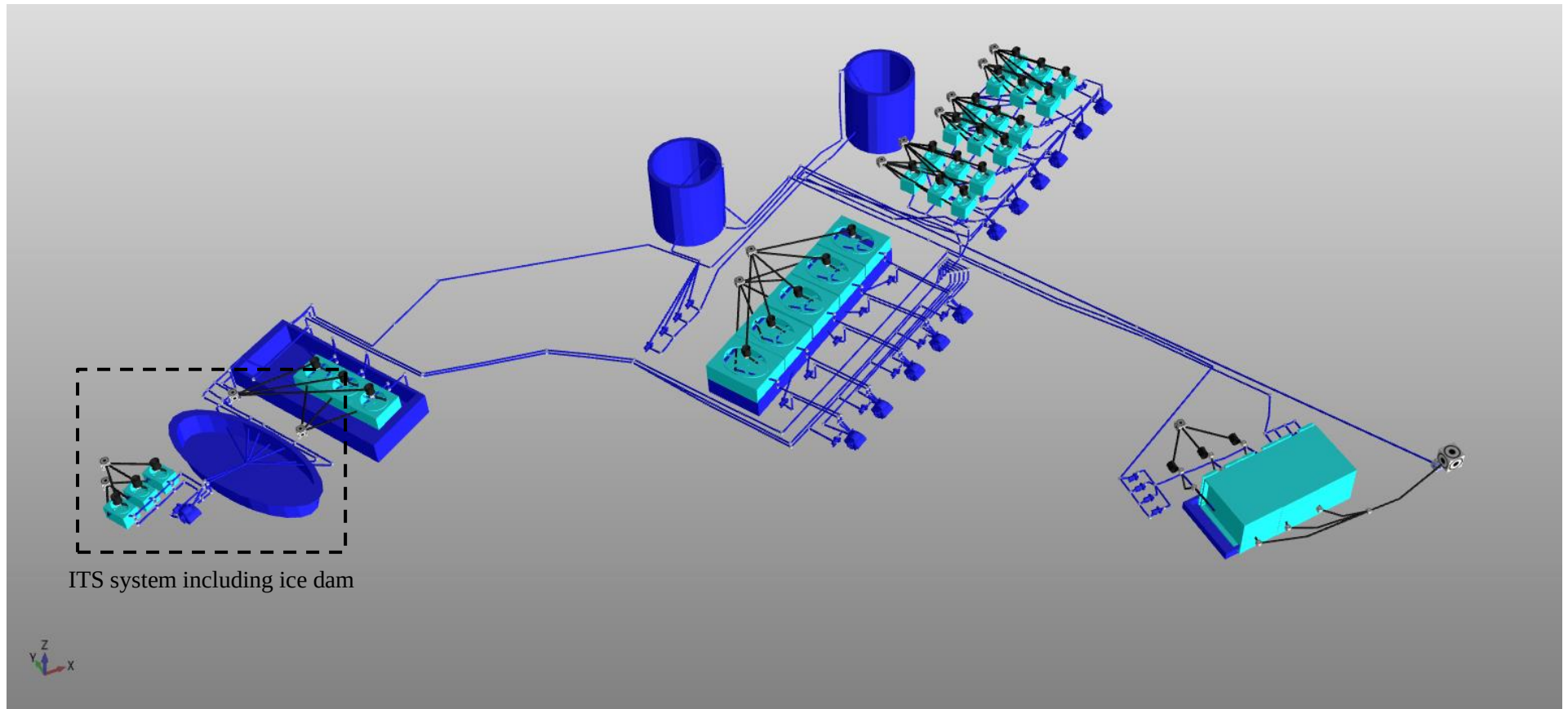
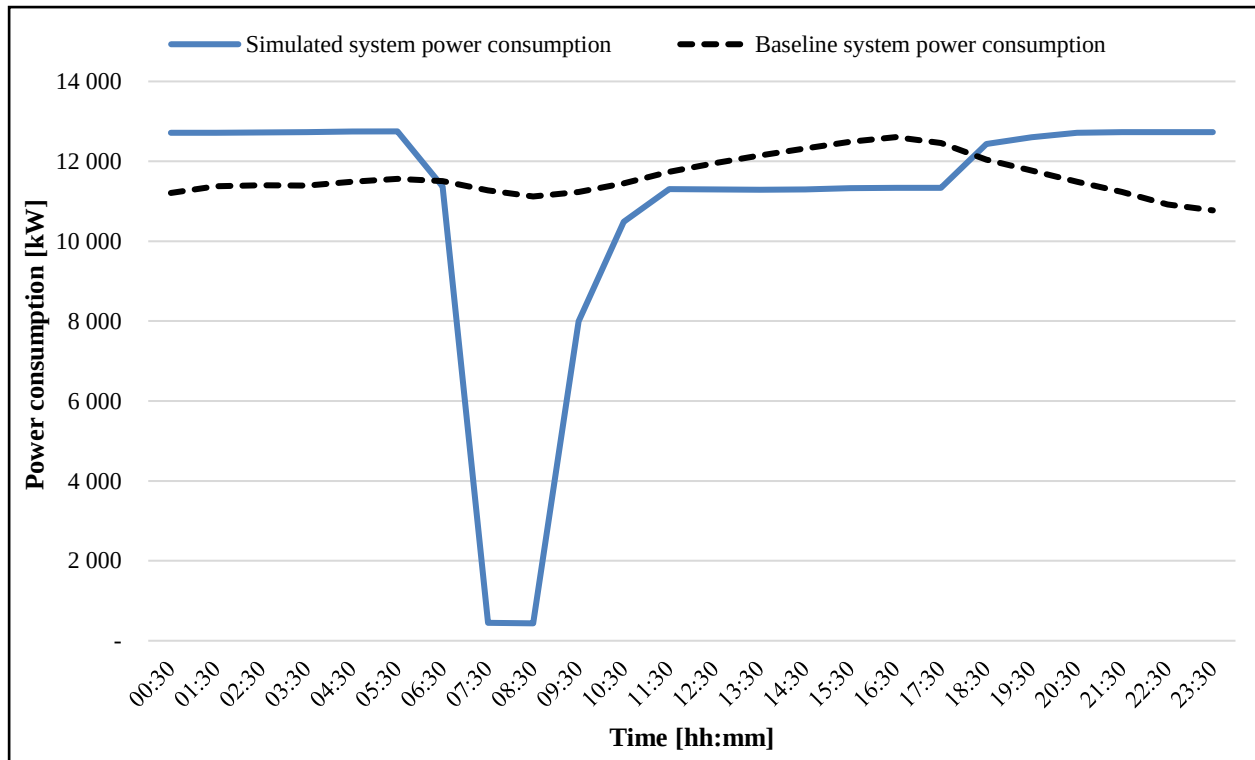
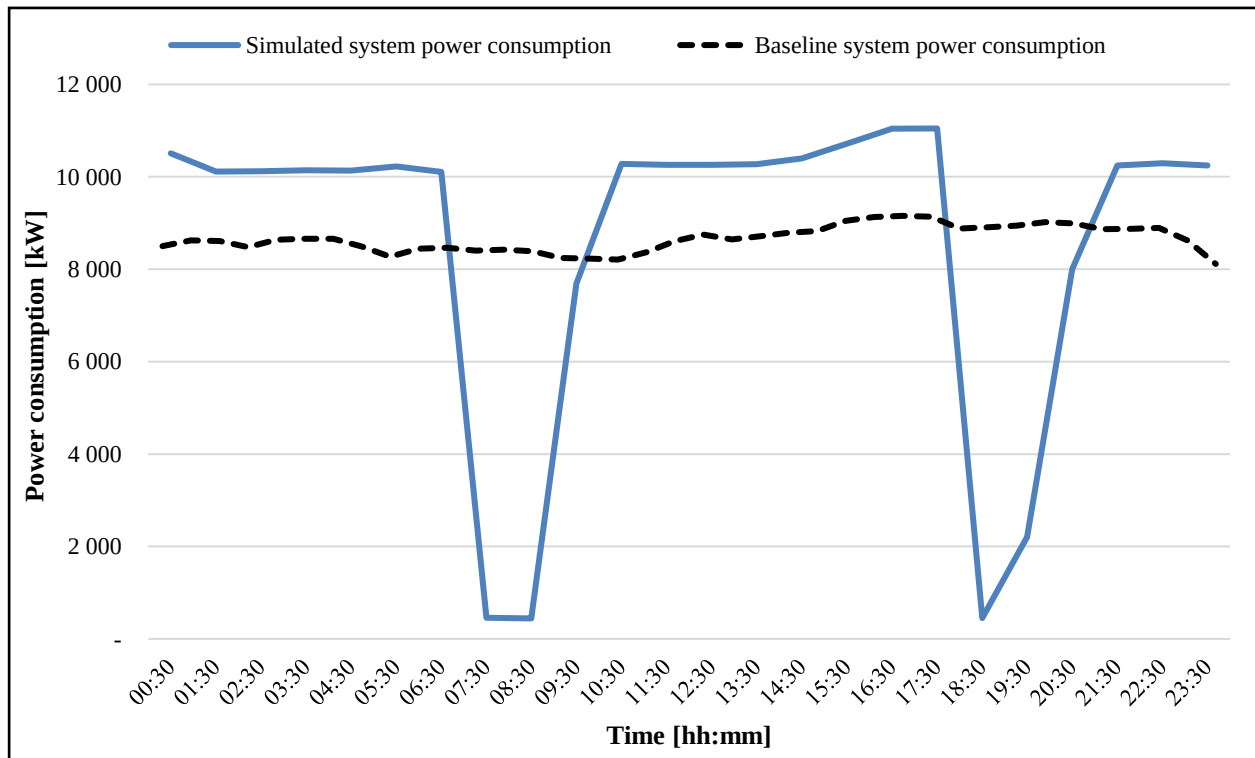


Figure 64: Integrated simulation model - incorporating an ITS system

E2: Simulation control philosophy

Table 38: Simulated load shift control philosophy – Mine P

Component	Baseline 1				Baseline 2				Baseline 3				Baseline 4			
	Preparation period (19:00 – 06:00)	Morning peak period (06:00 – 09:00)	Preparation period (09:00 – 17:00)	Evening peak period (17:00 – 19:00)	Preparation period (20:00 – 07:00)	Morning peak period (07:00 – 10:00)	Preparation period (10:00 – 18:00)	Evening peak period (18:00 – 20:00)	Preparation period (20:00 – 07:00)	Morning peak period (07:00 – 10:00)	Preparation period (10:00 – 18:00)	Evening peak period (18:00 – 20:00)	Preparation period (20:00 – 07:00)	Morning peak period (07:00 – 10:00)	Preparation period (10:00 – 18:00)	Evening peak period (18:00 – 20:00)
Hitachi chillers [-]	2	0	2	0	4	0	4	4	3	0	3	0	2	0	2	0
Evaporator pumps [-]	2	2	2	2	4	2	4	4	3	2	3	2	2	2	2	2
Ammonia chillers [-]	2	0	2	0	4	0	4	4	3	0	3	0	3	0	3	0
Ammonia feed pumps [-]	2	0	2	0	4	0	4	4	4	0	4	0	3	0	3	0
Ice plant [hours]	8	0	8	0	12	0	0	0	10	0	8	0	9	0	8	0

E3: Simulation results – Mine P**Figure 65: Simulated system power consumption - baseline 2****Figure 66: Simulated system power consumption - baseline 3**

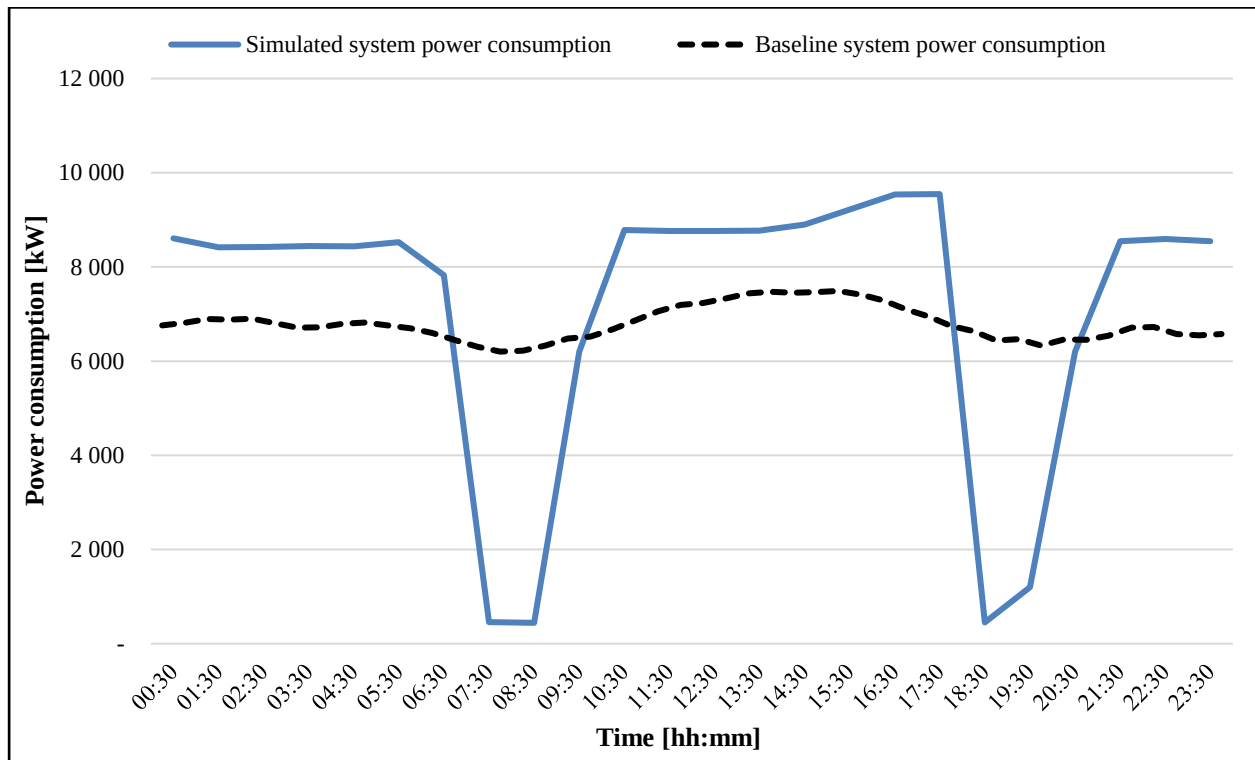


Figure 67: Simulated system power consumption - baseline 4

E4: Application of analytical approach for baseline period 2

Table 39 illustrates the final iterated ice plant system characteristics derived for baseline period 2.

Table 39: Application of analytical approach for simulation model - baseline period 2

Equation 6: Melting rate of stored ice		
$\dot{m}_w$	480 l/s	
$C_{p,w}$	4.187 kJ/kg.°C	
h_{fg}	334 kJ/kg	
$T_{w,i}$	17 °C	
$T_{w,o}$	2 °C	
MR	$MR = \left[\frac{\dot{m}_w C_{p,w} (T_{w,i} - T_{w,o})}{h_{fg}} \right] \times (3600)$	324 931 kg/hr
Equation 7: Required mass of ice		
MR	324 931 kg/hr	
t_{peak}	2 hours	
m_{ice}	$m_{ice} = MR \times t_{peak}$	649 863 kg

Equation 8: Ice building cooling duty		
$\dot{m}_{ice,b}$	Equation 14	
$C_{p,w}$	4.187 kJ/kg.°C	
$T_{ice-build}$	7.8 °C	
h_{fg}	334 kJ/kg	
Peak period duration	2 hours	
$\dot{Q}_{ice-build}$	$\dot{Q}_{ice-build} = \dot{m}_{ice,b}[C_{p,w}(T_{ice-build} - 0) + h_{fg}]$	5 514 kW
Equation 9: Required ice building rate		
m_{ice}	649 863 kg	
$t_{ice-build}$	12 hours	
$\dot{m}_{ice,b}$	$\dot{m}_{ice,b} = \frac{m_{ice}}{(t_{ice-build} \times 3600)}$	15.04 kg/s
Equation 10: Amount of stored energy in the form of ice		
m_{ice}	649 863 kg	
h_{fg}	334 kJ/kg	
Q_{ice}	$Q_{ice} = \frac{(m_{ice}h_{fg})}{3600}$	60 293 kWh
Minimum required dam size	$(0.023 \text{ m}^3/\text{kWh}) * Q_{ice}$	4 500 m³

Appendix F: Eskom's MegaFlex ToU tariff structure

Table 40 and Table 41 illustrate Eskom's 2018/2019 Megaflex tariff structure that was utilised to calculate the electricity cost savings as a result of the implementation of ITS. The tariff structure varies depending on the ToU tariff period. Colour coding red, yellow and green is utilised to distinguish between peak, standard and off-peak ToU tariffs.

The tariff structure is typically determined by the distance of the transmission zone and voltage range of the particular substation. The applicable tariff rate structure utilised in this dissertation incorporated a transmission zone of ≤ 300 km and voltage range of ≥ 500 V & < 66 kV respectively.

Table 40: Eskom's 2018/2019 MegaFlex ToU winter tariff structure [36]

2018/2019 MegaFlex tariff structure			
Winter tariffs			
Time [hour]	Weekday [c/kWh]	Saturday [c/kWh]	Sunday [c/kWh]
0	47.43	47.43	47.43
1	47.43	47.43	47.43
2	47.43	47.43	47.43
3	47.43	47.43	47.43
4	47.43	47.43	47.43
5	47.43	47.43	47.43
6	288.29	47.43	47.43
7	288.29	87.34	47.43
8	288.29	87.34	47.43
9	87.34	87.34	47.43
10	87.34	87.34	47.43
11	87.34	87.34	47.43
12	87.34	47.43	47.43
13	87.34	47.43	47.43
14	87.34	47.43	47.43
15	87.34	47.43	47.43
16	87.34	47.43	47.43
17	288.29	47.43	47.43
18	288.29	87.34	47.43
19	87.34	87.34	47.43
20	87.34	47.43	47.43
21	87.34	47.43	47.43
22	47.43	47.43	47.43
23	47.43	47.43	47.43

Table 41: Eskom's 2018/2019 MegaFlex ToU summer tariff structure [36]

2018/2019 MegaFlex tariff structure			
Summer tariffs			
Time [hour]	Weekday [c/kWh]	Saturday [c/kWh]	Sunday [c/kWh]
0	41.06	41.06	41.06
1	41.06	41.06	41.06
2	41.06	41.06	41.06
3	41.06	41.06	41.06
4	41.06	41.06	41.06
5	41.06	41.06	41.06
6	64.73	41.06	41.06
7	94.03	64.73	41.06
8	94.03	64.73	41.06
9	94.03	64.73	41.06
10	64.73	64.73	41.06
11	64.73	64.73	41.06
12	64.73	41.06	41.06
13	64.73	41.06	41.06
14	64.73	41.06	41.06
15	64.73	41.06	41.06
16	64.73	41.06	41.06
17	64.73	41.06	41.06
18	94.03	64.73	41.06
19	94.03	64.73	41.06
20	64.73	41.06	41.06
21	64.73	41.06	41.06
22	41.06	41.06	41.06
23	41.06	41.06	41.06

Table 42: Eskom's MegaFlex ToU tariff history [36]

Financial Year	Low demand season [Sep - May]			High demand season [Jun - Aug]		
	Peak [c/kWh]	Standard [c/kWh]	Off-peak [c/kWh]	Peak [c/kWh]	Standard [c/kWh]	Off-peak [c/kWh]
2009/2010	32.19	19.72	13.79	115.29	29.97	16.01
2010/2011	39.75	24.35	17.03	142.38	37.01	19.77
2011/2012	51.04	31.27	21.87	182.83	47.52	25.39
2012/2013	58.75	36	25.17	210.46	54.7	29.23
2013/2014	65.98	45.2	28.6	201.33	60.99	33.12
2014/2015	70.93	48.82	30.97	217.44	65.87	35.77
2015/2016	79.79	55.02	34.9	245.03	74.23	40.31
2016/2017	87.44	60.19	38.18	268.06	81.21	44.1
2017/2018	89.36	61.51	39.02	273.96	83	45.07
2018/2019	94.03	64.73	41.06	288.29	87.34	47.43
2019/2020	107.07	73.71	46.76	328.28	99.45	54.01

Appendix G: Mine P's cooling system layout incorporating an ITS system

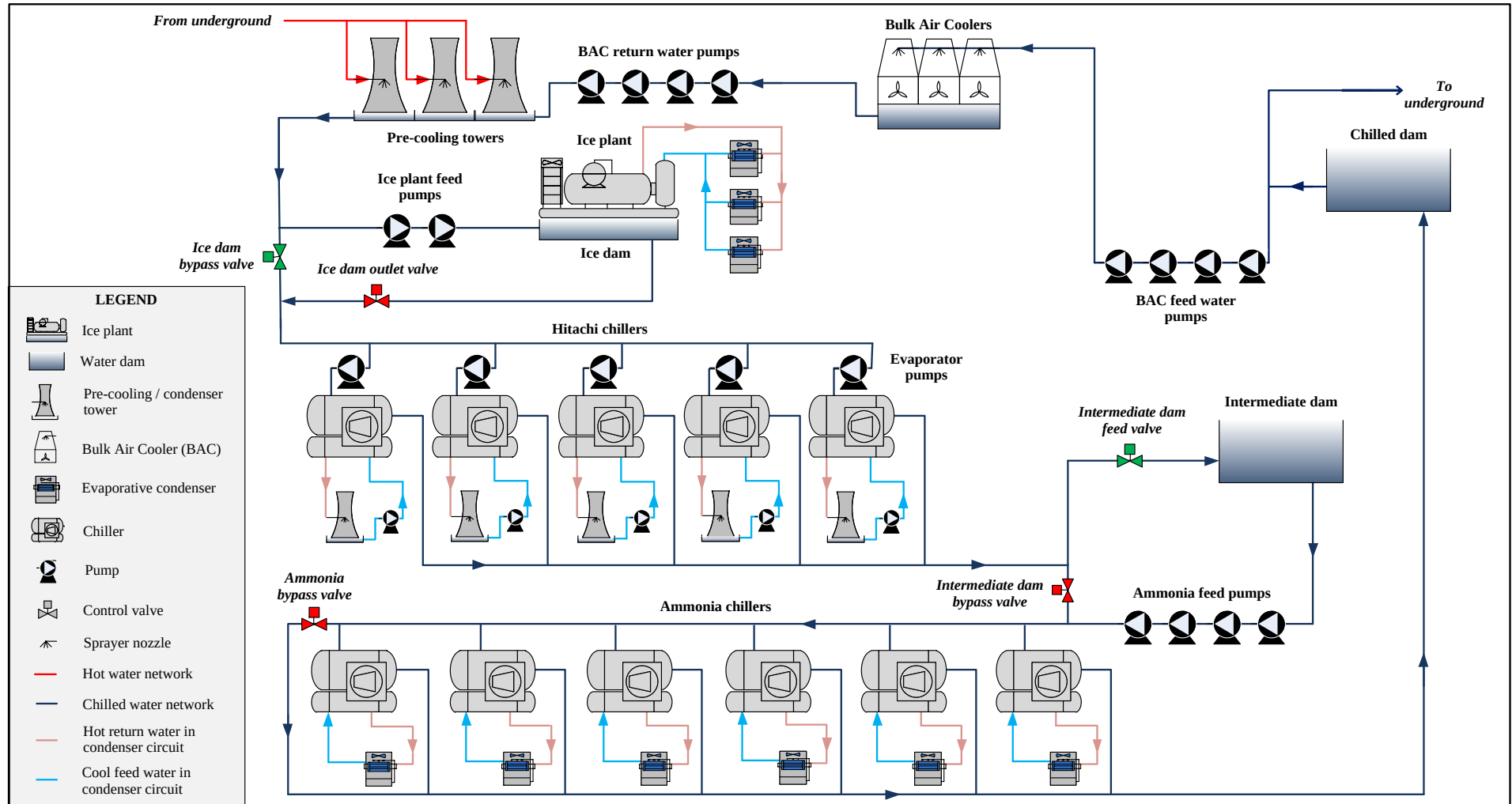


Figure 68: Mine P's surface cooling system during the ice-making cycle (preparation period)

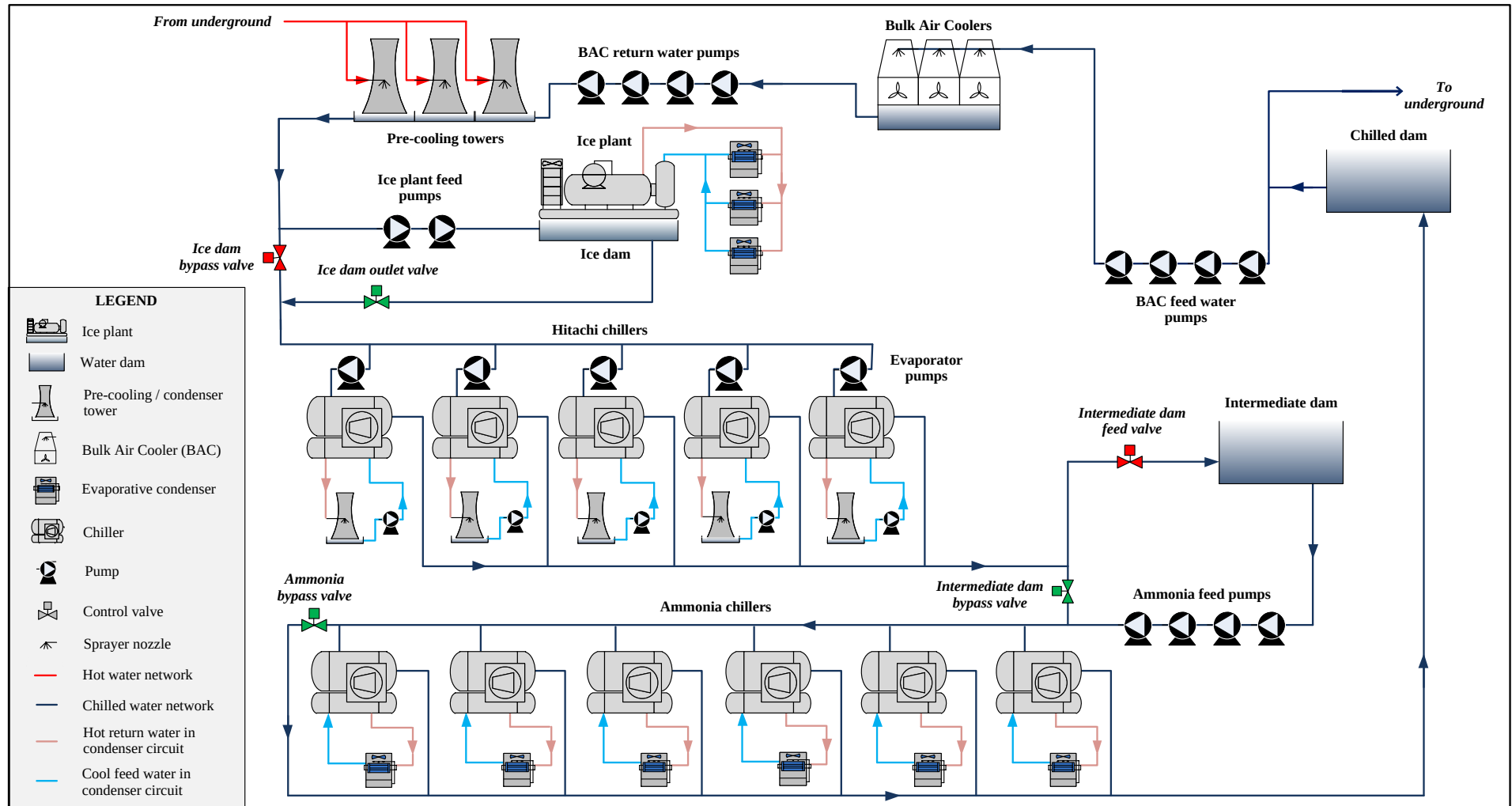


Figure 69: Mine P's surface cooling system during the ice-melting cycle (peak periods)

Appendix H: Ice thermal storage risk assessment

Table 43: Ice thermal storage risk assessment matrix

Risk Matrix		Likelihood of occurrence					
		0 - Never	1 - Seldom	2 - Low moderate	3 - Moderate	4 - Frequent	5 - Recurring
Hazard severity	0-Null	0	0	0	0	0	0
	1-Insignificant	0	1	2	3	4	5
	2-Minor	0	2	4	6	8	10
	3-Moderate	0	3	6	9	12	15
	4-Serious	0	4	8	12	16	20
	5-Critical	0	5	10	15	20	25
Evaluation							
Hazard/Risk identification		Hazard severity	Likelihood	Total	Weight	Weighted total	
Health and safety impact		5	1	5	0.4	2	
Service delivery requirements		2	4	8	0.2	1.6	
Production		3	4	12	0.3	4.5	
Cost		2	3	6	0.1	0.6	
Results							
Weighted risk:					7.8		
Maximum possible risk:					25		
Weighted risk / maximum possible risk:					31%		

Appendix I: Actual implementation results Mine P

Implementation results – Baseline period 3

Similar to baseline period 2, the daily average energy usage was less incorporating the use of an ITS system when compared to baseline conditions. Although one may expect an increase in the overall daily energy consumption, following a double ice melt, the energy shifted outside of Eskom's peak periods was significantly higher than that required to charge the ice dam. Figure 70 illustrates Mine P's surface refrigeration power consumption, comparing baseline conditions to that obtained from the assessment period. By implementing an ice melt during both morning and evening peak periods, an average hourly load shift of 7.6 MW and 7.7 MW was achieved.

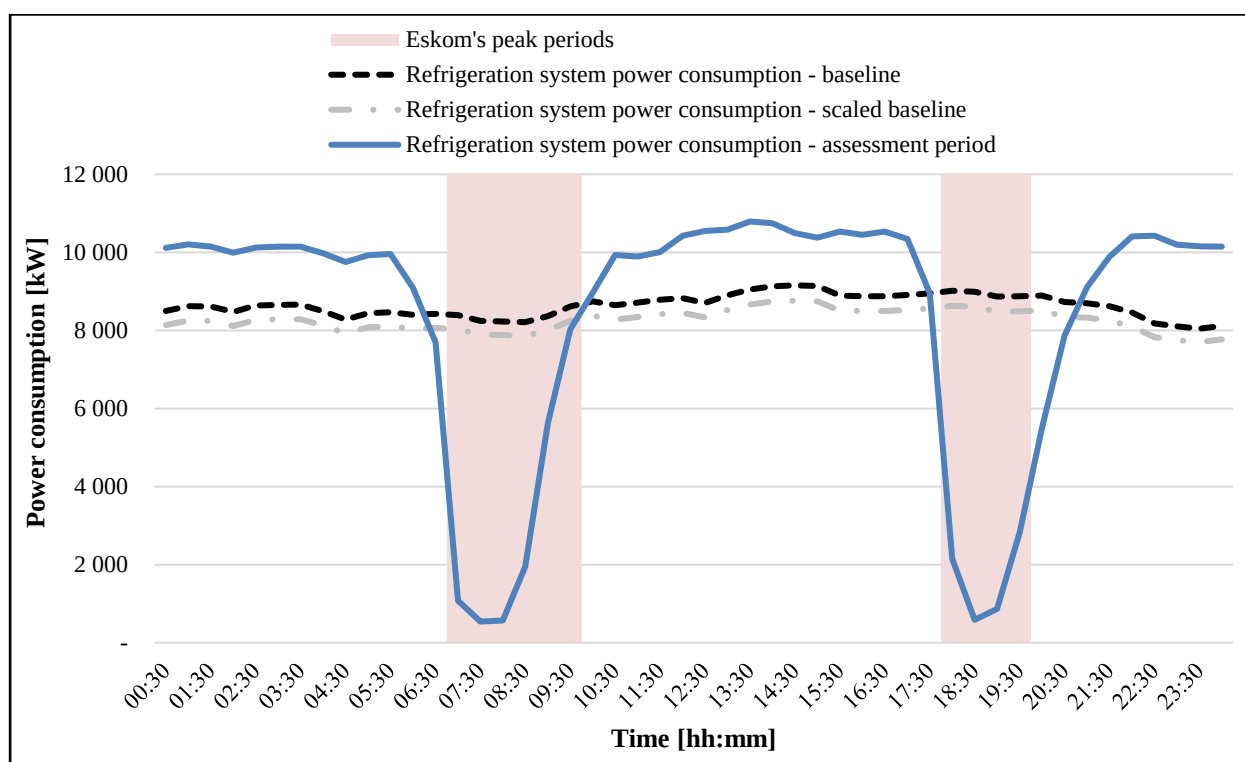


Figure 70: Refrigeration system power consumption - Mine P, baseline period 3

Table 44 presents a summary of the implementation results recorded for baseline period 3. Upon assessment period selection, comparable boundary conditions were established and subsequently compared to baseline conditions. Illustrated in Table 44, it is clear that the proposed assessment period was considered feasible for comparisons with an average percentage difference of 1.4% and 2.3% respectively. Implementation results reveal that by performing a morning and evening ice melt, an average chilled water temperature increase of 0.4°C was recorded. Although the temperature of the chilled water increased, it was considered negligible. The maximum temperature experienced throughout the assessment period occurred proceeding the evening ice melt, reaching 3.9°C. Still within service delivery requirements. Compared to normal BAU operating conditions, the average BAC air outlet WB temperature increased by 13.6%, from 8.8°C to 10°C. Similar to that of baseline period 2, the increase in the average BAC air outlet temperature was attributed towards the mine switching off the BAC fans and pumping auxiliaries during Eskom's evening peak period. A maximum WB outlet air temperature of 13.4°C was recorded. Utilising ITS as a load management strategy on Mine P resulted in an 10.2% deterioration in service delivery requirements for baseline 3.

Table 16 reveals a 5.0% decrease in the pre-cooling sump temperature for the assessment period. As mentioned previously, this cannot directly be linked to the installation of the ice system. Due to the average increase in the chilled water temperature circulating the system, one would expect the pre-cooling sump to follow suit. When compared to baseline conditions, it is worthwhile to mention that the return water flow from the BACs was on average 1 l/s more during the assessment period. Conducting a simple mass balance across the pre-cooling sump, accounting for all the water inflows, outflows and corresponding water

temperatures, an almost negligible impact is attained. Considering the flow received from underground and the BAC sump is significantly large, approximately 450 l/s and 192 l/s, introducing an extra 1 l/s chilled water flow from the BACs has little to no impact on the overall temperature of water stored in the pre-cooling sump. Therefore, a reduction in the pre-cooling sump temperature is attributed towards uncontrollable variables underground, influencing the temperature of return water sent to surface.

Due to the reduction in the approach temperature of water feeding the Hitachi chillers (pre-cooling sump temperature), a reduction in chiller performance was recorded. Post-implementation results reveal an average reduction in the Hitachi chillers COP of approximately 3.9%. Conversely, as mentioned previously, an ever so slight improvement in efficiency of the ammonia chillers results due to both the morning and evening extended ice melts. Receiving a higher approach temperature allows the ammonia chillers to ramp up, improving the temperature difference across the evaporator, subsequently improving the plants COP.

As a result of a decrease in the temperature difference between the pre-cooling sump and surface chill dam, the same number of operational chillers between the baseline and assessment period, and the addition of an ITS system consuming a significant amount of energy for the majority of the day, the global COP of Mine P's cooling system decreases by 21.4%.

Table 44: Summary of baseline period 3 implementation results - baseline and assessment period

Description	Baseline period 3				
	Minimum	Maximum	Average		Percentage error [%]
			Baseline	Assessment	
Overall system power [kW]	540.9	10 442	8 638	8 308	3.8
Average daily energy consumption [MWh]	-	-	207.3	199.4	3.8
DB Ambient air temperature [°C]	12.3	30.7	21.3	21.6	-1.4
WB Ambient air temperature [°C]	9.5	16.2	13.0	13.3	-2.3
Hitachi chillers utilisation [-]	3	3	3	3	0
Ammonia chillers utilisation [-]	3	3	3	3	0
Surface chill dam temperature [°C]	1.5	3.9	2.4	2.8	-16.7
Surface chill dam level [%]	75.1	89.5	42.3	80.4	-90.1
Pre-cooling sump temperature [°C]	10.7	15.2	14.0	13.3	5.0
Pre-cooling sump level [%]	54.9	96	41.0	78.2	-90.7
BAC air outlet WB temperature [°C]	7.9	13.4	8.8	10.0	-13.6
Combined Hitachi chillers COP [-]	3.9	5.3	5.1	4.9	3.9
Combined ammonia chillers COP [-]	2.02	4.6	3.3	3.4	-3.0
Total daily volume of water received by the surface chill dam [Ml]	-	-	46.13	45.94	0.4

Global system COP [-]	1.4	3.1	2.8	2.2	21.4
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Analysing Table 45, illustrating the ITS system characteristics for baseline period 3, it is apparent that if it weren't for the extended ice melts, the ice system would have struggled to capitalise on a complete peak period load shift. In preparation for the morning and evening ice melts, the ice plant was operational for an average of 17 hours of the day throughout baseline period 3. Factors such as a decrease in the ice building time, a reduction in the cooling capacity of the ice plant throughout midday when compared to night-time operation, and an increase in pre-cooling sump temperatures towards the end of the day resulted in a shorter ice melt during the evening peak period. This is confirmed when comparing the morning ice melts resultant ice dam outlet temperatures to that experienced during the evening. The morning ice melt achieved an average ice dam outlet temperature of 4.4°C, whereas, the evening ice melt averaged at 5.1°C.

Table 45: ITS system characteristics - baseline period 3

Description	Baseline period 3			
	Morning ice melt	Extended melt	Evening ice melt	Extended melt
Charging time [hh:mm]	09:04	-	08:02	-
Duration of ice melt [hh:mm]	01:43	00:39	01:21	00:25
Ice plant COP during ice building process [-]	3.4	-	3.3	-
Flow of water through the ice dam [l/s]	480		445	
Ice dam outlet temperature [°C]	Minimum = 1.4	Maximum = 9.6	Minimum = 1.8	Maximum = 9.8
	Average = 4.4		Average = 5.1	

Implementation results – Baseline period 4

Table 46 summarises the operational impact proceeding ITS implementation on Mine P. Based on comparable boundary conditions, namely the ambient air DB and WB temperatures, the selected assessment period revealed no considerable difference when compared to baseline conditions. The average percentage DB and WB temperature difference is 6.3% and 4.9% respectively. The implementation results in Table 46 reveal no significant operational performance change due to the implementation of an ITS system. On average, the surface chill dam temperature increases by 3.6%, or 0.1°C. A maximum chill dam temperature of 3.3°C was recorded. Although the BAC outlet air WB temperature increases by 17.5% from 7.4°C to 8.7°C, it still remains well within temperature limits specified by mine personnel. Again, the maximum BAC air outlet WB temperature of 12.9°C is experienced during Eskom's evening peak period when the BAC fans and pumping auxiliaries are not operational. Analysing the impact on service delivery requirements, an 8.2% deterioration was revealed.

According to implementation results, it may be observed that the pre-cooling sump temperature increased on average by 1.1°C throughout the day. This inevitably resulted in an increase in the temperature difference across the evaporators of the Hitachi chillers. An average increase of 0.56°C was recorded. Intuitively, an increase in the temperature difference across the evaporator results in an improvement in chiller performance. From Table 46, the COP of the operational Hitachi chillers increase by 4.1% from 4.9 to 5.1. In conjunction to the increase in Hitachi chiller performance, the ammonia chillers revealed an improvement in COP of 2.6%.

Table 46: Summary of baseline period 4 implementation results - baseline and assessment period

Description	Baseline period 4				Percentage error [%]
	Minimum	Maximum	Average		
			Baseline	Assessment	
Overall system power [kW]	584.1	9 536	6 797	6 760	0.5
Average daily energy consumption [MWh]	-	-	163.1	162.2	0.5
DB Ambient air temperature [°C]	9.4	22.7	15.8	16.8	-6.3
WB Ambient air temperature [°C]	5.6	14.7	12.2	11.6	4.9
Hitachi chillers utilisation [-]	2	2	2	2	0
Ammonia chillers utilisation [-]	3	3	3	3	0
Surface chill dam temperature [°C]	2.4	3.3	2.8	2.9	-3.6
Surface chill dam level [%]	60.1	86.4	57.2	72.3	-26.3
Pre-cooling sump temperature [°C]	12.6	16.5	12.8	13.9	-8.6
Pre-cooling sump level [%]	40.2	95.9	59.2	71.2	-20.3
BAC air outlet WB temperature [°C]	4.1	12.9	7.4	8.7	17.5
Combined Hitachi chillers COP [-]	2.4	5.4	4.9	5.1	-4.1
Combined ammonia chillers COP [-]	1.6	5.6	3.9	4.0	-2.6
Total daily volume of water received by the surface chill dam [MI]	-	-	41.64	43.04	-3.4
Global system COP [-]	2.0	3.6	2.9	2.6	10.3

Analysing the overall average daily energy consumption, a slight decrease in energy usage proceeding ITS implementation was revealed. This implies that the energy shifted outside of Eskom's peak ToU tariff periods almost exactly matches that required to charge the ice dam during off-peak periods. Therefore, due to the successful execution of a double ice melt as depicted in Figure 71, the daily average energy usage is minimised. Since the average daily energy usage decreased by only 0.5%, the scaled baseline almost exactly mimics that of the original baseline, therefore, no SLA is required for baseline period 4. By achieving both a morning and evening peak period ice melt, an average hourly load shift of 5.6 MW and 5.8 MW is realised.

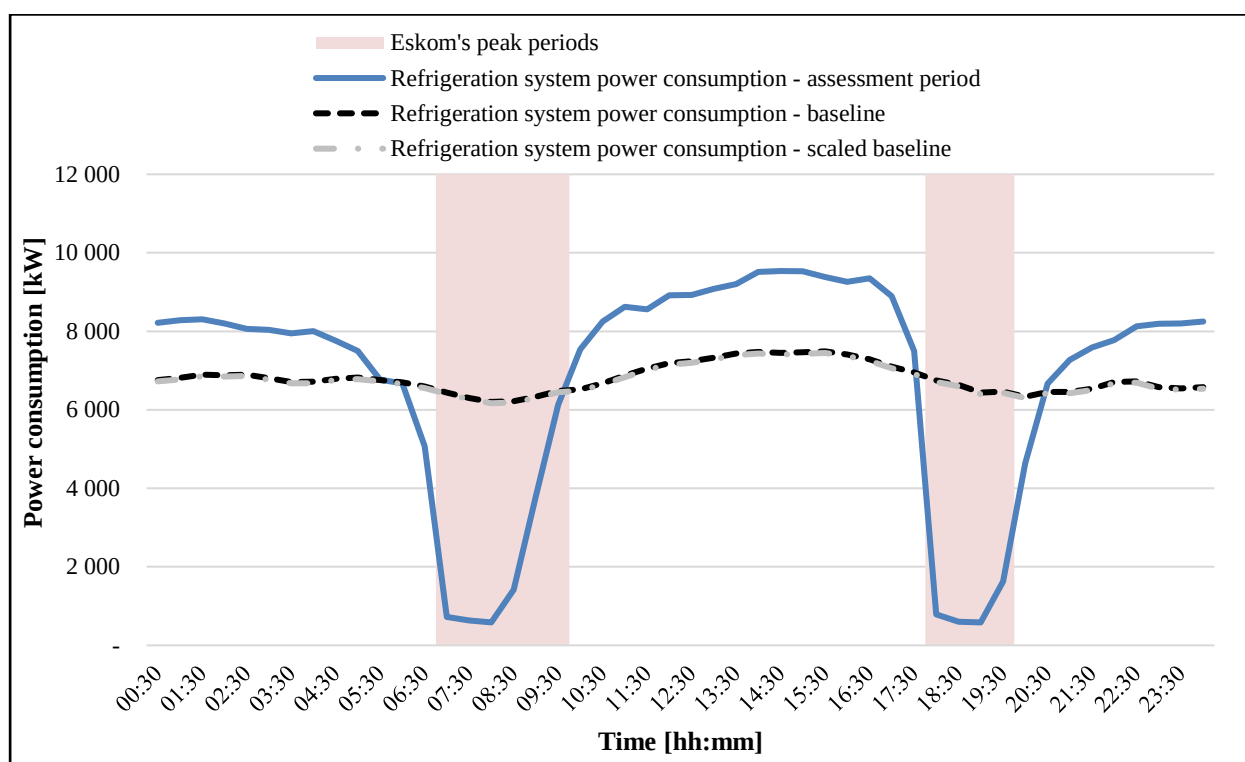


Figure 71: Refrigeration system power consumption - Mine P, baseline period 4

Table 47 reveals the ITS characteristics recorded for baseline period 4. To build the required amount of ice to enable a successful morning and evening peak load shift, an average of eight hours ice building was required. Therefore, the ice plant was operated for an average of 16 hours per day. Based largely on ambient temperature conditions, as expected the ice plant building COP is slightly higher compared to baseline periods 2 and 3, however, less than baseline period 1. A minimum ice dam outlet temperature of 0.8°C and 1.1°C was attained for the morning and evening peak ice melts. The evening ice melt resulted in slightly higher ice dam outlet temperatures with an average temperature difference of 0.4°C when compared to the morning ice melt.

Table 47: ITS system characteristics - baseline period 4

Description	Baseline period 4			
	Morning ice melt	Extended melt	Evening ice melt	Extended melt
Charging time [hh:mm]	08:01	-	08:01	-
Duration of ice melt [hh:mm]	01:56	00:40	01:46	00:26
Ice plant COP during ice building process [-]	3.5	-	3.4	-
Flow of water through the ice dam [L/s]	530		550	
Ice dam outlet temperature [°C]	Minimum = 0.8	Maximum = 8.6	Minimum = 1.1	Maximum = 9.9
	Average = 4.3		Average = 4.7	