

Cost savings on mine dewatering pumps by reducing preparation- and comeback loads

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ABSTRACT

Title: Cost savings on mine dewatering pumps by reducing preparation- and comeback loads
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Keywords: Electrical energy saving, demand side management, dewatering pumps, energy services company, Eskom

Using chilled water within South African gold mines is paramount to the purpose of extracting gold ore efficiently. Using water for cooling, drilling and sweeping and the release of underground fissure water causes the accumulation of vast amounts of water in underground dams. Deep mines use cascading pump systems for dewatering, which is an electrical energy intensive dewatering method.

Due to the recent equalisation of demand to generation capacity of electrical energy in South Africa, various methods towards demand side reduction have been implemented. With the introduction of a time-of-use (TOU) tariff structure by Eskom, the implementation of projects that shift load from peak TOU times to times of the day when electrical energy is less expensive has increased. To enable load shifting on mine dewatering pumps, preparation before and recovery after peak TOU is needed for effective results. This induces a preparation- and comeback load in the standard TOU.

With an annual increase in TOU tariffs and the rate of increase of standard TOU being greater than that of the peak TOU, a reduction in electrical energy consumption before and after peak TOU is needed. To enable this, a step-by-step control technique was developed to promote the shifting of load from standard- to off-peak TOU, while still realising a full load shift from peak TOU. This technique entails dynamic control ranges of underground dam levels as opposed to the conventional constant control range method.

Two case studies were used to test the developed technique. Results indicated significant additional financial savings when compared to conventional control methods. Additional savings of **R1,096,056.65** and **R579,394.27** per annum were respectively achieved for both case studies.

SAMEVATTING

Title: Kostebesparings op myn ontwateringspompe deur die vermindering van voorbereidings- en terugkeerlas

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Supervisor: Prof. M Kleingeld

Keywords: Elektriese energie besparing, aanvraagkant besturing, ontwateringspompe, energie diens maatskappye, Eskom

Die gebruik van verkoelde water in Suid-Afrikaanse goudmyne is uiters belangrik om gouderts doeltreffend te ontgin. Water wat benut word vir afkoeling, boor en vee, asook vrygelate ondergrondse water veroorsaak 'n opeenhoping van groot hoeveelhede water in ondergrondse damme. Vir diep myne word die elektriese energie-intensiewe metode van ontwatering deur pompstelsels gebruik.

Omdat die vraag na elektrisiteit en die opwekkingsvermoë in Suid-Afrika onlangs gelyk geword het moes verskeie metodes ontwikkel word en in werking gestel word om 'n verminderde vraag te handhaaf. Met die bekendstelling van 'n tyd-van-gebruik (TVG) tariefstruktuur deur Eskom het die inwerkingstelling van lasskuif projekte toegeneem. Om lasskuif op myn ontwateringspompe te handhaaf moet voorbereiding voor, en herstel na, die piek TVG gebeur. Dit veroorsaak 'n voorbereiding- en terugkeerlas in die standaard TVG.

As gevolg van die jaarlikse verhoging in TVG tariewe en 'n hoër toename in die tempo van standaard TVG ten opsigte van piek TVG is 'n vermindering van elektriese energie verbruik voor en na piek TVG benodig. Om dit te bereik is 'n stap-vir-stap beheertegniek ontwikkel om die verskuiwing van las van standaard- na buite-piektyd TVG te bereik terwyl 'n vol lasskuif vanaf piek TVG steeds gehandhaaf word. Hierdie tegniek behels die gebruik van dinamiese beheer van ondergrondse damvlakke in teenstelling met die gewone konstante beheermetolde.

Twee gevallestudies is gebruik om die ontwikkelde tegniek te toets. Hierdie gevallestudies het beduidende bykomende finansiële besparings in vergelyking met die gewone beheermetodes getoon. Bykomende besparings van **R1,096,056.65** en **R579,394.27** per jaar is onderskeidelik behaal op beide gevallestudies.

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All information portrayed in this dissertation was done acknowledging sources and referencing published work. Please inform me if any oversights are noticed by the reader so it can be rectified.

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NOMENCLATURE

Symbol	Unit	Description
C_v	-	Valve flow coefficient
E	J	Energy
g	m/s^2	Gravitational constant
h	m	Head
K_v	-	Valve flow factor
P	bar/kPa	Pressure
Q	m^3/s	Volume flow
t	hours	Time in hours
η	-	Efficiency
ρ	kg/m^3	Density

ABBREVIATIONS

3CPFS	Three chamber pipe feeder system
BAC	Bulk air cooler
C	Celsius
CL	Comeback load
DE	Drive end
DSM	Demand side management
ESCO	Energy services company
kPa	Kilopascal
kWh	Kilowatt-hour
m	Metre
MI	Megalitre
MCC	Motor control centre
MVA	Megavolt ampere
MW	Megawatt
MWh	Megawatt-hour
NDE	Non-drive end
NERSA	National Energy Regulator of South Africa
NL	Normal load
OCGT	Open cycle gas turbine
PID	Proportional integral derivative
PL	Preparation load
PLC	Programmable logic controller
PRV	Pressure-reducing valve
REMS-P	Real-time Energy Management System for Pumping
REMS-WSO	Real-time Energy Management System for Water Supply Optimisation
SCADA	Supervisory control and data acquisition
TOU	Time-of-use
ZAR	South African Rand

1 ELECTRICAL ENERGY



Figure 1: Power lines¹

(Figures with no academic contribution to this study will be referenced as footnotes and not in the bibliography)

¹ D. Schilling, "Electromagnetic Harvesters: Free Lunch or Theft!," *Industry Tap*, 2013. [Online]. Available: <http://www.industrytap.com/electromagnetic-harvesters-free-lunch-or-theft/1805>. [Accessed 18 May 2013].

1.1 ELECTRICITY IN SOUTH AFRICA

Eskom is the main supplier of electricity in South Africa with an estimated 95% of all electricity being used, generated by this utility company. With a maximum generating capability of about 41 000 MW, Eskom finds itself in the top twenty utility companies in the world regarding generation capacity [1].

Of Eskom's total generation capacity, coal-fired power stations provide the largest contribution at 85%. Liquid fuel turbines, hydroelectric stations, pumped storage schemes and nuclear power stations generate the remaining 15% of electricity [1]. The percentage of power generated by each source in South Africa is shown in Figure 2.

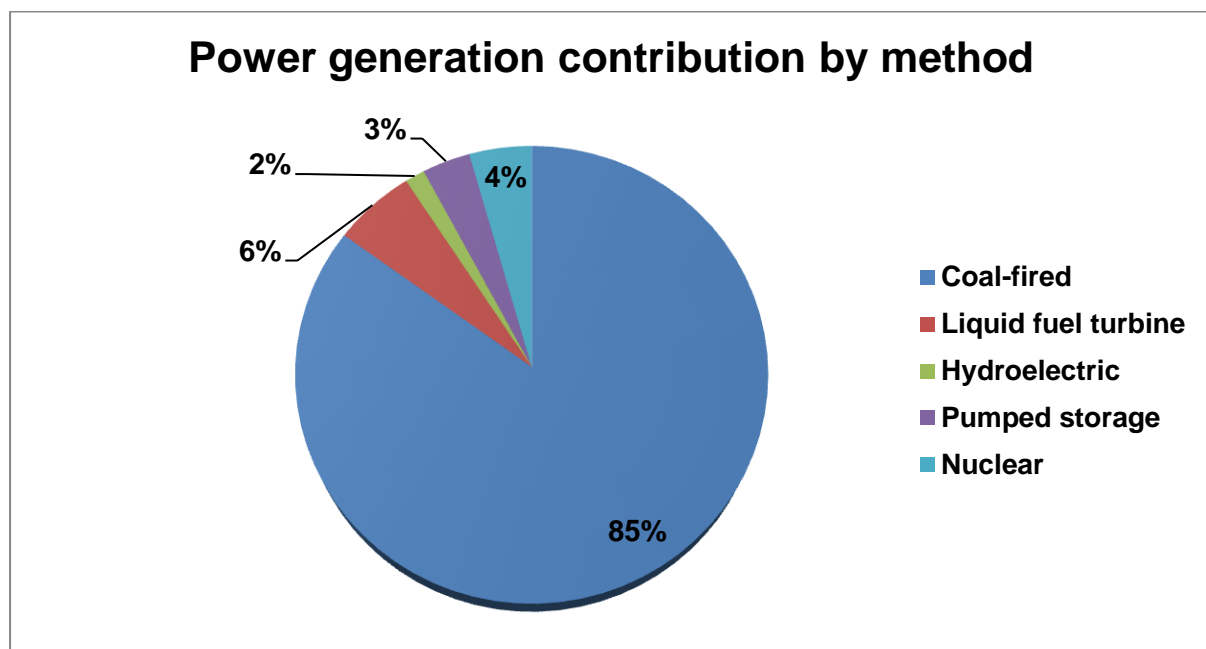


Figure 2: Contribution of power generation by source [1]

Coal burning is the most cost-effective method for generating electricity [2]. The low cost, together with South Africa's approximate 200-year coal reserve, makes it clear why coal-fired power stations contribute 85% towards the country's electricity generation [2].

Various South African and foreign customers use electricity generated by Eskom. Municipalities, which represent Eskom's largest customer base, use the most electricity (41%). The second and third largest electrical energy users in South Africa - industry (26.1%) and mining (14.5%) - represent a relatively low number of Eskom's clients and

therefore use an immense amount of electricity per operation [1]. Figure 3 displays the percentage of electricity used by customer type.

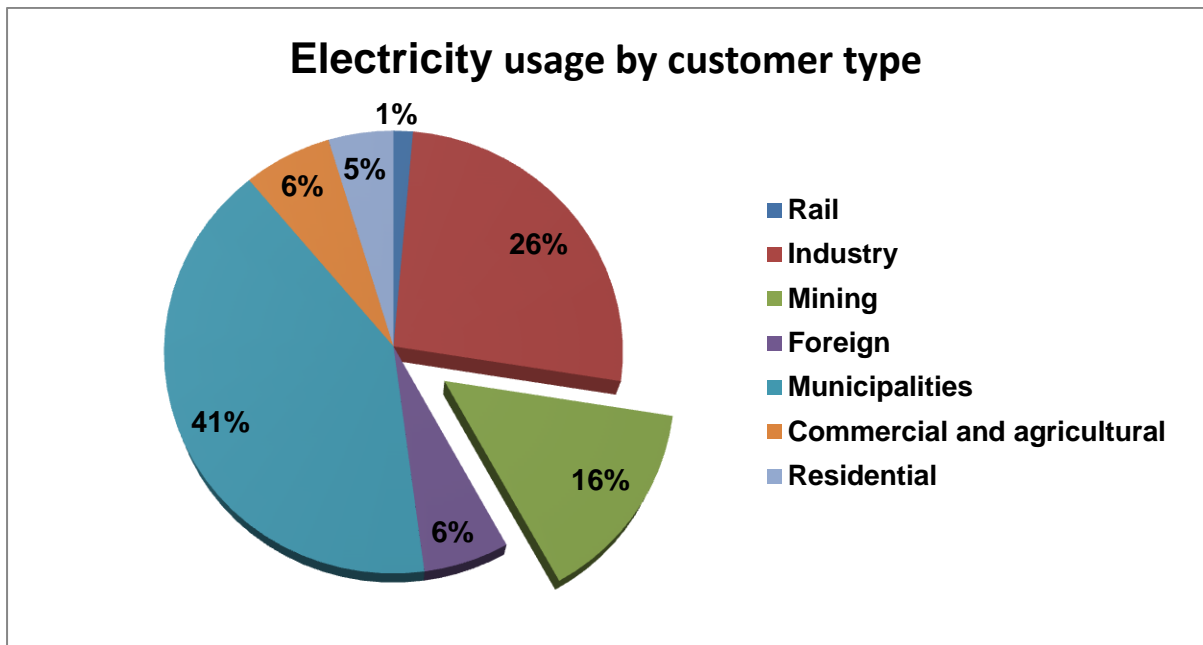


Figure 3: Electricity usage by customer type [1]

Due to the high electricity usage of industrial and mining companies, time-of-use (TOU) tariff structures were introduced by Eskom. These tariff structures are used to bill customers for electricity usage according to the amount of electricity used at certain times of the day. Megaflex is the tariff structure for customers who use a notified maximum demand of greater than 1 MVA. Industrial and mining companies typically fall within this clientele [3].

The Megaflex tariff structure charges consumers according to their usage in three TOU periods; namely peak, standard and off-peak times. Electricity cost (charged as c/kWh) changes on a time-of-day as well as a seasonal basis [3]. Figure 4 shows the current Megaflex tariffs for a typical gold mine within 300 km of Johannesburg, South Africa. From Figure 4 it is clear that during the months of June to August, Eskom increases tariffs drastically during the peak TOU for Megaflex customers.

The National Energy Regulator of South Africa's (NERSA) decision to allow an average annual tariff increase of 8% over the next five years will result in major electricity cost increases for all consumers [4].

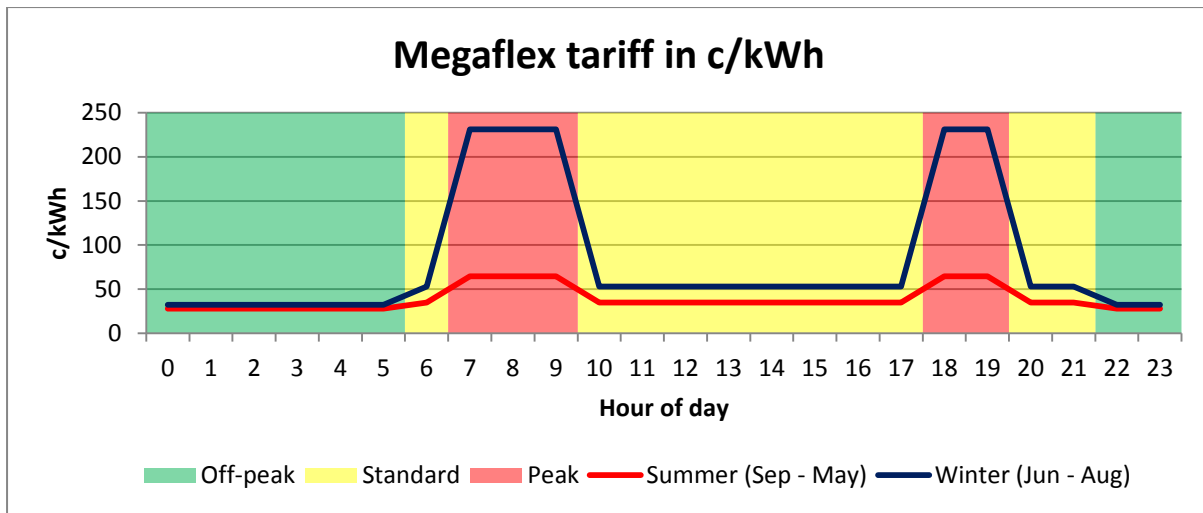


Figure 4: Megaflex tariff in ZAR c/kWh [3]

1.2 PEAK DEMAND

In the last decade it has become increasingly apparent that South Africa's electricity demand is approaching the total generation capacity of Eskom [5]. Peak times (07:00-10:00 and 18:00-20:00 on weekdays) are the most heavily affected and it was predicted that demand within these times would surpass the supply capacity during the winter of 2007 [6]. A solution was needed for Eskom to keep up with the demand. This solution had to have a short lead time to ensure swift addressing of the problem [6].

As discussed in Section 1.1 there are various methods of electricity generation. Building a new cost-effective coal-fired power station takes approximately 8-10 years [2], [6]. As the potential 2007 winter peak demand shortage was only forecasted as problematic in 2004, a different technology with a much shorter lead time was needed. A solution in the form of an open cycle gas turbine (OCGT) was identified [6].

Development of gas turbines began after the Second World War and was predominately used for advances in aircraft propulsion [7]. Today, however, there are many uses for gas turbines; one of which is power generation [8]. The shaft of a liquid-fuelled gas turbine is directly connected to a generator. As combustion occurs within the gas turbine and the shaft is rotated, the generator is turned and power is generated. Running at a low efficiency of 30-40% a substantial amount of heat and noise is released to the atmosphere during operation [9].

The decision to use OCGT technology was based on the following [6]:

- One to three year lead time.
- Technology is readily available.
- Proven track record.
- Numerous suppliers worldwide.
- Rapid start-up and shutdown times.

Construction of the first phase of Ankerlig and Gourikwa gas turbine power stations started in 2006 and was completed by June 2007. Phase two of both power stations was completed by early 2009. Fourteen gas turbine units using similar technology to the aviation industry were commissioned with a total output capacity of 2 072 MW [6].

1.3 DEMAND SIDE MANAGEMENT

Extensive load shedding took place in 2008 due to a postponed decision by the South African Government to allocate funds for a new power station. This was only realised in 2004 [10], [11]. Because of the substantial lead times associated with supply side strategies, such as the building of a new power station, an alternative solution had to be sought. One such a solution was demand side management (DSM) [12].

DSM is defined as an initiative taken to control and/or change the electricity usage of a client on the demand side. The first step in project-based solutions is investigating the potential for a DSM project. This is followed by planning and implementing an electrical energy savings strategy and finally monitoring the system for sustainability [13]. Funding for small DSM projects have been provided by Eskom since 1994; however, these projects did not have the potential to counter the imminent electrical energy crisis [14].

With substantial capital support from Eskom, 2003 saw the birth of larger DSM projects focussed on industrial demand [15]. Energy savings companies (ESCOs) registered with Eskom to gain access to the funds made available for DSM initiatives. An ESCO needs to identify and implement DSM projects and reach a predetermined savings “impact” that is usually determined by simulation models [16]. There are various ways of managing the electrical energy usage on the demand side. The three generally used initiatives are energy efficiency, load shifting and peak clipping.

Energy efficiency

By implementing an energy efficiency strategy, a client's average electrical energy consumed over a 24-hour time span is lowered [14]. An average hourly energy efficiency of 500 kW will result in an electrical energy reduction of 12 MWh over 24 hours. This reduction in energy will save the client money, as well as decrease the client's demand from the supplier (Eskom). Figure 5 shows the average 500 kW energy efficiency demand profile compared to the pre-DSM baseline.

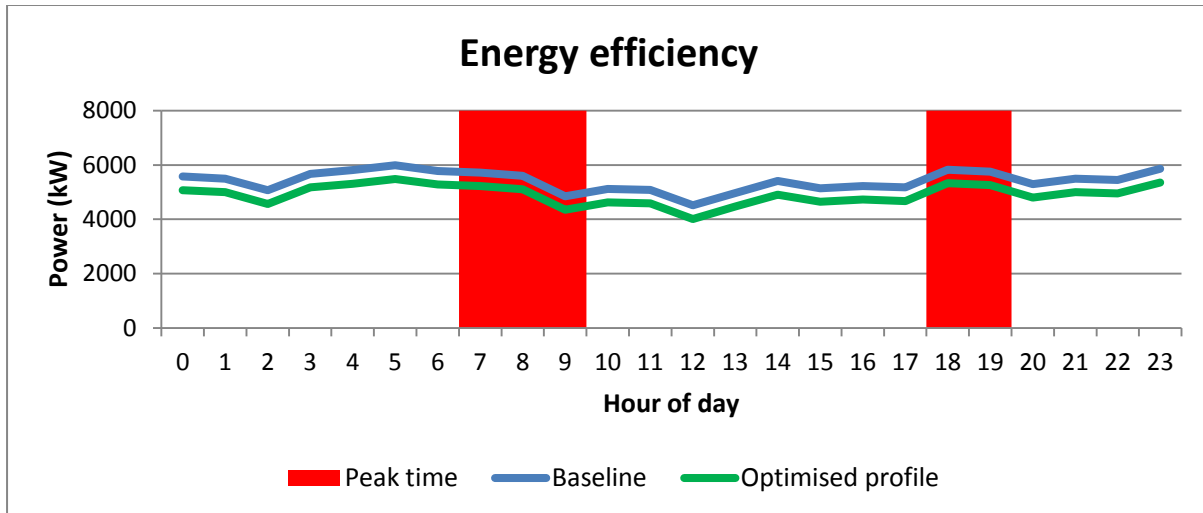


Figure 5: Energy efficiency

Load shifting

Since the TOU tariff structure was introduced by Eskom, clients billed according to these tariffs were motivated to use less electrical energy during high-cost peak hours. To decrease peak demand from industrial clients further, load shifting as a DSM possibility was introduced. The objective of load shifting is not to decrease the total electrical energy consumption as is the case with energy efficiency, but rather to “shift” or move demand load to the times of the day when national demand is lower [17]. Although client cost savings will be realised by implementing this strategy, the most important benefit will be that Eskom will have more capacity during peak times [18].

A 3 MW evening load shift and 2 MW morning load shift is shown in Figure 6. This represents an average demand reduction of 3 MW over the evening and 2 MW over the morning peak hours, or a total electrical energy shift of 12 MWh.

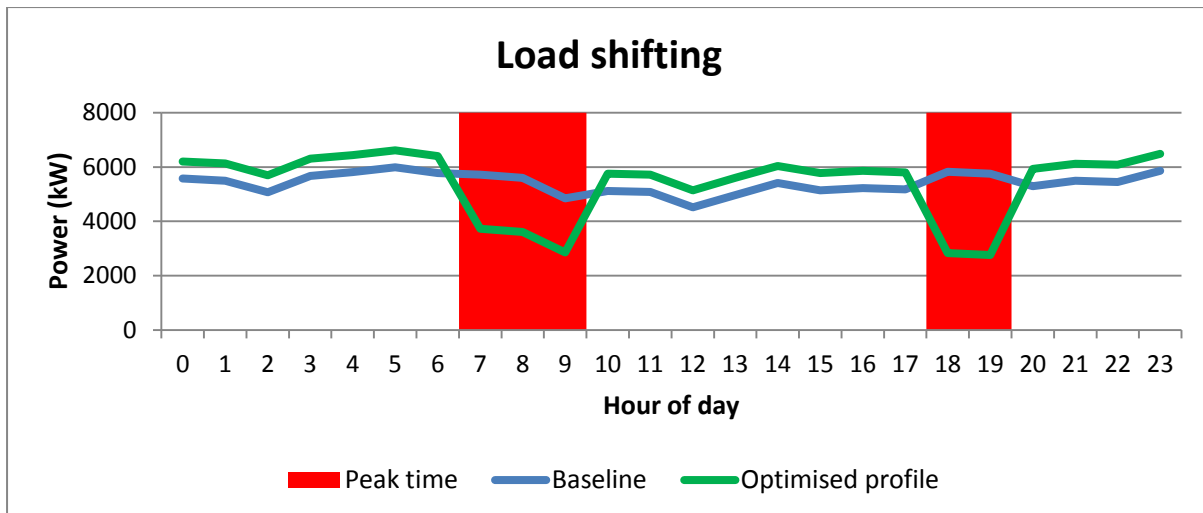


Figure 6: Load shifting

Peak clipping

By using a peak-clipping strategy, less electrical energy is consumed by the client. This is the same as an energy efficiency project but the reduction in electrical energy will only be made during peak TOU. Figure 7 shows a peak clip of 3 MW average over the entire evening peak; this represents an electrical energy reduction of 6 MWh during peak time.

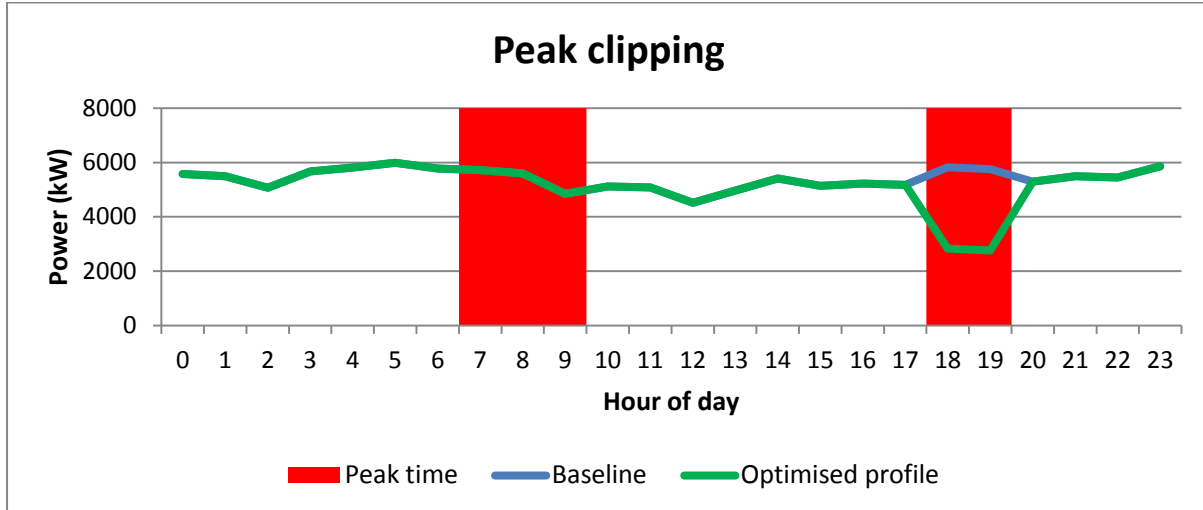


Figure 7: Peak clipping

1.4 MINING INDUSTRY ELECTRICITY USAGE

The mining industry contributes greatly towards South Africa's economic growth and exports [19]. This is made possible by the use of vast amounts of electricity for the day-to-day

operation of mines. A typical gold mine in South Africa will use between 100 GWh and 600 GWh of electrical energy annually [20].

With about 47% of the industry's total consumption, gold mines consume the most electrical energy within the mining industry of South Africa [16]. Mine water cooling, ventilation and underground pumping are the most electrical energy intensive systems on a mine and can contribute to more than 20% of the peak demand [21].

Cooling, ventilation and pumping are of great importance to a mine. Water is usually cooled by the use of large surface or subsurface fridge plants. This water is used for the cooling of air as well as the cooling of underground mining equipment. Subsequently, when cold water is used underground, the immediate surroundings are cooled. After mine water has been used, it needs to be pumped back to surface by large energy intensive dewatering pumps to prevent underground flooding.

1.5 PROBLEM DEFINITION

As the pumps used for mine dewatering purposes are energy intensive, a reduction in electrical energy usage throughout the day is required; but most importantly, during morning and evening peak demand times.

Load-shifting strategies for mine dewatering pumps have been successfully implemented on a number of mines in South Africa. The shifting of peak load to times of the day when electricity is less expensive has created new problems because industrial "peak demands" are created.

The increase in energy demand can be classified in one of two ways: the "preparation load" (PL) and the "comeback load" (CL). PL is an increase in energy usage to prepare a system (such as a mine dewatering scheme) for load shifting. As certain requirements in terms of underground dam levels are needed before load shifting can commence, aggressive pumping strategies are needed. The CL is encountered after the period of load shifting has been concluded. CL is caused by the need to bring the system back to normal operating conditions.

TOU standard time tariffs are significantly lower than peak-time tariffs. The following graph shows that the standard-time tariff increase exceeded the peak-time tariff increase over the past few years. This demonstrates that Eskom is starting to focus on a greater increase in standard time prices, which may counter the new PL and CL peaks associated with load shifting.

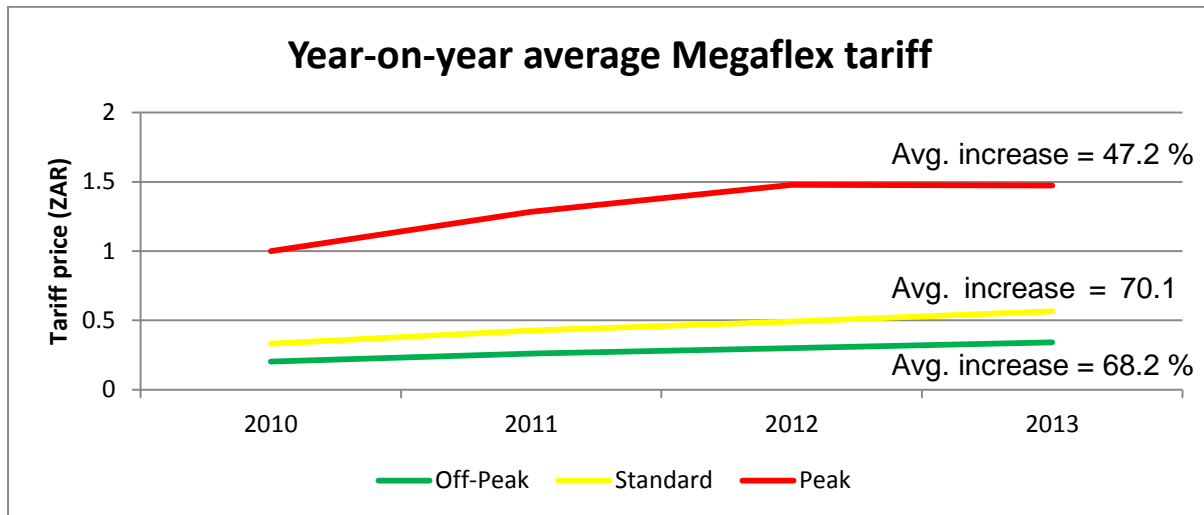


Figure 8: Year-on-year average Megaflex tariff (adapted from [3], [22], [23], [24])

With the majority of electrical energy used for the PL and CL encountered during late morning to late afternoon, a great amount of money is spent due to the existence of Eskom's TOU standard time tariff throughout this period.

1.6 STUDY OBJECTIVE

In order to meet the objectives of this study, the problem defined in Section 1.5 has to be addressed. With the implementation of load-shifting projects, great amounts of money are saved and demand is reduced during peak TOU. Although encouraging, the current cost savings can be further increased, particularly during standard TOU.

The objective of this study is to increase electricity cost savings on existing load-shifting projects. This will be done by reducing PL and CL during standard TOU. The reduction of PL and CL within system constraints will effectively decrease electrical energy usage during standard TOU and consequently fulfil the study objective.

1.7 STUDY LAYOUT

Chapter 1 – Electrical Energy

Chapter 1 serves as an introductory chapter. The background and a brief overview of electricity usage on South African mines are given. The need for the study and the objective are presented.

Chapter 2 – Mine Water Reticulation Systems

A literature study and review are conducted throughout the course of Chapter 2. Research focussing on the water reticulation system of a mine is presented, as well as critical reviews of previous similar studies.

Chapter 3 – Development of an Optimised Load Control Strategy on Mine Dewatering Pumps

The development of a step-by-step methodology with the purpose of meeting the study objective is discussed in Chapter 3. Knowledge obtained throughout the literature study and reviews of previous studies are used in this development.

Chapter 4 – Optimisation of Load-Shifting Projects on South African Gold Mines

Through the simulations and implementation of two case studies, the hypothesised method is tested and validated.

Chapter 5 – Conclusion and Recommendations

Chapter 5 describes the outcome of the study as well as recommendations for further work.

2 MINE WATER RETICULATION SYSTEMS



Figure 9: Dewatering pump²

² Cleveland-Cliffs Iron Company, "Plate No. 207: Worthington Centrifugal Pump & Motor - Barnes-Hecker Mine – Mechanical Dept.," *Mining Agents Annual Report, Ishpeming, Cleveland-Cliffs Iron Company, 1920, p. 699.*

2.1 FOREWORD

When viewing statistics for the peak-time electricity demand versus the supply capacity available from Eskom, it is clear that for the last few years the supply capacity has failed to increase proportionally to keep up with the ever-growing South Africa [1]. As discussed in Chapter 1, a substantial contribution towards electricity usage throughout the day comes from the mining industry and particularly from water reticulation systems. [1]. During the course of this chapter all aspects regarding water reticulation systems, as well as previous attempts to decrease electricity costs prompted by these factors, are discussed.

2.2 MINE WATER SUPPLY

The use of water in a South African gold mine is of great importance. Rock drilling, dust suppression and cooling use the majority of water in a mine [25]. Water consumption is approximately proportional to production rate and is supplied primarily to production areas within a mine [26].

There are various methods for supplying water to different areas in a mine. As mines become deeper, the need to break pressure is necessary for safe operation [27]. Water is typically gravity-fed from the surface, which can be up to 4 000 m above the working levels in a mine. With the pressure of water increasing roughly 1 000 kPa per 100 m of head, pressure needs to be broken by the use of turbines (for example Pelton wheels), cascade dams or pressure-reducing valves (PRVs) [27]. Water is most commonly supplied via cascading dams and shaft column water supply systems in South African mines.

In the cascading dam system, water is gravity-fed from surface to a starting dam from where it cascades down to dams on the other levels by means of overflowing. Service water is then fed to lower levels from the cascade dams. The required pressure on a level is provided by the head between the cascade dam and the level serviced by the dam [27].

The shaft column supply system operates by taking water from the column at different levels. PRVs installed in the levels are used to reduce the pressure to avoid danger [27]. The basic layouts of a cascade dam system and a shaft column supply system is presented in Figure 10.

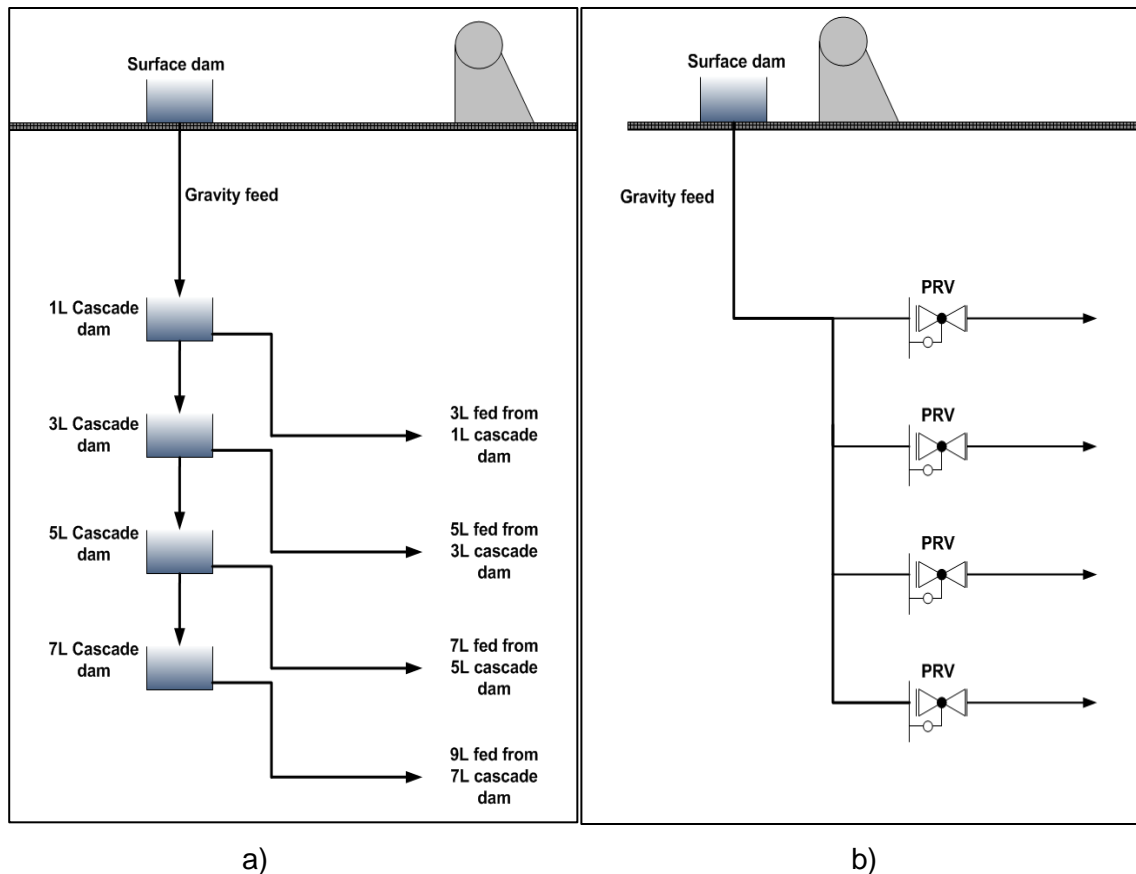


Figure 10: Cascade (a) and column supply (b) mine water supply systems (adapted from [27])

2.3 USES OF MINE WATER

2.3.1 COOLING WATER

Virgin rock temperatures increase nearly 12°C per kilometre due to geothermal energy. Cooling supplied by refrigerated water has therefore become increasingly important in deep gold mines. It is believed that mining depth limitations are imposed by cooling technology and the future of the development of cooling technologies [27], [28].

A gold mine's water reticulation system includes both the cooling of water and air. Water is cooled through the use of evaporative cooling or large refrigeration plants. Since ammonia has replaced chlorofluorocarbon refrigerants (such as Freon) the use of underground refrigeration plants has decreased due to the potential health hazard and causticity of the refrigerant [29].

Water is cooled using a standard vapour-compression cycle in fridge plants. A liquid refrigerant such as ammonia is compressed to a superheated vapour. The hot vapour moves through a

condenser where it is condensed with the use of cold water. Heat is rejected at this stage and is moved away by the water. The cooled condensate is then flashed over an expansion valve where a sudden reduction in pressure occurs. This reduction in pressure results in partial flash evaporation of the liquid refrigerant that radically lowers the temperature. The liquid-vapour mixture moves through an evaporator through which water is circulated. The water is cooled by rejecting heat to the refrigerant. After the evaporator, the refrigerant completes the cycle by entering the compressor again as vapour [30]. A basic layout of the vapour-compression cycle is illustrated in Figure 11.

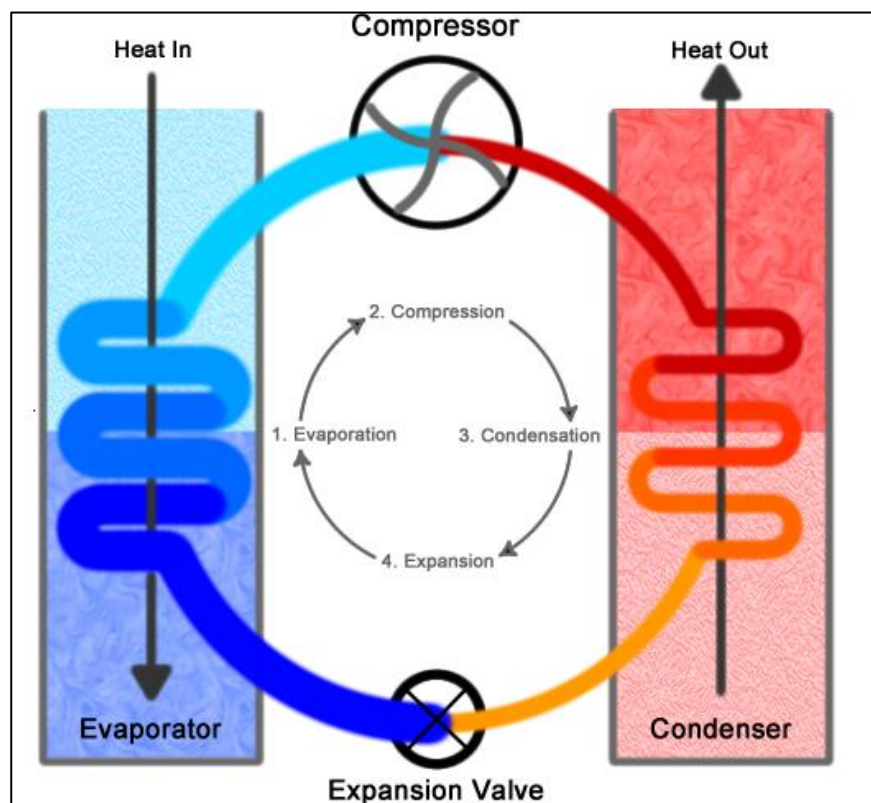


Figure 11: The vapour-compression cycle [31]

Water exits the evaporator at a cooled down temperature of about 2°C [32]. This water is pumped to “cold” dams where it is either gravity-fed as service water to underground mining levels, or pumped through bulk air coolers (BACs).

The required wet-bulb temperature of 27.5°C within South African mines is usually achieved by circulating ambient air from the surface [32], [33]. As mining development deepens beyond 700 m, the increase in temperature forces alternative cooling strategies, such as BACs, to be implemented [34].

Figure 12 shows a surface BAC. BACs are designed to keep the temperatures of shaft and near-shaft operations within an acceptable range [33]. Generally, and in most South African mines, secondary cooling has to be supplied by underground BACs due to considerable mining depths [34]. Underground BACs use cooled down service water and is located as close as possible to production areas or other areas where the cooling effect of primary surface BACs is not adequate [35].



Figure 12: Industrial size BAC³

A BAC cools air through evaporation. Water stored in “cold” dams are sprayed through a cooling tower where direct contact heat exchange takes place with ambient air forced through the tower by industrial sized fans [32], [36]. The air is cooled to between 6°C and 9°C; this air is then blown down either a main shaft or ventilation shaft [36].

2.3.2 SERVICE WATER

Service water is not used in BACs, but is sent down the mine to be used for additional cooling or various tasks within active mining areas (such as rock drilling and dust suppression) [32].

³ C. Cilliers, Personal photograph. "Bulk air cooler", Welkom, 2013.

The mean rate of face advance in a typical gold mine is five metres per month [37]. To achieve this, pneumatic drills have to be used to create blast holes for explosives. The drilling of these holes generates a great amount of heat and dust that can be harmful when inhaled by drill operators. Water is used to counteract this problem by cooling drill bits and suppressing dust within the immediate drilling area [29]. Both water and air are supplied to a drill via hoses that connects directly to a drill as can be seen in Figure 13. As pneumatic drills are often used, compressed air is expanded through an exhaust after powering the drill. This expansion of air acts as a refrigerant and cools the immediate area around the drill [38].



Figure 13: Drill operator with pneumatic drill⁴

After blasting has occurred, a large amount of ore and waste rock has to be moved. High pressure water jets are used to move the material to loadings stations. The pressure in service-water supply pipes is used to power the water jets. After being used at the rock face, all surface water accumulates in canals and flows to collection areas from where it flows to underground storage dams [27].

Cooling cars are used at working faces where primary cooling from surface BACs and secondary cooling from underground BACs do not reach. Chilled water is taken directly from service-water supply pipes and is moved through a radiator that expels cool air. This is known

⁴ D. Thompson, "Stream of molten gold signals return of large-scale underground mining to Calif.'s Mother Lode," *Times Colonist*, 17 December 2012. [Online]. Available: <http://www.timescolonist.com/news/world/stream-of-molten-gold-signals-return-of-large-scale-underground-mining-to-calif-s-mother-lode-1.30191>. [Accessed 22 October 2013].

as in-stope tertiary cooling within a mine and is commonly found in operations below 1 300 m [36]. A typical cooling car is shown in Figure 14.



Figure 14: Cooling car⁵

2.4 PROBLEMS WITH WATER SUPPLY

Because of the high pressures and flows encountered within mine water supply columns, and not to mention the underground conditions in a mine, various potential problems with water supply may arise. As discussed previously, water may be supplied via a single column or cascade dam system.

Pipe leaks (shown in Figure 15) are one of the most prominent problems that could be caused by high pressure and the lack of proper maintenance. High pressure leaks are commonly found between pipe flanges where worn gaskets are not able to hold back the force of water. Because this water was chilled by fridge plants on surface, a large amount of energy is subsequently lost through leaks. If maintenance is not done regularly, small leaks can increase in size until total failure of a water column occurs. As mine water is used for various purposes, not only a loss of energy, but also a total standstill of mining activities could result from total column failure [39].

⁵ M. E. (Pty.) Ltd., "Gallery," Manos Engineering (Pty.)Ltd., 2012. [Online]. Available: http://www.manos.co.za/gallery_original.html. [Accessed 25 April 2013].



Figure 15: Water leak⁶

Because of the increase in pressure as water moves down a column in a mine, water molecules tend to move closer to each other causing internal friction within the water. This phenomenon is known as the Joule-Thomson effect [40]. An increase in water temperature by as much as 2.33°C for every 1 000 m of head within a water column might be measured [41]. By breaking the water pressure with methods discussed previously, the heating effect will decrease and less energy will be required to cool the water again.

At mines where cascade dam supply systems are used, dam levels should always be kept above a minimum level to ensure adequate water supply throughout mining shifts. Inadequate planning during the design phases of a mine can result in a lack of capacity. This may lead to interventions in mining activities and will last as long as it takes for the affected dam in the cascade system to fill up again.

2.5 MINE WATER CONTROL

It is very important to control the amount of water that that goes down a mine. Pressure within water pipes caused by considerable head may result in great damage if the water is not

⁶ Abandoned Kasnsai, "Kasuga Mine B: Water Leak," Abandoned Kansai, 3 September 2012. [Online]. Available: <http://abandonedkansai.com/2012/09/03/kasuga-mine-b/water-leak/>. [Accessed 31 August 2013].

controlled properly [27]. There are different processes for controlling water to enable a safer working environment. A common method is the use of actuated valves [42].

General valve usage goes towards opening, closing and partial obstruction of a pipeline with a medium (such as water) flowing through it [43]. Valves can vary from simple flow obstructions to complex structures specially designed to strict specifications. The butterfly valve and the globe valve are common valves that represent both simple and complex constructions.

2.5.1 VALVE TYPES

Butterfly valve

The butterfly valve (displayed in Figure 16-a) consists of a valve body, a seat and a disc. The disc is located directly in the pipe through which the liquid flows. A shaft is situated through the disc and is connected to an actuator. When the disc is turned perpendicular to the flow, the valve will press against the seat and complete closure will be obtained. When the valve is opened entirely, the disc will be parallel with the flow. Because the disc restricts flow even when the valve is entirely open, a pressure drop will be observed regardless of valve position [44].

As minimum space is needed for installation, butterfly valves are popular among today's industrial water control applications [45]. The lightweight, simple design of a butterfly valve ensures a low pressure drop at larger valve openings and allows for good on/off control and throttling [46]. Due to the nature of the valve design, the pressure drop over a butterfly valve increases dramatically as complete closure is approached. This could cause problems such as cavitation [47]. Advances in valve geometry and design in conjunction with the advantages as mentioned before will strengthen the usability of butterfly valves for controlling purposes [48].

Globe valve

Unlike butterfly valves, the globe valve's construction is of a more complicated tortuous path type [49]. The main valve body consists of a round "globe"-like structure that is divided by an internal baffle. The obstruction of flow through the baffle is created by the use of a linear motion plug [50]. Because of this baffle-using construction, globe valves can be used for either on/off control purposes, as well as intricate and accurate flow control throughout the valve's travel range [43], [50]. The tortuous path of a globe valve is shown in Figure 16-b.

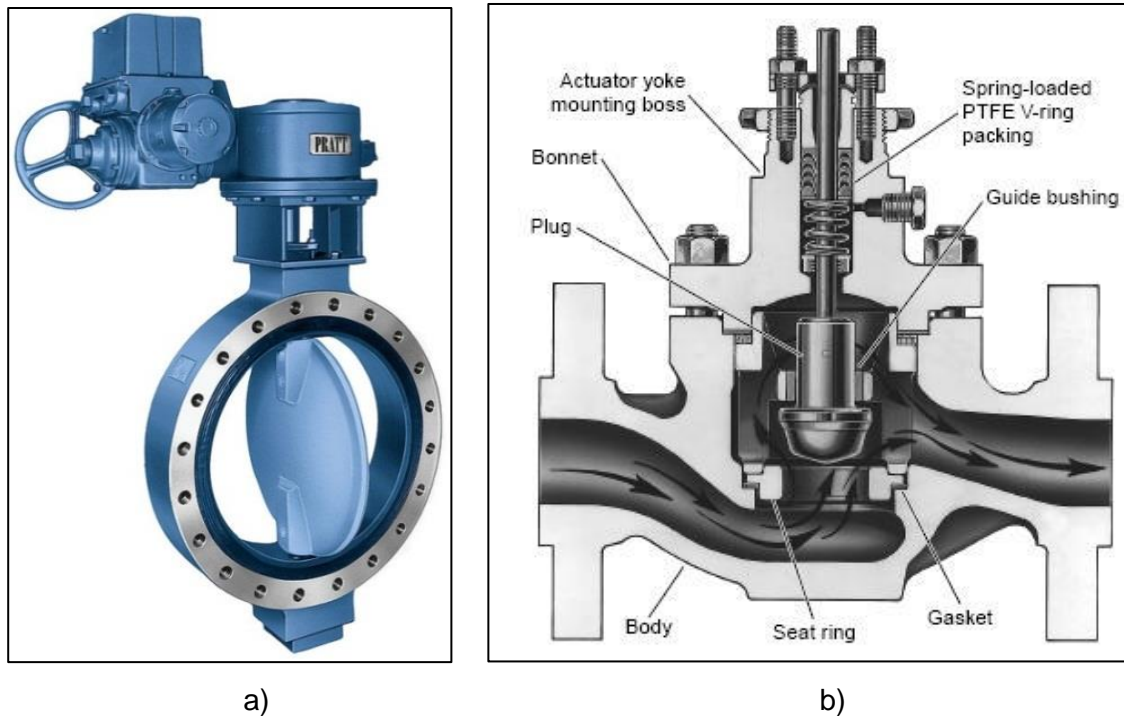


Figure 16: a) Butterfly valve⁷, b) Globe valve⁸

Figure 17 shows that globe valves have a considerably larger control range as opposed to butterfly valves [45].

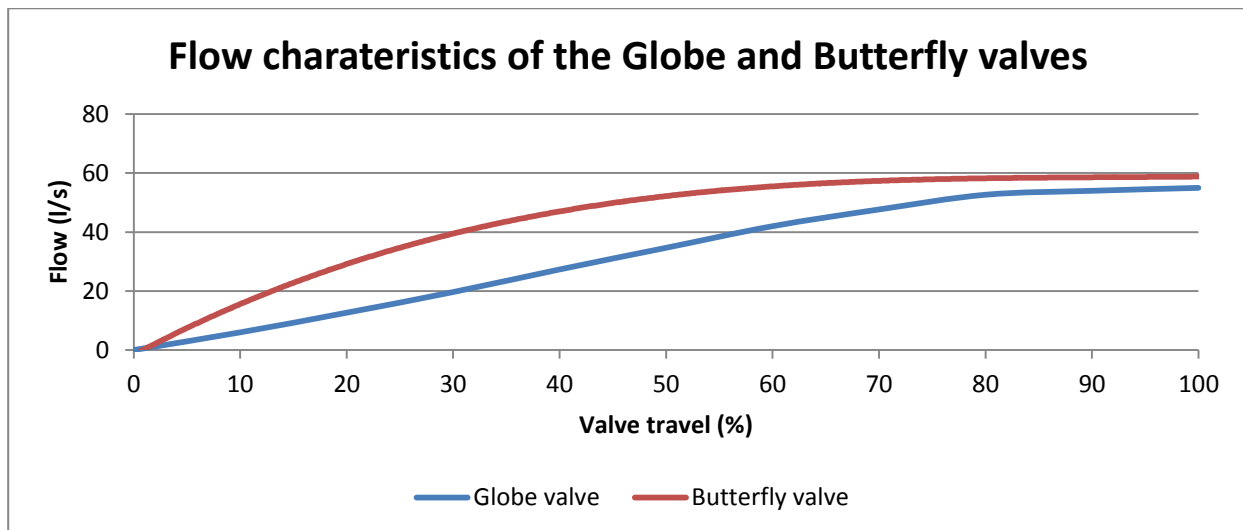


Figure 17: Flow characteristics of globe and butterfly valves (adapted from [45])

⁷ Power-Technology.com, "The Henry Pratt Company - Resilient Seated Butterfly Valves," The Henry Pratt Company, 2012. [Online]. Available: <http://www.power-technology.com/contractors/valves/henry-pratt/henry-pratt3.html>. [Accessed 2 May 2013]

⁸ Pump, Valve and Heat exchanger, "Control Valves," 25 October 2008. [Online]. Available: <http://pump-heat-exchanger.blogspot.com/2008/10/control-valves.html>. [Accessed 4 May 2013]

Specialised globe valves may have cages as part of the construction. The cage is situated within the baffle where the plug is inserted to regulate flow. Different flow characteristics such as linear flow, equal-percentage flow and quick-opening flow can be achieved by using these cages [45].

A valve with linear flow characteristics allows a flow rate that is directly proportional to the valve plug travel. This specification will be required if a very wide range of valve travel is needed with accurate flow control throughout the range. Cages providing equal-percentage flow allow for constant percentage changes of flow with equal increments of valve plug travel. This means that the increase in flow rate will be relatively low at near-seat plug travel and high at near-open plug travel. Quick-opening flow characteristics, as the name states, allows for maximum change in flow rate within the first 40-50% of plug travel. Thereafter, the curve of flow rate versus plug travel will flatten out [45]. The discussed flow characteristics are obtained by the cages as displayed in Figure 18.



Figure 18: Globe valve cages for different flow characteristics [45]

2.5.2 VALVE SIZING AND SELECTION

It is very important to select the correct size and type of valve for a particular application. The basic concept of obstructing or allowing flow is the same for all valves. The difference between valves lies in the obstruction method. The butterfly valve is used for simple isolation purposes where the flow needs to be stopped completely from time to time [48]. If more accurate and precise flow control is required, a torturous flow valve such as the globe valve may be used [50].

The first step while selecting a valve is to determine the service conditions that the valve needs to adhere to. These conditions include pressure drops, flows, temperatures and fluid properties [45]. Secondly, the optimum valve flow factor (K_v) needs to be calculated. The K_v indicates the relationship between the pressure drop over a valve and the flow through a valve [51]. A higher K_v value indicates that more flow is allowed through the valve. Because this characteristic plays an influential part in the physical capabilities of a valve, it is imperative that the K_v is calculated correctly. The K_v of a valve is calculated using Equation 1.

Equation 1: Valve flow factor

$$K_v = Q \left(\frac{\Delta P}{SG} \right)$$

With: K_v = Valve flow factor
 Q = Volume flow (m^3/s)
 ΔP = Pressure drop (bar)
 SG = Specific gravity (water = 1)

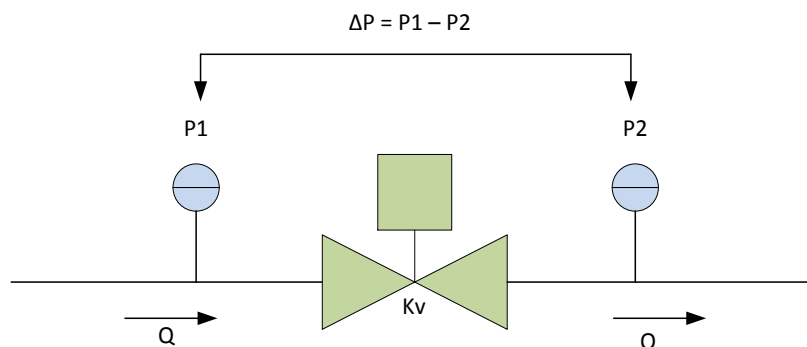


Figure 19: Control valve K_v calculation

It is a world standard to use the valve flow coefficient (C_v) for valve sizing and selection. This dimensionless characteristic of valves is the equivalent of K_v , but in imperial units as opposed to metric units.

The C_v to K_v conversion equation is:

Equation 2: C_v to K_v converter

$$K_v = 0.865 \times C_v$$

With: K_v = Valve flow factor
 C_v = Valve flow coefficient

Figure 20 shows the typical K_v of a valve as a function of its opening:

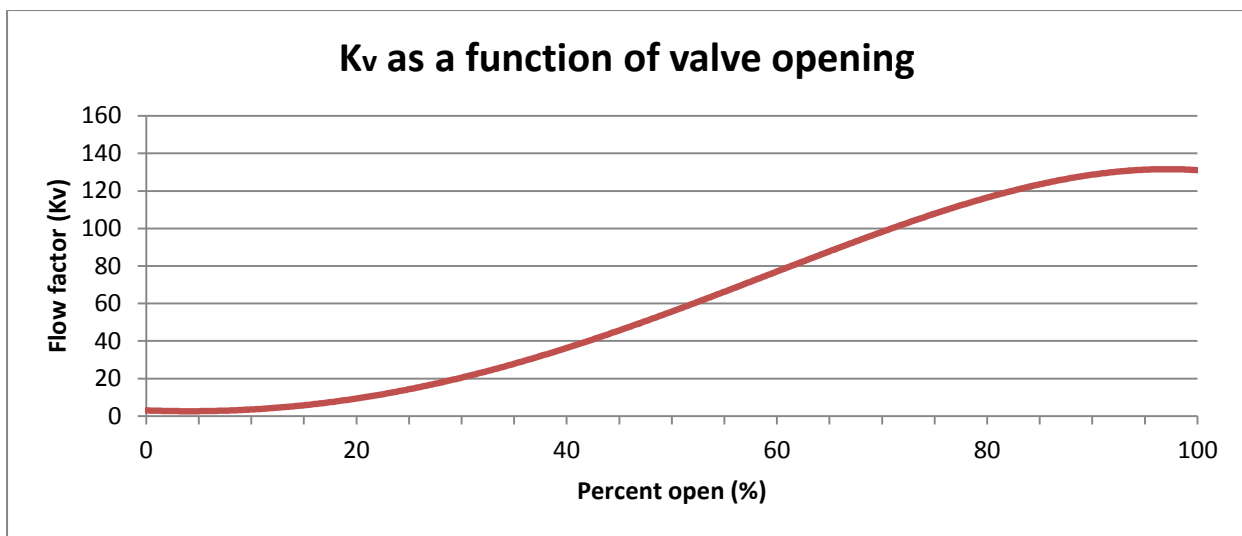


Figure 20: K_v as a function of valve opening (adapted from [51])

2.5.3 GENERAL VALVE PROBLEMS

Because of the high pressures and flows associated with the industrial usage of water, common problems related to valve control may occur. The obstruction in flow caused by valve discs or plugs may accelerate the water to a turbulent flow. This turbulence can cause unwanted noise and actually damage under-engineered parts of the valves [52].

Cavitation

Due to high flow velocities, liquid static pressure falls below the vapour pressure and vapour bubbles form; this is called cavitation [47]. Cavitation is one of the major problems associated with valve control. The downstream static pressure is typically higher than vapour pressure resulting in implosion of the vapour bubbles. When this happens, great pressure is

concentrated on a very small area and generates shock waves that destroy the valve trim [47]. Studies have shown that rough surfaces are most susceptible to cavitation [53]. A decrease in cavitation might be realised by using smoother surfaces within the valve body. Cavitation damage on a plug and a cage is shown in Figure 21.

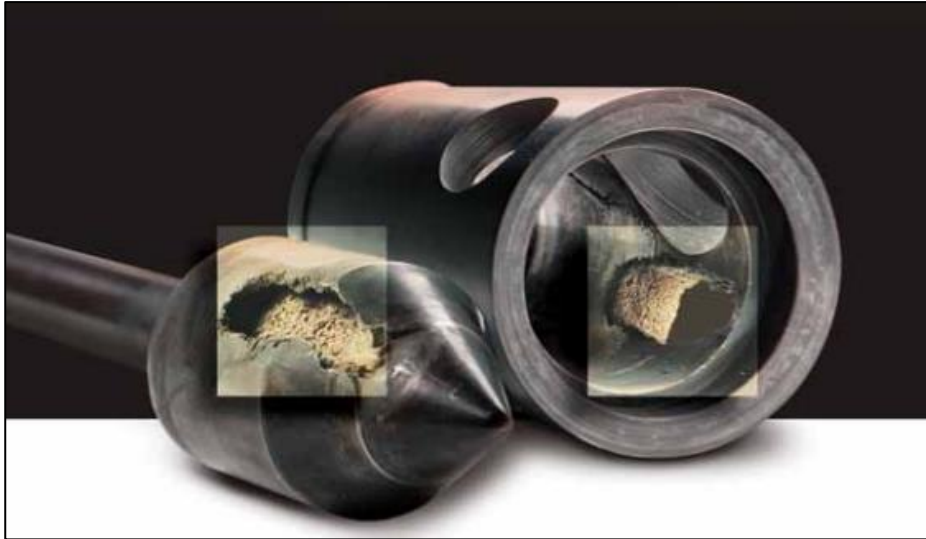


Figure 21: Cavitation on a plug and a cage⁹

Water hammer

The sudden closure of a valve may result in a phenomenon known as water hammer. When a valve is closed abruptly, the conservation of the fluid's momentum results in motion being converted into pressure [54]. This change in pressure results in a shock wave that propagates through the water column [55]. Water hammer can be very harmful to any in-column instrumentation or components and may lead to column separation [56]. Column separation occurs when water columns are physically destroyed and are rendered useless due to extreme high pressure waves [57]. Physical damage due to water hammer is shown in Figure 22.

⁹ Emerson Process Management, *Fisher Cavitation: Control Technologies, Marshalltown: Fisher - Emerson Process Management, 2011.*

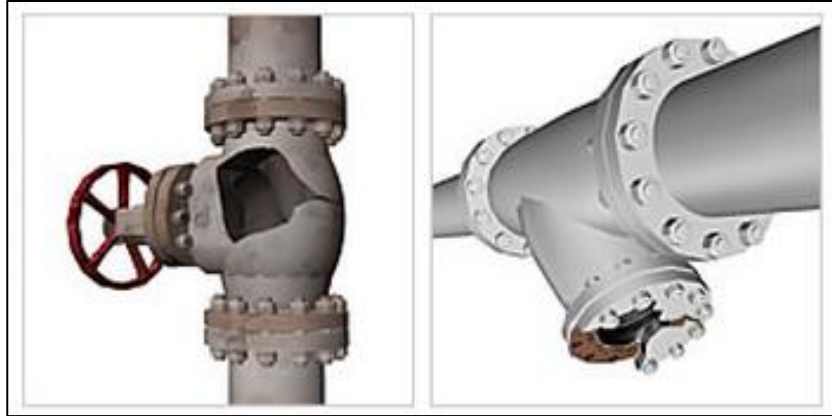


Figure 22: Water hammer damage on columns¹⁰

2.5.4 WATER CONTROL INSTRUMENTATION

Actuators

To move or actuate a valve, in other words to prompt flow obstruction, an actuator is needed. Actuators can vary from manual wheels connected to a gearbox, to electric or pneumatic actuators that are automatically triggered. Electric actuators consist of a motor and an actuator housing. The motor is connected to a pinion gear that generates enough torque to rotate a gear train [58]. If radial actuation is needed, as in the case of a butterfly valve, the gear train simply rotates a shaft connected to a disc. For axial movement needed to operate a globe valve plug, a worm gear is driven by a gear train [59].

Pneumatic actuators convert pressure into movement by using air cylinders [60]. Radial or axial movement of pneumatic actuators is achieved through the same principles as discussed before. Because of the simple and lightweight design, as well as the abundance of compressed air, the most widely used actuator for mining purposes is the pneumatic actuator [61].

Pressure transmitters and flow meters

Control valves are typically used to achieve certain down- or upstream conditions. Generally, a flow or pressure requirement is needed and is communicated to a valve positioner and an actuator through a set point. The set point will indicate that an increase or decrease of flow or pressure is necessary. In order for required set points to be met, positioning equipment will change valve positions according to the in-column measuring instrumentation.

¹⁰ TLV, "What is Water Hammer/ Steam Hammer?," TLV, 2013. [Online]. Available: <http://www.tlv.com/global/TI/steam-theory/what-is-waterhammer.html>. [Accessed 6 May 2013].

There are numerous types of flow meters available on the market today. One of the most accurate flow meters (with an error approaching $\pm 0.05\%$) is the electromagnetic flow meter [62]. The electromagnetic flow meter (shown in Figure 23) is a nonintrusive instrument that uses fluid mechanics and electromagnetism to calculate flow [63], [64]. A magnetic field is created by energised coils around the water column. A voltage is generated when water flows through the magnetic field. The voltage is directly proportional to the flow rate [65].

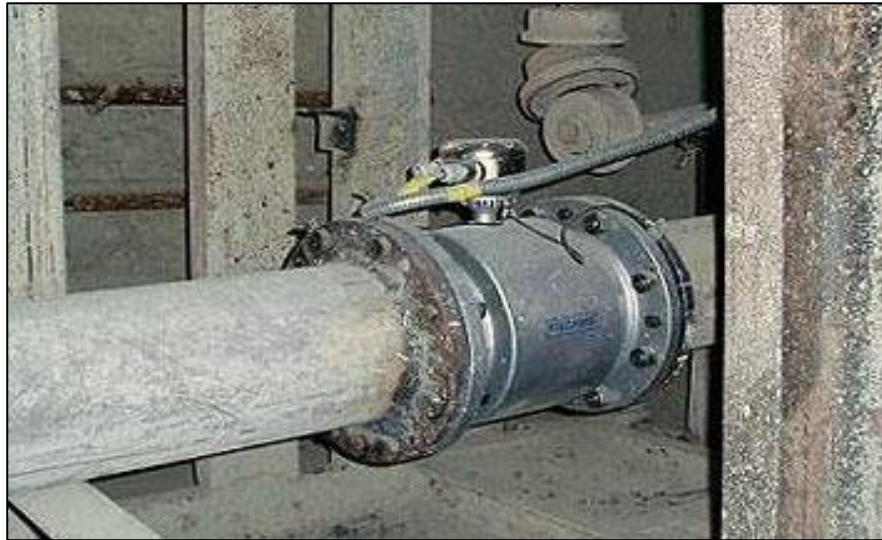


Figure 23: Electromagnetic flow meter¹¹

Pressure sensors convert pressure into displacement through the movement of an elastic sensing element. This displacement is converted into an electrical signal that is presented as a numerical value for reading pressure [66]. When a reading is transmitted to a remote location such as a control room, the pressure sensor is referred to as a pressure transmitter [67]. Good accuracy is imperative for optimal and safe valve control [66].

All signals to and from pressure transmitters, flow meters and valve actuators are controlled by a programmable logic controller (PLC). A PLC uses digital and analogue inputs and outputs to send set points, retrieve measurements and read feedback values from instrumentation [68]. Most of the mining and auxiliary processes found on a South African gold mine are controlled by PLCs. The introduction of PLCs led to greatly accelerated progress in industrial applications and industrial automation [69].

¹¹ Krohne, "Krohne: Process Control and Industrial Instrumentation, Flow and Level Measurement," *Mining Technology*, 2012. [Online]. Available: <http://www.mining-technology.com/contractors/controls/krohne2/krohne22.html>. [Accessed 7 May 2013].

2.6 DEWATERING

In order to prevent flooding, water sent down a mine must be removed to the surface. This includes service water used for mining purposes as well as cooling water. In some circumstances, depending on geology and the movement of the earth's crust, water can accumulate in subsurface cracks and fractures; it is then called fissure water [70].

Fissure water released by mining operations needs to be channelled to underground accumulation dams together with mining and cooling water. Data analyses have shown that in some cases fissure water can have a constant flow of as much as 100 l/s into the water reticulation system. This flow was also confirmed by mine personnel. Figure 24 shows the dewatering scheme of a mine water reticulation system.

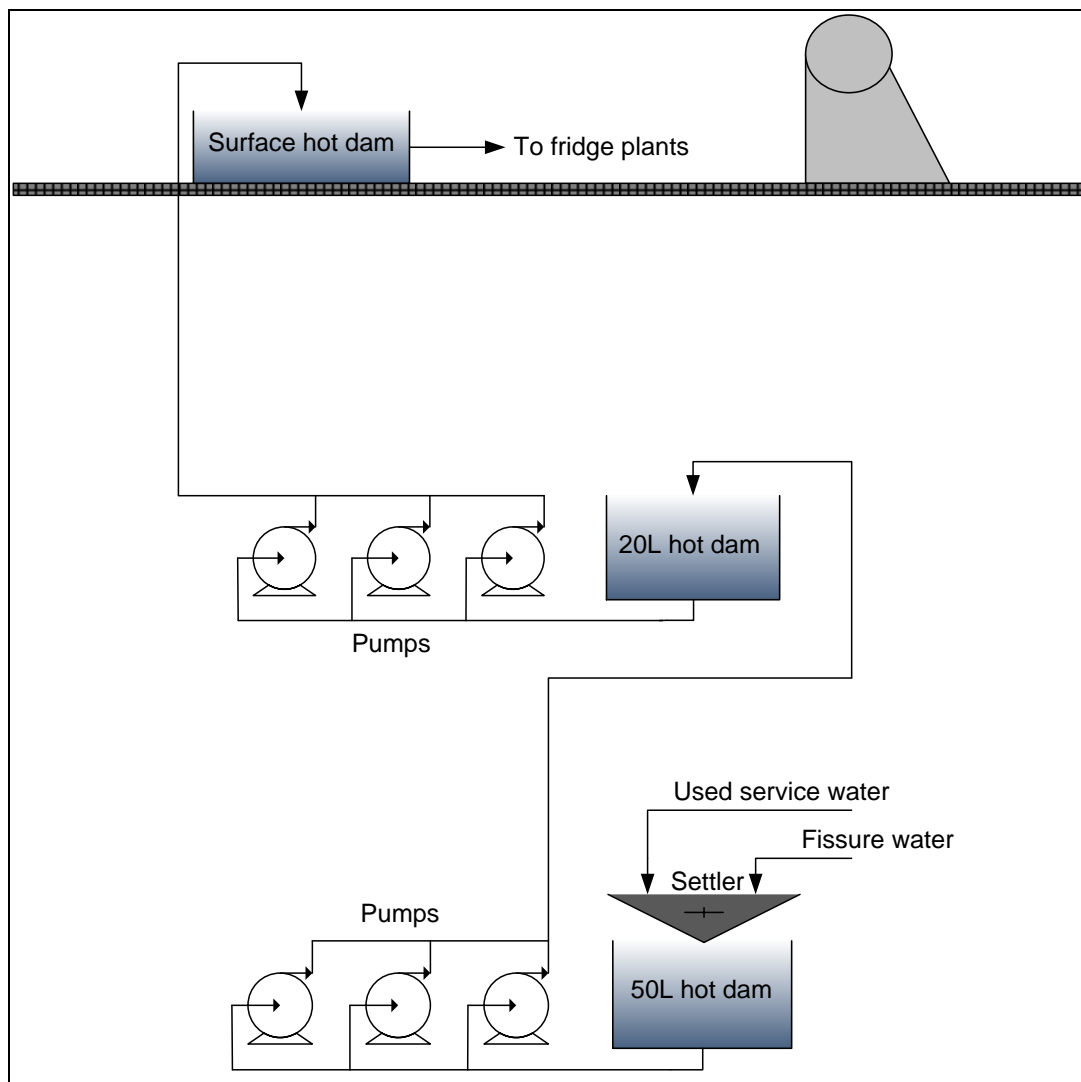


Figure 24: Dewatering system

2.6.1 SETTLERS AND CLEAR WATER DAMS

The accumulation of all service, cooling and fissure water is the first step in the dewatering of a mine. Due to dust and rock particles within the water, separation is required before water can be removed from underground. Settlers serve this purpose and are widely used in extraction processes [71].

Flocculant is added as water enters the settler. Flocculant is a chemical that reacts with solid particles coming out of suspension and stick together to form larger particles [72]. Due to gravitational forces, large particles descend to the bottom of a settler as sediment [73]. The sediment (known as “sludge”) is drawn off at the bottom of the settler into mud dams from where it is pumped to the surface for mineral extraction. Water separated from the particles (known as “clear water”) spills over the settler into columns where it flows into clear water dams.

Clear water dams have large capacities to ensure that water can be stored before removal from underground is required. According to mine personnel, a typical cylindrical clear water dam can have a diameter of 12 m and a height of 33 m. This translates roughly to a volume of 3 730 m³ (3.73 M l). A dam with such a substantial vertical height is commonly built with the intention to provide enough head pressure for the suction side of dewatering pumps. It must be noted that underground clear water dams must be built in areas free from fissures or cracks to prevent possible structure failure [74].

Generally, more than one clear water dam is built at a single location within a mine to have enough storage capacity in the event of dam cleaning. Although settlers extract most of the sludge from water, a fair amount still escapes into clear water dams. This sludge settles at the bottom of the dams and can cause damage to pumps as well as lower the storage capacity of a dam. The presence of sludge in clear water dams forces a minimum level limit that cannot be passed.

2.6.2 DEWATERING PUMPS

The most common method for dewatering a mine is by using dewatering pumps [75]. Pump stations (housing anywhere from two to twelve pumps) are found in close proximity to clear water dams within a mine. By using a cascading approach, clear water is pumped from the lowest dam in a mine to dams on upper levels from where it is pumped to the surface.

Although the most economical vertical distance between pump stations is 600 m, it is not uncommon for pumps to be able to move water to a head of more than a 1 000 m [29]. This is especially true for deep South African gold mines.

The most common pump used for dewatering purposes is the centrifugal pump [76], [77]. The key purpose of a centrifugal pump is to convert electrical energy from a motor to kinetic energy; the kinetic energy is then converted to pressure energy. Kinetic energy is converted from electrical energy by rotating an impeller within a pump. The kinetic energy within the water forces the water centrifugally outward against the pump diffuser. At this stage, kinetic energy is converted to pressure energy and forces the water through the pump's discharge [78].



Figure 25: Mine dewatering pump station¹²

Due to the considerable vertical distance that water needs to be pumped, multistage centrifugal pumps are used. The multistage centrifugal pump uses separate pressure increasing stages to deliver a maximum final discharge pressure. A suction intake, impeller, volute or diffuser and discharge outlet form one stage. In Figure 26 the head increasing stages within a multistage centrifugal pump can be seen.

¹² C. Cilliers, Personal photograph. "Dewatering pump station", Welkom, 2013.

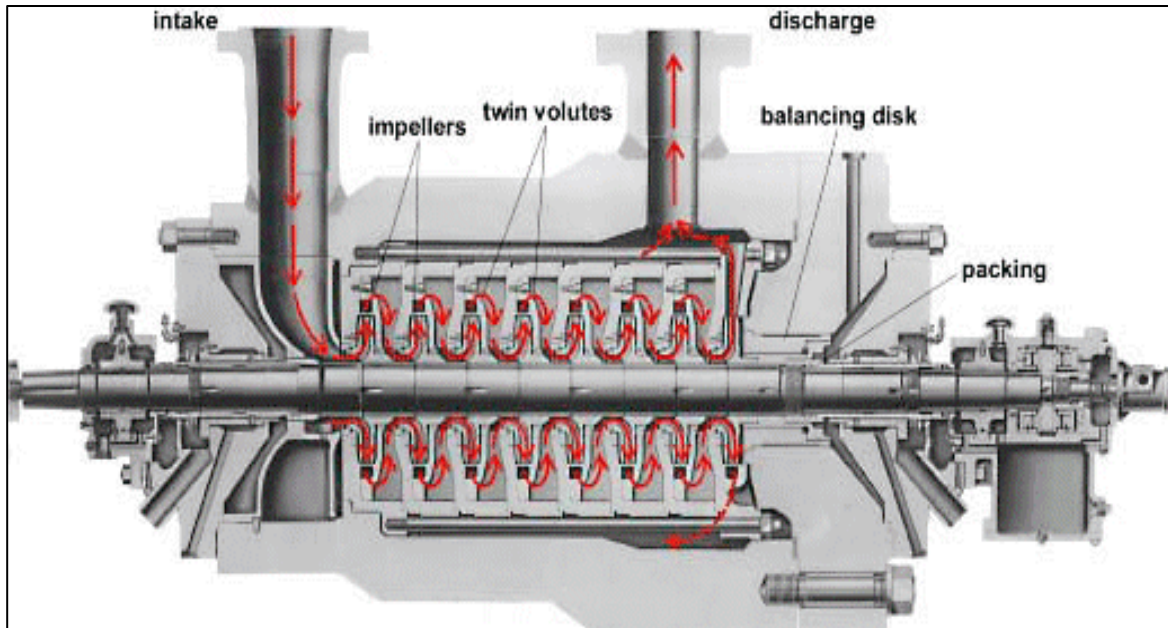


Figure 26: Multistage centrifugal pump¹³

Dewatering pumps are operated in parallel while discharging into a common manifold for maximum flow delivery [79]. Although flow increases when more than one pump is used, limitations arise due to the maximum flow and pressure allowed by certain column sizes. If more than one pump discharges into a common manifold, discharge pressure and flow will increase up to a certain point, but the efficiency of the pump set will decrease. As shown in Figure 27, when the maximum flow allowed by a column is reached, flow gained by the starting of another pump will be negligible. The system efficiency will drop and the total flow will stay the same.

A certain amount of electrical energy (in kWh) is required to pump water. Theoretically the energy to pump a liquid at a given flow, head and duration can be calculated using Equation 3 [80].

¹³ E. Wright, "Access Science: Centrifugal Pump," McGraw-Hill Education, 2013. [Online]. Available: <http://www.accessscience.com/overflow.aspx?SearchInputText=Centrifugal+pump&ContentTypeSelect=10&term=Centrifugal+pump&rootID=791293>. [Accessed 20 May 2013].

Equation 3: Calculation of energy

$$E = \left(\frac{\rho \times g \times Q \times h}{\eta} \right) \times t$$

With: E = Energy (kWh)
 ρ = Density of fluid (kg/m³)
 g = Gravitational constant (m/s²)
 Q = Flow in (m³/s)
 h = Head (m)
 η = Efficiency of system
 t = Time (hours)

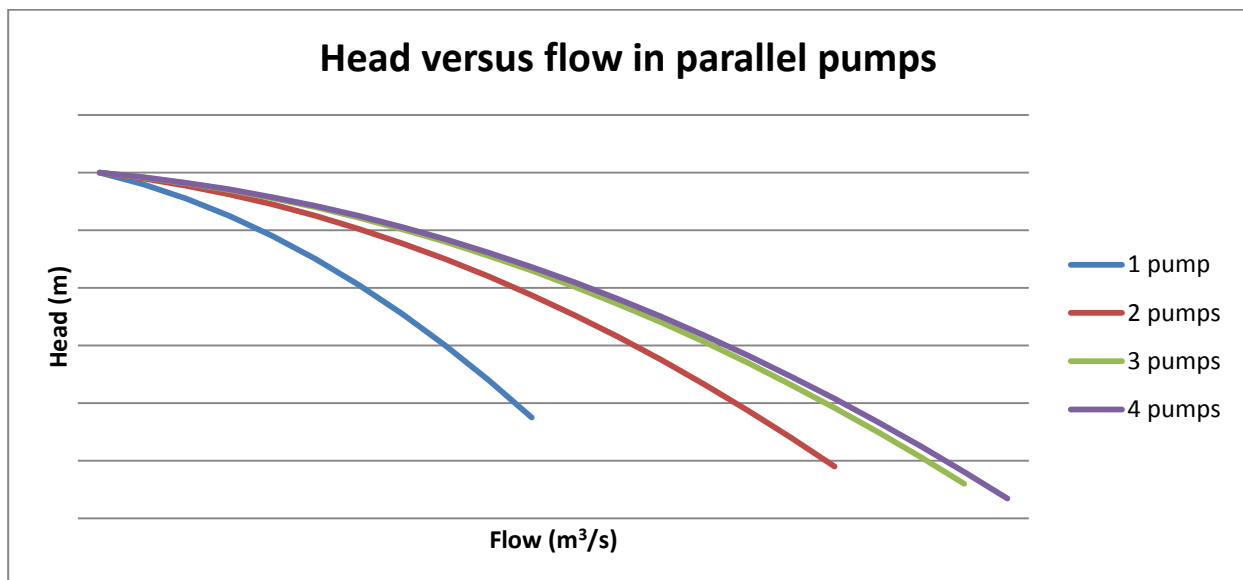


Figure 27: Head versus flow in parallel pumps (adapted from [80])

2.6.3 AUTOMATION OF DEWATERING PUMPS

Pump automation is required to control pumps from remote locations. By automating a pump, the human factor that can influence optimum control is removed. The most important part of automating a pump is to make sure that the remote usage of the pump, as well as the motor driving the pump, can be done safely and effectively. Various monitoring systems must be implemented to ensure that all the workings of the pump and the motor stay within operational limits.

For an automated pump to start or stop, a certain predetermined and programmed sequence is used. This is to make sure that the pump and the motor are in optimum condition and ready for the desired status change. Control equipment, as well as monitoring instrumentation to measure critical components, is required to make sure that a pump system adheres to all conditions. The following list shows common installations required for pump automation [81]:

- Automatically actuated valves on suction and discharge ends.
- Suction and discharge pressure transmitters.
- Temperature probes on motor windings.
- Temperature probes on drive end (DE) and non-drive end (NDE) bearings of both the pump and motor.
- Shaft displacement probes.
- Vibration transmitters.

Instrumentation is monitored and controlled by a PLC. A typical pump start-up or shutdown sequence is given below [82]:

1. Open suction valve.
2. Close delivery valve.
3. Measure bearing temperatures.
4. Measure winding temperatures.
5. Measure delivery and suction pressures.
6. Ensure displacement probes are in working condition.
7. Ensure vibration transmitters are in working condition.

Instrumentation locations on an automated pump are shown in Figure 28.

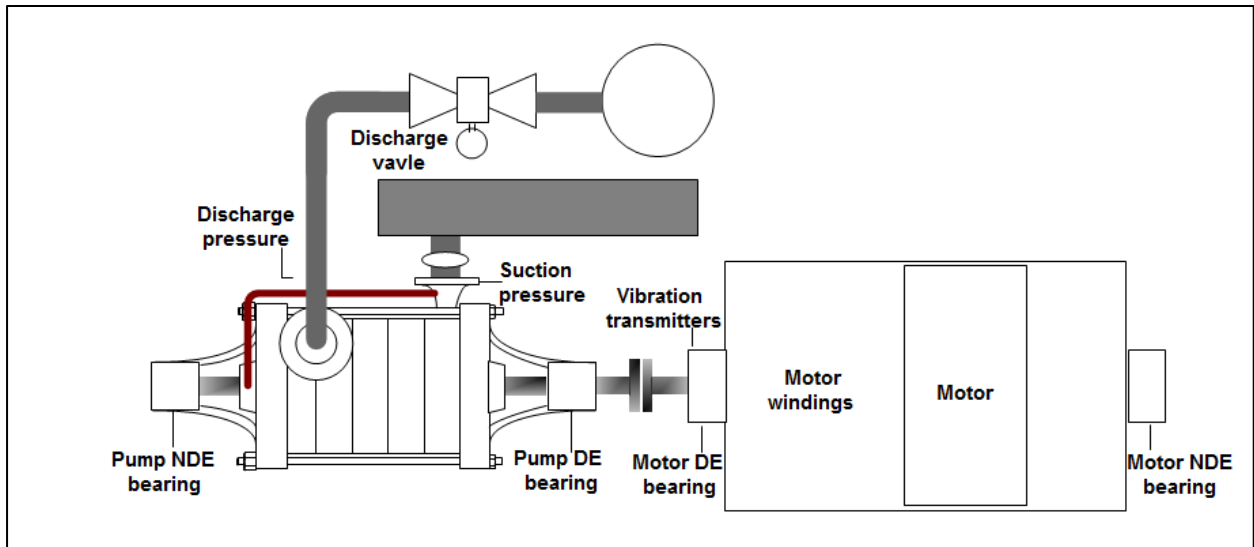


Figure 28: Automated pump instrumentation locations

If all measurements fall within preset parameters, the go-ahead will be given and the PLC will start the motor connected to the pump. As soon as any of the abovementioned measurements fail to comply with requirements, a tripping state will be entered. The sequence will start over and repeat until the pump can be safely started or the preprogrammed repeat limit is reached. Continuous monitoring while a pump is in a running state will also initiate a trip if necessary [83]. Figure 29 shows an example of an automated dewatering pump with a temperature probe (A), as well as a proximity sensor (B) attached to the NDE.

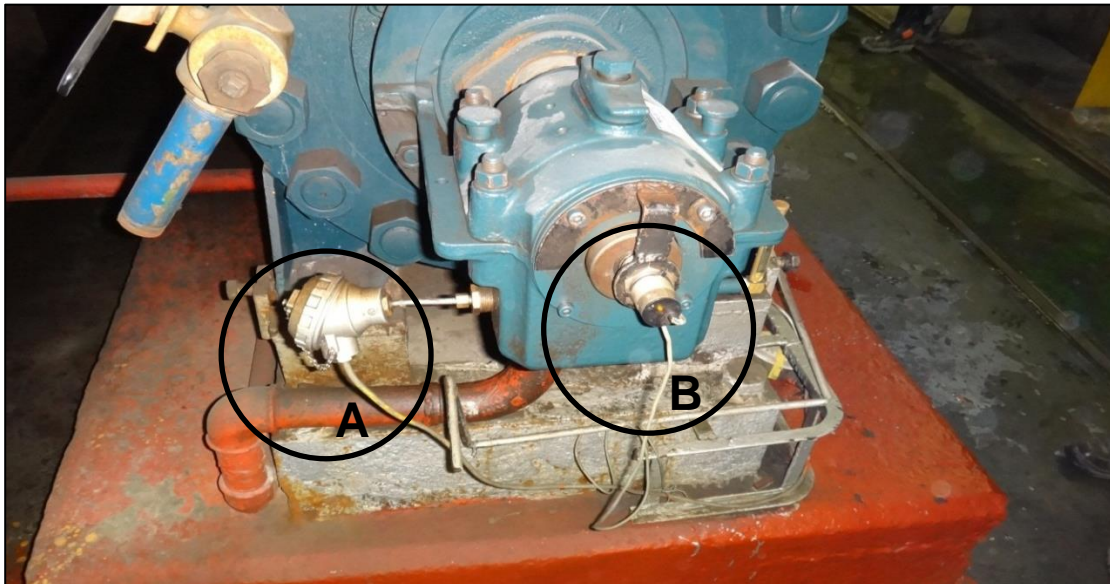


Figure 29: Non-drive end of a pump¹⁴

¹⁴ C. Cilliers, Personal photograph. "Dewatering pump", Welkom, 2013.

2.6.4 ALTERNATIVE DEWATERING METHODS

3CPFS

Due to the large installed capacities of dewatering pumps, as much as 20% of the total energy usage on a mine can be attributed to dewatering pumps [84]. An alternative method for removing water from a mine is to use a three chamber pipe feeder system (3CPFS).

A 3CPFS system entails a u-tube with a chilled water delivery end, as well as a hot water receiving end that is used for dewatering. Potential energy from chilled water sent down the mine displaces or “pumps” used mining water to surface [85]. This is achieved by the use of small pumps to overcome system friction, together with the sequential controlling of actuated valves.

Because the 3CPFS is a closed-loop system, the dewatering of additional water that is not included in this system is not possible. Fissure water and water that does not enter the mine through the 3CPFS have to be removed through conventional pumping [84]. Fully operational pumping systems should always be on standby to take over the dewatering load if required [36]. The structure and operation of 3CPFS system is shown in Figure 30.

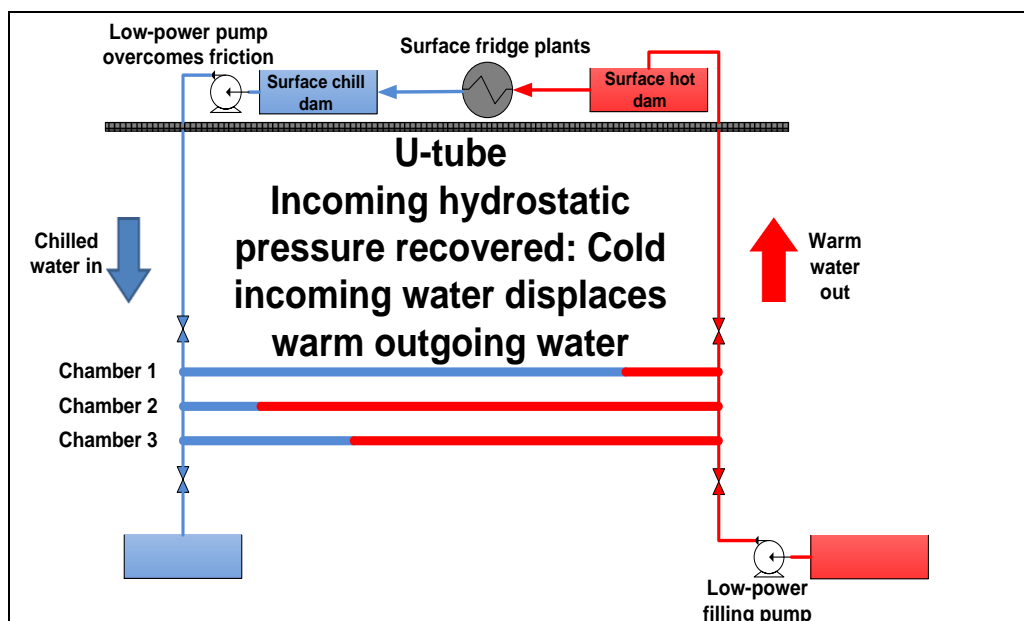


Figure 30: 3CPFS operation (adapted from ¹⁵)

¹⁵ Hydro Power Equipment – South Africa, “Energy savings solutions: Energy Recovery (3CPS – 3 Chamber Pump System),” 2012. [Online]. Available: <http://www.hpesa.com/products-3cps-3-chamber-pump-system.html>. [Accessed 14 May 2013].

Ice plants

Using ice plants is a cooling method that reduces the amount of water sent from surface. Water is frozen into ice and sent down the mine to an ice dam. Because the ice is at a very low temperature, the addition of warmer mining water from lower levels will result in cooled service water that is ready to be used again. Using ice plants cuts the total head and reduces the total amount of water required to be pumped out of the mine with energy saving as the result [86].

Both “hard” and “soft” ice plants are found on mines [87]. Using ice plants is very beneficial when a reduction in electrical energy usage is desired. Converting an existing fridge plant to an ice plant, or building a new ice plant will, however, require additional specialised infrastructure and result in a great financial expense [87], [88].

2.7 PREVIOUS WATER RETICULATION OPTIMISATION STUDIES

Various studies towards the optimisation of mine water reticulation systems have been completed. Many of these studies were based on the implementation of DSM projects on South African mines. The purpose of this section is to provide a critical review of previous studies on water reticulation. The previous studies will be reviewed according to the following parameters:

- Objective.
- Method.
- Outcome.

2.7.1 PREVIOUS STUDIES ON DEWATERING OPTIMISATION

Study A [89]

The motive for the first study, as was done by Schoeman et al. in 2011, was to enable financial savings on the electricity cost of a deep mine dewatering system through the reduction of peak TOU load. It was shown that by using a combination of pump automation and optimised scheduling, substantial load shifting could be realised. Necessary monitoring instrumentation, communication networks and control software were implemented to start and stop dewatering pumps at predetermined dam levels [89].

The study resulted in an hourly average of 5.6 MW shifted from the evening peak (or 11.2 MWh electrical energy shift). Although a creditable result, new load shift preparation load (PL) and comeback load (CL) were created during Eskom's TOU standard time hours. The reason for the PL was to prepare the system for the coming shutdown of dewatering pumps during the Eskom peak time.

Clear water dams had to be pumped down to a minimum level before peak time to enable the shutdown of pumps throughout the entire peak period. This resulted in a large amount of electrical energy being used during Eskom's TOU standard time hours before peak time. The CL was due to high intensity pumping to get the dam levels down again after the increase during peak times [89]. Figure 31 shows the results obtained from Study A.

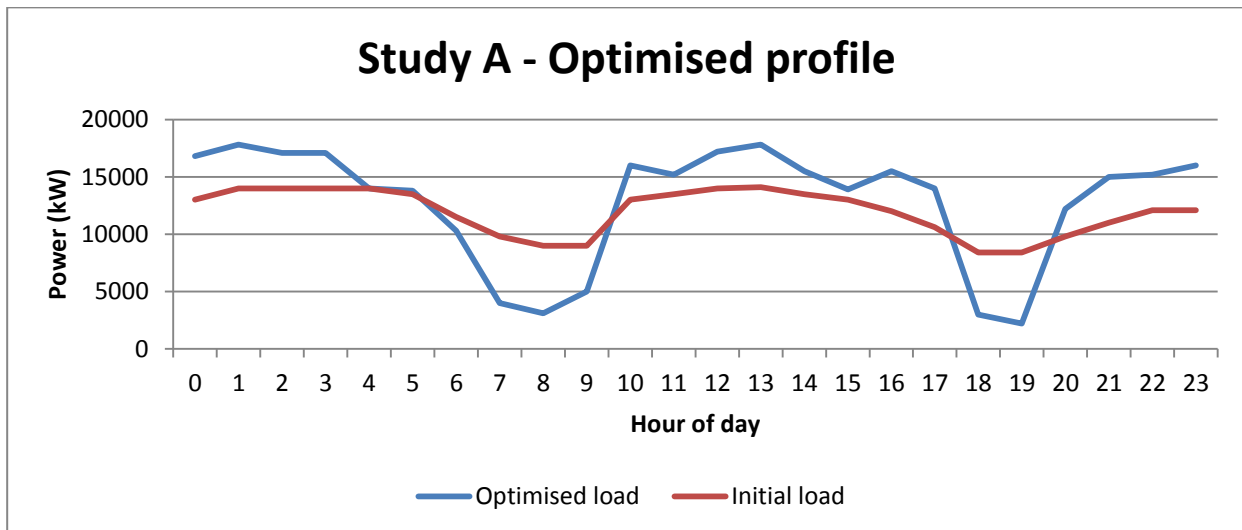


Figure 31: Study A - Optimised profile (adapted from [89])

A TOU breakdown of Figure 31 (as taken from Schoeman et al.) yields the following approximate results:

Table 1: Study A - Results (adapted from Figure 31)

STUDY A						
	Initial load			Optimised load		
	Off-peak	Standard	Peak	Off-peak	Standard	Peak
Average load (MW)	13.34	12.36	8.92	15.98	14.78	3.46
Electrical energy usage (MWh)	106.70	136.00	44.60	127.80	162.60	17.30

Analysis of the results shows that during the TOU standard time, an average load of 12.36 MW was demanded by the dewatering system before and 14.78 MW after the implementation of the study. This resulted in an approximate 2.42 MW increase in standard TOU load, or 26.6 MWh of electrical energy usage. Seeing as this was a load-shifting project, an overall increase of electrical energy usage outside of peak times was inevitable.

It is, however, apparent that the TOU standard time was not taken into consideration when optimisation was done. The TOU off-peak and standard times both received approximately 50% of the load shifted from peak time. As standard time tariffs are almost double the cost of off-peak times, more accurate optimisation with an aim to increase financial savings could have been endeavoured.

Study B [26]

Similar to Study A, Vosloo et al. conducted a study in 2012 on mine water reticulation optimisation. Not only was the same objective of decreasing peak load achieved, but reducing electrical energy usage was also made possible. Vosloo et al. integrated a broader range of mine water reticulation components in the study resulting in the decrease in electrical energy [26].

Dewatering pumps, turbines and fridge plants were integrated into a control system to achieve a reduction in peak load demand and to reduce overall electrical energy usage. The software package Real-time Energy Management System for Pumping (REMS-P) was used to monitor conditions throughout the system and to optimally control the abovementioned integrated subdivisions of the system. Fridge plants were used to build up chilled water capacity before peak times to enable load shifting and a combination of pump scheduling and turbine utilisation allowed dewatering pump load shifting [26].

Initial and optimised load profiles of the dewatering pumps and fridge plants are shown in Figure 32 and Figure 33 respectively.

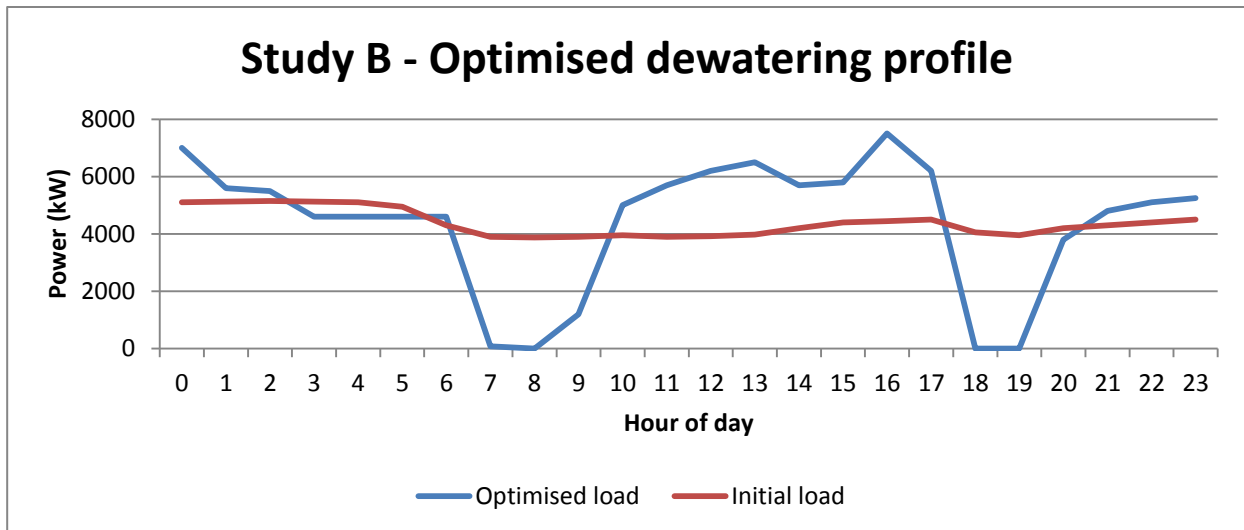


Figure 32: Study B - Optimised dewatering profile (adapted from [26])

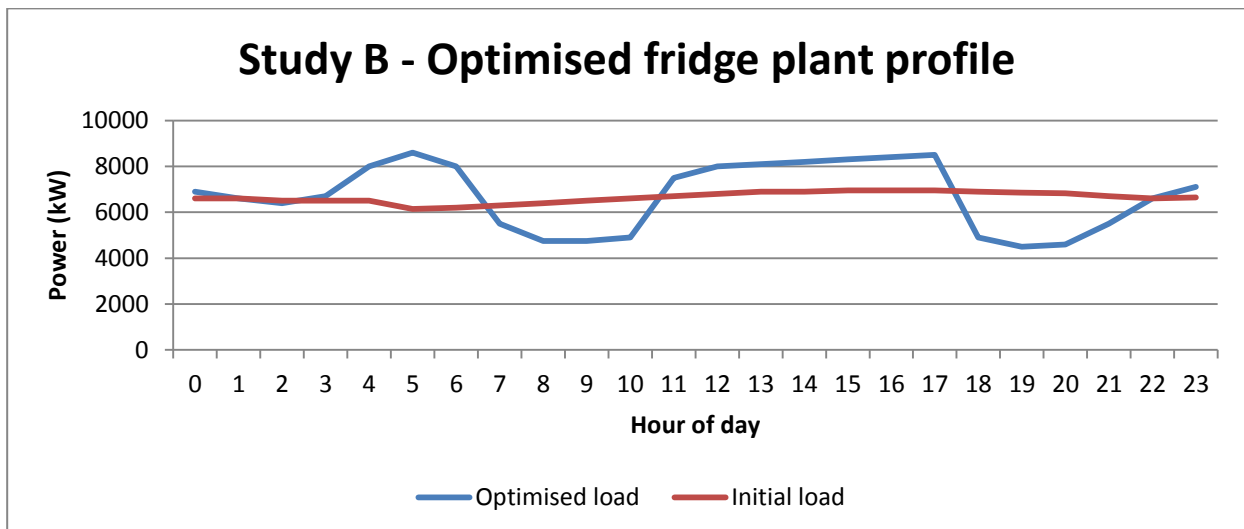


Figure 33: Study B - Optimised fridge plant profile (adapted from [26])

The results of the study showed that a morning load shift of 3.3 MW and an evening load shift of 4 MW were achieved. Together with the reduction in peak demand load, an electrical energy saving of 4.8 MWh per day was also achieved by optimising the water cooling system and its auxiliaries. Table 2 and Table 3 give a TOU breakdown of the pre- and post-implementation data of both the dewatering pumps and fridge plants included in the study.

Table 2: Study B - Dewatering results (adapted from Figure 32)

STUDY B - Dewatering						
	Initial load			Optimised load		
	Off-peak	Standard	Peak	Off-peak	Standard	Peak
Average load (MW)	4.93	4.19	3.94	5.28	5.62	0.26
Electrical energy usage (MWh)	39.45	46.10	19.68	42.25	61.80	1.28

Table 3: Study B - Fridge plant results (adapted from Figure 33)

STUDY B - Fridge plants						
	Initial load			Optimised load		
	Off-peak	Standard	Peak	Off-peak	Standard	Peak
Average load (MW)	6.51	6.77	6.59	7.11	7.27	4.88
Electrical energy usage (MWh)	52.10	74.48	32.95	56.90	80.00	24.40

Analysis of Table 2 and Table 3 shows a repeat of Study A in terms of load shifted to standard TOU. 80% of the load shifted from the dewatering pump peak TOU was encountered in the standard TOU with a load increase of 1.43 MW, and 46% of the fridge plant load (0.503 MW).

The substantial amount of load shifted to standard TOU indicates once again that only load shifting from peak TOU was included in the scope. Optimisation in terms of ideal TOU destinations was not accounted for. It should be mentioned, however, that optimising the fridge plant schedule (Figure 33) will most likely not result in a reduced standard TOU load due to strict operational and water temperature constraints.

2.7.2 PREVIOUS STUDIES ON WATER SUPPLY OPTIMISATION

Study C [39]

In 2010, Botha conducted a study on the optimisation of mine water supply via the controlling of level supply valves [39]. The study objective was to decrease water usage on mining levels during times of the day that less water was required. By reducing water usage, less water accumulated in clear water dams and thus, less water needed to be pumped out. The study's objective of reducing electrical energy consumption was achieved by reducing pump usage.

During the study Botha used the Real-time Energy Management System for Water Supply Optimisation (REMS-WSO) to evaluate pressure and flow readings. A PID controller made adjustments to control valves to attain the pressure set point as required by the mine [39].

Two case studies were used to verify Botha's study. After implementing the first case study, an average reduction of 0.4 MW over a 24-hour profile was found. This equates to an electrical energy reduction of 9.6 MWh [39]. Figure 34 shows Botha's expected results from Case Study 1.

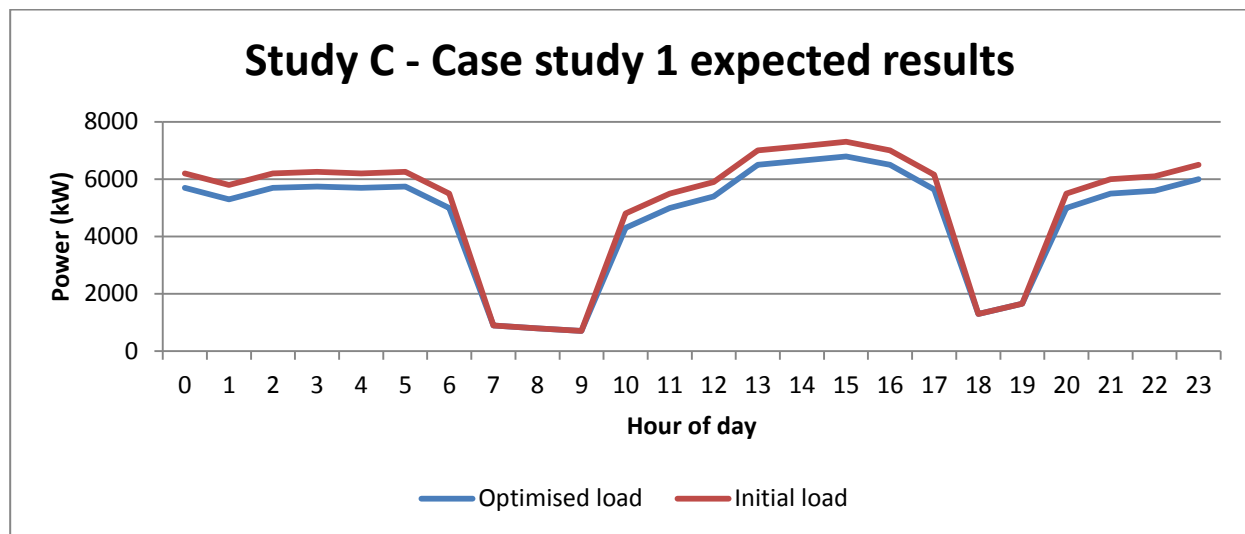


Figure 34: Study C - Case Study 1 expected results (adapted from [39])

Case Study 2 was done on a mine with a substantial number of water leaks within the water reticulation system. By managing and repairing leaks, a decrease of 7 ML in water consumption was achieved. This equated to the considerable average reduction in electrical energy usage of 73.6 MWh per day. Valve control was not implemented during the study duration. Because of leaks, water reduction through valve control would not have produced very large electrical energy savings [39]. Figure 35 shows the leak management results on Botha's Case Study 2.

Botha's Case Study 1 in 2010 showed a very small constant energy saving throughout a 24-hour period. This result is expected when a reduction in pumping needs is achieved without altering pumping schedules. Case Study 2 showed that by simply repairing water leaks, substantial amounts of electrical energy could be saved. The 73.6 MWh reduction in electrical energy was, also as expected, evenly spread throughout a 24-hour period.

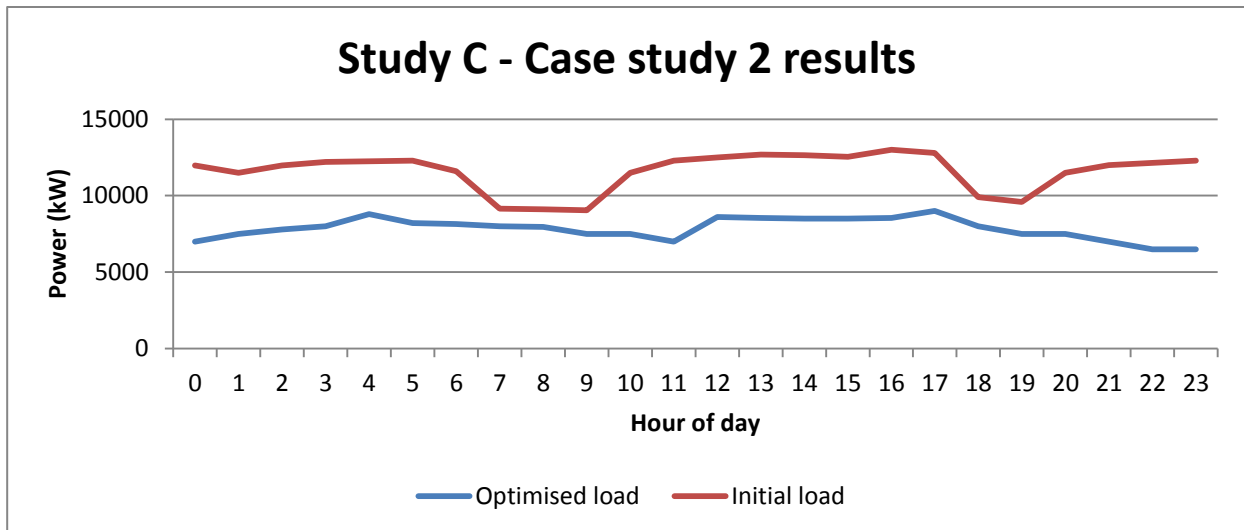


Figure 35: Study C - Case Study 2 results [39]

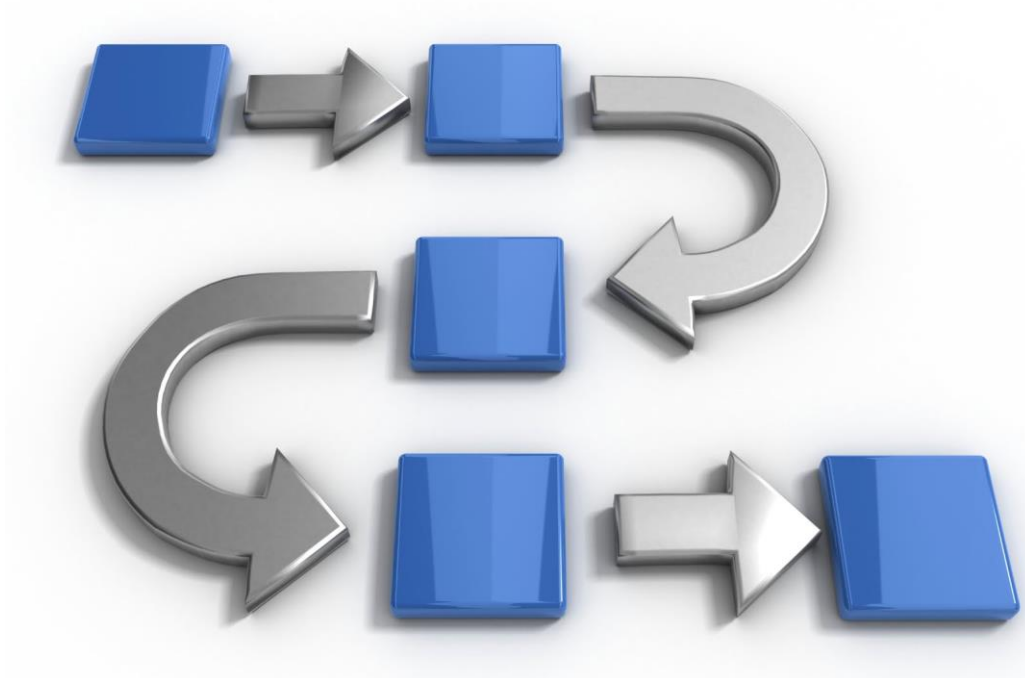
The principle of reducing pumping electrical energy due to the flow reduction to clear water dams worked very well and substantial electrical energy savings were achieved. However, a greater reduction of electrical energy usage within standard TOU as to an almost equal reduction throughout the day found in Botha's 2010 study would yield greater financial savings. If these water reduction methods were integrated with an optimised dewatering pump schedule, improved financial savings with regards to less electrical energy usage during standard TOU might have been achieved.

2.8 SUMMARY

A mine's water reticulation system has various components. Water chilled by fridge plants on surface is supplied to underground mining levels where it is used for various purposes. The control of supply water is possible by using valves; a globe valve is most favourable for accurate controlling. Used mining water is channelled to underground dams where it is pumped out back to surface by manually operated or automated dewatering pumps.

Previous studies towards electrical energy and cost savings have been conducted and implemented on an industrial scale in South Africa. These studies were conclusive towards their aim of reducing electrical energy costs and peak demand. Due to increasing electricity tariffs, and specifically the higher rate of escalation of standard TOU tariffs, further optimisation of existing electrical cost saving projects needs to be realised. Thus, focus must be placed on reducing electrical energy usage during standard TOU.

3 DEVELOPMENT OF AN OPTIMISED LOAD CONTROL STRATEGY ON MINE DEWATERING PUMPS



3.1 FOREWORD

The objective of this study is to maximise savings achievable by optimising existing load-shifting strategies. This study focusses on PL and CL reduction of mine dewatering pumps. This chapter focusses on the development of the methodology to accomplish the desired result.

3.2 METHODOLOGY

A step-by-step method was designed to achieve the study objective. This method had to take into consideration all aspects of related studies as well as the knowledge obtained through the literature survey.

Existing load-shifting projects on mine dewatering pumps do exactly as the designation suggests; load is shifted from certain times of the day to other times of the day. As described in Chapter 1, this load is moved from TOU peak times to standard- and off-peak times. Preparation is needed to enable optimal load shifting and has PL and CL as a result. Step 1 towards achieving the project objective will be to identify a mine that utilises a load-shifting initiative on the dewatering pumps. Step 2 is to determine if substantial PL and CL are taking place within the standard TOU.

Direct PLC programming or specialised software that communicates through a mine's SCADA system gives a status change order to dewatering pumps. These status changes are linked to certain conditions that are monitored and have to meet preselected set points or ranges. In the case of dewatering pumps, load shifting can only be accomplished if dam levels are within the required ranges. The conditions for load shifting on dewatering pumps are thus dependent on dam storage capacity, as well as pump flow capacity.

Step 3 will be to modify the pump schedules and pump control philosophies that were associated with load shifting. The control philosophy will have to be changed in such a manner that the desired effect of financial savings by load reduction during standard TOU be realised. Optimising the available resources on an existing load-shifting system will yield a positive result, but for more significant savings an increase in storage capacity will be needed.

During Step 4 the water flow towards storage dams is reduced. Due to the financial commitment that has to be made to enlarge dam storage and to increase pump flow capacity by installing larger or more efficient pumps, a solution must be found regarding the common feature, water. A reduction in water flow towards storage dams will theoretically “increase” the storage capacity and promote more effective load shifting to accomplish the set objective. This will be reflected by the cost saving calculation known as Step 5.

Therefore, the methodology will consist of the five steps shown in Figure 36.

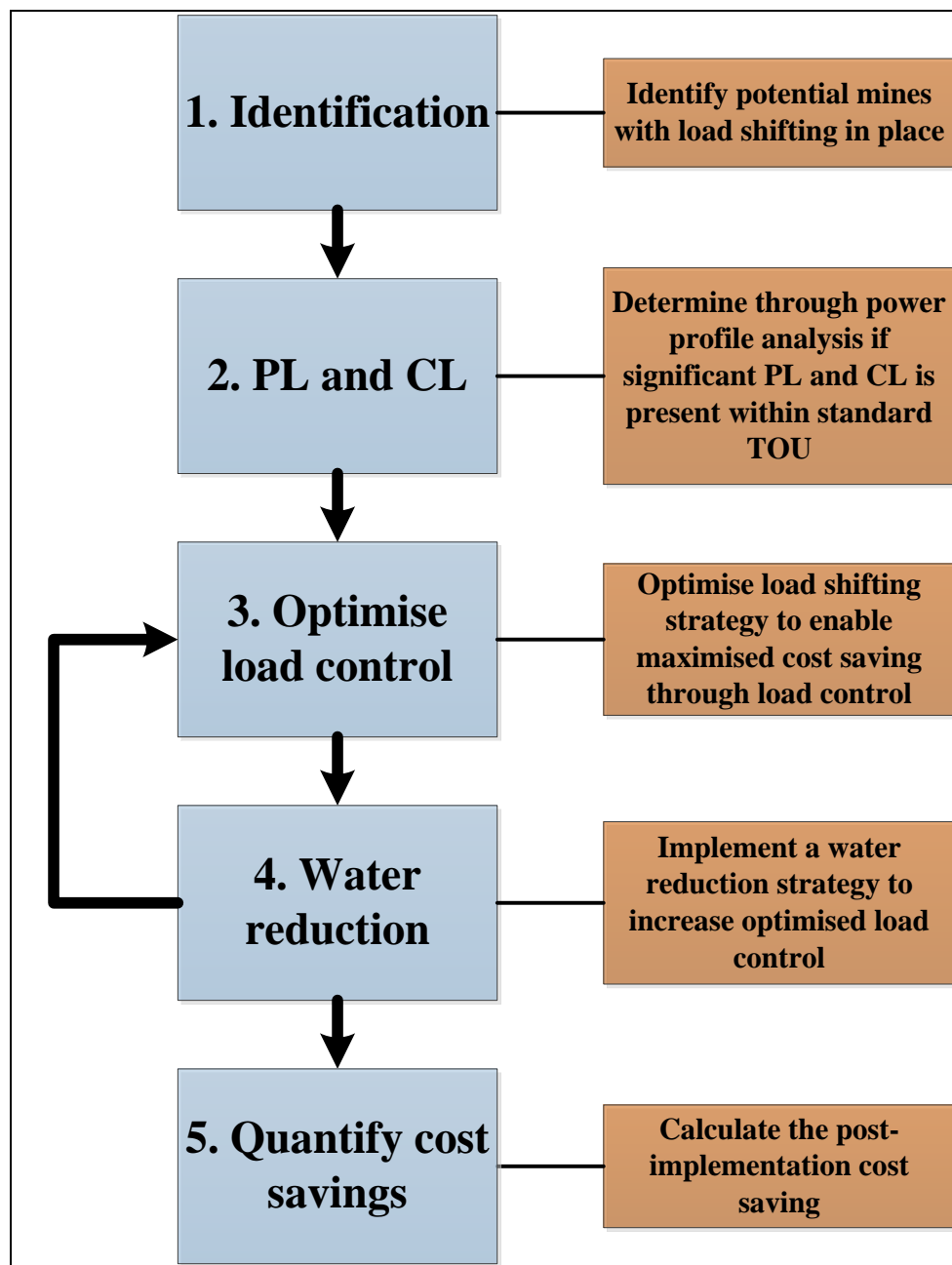


Figure 36: Methodology flow diagram

It must be noted that this methodology should not be used to completely replace an existing load-shifting system. Integration of the existing and optimised system must be done in such a manner that all existing constraints are met. Production and safety requirements should stay unaltered.

3.3 STEP 1 – IDENTIFICATION OF POTENTIAL SITES

Load-shifting projects on South African mines have become more and more common as Eskom's electricity tariffs increased. Load shifting can basically be done on any system that has ample storage capacity. Table 4 shows examples commonly found in the South African industry and which are usually integrated with control systems to promote load shifting:

Table 4: Industrial load shift technologies

Technology	Storage capacity
Mine dewatering pumps	Underground accumulation dams
Fridge plants	Surface chill dams
Cement plant raw mills	Raw meal silos
Gold plant mills	Silos or flotation tanks

Seeing as this study pursues the objective of decreasing mine dewatering electricity costs, potential mines with existing load-shifting strategies in place need to be identified. The identification process is started by interviewing mine personnel to determine if load shifting on dewatering pumps is actually being done.

After a mine has confirmed that load shifting is used on the dewatering system, data needs to be collected to determine the level and effectiveness of the load-shifting strategy that is used. If the mine's SCADA system includes a historian (database of recorded data), digital data may be collected for the required time to be analysed. If no SCADA or historian exists on the mine, manually completed pump log sheets may be used to get the same data. Power loggers may also be connected to motor electricity feeders to acquire the needed data.

Typically, a period of three recent months' data will be needed to create an accurate picture of a mine's load shifting effectiveness. After data collection has been finished, analysis and processing is needed. Using the appropriate functions of a spreadsheet program, raw data

should be processed to attain hourly data points. The result of the data collection and processing procedure should be an average load per hour over a period of 24 hours. Using the average load over 24 hours a profile may be drawn on a power versus hour-of-day graph to clarify the findings required to complete Step 1 of the methodology as shown in Figures 37-39.

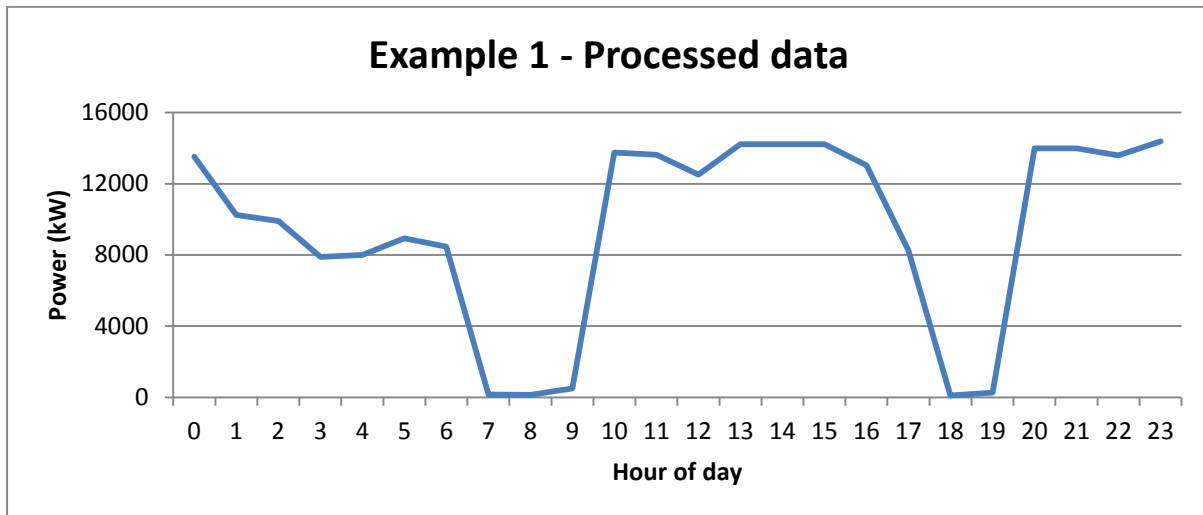


Figure 37: Processed data - Example 1

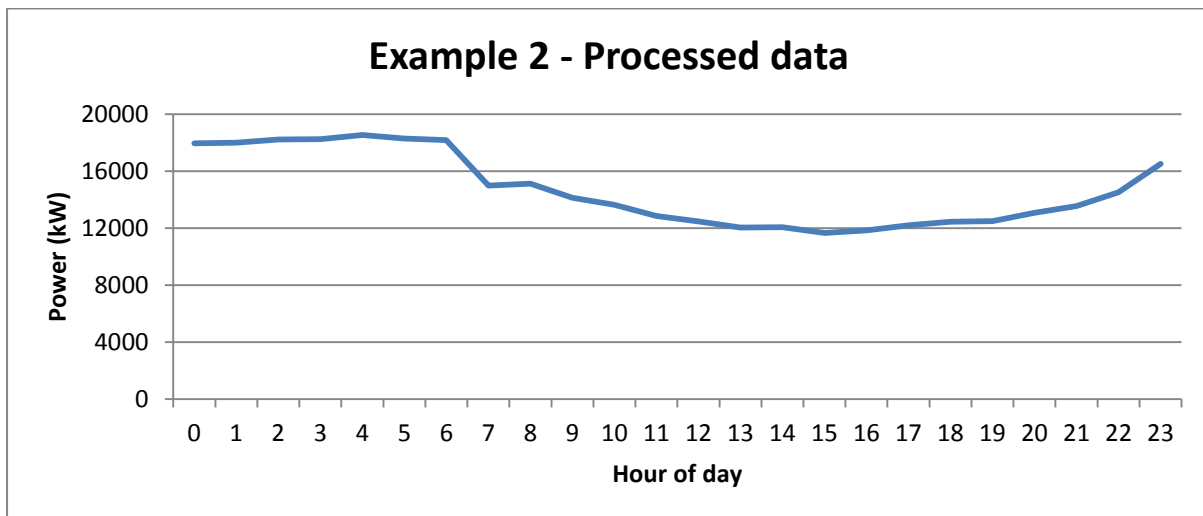


Figure 38: Processed data - Example 2

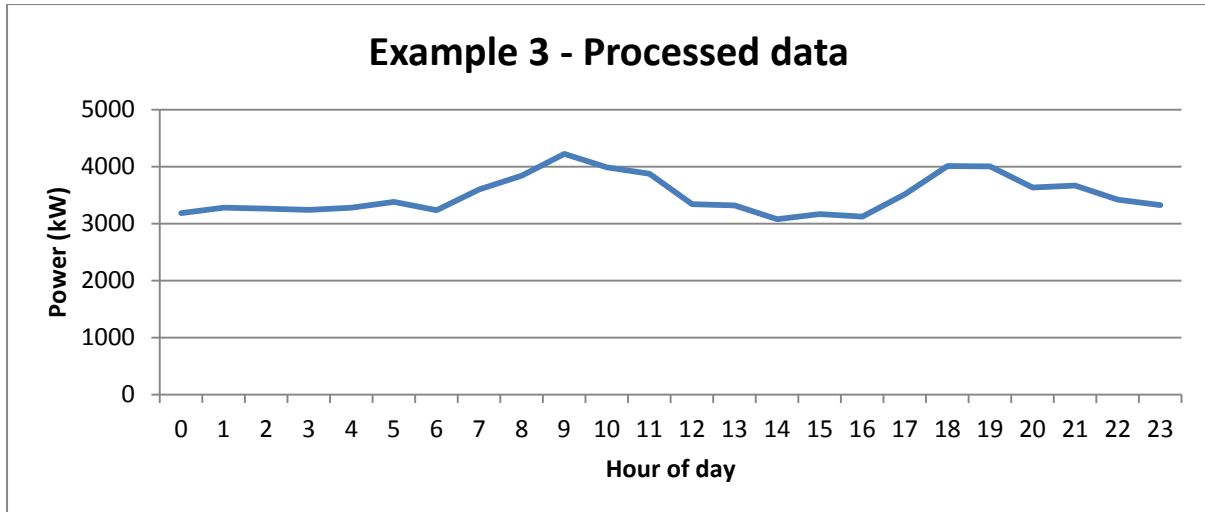


Figure 39: Processed data - Example 3

Although a trained eye will immediately see that load is shifted from peak times in Example 1 and not in Example 2 and Example 3, Equation 4 can be used to aid in determining load-shifting effectiveness.

Equation 4: Peak-to-overall ratio

$$Peak\ to\ overall\ ratio = \frac{\left(\frac{\sum P}{5}\right)}{\left(\frac{\sum O}{24}\right)}$$

With: P = Load corresponding to each peak hour (07:00, 08:00, 09:00, 18:00 and 19:00)
 O = Load corresponding to each hour of the day

Equation 4's answer will be a positive ratio that is expressed as X:1. The lower the ratio the more effective the load shifting; with 0:1 meaning total load shift and 1:1 or larger meaning no load shift. By applying Equation 4 to the processed data from Table 22 in Appendix A, and shown in Figure 37–39, the results of Table 5 are obtained.

Table 5: Peak-to-overall ratio of Figures 37–39

	Example 1	Example 2	Example 3
Peak-to-overall ratio:	0.019:1	0.926:1	1.163:1

Table 5 indicates that Example 1 has a better load-shifting performance than Example 2 and Example 3. There might be two reasons why Example 2 and Example 3 do not show active load shifting: either the mine personnel mistakenly gave wrong information regarding load shifting being done on the mine's dewatering pumps, or a load-shifting system that is in place is not being used. The load-shifting system might be reinstated for this study to identify the mine as a potential candidate. However, wrong information regarding load shifting will require implementation of a load-shifting strategy and does not form part of this study.

3.4 STEP 2 – PREPARATION- AND COMEBACK LOAD

The load required by mine dewatering pumps may be divided into three different groups: PL, CL and normal load (NL). PL primes the system for an upcoming shutdown of pumps for load-shifting purposes. CL brings the dewatering system back to normal operating conditions as was experienced prior to the implementation of load-shifting strategies. The load requirement after CL has completed will be labelled as NL.

Preparation load (PL)

PL is found in the hours before peak TOU (refer to Figure 40). A certain minimum dam level needs to be reached prior to the shutdown of dewatering pumps. The minimum dam level usually requires the start-up of the maximum allowable pumps per pump station.

Comeback load (CL)

CL is found in the hours after peak TOU (refer to Figure 40). As dam levels typically rise to close to, or over the maximum allowed limit during peak TOU, maximum allowable pumps are again simultaneously operated to lower dam levels to normal conditions.

Normal load (NL)

NL is found between CL and the next PL (refer to Figure 40). NL maintains the dewatering system within operational limits without unnecessary additional pumping.

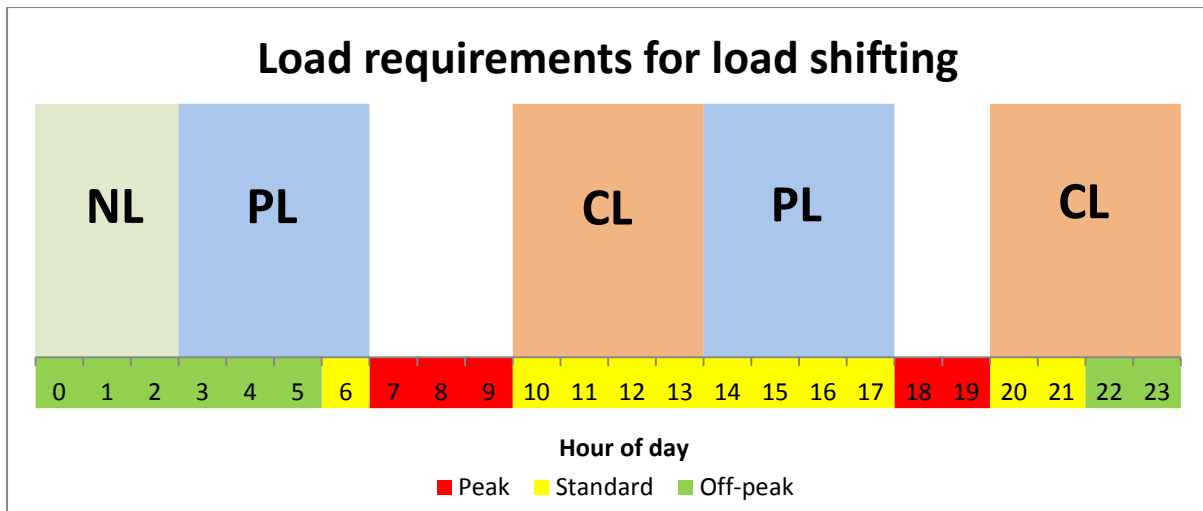


Figure 40: Load requirements for load shifting

The load requirements displayed in Figure 40 will differ slightly from mine to mine. Factors such as dam capacities, pump capacities and number of pumps may influence the PL, CL and NL associated with a dewatering system that uses load-shifting strategies. What is clear, however, is that the CL and PL experienced between morning peak TOU and evening peak TOU will always fall within the standard TOU from 10:00 to 17:59. The standard TOU hour before morning peak and two hours after evening peak also falls within PL and CL.

Step 2 (as described in Section 3.3) after a mine has been identified is to determine if significant PL and CL are experienced within standard TOU. By modifying Equation 4, a standard-to-overall ratio can be determined to aid in the further filtering of potential sites as was selected by the criteria explained in Section 3.3. Replacing the load corresponding with peak TOU (P from Equation 4) with load corresponding to standard TOU, Equation 5 is derived.

Equation 5: Standard-to-overall ratio

$$\text{Standard to overall ratio} = \frac{\left(\frac{\sum S}{11}\right)}{\left(\frac{\sum O}{24}\right)}$$

With: S = Load corresponding to each standard hour (06:00, 10:00-17:00, 20:00-22:00)
 O = Load corresponding to each hour of the day

A ratio of 1:1 or greater will indicate that the average standard-time load is equal to or higher than the total average load throughout a day. In other words, significant PL and CL will be present. By applying Equation 5 to the data found in Table 22 in Appendix A the results in Table 6 are obtained.

Table 6: Results of applying Equation 5 to Table 22

	Example 1	Example 2	Example 3
Standard-to-overall ratio:	1.343:1	0.887:1	0.986:1

With a standard-to-overall ratio of 1.343:1 for Example 1, PL and CL are contributing significantly towards electrical energy usage and will thus be a desired candidate for this study.

3.5 STEP 3 – LOAD SHIFT OPTIMISATION

The next step is optimising previously implemented load-shifting strategies on mine dewatering systems. There are various ways to approach the execution of load shifting on a dewatering pump. If pumps are not automated, pump attendants can essentially just switch off pumps during peak TOU. The problem with this approach, however, is that total system analysis is usually not done for load-shifting preparation. This may result in an unsustainable outcome.

Most mine dewatering systems control pumps by monitoring dam levels directly affected by moving water within the dewatering system. Mines that aim to have sustainable load shifting on dewatering pumps will automate the pumps and implement a control system that will monitor all the necessary parameters. This control can be directly programmed into a PLC, or by using third party control and management software that sends signals to a PLC. The most important parameter that determines load-shifting performance on a dewatering system is dam levels.

The typical control philosophy of a load-shifting system on dewatering pumps is to switch off pumps at certain dam levels and switch pumps back on at other dam levels. Each dam will thus have a safe control range that the dam level is kept within. The maximum and minimum levels of a dam are determined according to the shape and size of the dam, as

well as the amount of mud present in a dam. Pump control thus ensures that dam levels stay within these constraints as represented in Figure 41.

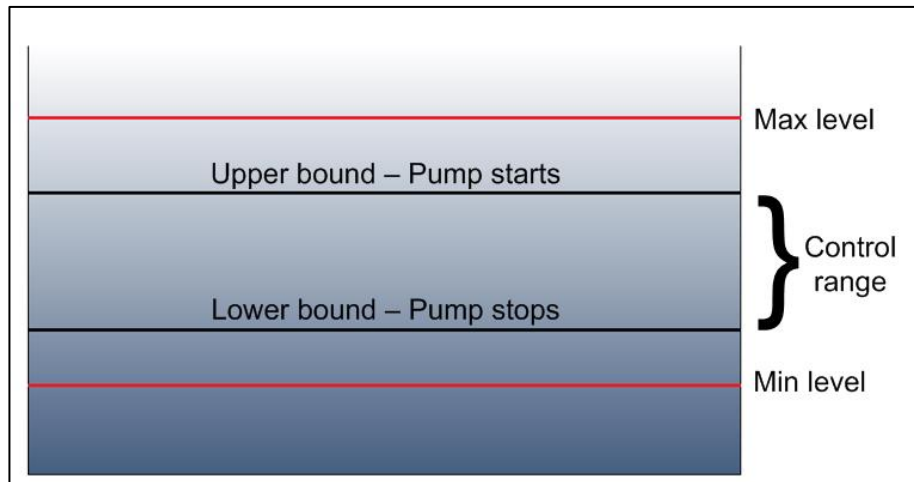


Figure 41: Representation of dam level constraints

For an underground dam that experiences constant inflow from mining as well as fissure water, almost constant pumping is needed to keep the dam level within the desired control range.

Dams are situated on both the suction- (upstream) and delivery (downstream) side of dewatering pumps as seen in Figure 42. When automated pump control is used, monitoring of both up- and downstream dam levels are essential to ensure constraints are met. A primary control dam must, however, be selected to which main control privilege is given.

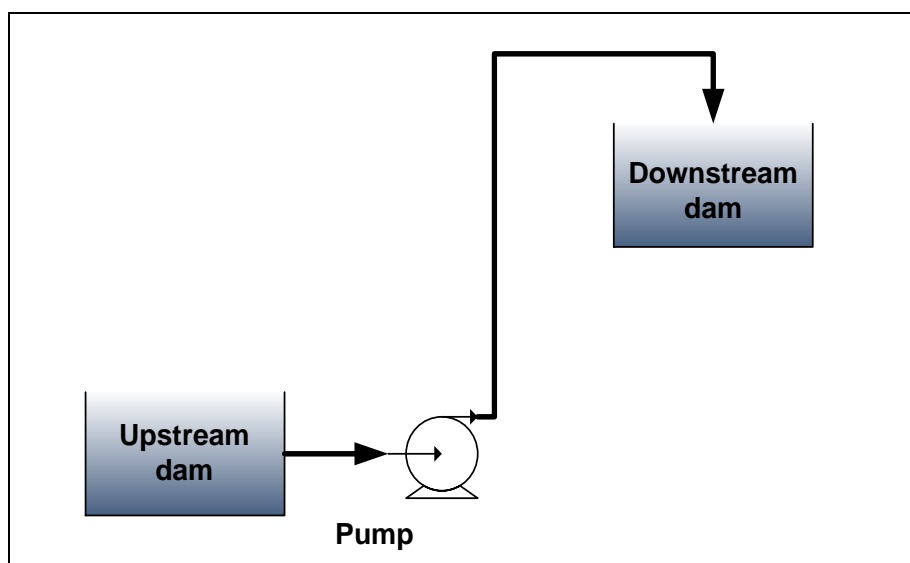


Figure 42: Up- and downstream dams

Mining activity is usually concentrated at lower levels. Upstream dams are also situated at lower levels and therefore pose a greater risk in the event of flooding due to pump failure. For this reason preference will be given to upstream dams. All optimisations will be done on upstream control with secondary safety control in place for downstream dams when needed.

3.5.1 CONTROL RANGE ADJUSTMENT

Automated dewatering pumps are typically stopped at the bottom of a control range and started again when the upper bound is reached. In order for a load-shifting strategy to work, the control range that a dam level is kept within should be adjusted up and down within the maximum and minimum dam level boundaries throughout a 24-hour period. This movement of the control range is dependent on the TOU.

Off-peak TOU

Within off-peak times, the control range is usually kept close to the minimum allowable level of a dam. This is to ensure that when peak time is imminent, enough capacity will be available to keep pumps off throughout this expensive TOU.

Standard TOU

The control range during standard TOU is usually identical to the off-peak TOU control range.

Peak TOU

In order for dewatering pumps to turn off automatically when the peak TOU arrives, the control range is moved closer to the maximum allowable dam level. Since the upper bound that triggers a pump to start is now much higher than during off-peak and standard TOU, pumps will stay off for longer.

If no load-shifting strategies have been implemented on a mine, the control range will be constant throughout a 24-hour period. This will result in dam levels being anywhere within the control range upon the start of peak TOU.

In Figure 43 and Figure 44, non-load shift enabling and load shift enabling control ranges are presented respectively. An increase in dam level indicates a switched off pump while a decrease represents a running pump.

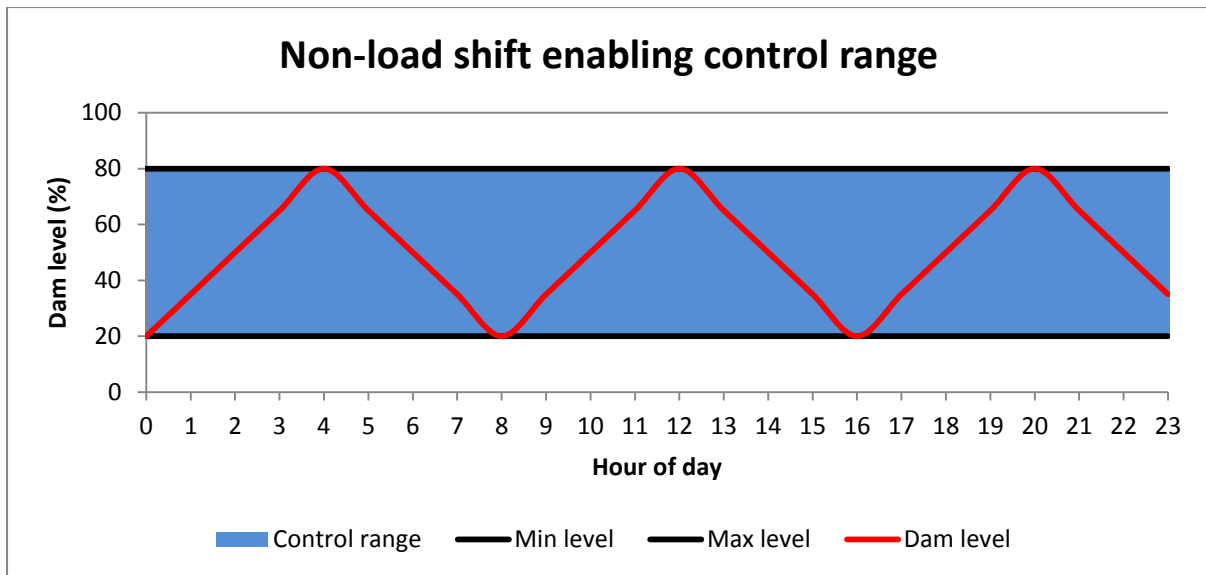


Figure 43: Non-load shift enabling control range

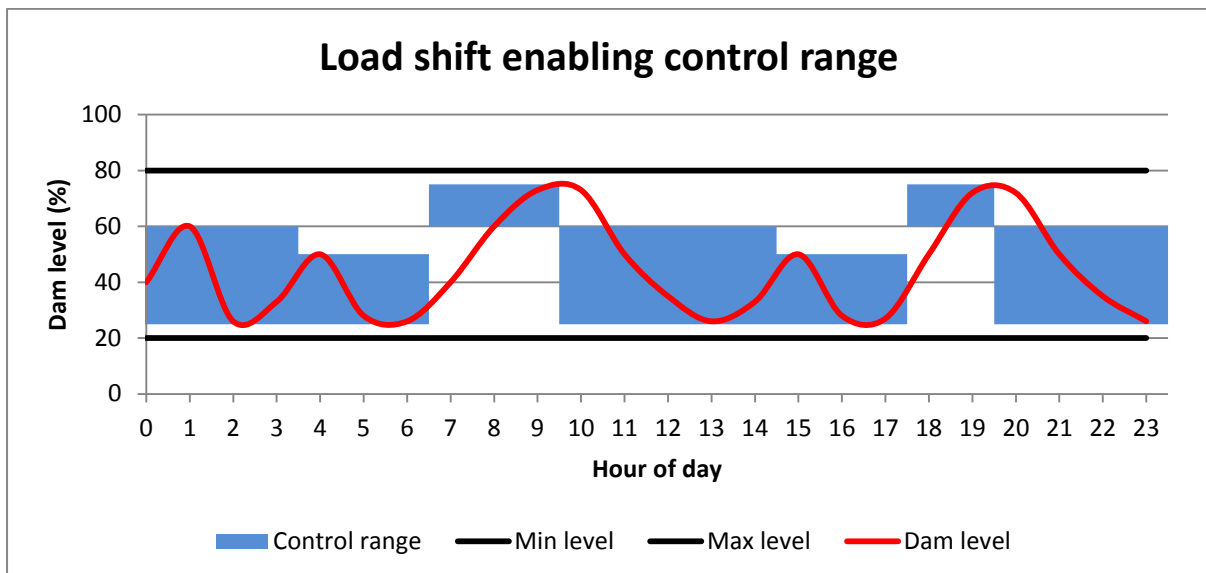


Figure 44: Load shift enabling control range

Assessment of the above figures makes it clear that the control range adjustment in Figure 44 “forces” dewatering pumps to stay off throughout the morning and evening peak TOU. Figure 43 has a constant control range and does not allow sustainable load shifting. The following hypothesis may then be made regarding the adjustment of a dewatering pump control range:

Constant control range

The amount of pumping over a time period will stay constant provided that water inflow to the dam stays constant. This is seen between 00:00 and 23:59 on Figure 43, as well as between 20:00 and 04:00 on Figure 44.

Elevated control range

Pumps are switched off and stay off until the elevated upper bound is reached. This is seen between 07:00 and 10:00 as well as between 18:00 and 20:00 on Figure 44.

Lowered control range

Pumps are switched on and stay on until the decreased lower bound is reached. This is seen between 04:00 and 07:00, 10:00 and 14:00, 15:00 and 18:00 and also 20:00 and 23:00 on Figure 44. PL and CL (as discussed in Section 3.4) is the result of a lowered control range.

3.5.2 CONTROL RANGE OPTIMISATION

In order to optimise an existing load-shifting implementation, the control range can be further adjusted. As the goal of this study is to achieve cost savings by reducing electrical energy usage within standard TOU, dewatering pump control within this time should be considered.

The duration of time that a pump may be kept off depends on various parameters. Firstly, the dam level when the pump stops as well as the dam level when the pump starts again should be considered. Secondly, the amount of water flowing into the dam during the period when no pumping is done must be taken into account. As discussed in Section 3.5.1, an elevated control range will allow a longer time for pumps to be kept off. Implementing an elevated control range approach at critical times during a 24-hour period will result in less electrical energy usage within standard TOU.

To start determining the optimal location of control ranges, information is needed regarding the existing load-shift control system. The following is needed in order for calculations to be done:

- Pump flow capacities.
- Average flow into dams per hour over a 24-hour period.

- Dam sizes.
- Maximum dam levels.
- Minimum dam levels.
- Preferred control range size by the mine.

Referring back to Figure 44, control range optimisation is needed within the standard TOU. Figure 45 shows the typical control range of a load-shifting mine during standard TOU. Optimisation will be done on the control range at areas numbered 1 to 5.

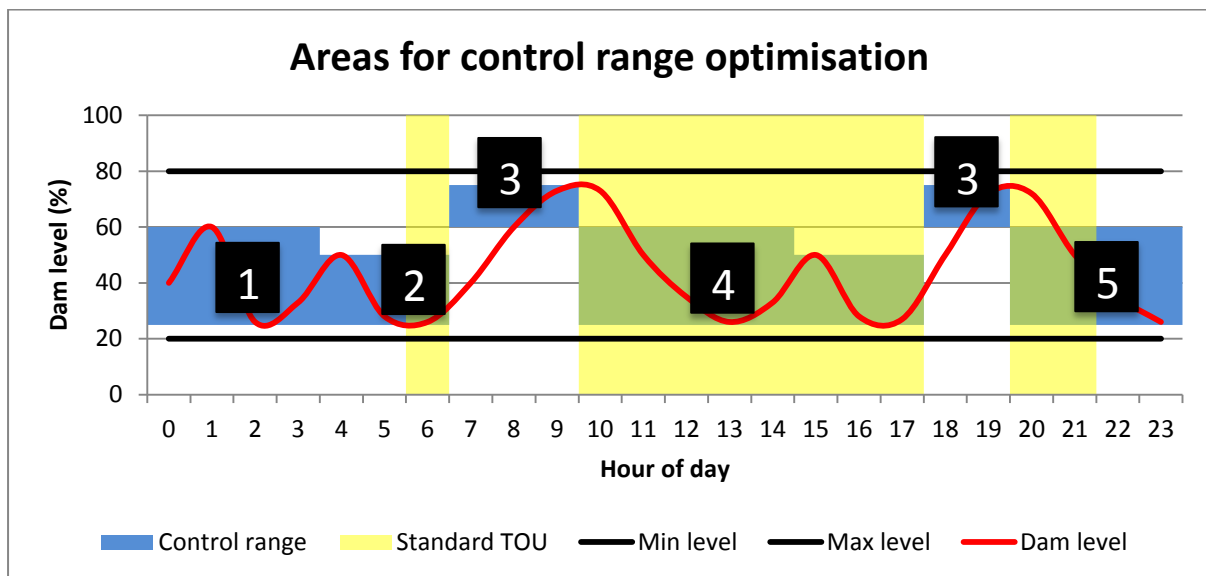


Figure 45: Areas for control range optimisation

Area 1 (22:00–06:00)

Area 1 consists of only off-peak TOU with a constant control range. As load from standard TOU needs to be shifted to off-peak TOU, maximum pumping needs to be enforced by the lowering of the control range. The upper and lower bound of the optimised control range for Area 1 is determined by the use of Equation 6 and Equation 7.

Equation 6: Calculation of lower bound 1

$$Lowerbound_1 = AbsMin$$

With: $AbsMin$ = Absolute minimum allowable dam level (%)

Equation 7: Calculation of upper bound 1

$$Upperbound_1 = AbsMin + CR$$

With: <i>AbsMin</i>	= Absolute minimum allowable dam level (%)
<i>CR</i>	= Control range size as preferred by mine (%)

Area 2 (06:00–07:00)

Area 2 includes the first standard TOU hour of the day (06:00–07:00). Seeing as dewatering pumps will have to be switched off for three peak TOU hours directly after this first standard TOU hour, preparation is needed. There are three parameter-dependent options that may be used to optimise Area 2's control range. Before the correct option can be chosen for a specific application, a preparation level needs to be calculated.

Equation 8: Calculation of preparation level 2

$$PreparationLevel_2 = AbsMax - \left(\left(\frac{PeakVol_1}{Cap} \right) \times 100 \right)$$

With: <i>AbsMax</i>	= Absolute maximum allowable dam level (%)
<i>PeakVol₁</i>	= Volume of water flowing into dam during morning peak (l)
<i>Cap</i>	= Volume capacity of dam (l)

Particular dams in a mine dewatering system may experience very low or even zero water inflow during the three-hour morning peak TOU shutdown. If this is the case, **PreparationLevel₂** will be equal or close to **AbsMax**. Seeing as **PreparationLevel₂** is the upper bound of a control range, the dam level will be anywhere within this control range during the timeframe that Area 2 falls within. To ensure that the dam level is not close to **AbsMax** when the morning peak TOU starts, a lowering of Area 2's upper bound is required.

In the case where water inflow is experienced during the three-hour morning peak TOU, the upper and lower bounds of Area 2 must be chosen in such a manner that a lowered control range from Area 1 to Area 2 is not formed. In other words, the upper bound of Area 1 should not be higher than the upper bound of Area 2 as this might force pumps to start up. After

PreparationLevel₂ has been determined and the above has been taken into consideration, the upper and lower bounds of Area 2 should be chosen from the following table:

Table 7: Upper bound and lower bound 2

Condition	<i>Upperbound₂</i>	<i>Lowerbound₂</i>
$PreparationLevel_2 \geq AbsMax - CR$	$AbsMax - CR$	$AbsMax - 2CR$
$PreparationLevel_2 > Upperbound_1$	$PreparationLevel_2$	$PreparationLevel_2 - CR$
$PreparationLevel_2 < Upperbound_1$	$Upperbound_1$	$Lowerbound_1$

Area 3 (07:00–10:00 and 17:00/18:00–20:00)

The morning and evening peak TOUs are found within Area 3. The control range for these areas should be moved as high as possible in order to allow dewatering pumps to stay off throughout. The upper and lower bound limits for Area 3's control range can be calculated by Equation 9–10.

Equation 9: Calculation of upper bound 3

$Upperbound_3 = AbsMax$	
With: <i>AbsMax</i>	= Absolute maximum allowable dam level (%)

Equation 10: Calculation of lower bound 3

$Lowerbound_3 = AbsMax - CR$	
With: <i>AbsMax</i>	= Absolute maximum allowable dam level (%)
<i>CR</i>	= Control range size as preferred by mine (%)

Due to earlier electricity demand by the public in winter evenings, Eskom requested mines to start load shifting from 17:00 and not 18:00 if possible. Care should thus be taken when identifying the time span of Area 3.

Area 4 (10:00–17:00/18:00)

With eight of the eleven standard TOU hours residing within Area 4, the bulk of this study's objective must be achieved within this period. Seeing as the dam level will be between

Upperbound₃ and **Lowerbound₃** by the start of Area 4, load will be required to bring the dam levels back to a safer control range. As discussed in Section 3.5.1, the lowering of a control range will increase electrical energy usage. To enable a reduction of electrical energy usage within this time when compared to the existing control range, the upper and lower bounds of Area 4 must be chosen as high as possible, but still low enough to enable a full two-hour shutdown when the evening peak TOU arrives.

In order to determine the optimum control range location for Area 4, a preparation level will again be needed.

Equation 11: Calculation of preparation level 4

$$\mathbf{PreparationLevel}_4 = \mathbf{AbsMax} - \left(\left(\frac{\mathbf{PeakVol}_2}{\mathbf{Cap}} \right) \times 100 \right)$$

With: <i>AbsMax</i>	= Absolute maximum allowable dam level (%)
<i>PeakVol₂</i>	= Volume of water flowing into dam during evening peak (l)
<i>Cap</i>	= Volume capacity of dam (l)

As was the case with the calculation of Area 2's bounds, the amount of water flowing into a dam during the evening peak TOU has to be considered. **PreparationLevel₄** will be equal or close to **AbsMax** if zero or low inflow of water occurs within peak TOU. The lowering of Area 4's upper bound will thus be required to ensure that a full two-hour load shift is possible. If a substantial inflow of water is experienced within evening peak TOU, the upper bound of Area 4 will be equal to the preparation level needed for load shifting. Taking this into consideration, **Upperbound₄** must be chosen from Table 8.

Table 8: Upper bound 4

Condition	Upperbound₄
$\mathbf{PreparationLevel}_4 \geq \mathbf{AbsMax} - \mathbf{CR}$	$\mathbf{AbsMax} - \mathbf{CR}$
$\mathbf{PreparationLevel}_4 < \mathbf{AbsMax} - \mathbf{CR}$	$\mathbf{PreparationLevel}_4$

After **Upperbound₄** has been determined, the lower bound of Area 4 must be calculated using Equation 12.

Equation 12: Calculation of lower bound 4

$$\mathbf{Lowerbound_4 = Upperbound_4 - CR}$$

With: $Upperbound_4$ = Upper bound for area 4 (%)
 CR = Control range size as preferred by mine (%)

As mentioned during the Area 3 discussion, care should again be taken when identifying the time span of Area 4; either **10:00–17:00** or **10:00–18:00**.

Area 5 (20:00–22:00)

The final two standard TOU hours of a day falls within Area 5. As discussed in Section 3.4, these hours are found directly after the evening peak and are subject to aggressive pumping on existing load-shifting implementations. To realise a reduction in electrical energy usage within these hours, the control range will be kept at the same elevation as was used for Area 3. This will allow minimum pumping to maintain the dam level until 22:00 when Area 1 starts again.

The upper and lower bounds for Area 5 are thus determined as follows:

Equation 13: Calculation of upper bound 5

$$\mathbf{Upperbound_5 = Upperbound_3}$$

Equation 14: Calculation of lower bound 5

$$\mathbf{Lowerbound_5 = Lowerbound_3}$$

The calculated optimised control ranges may be programmed into the load-shift supporting software or pump control PLCs.

3.5.3 EXAMPLE

The following case in point is shown to demonstrate the outcome of implementing Equation 6 to Equation 14 on an underground dewatering pump station.

A dam with a volume of 5 Ml and minimum and maximum levels of 40% and 80% respectively and a constant in flow of 60 l/s exists within a mine dewatering system. The typical load-shift enabling control range limits of the abovementioned dam will be similar to the values found in Table 9 and is illustrated in Figure 46.

Table 9: Pre-implementation control range limits

Control range limits			
From	To	Lower %	Upper %
00:00	06:00	45	65
06:00	07:00	45	60
07:00	10:00	60	80
10:00	15:00	45	65
15:00	18:00	45	60
18:00	20:00	60	80
20:00	00:00	45	65

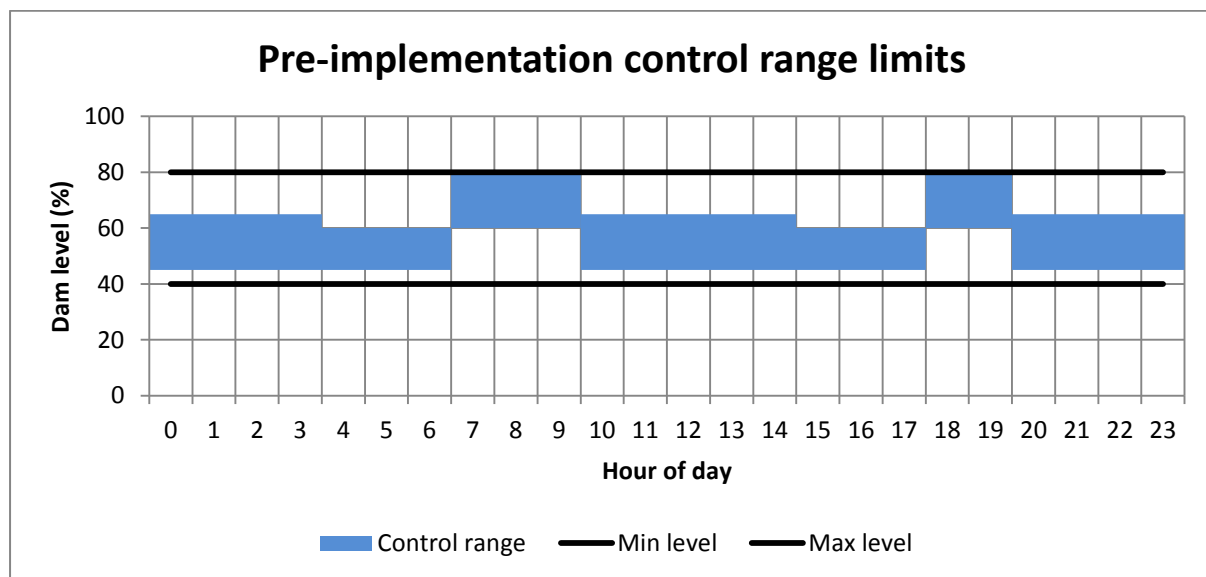


Figure 46: Pre-implementation control range limits

After applying Equation 6 to Equation 14 to the abovementioned example, the optimised control range limits are found (as illustrated in Table 10 and Figure 47).

Table 10: Post-implementation control range limits

Control range limits			
From	To	Lower %	Upper %
00:00	06:00	40	60
06:00	07:00	42.72	62.72
07:00	10:00	60	80
10:00	18:00	51.36	71.36
18:00	20:00	60	80
20:00	22:00	60	80
22:00	00:00	40	60

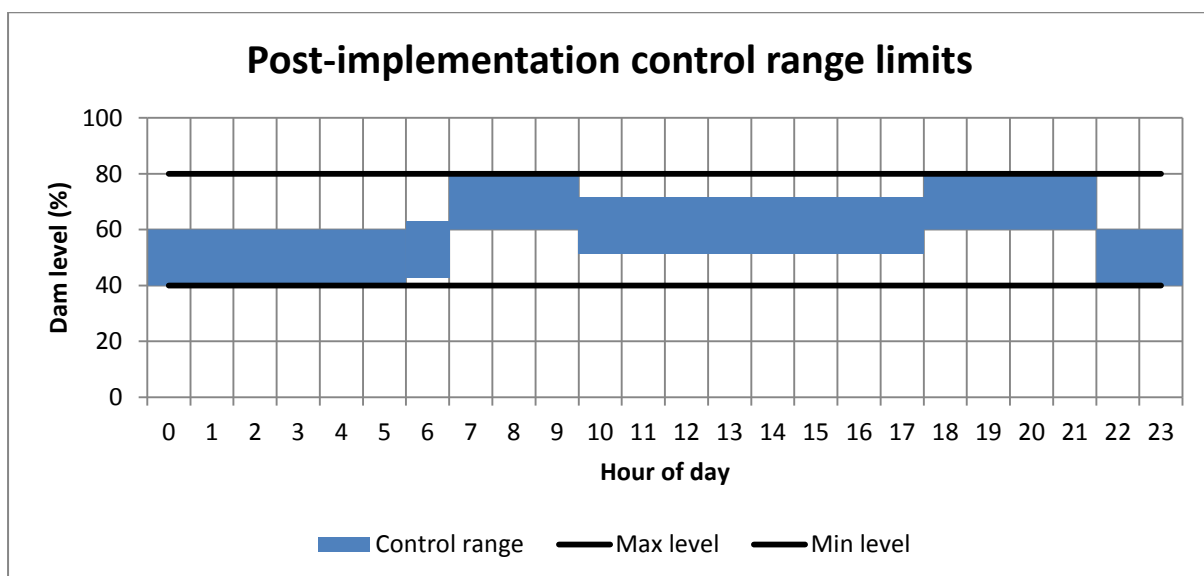


Figure 47: Post-implementation control range limits

3.6 STEP 4 – WATER SUPPLY OPTIMISATION

The calculation of *PreparationLevel₂* and *Upperbound₄* in Section 3.5.2 was done according to the amount of water flowing into a dam during the morning- and evening peak TOU. Less water flowing into a dam will result in a further elevated *PreparationLevel₂* and *Upperbound₄*. As the elevation of these two levels are paramount for the needed effect of

less standard TOU electrical energy usage, further cost savings may be incurred by additional optimisation of these control ranges.

As described in Section 2.2.5, mining and fissure water collect in canals that transport water to underground dams. The volume of water flowing into underground dams is thus equal to the volume of mining water sent down a mine plus fissure water. With this in mind, the amount of mining water flowing to dams may be reduced. Although the reduction of fissure water is possible, it does not fall within the scope of this study.

Referring back to Section 2.2.5, mining water is used for drilling, dust suppression, sweeping and cooling. Various shifts throughout a mining day use mining water for these different purposes (as described in Figure 48). By reducing water usage during any of the shifts, **PreparationLevel₂** and **Upperbound₄** may be optimised further.

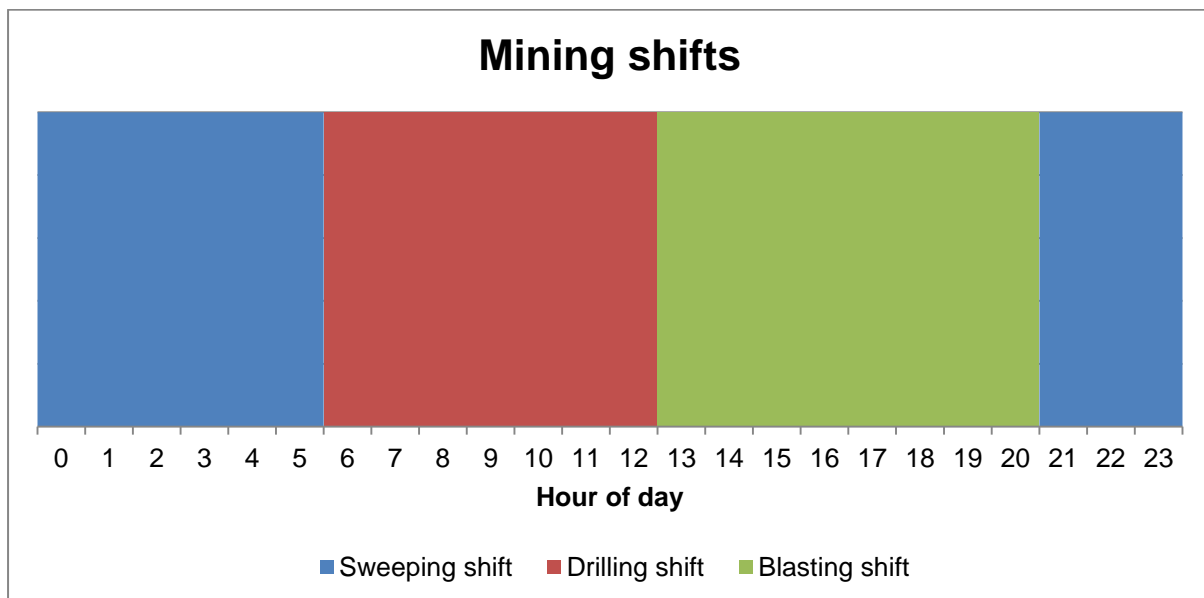


Figure 48: Mining shifts

3.6.1 WATER REDUCTION

The method that will be used to reduce the flow of mining water to underground dams is valve control. By installing valves on water supply columns to each level, water flow will be controlled to allow high flow when needed and reduced flow when the usage of water is not needed. This control will be done according to downstream pressure set points.

The reduction of water for each shift will be different and is dependent on the amount of water needed to accomplish the tasks as required by a shift. When valve control is introduced to a mine's water supply system, care should be taken to ensure that the required flow for a specific task is always available. No significant reduction in water will be realised during the drilling and sweeping shifts as an abundance of water is used for different duties. During blasting shifts, however, the water usage may be calculated as the required minimum flow needed by installed equipment, such as BACs and cooling cars on a specific level. In some cases where no cooling equipment is located on a level, total flow termination will be viable.

To enable downstream pressure control, pressure transmitters are needed to monitor pressure. With PID control, an actuator will adjust the aperture of a valve to maintain a predetermined pressure set point as needed to allow the required flow.

It is important to specify correct valves according to pressure and flow parameters directly influenced by the control of the valve. The sizing and type will affect the controllability and longevity of a valve as discussed in Section 2.2.4.

By using data from flow meters a flow baseline over a 24-hour period must be established. This baseline should then be compared with the reduced flow baseline resulting from valve control to determine the total volume of water reduced. If downstream pressure valve control created a flow reduction of 25 l/s during a drilling shift, the optimised water consumption profile will look similar to Figure 49.

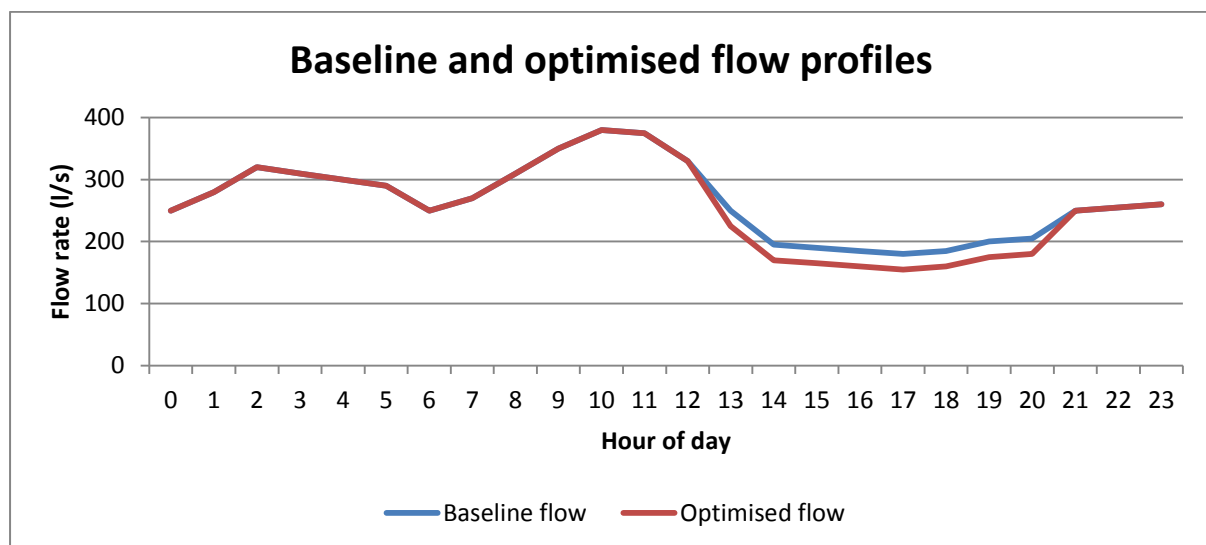


Figure 49: Baseline and optimised flow profiles

The total volume of reduced water is calculated using the following equation:

Equation 15: Calculation of reduced water volume

$$\mathbf{ReducedVolume} = (\mathbf{FlowReduction} \times 3600) \times \mathbf{Duration}$$

With: <i>ReducedVolume</i>	= Total volume of reduced water (l)
<i>FlowReduction</i>	= Average flow reduction during drilling hours (l/s)
<i>Duration</i>	= Flow reduction duration (h)

Although it is clear at what time of the day the water reduction took place, it is very difficult to determine when this will relate to a reduced flow to underground dams. For this reason it is assumed that the reduced water volume will result in a constant and equal reduction throughout the whole day. The reduction in water flow to underground dams may then be calculated accordingly.

Equation 16: Calculation of overall flow reduction

$$\mathbf{OverallFlowReduction} = \left(\frac{\mathbf{ReducedVolume}}{3600} \right) / 24$$

With: <i>OverallFlowReduction</i>	= Reduction of flow for each hour (l/s)
<i>ReducedVolume</i>	= Total volume of reduced water (l)

By reducing the water flowing to underground dams, the amount of water needed to be pumped out is lower. This will result in less pumping required and therefore less electrical energy usage by the pumps. To calculate the resultant electrical energy saving, the amount of energy that would have been needed to remove the reduced water must be calculated. Equation 3 must be used for this purpose.

Using the 25 l/s water reduction during blasting shifts (shown in Figure 49), the amount of electrical energy that would have been required to pump the reduced water out may be calculated. 25 l/s over eight blasting hours equates to a reduction of 720 kl. Assuming the dam was 1 500 m below surface and the system efficiency was 80%, the amount of

electrical energy that would have been required to remove the reduced water is 3.68 MWh. Theoretically this would be equal to the amount of electrical energy saved per day.

As this study focusses on the reduction of standard TOU electrical energy, the overall 24-hour energy efficiency resulting from water volume reduction can be used for further optimisation of dam level control ranges.

It should be noted that water reduction and re-optimisation of control ranges are optional steps. The costs involved with reducing water usage through valve control may be high and in some cases will not be justifiable by an extensive payback period depending on the system.

3.6.2 RE-OPTIMISATION OF DAM CONTROL RANGES

The equations used to calculate *PreparationLevel₂* and *PreparationLevel₄* in Section 3.5.2 use the volume (*PeakVol₁* and *PeakVol₂*) of water flowing into a dam during morning- and evening peak TOU. As the reduction of water flow (as accomplished in Section 3.6) directly affects the volume of water flowing into a dam, a recalculation must be done to establish a new *PreparationLevel₂* and *PreparationLevel₄*.

To recalculate *PreparationLevel₂* and *PreparationLevel₄*, Equation 8 and Equation 11 must be reapplied after first altering the equations to accommodate for a reduction in flow. By first calculating the morning- and evening peak TOU volume reduction (Equation 17 and Equation 18) and then subtracting it from Equation 8 and Equation 11, Equation 19 and Equation 20 are derived.

Equation 17: Calculation of reduced water volume during morning peak TOU

$$PeakVolRed_1 = \left(\frac{ReducedVolume}{24} \right) \times t_1$$

With: *PeakVolRed₁* = Volume reduction for morning peak TOU (l)
ReducedVolume = Total volume of reduced water (l)
t₁ = Duration of morning peak TOU (h)

Equation 18: Calculation of reduced water volume during evening peak TOU

$$PeakVolRed_2 = \left(\frac{ReducedVolume}{24} \right) \times t_2$$

With: $PeakVolRed_2$ = Volume reduction for evening peak TOU (l)
 $ReducedVolume$ = Total volume of reduced water (l)
 t_2 = Duration of evening peak TOU (h)

Equation 19: Calculation of new preparation level 2

$$PreparationLevel_{2-2} = PreparationLevel_2 + \left(\left(\frac{PeakVolRed_1}{Cap} \right) \times 100 \right)$$

With: $PeakVolRed_1$ = Volume reduction for morning peak TOU (l)
 Cap = Volume capacity of dam (l)

Equation 20: Calculation of new preparation level 4

$$PreparationLevel_{4-2} = PreparationLevel_4 + \left(\left(\frac{PeakVolRed_2}{Cap} \right) \times 100 \right)$$

With: $PeakVolRed_2$ = Volume reduction for evening peak TOU (l)
 Cap = Volume capacity of dam (l)

With new preparation levels for Area 2 and Area 4 calculated, an optimised upper bound for both areas must consequently be determined by using Table 7 and Table 8.

3.7 STEP 5 – QUANTIFYING COST SAVINGS

3.7.1 EQUATION DEVELOPMENT

With the study objective being to decrease PL and CL during standard TOU, financial expenditure towards electrical energy will be less. The need to determine a cost saving after implementation of the study is therefore vital.

To determine the amount of money saved by the implementation of this study, the total cost of electrical energy used by the dewatering pumps before and after implementation have to be compared. The same energy usage profile averaged out per hour over a 24-hour period (discussed in Section 3.3) must be used to determine what the electrical energy cost was before implementation. The cost per hour is calculated by multiplying the electrical energy usage for each hour with the corresponding tariff for that hour. Taking the sum of costs for each of the 24 hours of the profile, the average cost per day is calculated.

The total cost of electrical energy after implementation is calculated in exactly the same way as above, except for a new post-implementation energy usage profile that has to be created first. By subtracting the electrical energy cost of the new profile from the electrical energy cost of the pre-implementation profile, the cost saving will be calculated.

The number of peak-, standard- and off-peak TOU hours per day depends on whether cost saving is being calculated for a weekday, Saturday or Sunday. The quantification of a financial cost saving for this study can thus be realised by applying the following equations.

Equation 21: Calculation of electrical energy cost before implementation

$$A = \left(\sum_{n=1}^i E_{OP1_n} \right) \times R_{off-peak} + \left(\sum_{n=1}^j E_{S1_n} \right) \times R_{standard} + \left(\sum_{n=1}^k E_{P1_n} \right) \times R_{peak}$$

With: A	= Electrical energy cost per day before implementation
E_{OP1_n}	= Electrical energy for off-peak TOU hour before implementation
E_{S1_n}	= Electrical energy for standard TOU hour before implementation
E_{P1_n}	= Electrical energy for peak TOU hour before implementation
$R_{off-peak}$	= Megaflex tariff for off-peak TOU
$R_{standard}$	= Megaflex tariff for standard TOU
R_{peak}	= Megaflex tariff for peak TOU
i	= Number of off-peak TOU hours
j	= Number of standard TOU hours
k	= Number of peak TOU hours

Equation 22: Calculation of electrical energy cost after implementation

$$B = \left(\sum_{n=1}^i E_{OP2_n} \right) \times R_{off-peak} + \left(\sum_{n=1}^j E_{S2_n} \right) \times R_{standard} + \left(\sum_{n=1}^k E_{P2_n} \right) \times R_{peak}$$

With: B	= Electrical energy cost per day after implementation
E_{OP2_n}	= Electrical energy for off-peak TOU hour after implementation
E_{S2_n}	= Electrical energy for standard TOU hour after implementation
E_{P2_n}	= Electrical energy for peak TOU hour after implementation
$R_{off-peak}$	= Megaflex tariff for off-peak TOU
$R_{standard}$	= Megaflex tariff for standard TOU
R_{peak}	= Megaflex tariff for peak TOU
i	= Number of off-peak TOU hours
j	= Number of standard TOU hours
k	= Number of peak TOU hours

Equation 23: Calculation of electrical energy cost savings per day

$$R_{savings} = A - B$$

With: $R_{savings}$ = Total cost savings per day (ZAR)

3.8 VALIDATION OF METHODOLOGY

In order to validate the usability of the procedures described in the previous sections on a mine, it must first be simulated before testing it in a real-world scenario. True to real-world constraints regarding every aspect included in the dewatering system must be taken into consideration during simulation.

Requirements for a simulation include the capabilities to program upstream dam control-range upper- and lower bounds for any time of the day, as well as the simulation of the following:

- Advancing of time.
- Pump status.
- Pump flow.
- Starting and stopping of pumps.
- Linking of pumps to up- and downstream dams.
- Dam level changes due to flow.

Various methods of simulating mine dewatering can be used. For this study the software package REMS-P, as was used by previous studies discussed in Section 2.3, will be used to simulate an optimised load-shifting implementation. REMS-P is a powerful program that enables a user to change parameters rapidly; making it desirable for this study.

The optimised control range for upper and lower bounds is most important for the outcome of this study. Additional programming will, however, generally be necessary to meet system constraints. In some cases the constraints posed by any given existing load-shifting system might be such that applying the methodology will yield low results, if any. For this reason the validation process is paramount to ensure optimal application of the methodology to achieve the study's objective.

3.9 SUMMARY

Developing a step-by-step method to optimise existing load-shifting projects was discussed in this chapter. The main focus of this method is to reduce electrical energy consumption as a result of PL and CL. This in effect shifts the electrical energy from standard TOU to off-peak TOU.

This method can be introduced to any existing load-shifting system on dewatering pumps, but the efficiency of the method will be constrained by system parameters. Testing of the method will be done in the following chapter.

4 OPTIMISATION OF LOAD-SHIFTING PROJECTS ON SOUTH AFRICAN GOLD MINES



Figure 50: Mine shaft¹⁶

¹⁶ South African Broadcasting Corporation (SABC), "Search for man in mine shaft continues," South African Broadcasting Corporation (SABC), 2 April 2012. [Online]. Available: <http://www.sabc.co.za/news/a/2b7212004abd6fe6ac86be1cd6c4d3db/Search-for-man-in-mine-shaft-continues-20120402>. [Accessed 3 August 2013].

4.1 FOREWORD

In order to verify Chapter 3, the proposed methodology will be applied to two case studies that were chosen according to the procedures described in Sections 4.2.2.1 and 4.3.2.1. Firstly, real-world accurate simulations will be done to determine the possible electrical energy and financial savings. Thereafter verification will be done by comparing simulated results with results found by real-world application on the two case studies. The case studies were conducted on two South African gold mines; respectively referred to as Mine A and Mine B.

4.2 CASE STUDY A

4.2.1 MINE OVERVIEW

Mine A is a gold-producing mine situated in the Free State province of South Africa. Formerly used solely for the mining of uranium at a depth of 1 000 m, a sub-vertical shaft was sunk to reach gold deposits at 2 350 m below surface.

There are currently four main mining levels utilised for ore extraction at Mine A. 19L, 20L, 21L and 22L are levels that were created by blasting from the sub-vertical shaft. The levels extend between 1 000 m and 7 000 m horizontally. Four fridge plants situated on the surface are used to cool mining water. After leaving the fridge plants, chilled water is collected in two cold dams. This water is used by surface BACs to cool ventilation air and is also sent underground. The underground uses for chilled water at Mine A includes drilling and sweeping, as well as air cooling by two underground BACs situated on 20L.

By using a cascading dam water supply system (described in Chapter 2), chilled water from the surface is collected in dams and supplied to mining levels approximately 100 m beneath each cascade dam. This head ensures a pressure of roughly 10 bar for the supply water on 19L, 21L and 22L. Water for 20L is supplied from 16L that is situated approximately 200 m above 20L. A PRV is used on 20L to lower pressure to the desired level.

Used mining- and underground fissure water is collected and channelled through a settler and into a hot water dam on 25L. Fissure water from the previously used uranium-mining sections is channelled to a hot water dam located on 5L.

Figure 51 shows a simplified layout of Mine A's water reticulation system.

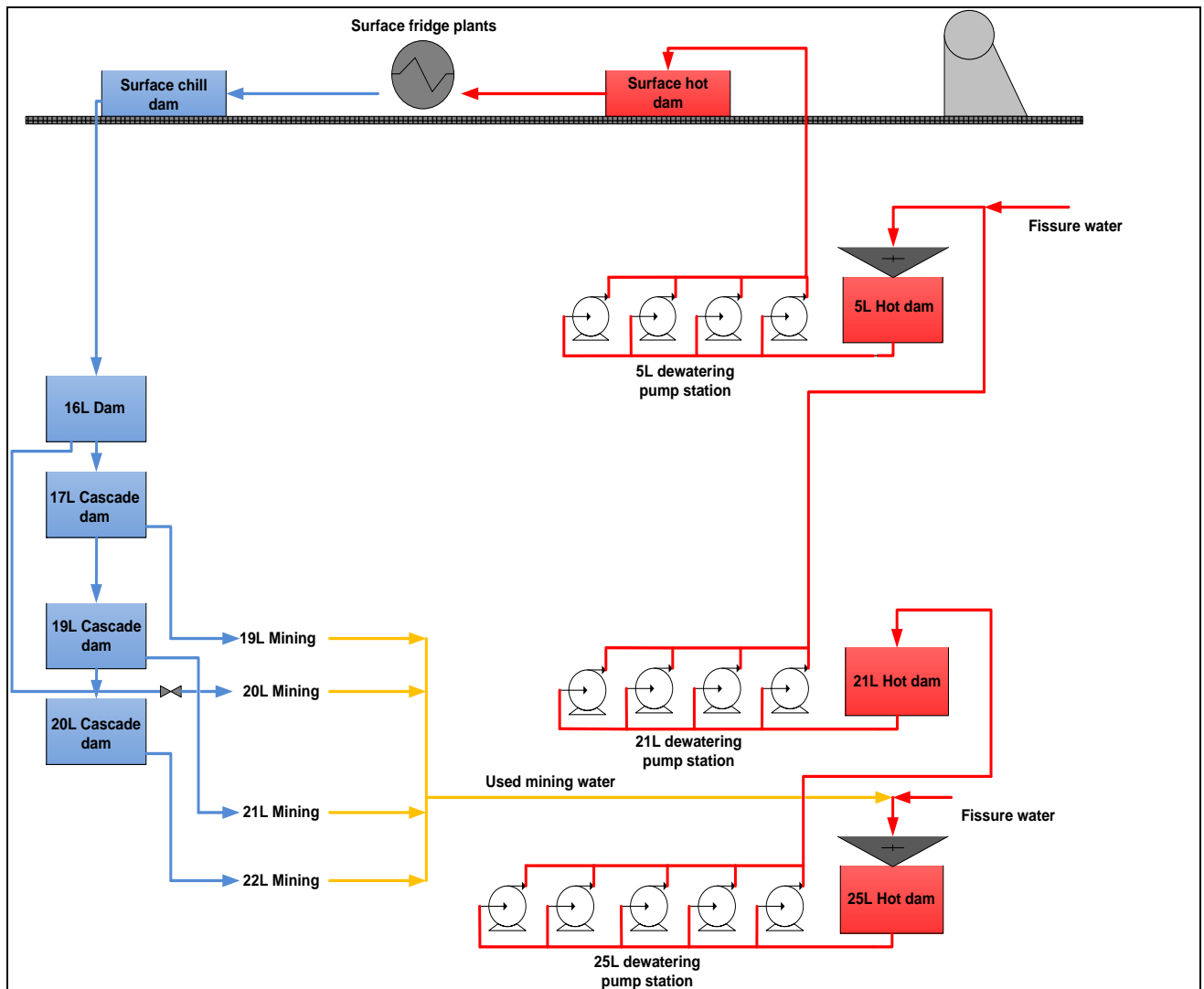


Figure 51: Mine A - Simplified water reticulation system

The water collected in 25L hot dam is pumped to another dam on 21L. Water is pumped from 21L to 5L and from there to a collection dam on the surface. These three pump stations form part of the dewatering system of Mine A. From the surface hot dam water is pumped through fridge plants and the entire water reticulation cycle is started again.

The specifications of the three dewatering pump stations at Mine A are shown in Table 11.

Table 11: Mine A - Pump station summary

Pump station	Pump no.	Installed capacity (kW)	Rated flow (l/s)	Depth (m)	Head required (m)
5L	Pump 1	3 200	170	1 000	1 000
	Pump 2	3 200	170	1 000	1 000
	Pump 3	3 200	170	1 000	1 000
	Pump 4	3 200	170	1 000	1 000
21L	Pump 1	3 200	150	2 100	1 100
	Pump 2	3 200	150	2 100	1 100
	Pump 3	3 200	150	2 100	1 100
	Pump 4	3 200	150	2 100	1 100
25L	Pump 1	1 100	70	2 350	250
	Pump 2	1 100	70	2 350	250
	Pump 3	1 100	70	2 350	250
	Pump 4	1 100	70	2 350	250
	Pump 5	1 100	70	2 350	250

4.2.2 APPLICATION OF METHODOLOGY

4.2.2.1 Site identification

The first step in identifying Mine A as a case study was to inspect the current implemented load-shifting strategy and its effectiveness. It was known that load shifting was practised on the mine and was done using a SCADA-based software package within which dam-level set points and control ranges could be altered.

As described in Section 3.3, a peak-to-overall ratio should be calculated to determine the load-shifting effectiveness of the mine. To do this calculation, the average power usage of all of the dewatering pumps per hour over a 24-hour period was needed. By using a remote data-logging system (implemented while the load-shifting project was done and accepted as accurate), data for three months was processed and averaged out to give the 24 data points shown in Table 23 in Appendix A.

Through the following visual representation of Table 23's data in Figure 52, the substantial morning- and evening peak TOU load shift is clear.

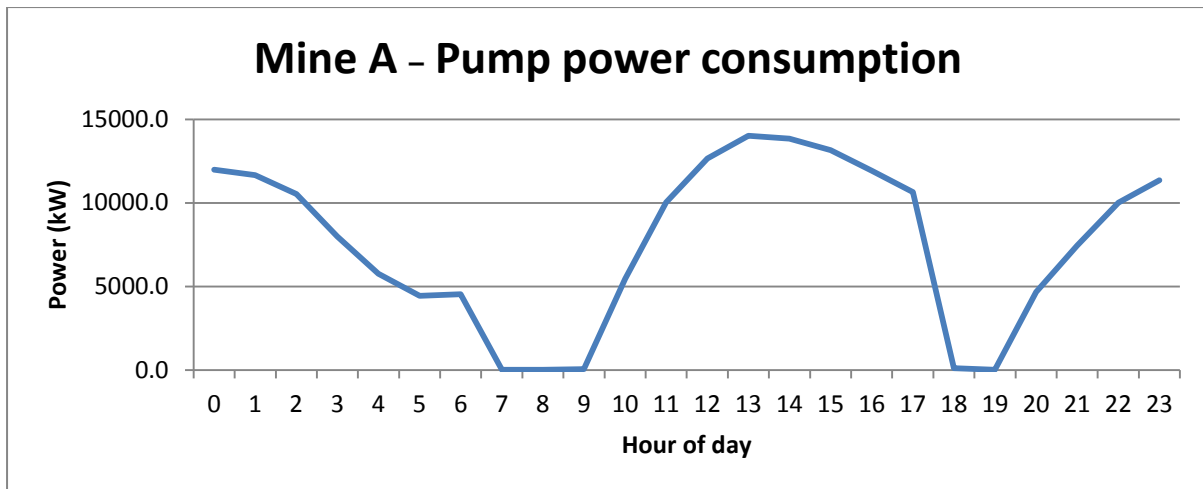


Figure 52: Mine A - Dewatering pump power consumption

By applying Equation 4 on the data obtained from Mine A, confirmation of effective load shifting is given with a peak-to-overall ratio of **0.006:1**. Total load shifting from peak TOU is thus nearly achieved.

4.2.2.2 Preparation- and comeback load

With the confirmation that Mine A does exercise effective load shifting, Step 2 of the methodology can be applied. This step (as described in Section 3.4) is used to determine if significant PL and CL exist on the site as chosen after verifying that load shifting is taking place. By analysing the data from Table 23 in Appendix A, the following is found regarding the average power and electrical energy usage during off-peak, standard and peak TOU.

Table 12: Mine A - TOU analysis

TOU	Hours per TOU	Average power (kW)	Electrical energy usage (kWh)
Off-peak	8	9 215.07	73 720.55
Standard	11	9 849.86	108 348.42
Peak	5	40.53	202.66
Total	24	19 105.46	182 271.64

Application of Equation 5 yields a standard-to-overall ratio of **1.10:1**. The high electrical energy usage during standard time is a result of significant PL and CL being present and further confirms the feasibility of using Mine A as a case study.

4.2.2.3 Optimisation of load shift control

Knowing that the selected site (Mine A) has a load-shifting system in place and that high electrical energy costs due to PL and CL occur during standard time, optimisation of the load-shifting strategy could be done. Using information as supplied by mine personnel, as well as through analysis of logged data it was found that each of the dewatering pump stations used more than one dam. The dams are, however, linked in such a manner that an average of all the dam levels may be used for pump controlling.

The following summarises preferences and constraints on each of the dewatering pump stations as required by personnel on Mine A, as well as further information needed for the application of Step 3 of the methodology:

25L

Total dam capacity:	7 000 m ³
Maximum dam level:	80%
Minimum dam level:	40%
Control range size:	5%
Maximum number of pumps running:	3
Inflow of mining water:	80 l/s
Inflow of fissure water:	50 l/s

21L

Total dam capacity:	6 000 m ³
Maximum dam level:	80%
Minimum dam level:	40%
Control range size:	10%
Maximum number of pumps running:	2
Inflow of mining water:	0 l/s
Inflow of fissure water:	0 l/s

5L

Total dam capacity:	3 000 m ³
Maximum dam level:	80%
Minimum dam level:	40%
Control range size:	10%

Maximum number of pumps running:	2
Inflow of mining water:	0 l/s
Inflow of fissure water:	5 l/s

With all the necessary information available, Step 3 of the methodology can commence. As described in Section 3.5.2, upper and lower bounds for the control range for each of the five areas over a 24-hour period have to be calculated. Mine A requested that the evening peak TOU be extended with one hour from 17:00 to 20:00 and the request had to be taken into consideration.

The following upper and lower bounds are calculated by applying Equation 6 to Equation 14 on Mine A (detailed calculations can be found in Appendix A):

Table 13: Mine A - Upper and lower bounds

	25L	21L	5L
<i>Upperbound₁</i>	45%	50%	50%
<i>Lowerbound₁</i>	40%	40%	40%
<i>Upperbound₂</i>	63.5%	70%	70%
<i>Lowerbound₂</i>	58.5%	60%	60%
<i>Upperbound₃</i>	80%	80%	80%
<i>Lowerbound₃</i>	75%	70%	70%
<i>Upperbound₄</i>	62%	70%	70%
<i>Lowerbound₄</i>	57%	60%	60%
<i>Upperbound₅</i>	80%	80%	80%
<i>Lowerbound₅</i>	75%	70%	70%

The 24-hour representations of the newly determined and optimised control range limits for Mine A's 25L, 21L and 5L are displayed in the figures that follow.

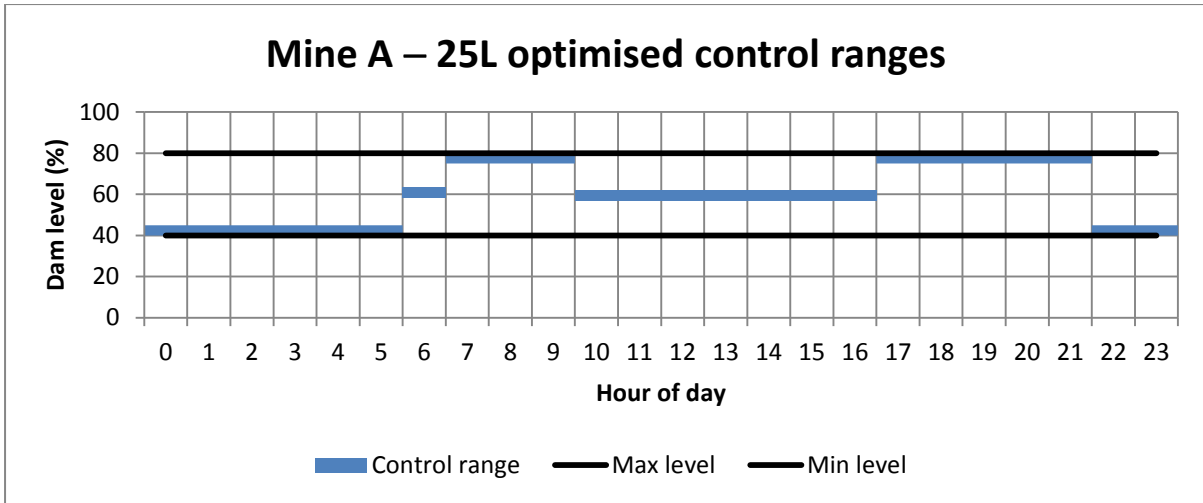


Figure 53: Mine A - 25L optimised control ranges

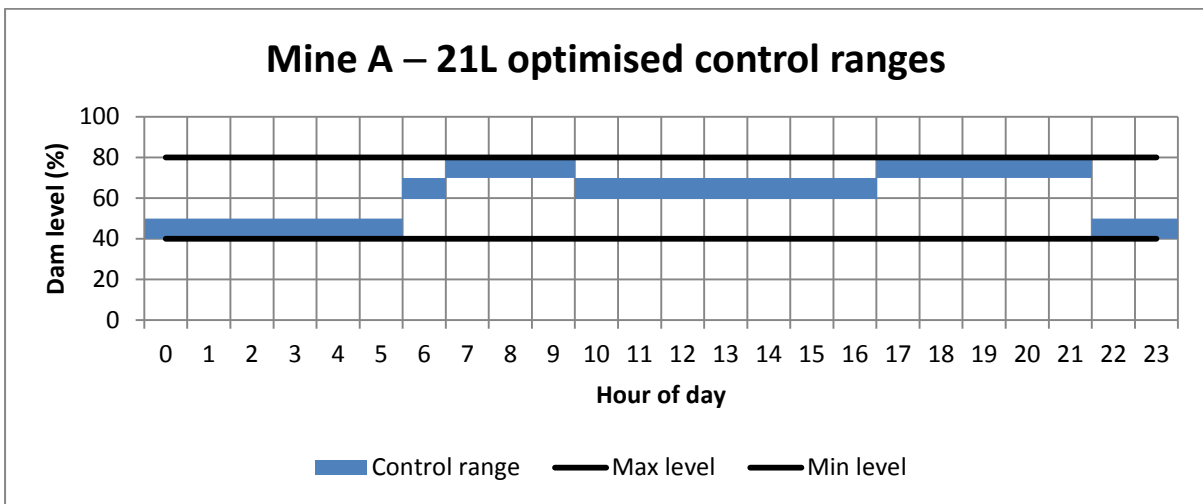


Figure 54: Mine A - 21L optimised control ranges

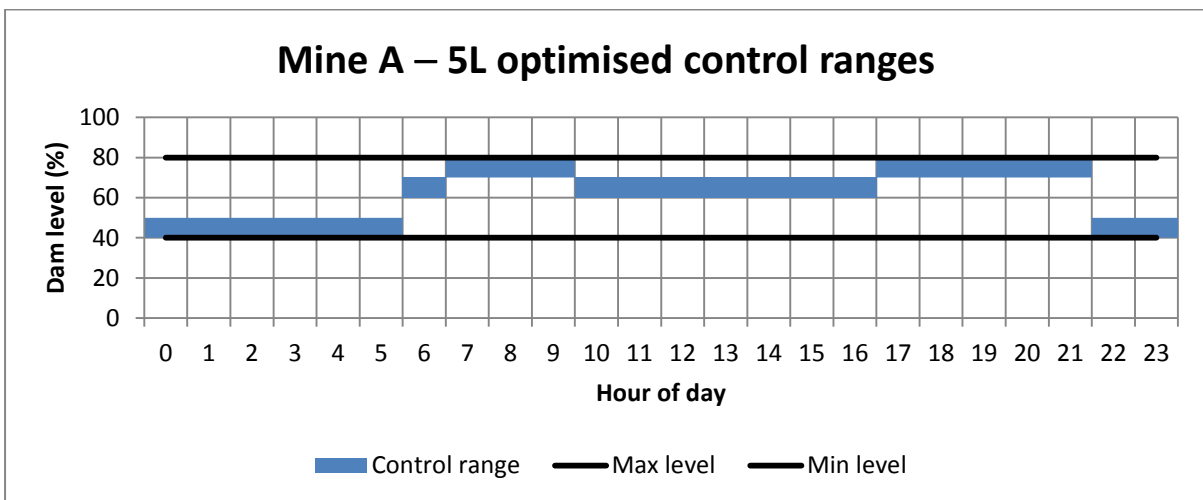


Figure 55: Mine A - 5L optimised control ranges

4.2.2.4 Water reduction

The water reduction method of valve control on water supply for each of the mining levels will now be considered. The average water flow per hour over a 24-hour period into each mining level needs to be established and used for sizing control valves. As the installed flow meters on Mine A are dated and inaccurate, the measurement of flow through a portable device was needed.

An ultrasonic flow meter was fitted to the outside of each mining level's water supply column. This instrument is considered highly accurate and measurements were taken over a period of three normal mining days [62]. Figure 56 shows the flow meter fitted to one of the water supply columns of Mine A.



Figure 56: Portable ultrasonic flow meter¹⁷

As described in Section 4.2.1, there are four main mining levels at Mine A. 20L is the only level that houses BACs and was not considered for valve control due to a constant design flow being needed for optimal BAC operation. 19L, 21L and 22L's 24-hour water flow profiles can be seen in Figure 57. The profiles indicate that relatively low water volumes are used for mining operations at Mine A as a result of production downscaling. This proved that water reduction through valve control would not be financially feasible. With this in mind the decision was made to still do a simulation and determine what the effect would have been if valves were installed.

¹⁷ N. Wilmans, Photograph. "Ultrasonic flow meter", Welkom, 2013.

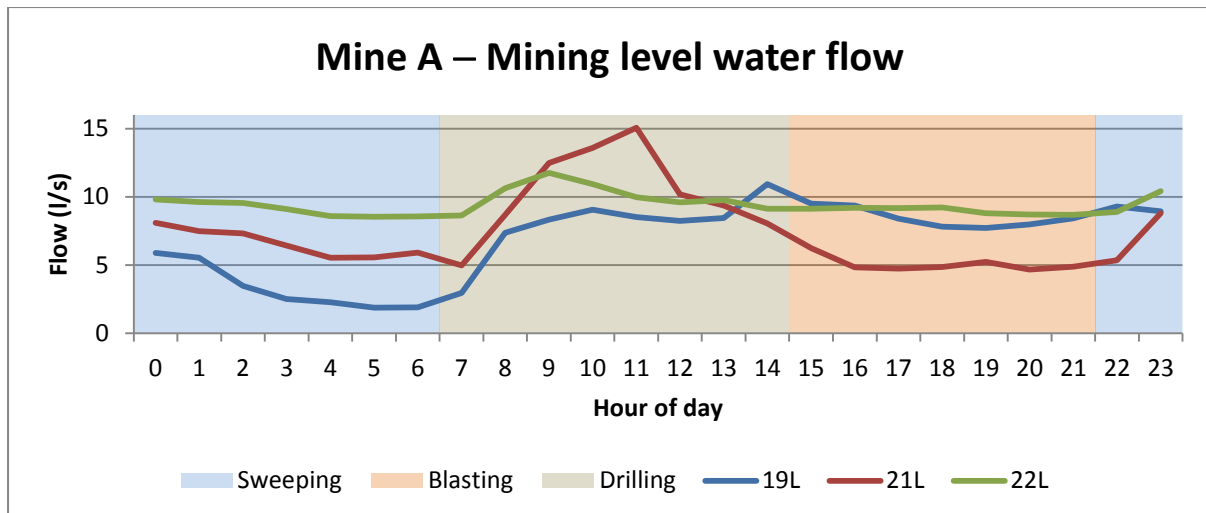


Figure 57: Mine A - Mining level water flow

Water reduction is only possible during shifts when water usage is low or when no water is needed. This would typically be during blasting shifts when mining levels are cleared of all personnel. Looking at Figure 57, one can see that high water usage occurred during blasting shifts. This usually indicates that water flow is increased by column leaks or water hoses that were left open after drilling was completed. At the end of the sweeping shift a drop in water usage is also observed. This is due to shift changing.

As water control and reduction are only possible during blasting shifts and the last few hours of sweeping shifts, control valves specified only for the flows within these times were needed. By using a butterfly valve in the main water column and a globe control valve on a bypass column, water flow can be directed through either valve depending on the time of day. During drilling shifts, the butterfly valve is fully open and delivers all the flow. During shifts when water reduction is possible, the butterfly valve closes and water is controlled through the bypass globe valve. Globe valve control is done by measuring downstream pressure and then opening and closing the globe valve according to specific downstream pressure set points through PID control.

A theoretical 100% water reduction during blasting and end-of-sweeping times as displayed in Figure 58 will result in a reduced volume (Equation 15) of **743 kL** water per day or an overall flow reduction (Equation 16) of **8.6 l/s**. With the use of Equation 3 this reduction equates to a power efficiency of **330 kW** for each hour or a total reduction in electrical energy of **7.9 MWh** per day.

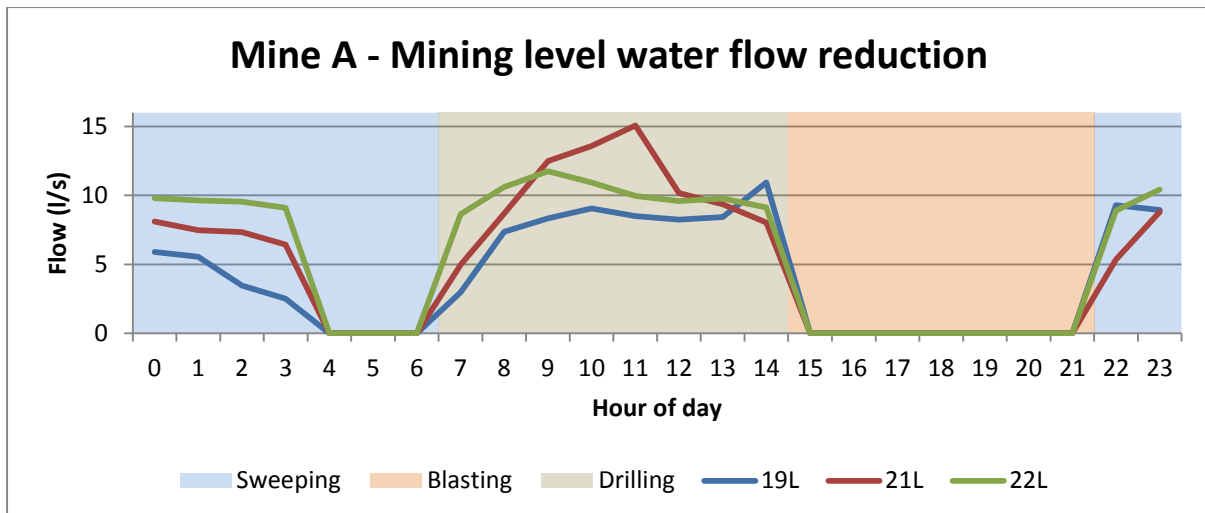


Figure 58: Mine A - Mining level water flow reduction

Together with the decrease in electrical energy achievable by the reduction of water, re-optimisation of load shift control is now also possible and will be the subsequent discussion.

4.2.2.5 Re-optimisation

With a theoretical reduction of water flowing to the 25L dam calculated as **8.6 l/s** after possible implementation of a water reduction system, further optimisation of the upper bounds of Area 2 and Area 4 must be done.

Using Equation 17 and Equation 18 it is calculated that a water volume reduction of **92.88 kl** during the morning peak TOU and **61.92 kl** during the evening peak TOU will occur. This results in a new **PreparationLevel_{2,2}** (Equation 19) of **68.89 %** and a **PreparationLevel_{4,2}** (Equation 20) of **63.32%**. Consequently the re-optimised upper bounds for Area 2 and Area 4 are **68.89%** and **63.32%** respectively (as determined by the use of Table 7 and Table 8).

Comparing the newly calculated upper bounds with those previously calculated in Section 4.2.2.3, it is seen that the low reduction in water (determined in Section 4.2.2.4) has very little effect on the actual re-optimisation of the control range limits. This indicates that the main advantage in reducing water on Mine A will be from a decline in electrical energy usage and not from further optimisation of control range limits that would result in increased load shift performance. Simulations for each scenario will be conducted in the following section.

4.2.3 VERIFICATION OF METHODOLOGY

A simulation platform that contains the total dewatering system of Mine A was built with the use of REMS-P. Water flows and control ranges were altered to obtain results for the following three scenarios:

1. Pre-optimised control range.
2. Optimised control range.
3. Optimised control range with further optimisation due to water reduction.

A screenshot of the simulation platform consisting of the dewatering system of Mine A is shown in Figure 59.

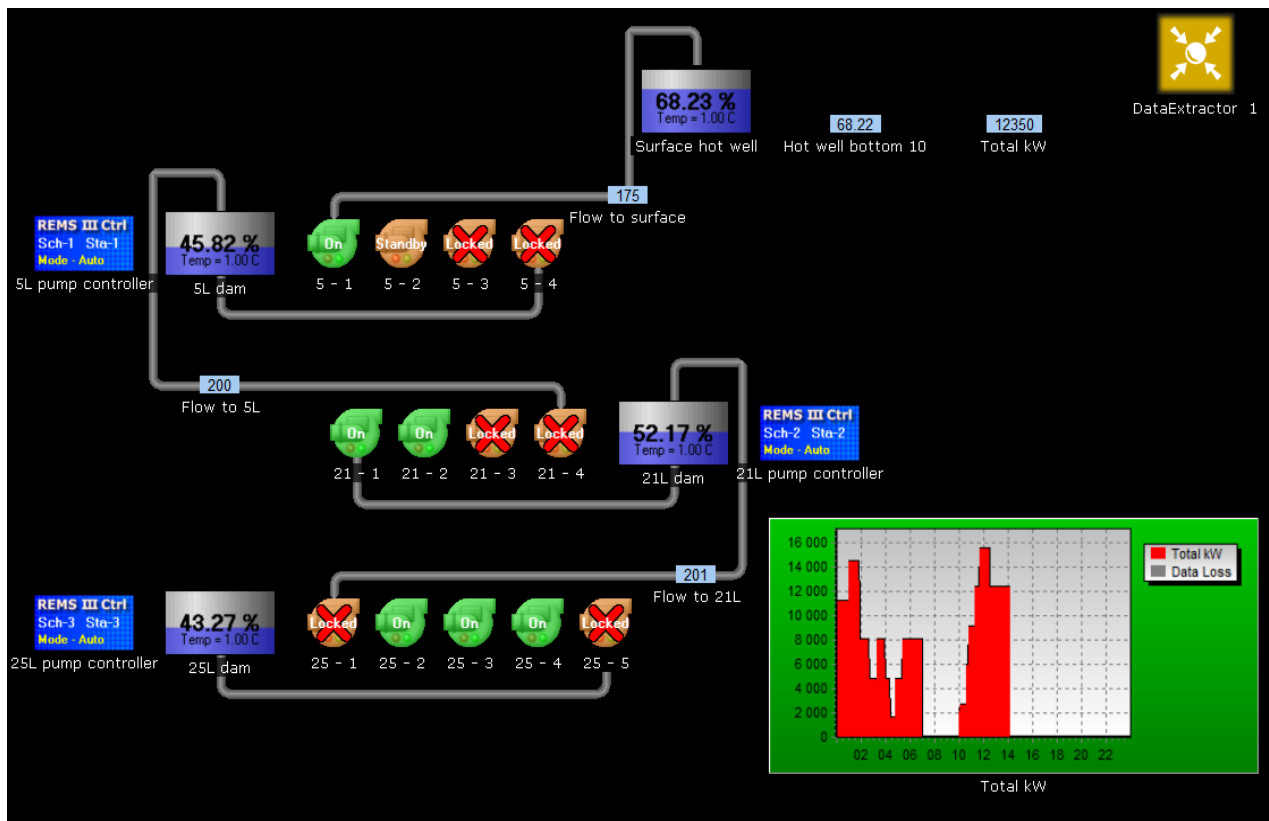


Figure 59: Mine A - Simulation platform screenshot

4.2.3.1 Simulation of pre-optimised control range

The original control range used to perform load shifting on Mine A was used to build the simulation platform. The control range was lowered close to minimum dam levels

throughout the day except during peak TOU when it was elevated to the maximum dam levels. Figure 60 shows a representation of Mine A's control range location used for all upstream dams throughout a 24-hour period.

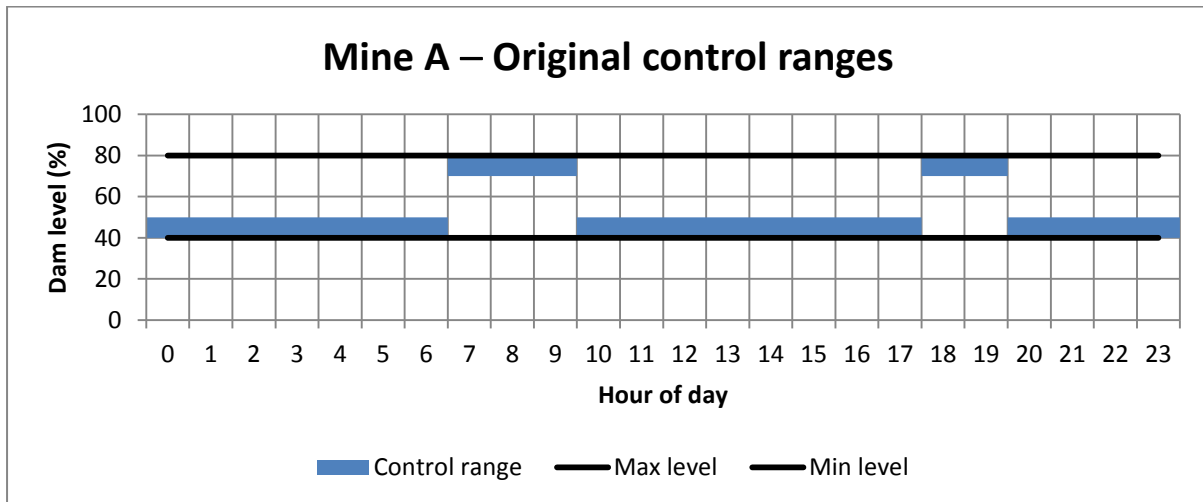


Figure 60: Mine A - Original control ranges

After running the simulation for the equivalent of ten days, the pre-optimised 24-hour power profile was obtained (Figure 61). Note that the actual power profile (as determined in Section 4.2.2.1) measured over a period of three months is very similar to the simulated profile. This shows that the simulation results can be considered highly accurate.

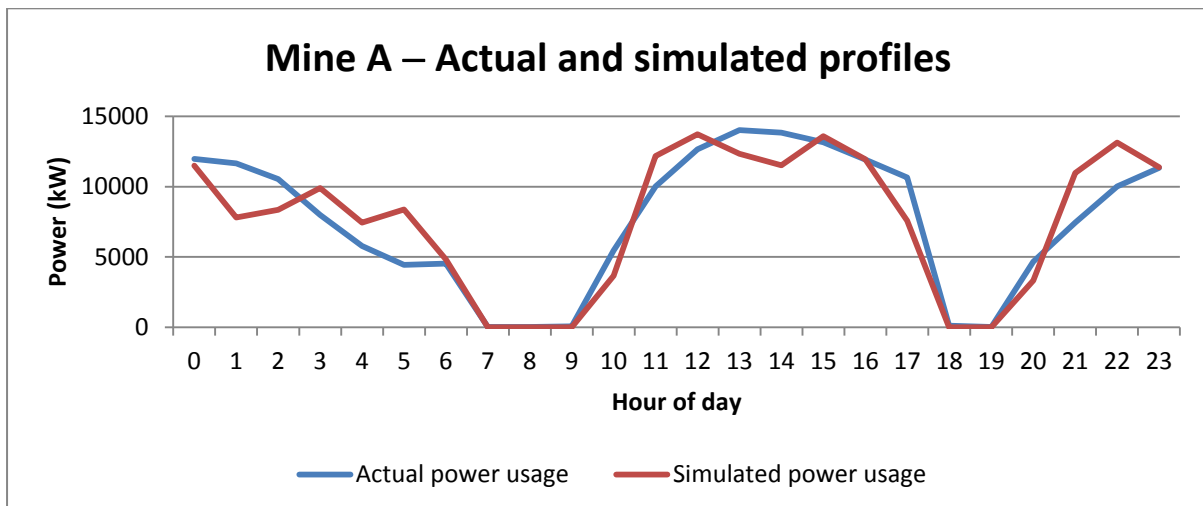


Figure 61: Mine A – Pre-optimisation actual and simulated power usage

4.2.3.2 Simulation of optimised control range

With the simulation calibrated to such an extent that similar results are obtained to the real-life electrical energy usage of Mine A, optimisation can commence. Using the optimised control range limits (as determined in Section 4.2.2.3) the simulation was reprogrammed to test the effectiveness of using the methodology as described in Chapter 3. An equivalent of ten days was again simulated to obtain the results.

The optimised simulated results are shown in Figure 62 and the data can be found in Table 24 in Appendix A.

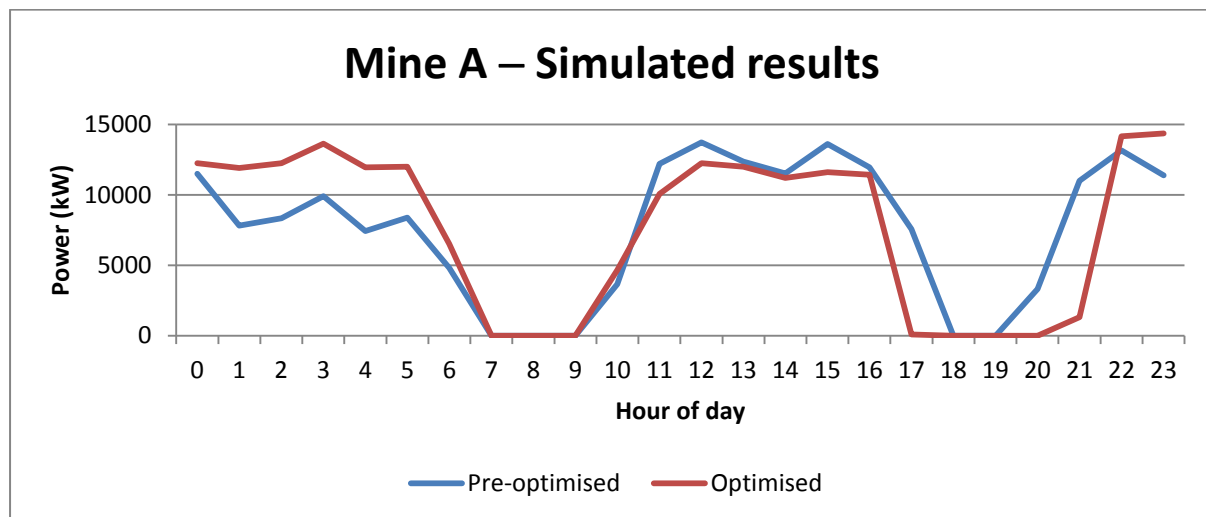


Figure 62: Mine A - Simulated results

The average power and total electrical energy usage for each of the standard, off-peak and peak TOU for both the pre-optimised and optimised simulations are found in Table 14. A reduction in electrical energy usage can be seen within the standard TOU. This will lead to the study objective of savings on electricity costs at Mine A when implemented.

Table 14: Mine A - Simulated TOU analysis

TOU	Pre-optimised		Optimised	
	Average power (kW)	Electrical energy usage (kWh)	Average power (kW)	Electrical energy usage (kWh)
Off-peak	9 737.94	77 903.54	12 813.61	102 508.89
Standard	9 606.86	105 675.42	7 370.01	81 070.06
Peak	0.00	0.00	0.00	0.00
Total	19 344.80	183 578.96	20 183.62	183 578.96

A shift of **24.605 MWh** was achieved from standard- to off-peak TOU and equates to an average annual financial saving of **R1,383,553.53** (2013 Megaflex tariffs calculations in Appendix C). This is an additional saving after optimisation of the existing load shift system.

The “surface hot dam” at Mine A is one of the study’s limiting constraints. Constant water flow from the dam is needed to a gold plant situated near Mine A as well as through surface fridge plants. This high demand of water at Mine A’s surface requires the dam level to be above a minimum level of **25%** at all times. As the 5L dewatering station pumps directly to this dam, secondary safety control had to be implemented on 5L that may have impeded a full potential outcome regarding cost savings.

4.2.3.3 Simulation of optimised control range with further optimisation (water reduction)

Now that a desirable result has been found regarding the optimisation of control ranges through simulation, further optimisation can be done using water reduction. The amount of water flowing into 5L’s underground dam needs be reduced by **8.6 l/s** (as calculated in Section 4.2.2.4). Simulating the new scenario, but still keeping all previous constraints in check, the following figure displays the final simulated results for Mine A (Data in Table 25 in Appendix A).

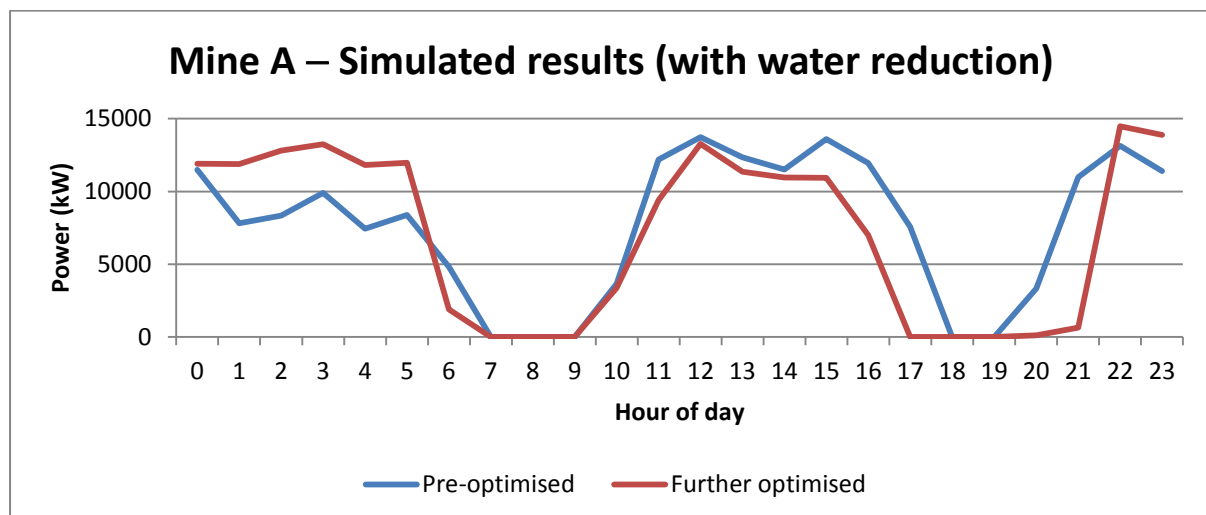


Figure 63: Mine A - Simulated results with water reduction

By analysing the average power and total electrical energy usage for each TOU of the optimised simulation after water reduction, a substantial electrical energy reduction is

noticed. The amount of electrical energy used during standard TOU was reduced by **36.754 MWh** of which **24.092 MWh** was shifted to off-peak TOU by optimising control ranges. The remaining decrease in overall electrical energy of **12.661 MWh** was due to reduced water flow to underground dams.

Table 15: Mine A - Simulated TOU analysis (further optimised)

TOU	Pre-optimised		Further optimised	
	Average power (kW)	Electrical energy usage (kWh)	Average power (kW)	Electrical energy usage (kWh)
Off-peak	9 737.94	77 903.54	12 749.52	101 996.14
Standard	9 606.86	105 675.42	6 265.57	68 921.23
Peak	0.00	0.00	0.00	0.00
Total	19 344.80	183 578.96	19 015.08	170 917.37

In financial terms an average annual saving will equate to approximately **R3,571,711.89** (2013 Megaflex tariffs calculations in Appendix C).

4.2.4 IMPLEMENTATION

4.2.4.1 Control range optimisation

With confirmation from simulated results that financial savings are viable by using the methods described in Chapter 3, implementation on Mine A can commence. The load-shifting system currently implemented at Mine A uses REMS-P for dewatering pump control. For this reason the migration of control settings used during the simulation stage to the actual installed platform on Mine A can be done without difficulty.

Optimised control ranges were programmed into the current system on the mine and were monitored to prevent unforeseen complications. The results of actual implementation of the methodology on Mine A are shown in Figure 64 with the data in Appendix A. The data used to calculate these results are from the same source as the pre-optimised data (power loggers with a remote database).

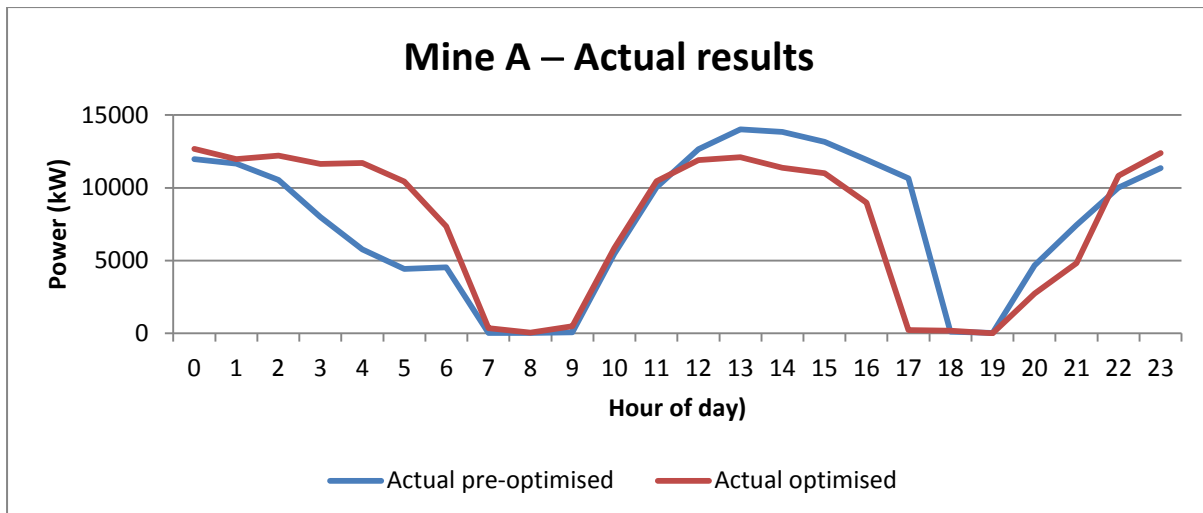


Figure 64: Mine A - Actual results

From Figure 64 a dramatic reduction in standard TOU and increase in off-peak TOU electrical energy usage is visible. A TOU power and electrical energy usage analysis yields the following results shown in Table 16.

Table 16: Mine A – Actual TOU analysis

TOU	Pre-optimised		Optimised	
	Average power (kW)	Electrical energy usage (kWh)	Average power (kW)	Electrical energy usage (kWh)
Off-peak	9 215.07	7 3720.55	11 732.36	93 858.91
Standard	9 849.86	108 348.42	7 885.34	86 738.79
Peak	40.53	202.66	208.22	1 041.10
Total	19 105.46	182 271.64	19 825.93	181 638.79

21.61 MWh was shifted from standard TOU to both peak and off-peak TOU. The electrical energy shift to peak TOU is not desirable for this study and is possibly due to the short testing time that was available to obtain these results. An average annual financial saving of **R1,096,056.65** is still achievable even with an increase in peak TOU electrical energy (2013 Megaflex tariffs calculations in Appendix C).

4.2.4.2 WATER REDUCTION

As simulated results regarding the implementation of a water reduction technique indicated substantial savings, the decision was made to use this technique at Mine A. Ordering of hardware and equipment was done but due to financial constraints, as well as an

underground fire at Mine A, implementation of a water reduction system via valve control was delayed and could not be completed as part of this study.

4.2.5 RESULT VERIFICATION

By comparing actual with simulated results for control range optimisation with no water reduction, an error of **13%** was found. This error is calculated through the amount of energy shifted from standard to off-peak TOU for both the actual and simulated results. The reason for this may vary but is most likely due to less water usage during the testing phase of methodology implementation on Mine A as well as a short testing time for the method. A more accurate result will be seen with a longer testing period.

The comparison of simulated to actual results for Mine A is presented in Figure 65 through a 24-hour power usage profile.

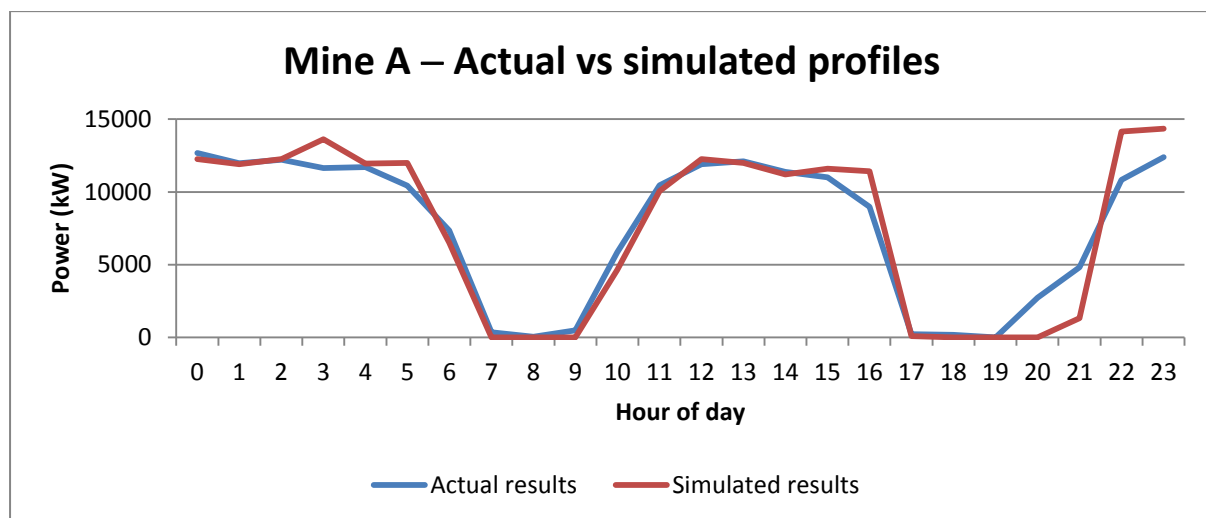


Figure 65: Mine A - Actual versus simulated profiles

A regression analysis of the whole 24-hour power usage of both the actual and simulated results reveals a linear trend line with a coefficient of determination (R^2) of **0.9456**, as seen in Figure 66.

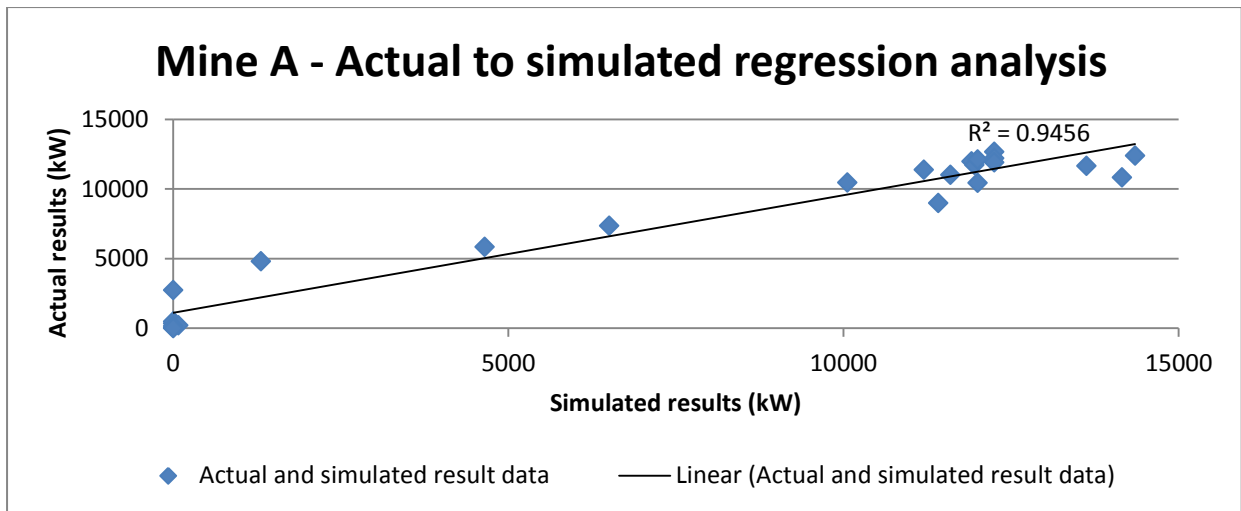


Figure 66: Mine A – Actual to simulated regression analysis

4.3 CASE STUDY B

4.3.1 MINE OVERVIEW

Mine B is also situated in the Free State province in South Africa. Five main mining levels namely 1750L, 1780L, 1810L, 1940L and 2010L are used for ore extraction. Chilled water from surface fridge plants is sent underground to each mining level for mining and cooling purposes after which it is channelled together with fissure water to the shaft bottom roughly 2 200 m below surface.

A dewatering pump station on 2180L is situated 2 180 m below the surface and utilises three 1.25 MW and one 1.5 MW multistage centrifugal dewatering pumps. Water is pumped from 2180L to another dewatering pump station situated on 1200L. Four 1.5 MW pumps are also situated on 1200L and transfer water to a surface precool dam where water is collected before being sent through fridge plants again for cooling.

Figure 67 shows a simplified layout of Mine A's water reticulation system.

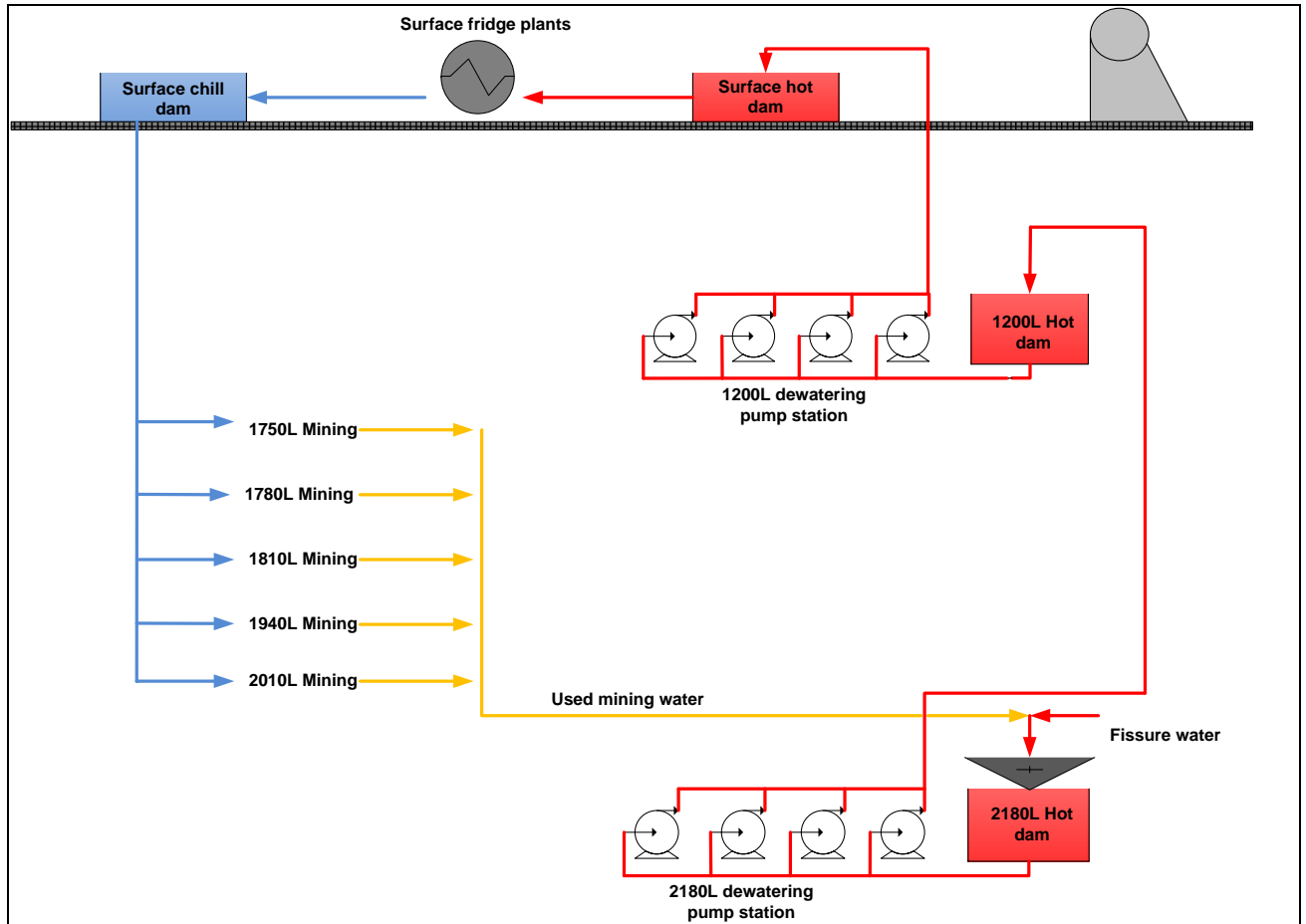


Figure 67: Mine B - Simplified water reticulation system

The pump specifications of the two dewatering pump stations at Mine B are shown in Table 17.

Table 17: Mine B - Pump station summary

Pump station	Pump no.	Installed capacity (kW)	Rated flow (l/s)	Depth (m)	Head required (m)
1200L	Pump 1	1 500	95	1 200	1 200
	Pump 2	1 500	95	1 200	1 200
	Pump 3	1 500	95	1 200	1 200
	Pump 4	1 500	95	1 200	1 200
2180L	Pump 1	1 500	95	2 180	980
	Pump 2	1 250	95	2 180	980
	Pump 3	1 250	95	2 180	980
	Pump 4	1 250	95	2 180	980

4.3.2 APPLICATION OF METHODOLOGY

4.3.2.1 SITE IDENTIFICATION

To identify Mine B as a potential candidate for this study, firstly a peak-to-overall ratio had to be calculated to determine if load shifting was as effectively utilised as claimed by mine personnel. The collection of data from a database historian on Mine B's SCADA system allowed processing to determine 24 data points needed to calculate the ratio. This data was accepted as accurate.

The peak-to-overall ratio of Mine B as calculated by using Equation 4 is **0:1**. This indicates a total shifting of load from peak TOU to the rest of the day. Figure 68 displays a 24-hour profile of power versus time of day to show the effective morning and evening peak load shifting accomplished at Mine B (data can be found in Appendix A).

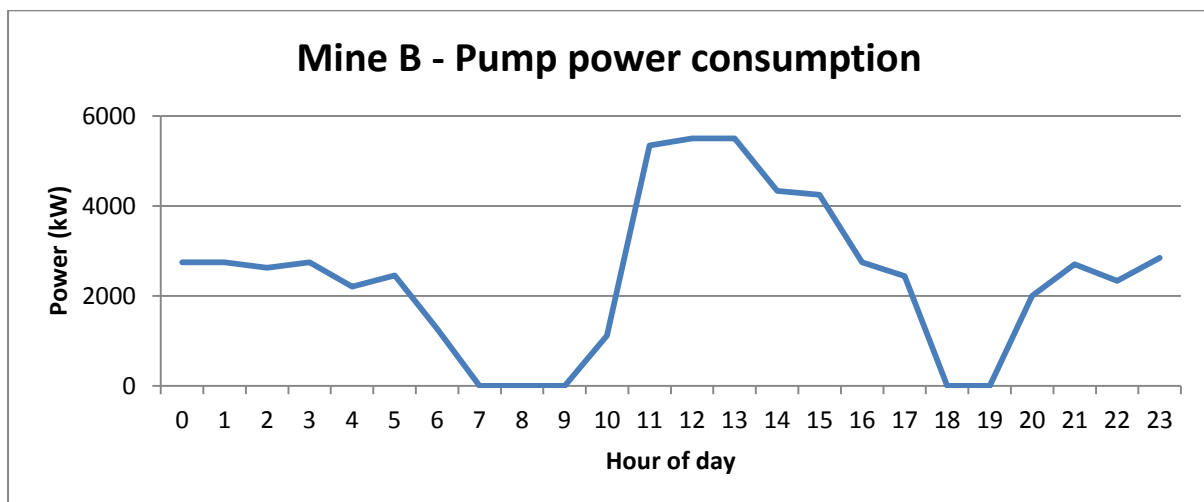


Figure 68: Mine B - Dewatering pump power consumption

4.3.2.2 PREPARATION AND COMEBACK LOAD

By applying Step 2 of the methodology on Mine B the significance of PL and CL can be determined. Equation 5 applied to the 24 data points (determined in Section 4.3.2.1) yields a standard-to-overall ratio of **1.40:1**. This high ratio indicates that the majority of electrical energy usage on Mine B's dewatering system exists within the standard TOU and therefore indicates high PL and CL. Mine B is therefore a desirable candidate for this study and was chosen as Case Study B.

Table 18 displays a TOU analysis of Mine B's electrical energy usage by dewatering pumps.

Table 18: Mine B - TOU analysis

TOU	Hours per TOU	Average power (kW)	Electrical energy usage (kWh)
Off-peak	8	2 590.62	20 724.99
Standard	11	3 384.04	37 224.40
Peak	5	0.00	0.00
Total	24	5 974.66	57 949.39

4.3.2.3 OPTIMISATION OF LOAD SHIFT CONTROL

Now that it has been confirmed that Mine B has a load-shifting system in place and that significant PL and CL occur within standard TOU, optimisation of current control range limits can be done.

Information provided by mine personnel and analysing the dewatering system provide the following specifications regarding the two dewatering pump stations at Mine B. This information will be taken into account when designing an optimised control system for load shifting using the methodology described in Chapter 3.

2180L

Total dam capacity:	6 500 m ³
Usable dam capacity:	5 000 m ³
Maximum dam level:	80%
Minimum dam level:	45%
Control range size:	10%
Maximum number of pumps running:	2
Inflow of mining water:	50 l/s
Inflow of fissure water:	20 l/s

1200L

Total dam capacity:	1 508 m ³
Usable dam capacity:	1 508 m ³
Maximum dam level:	80%
Minimum dam level:	45%

Control range size:	10%
Maximum number of pumps running:	2
Inflow of mining water:	0 l/s
Inflow of fissure water:	0 l/s

With all the necessary information available, Step 3 of the methodology can commence. As described in Section 3.5.2, upper and lower bounds for the control range for each of the five areas over a 24-hour period have to be calculated. Mine B had the same request as Mine A: extending the evening peak TOU even further from 17:00 to 20:00 if possible. The following upper and lower bounds are calculated through application of Equation 6 to Equation 14 on Mine B (detailed calculations can be found in Appendix A):

Table 19: Mine B - Upper and lower bounds

	2180L	1200L
<i>Upperbound₁</i>	55%	55%
<i>Lowerbound₁</i>	45%	45%
<i>Upperbound₂</i>	64.88%	70%
<i>Lowerbound₂</i>	54.88%	60%
<i>Upperbound₃</i>	80%	80%
<i>Lowerbound₃</i>	70%	70%
<i>Upperbound₄</i>	64.88%	70%
<i>Lowerbound₄</i>	54.88%	60%
<i>Upperbound₅</i>	80%	80%
<i>Lowerbound₅</i>	70%	70%

24-hour representations of the newly determined and optimised control range limits for Mine B's 2180L and 1200L are displayed in the figures that follow.

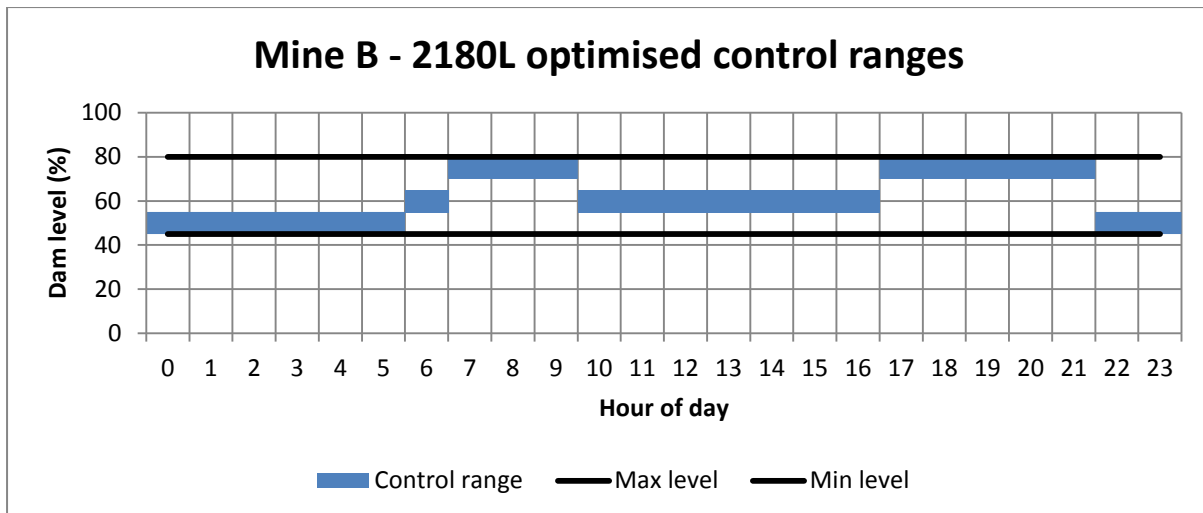


Figure 69: Mine B - 2180L optimised control ranges

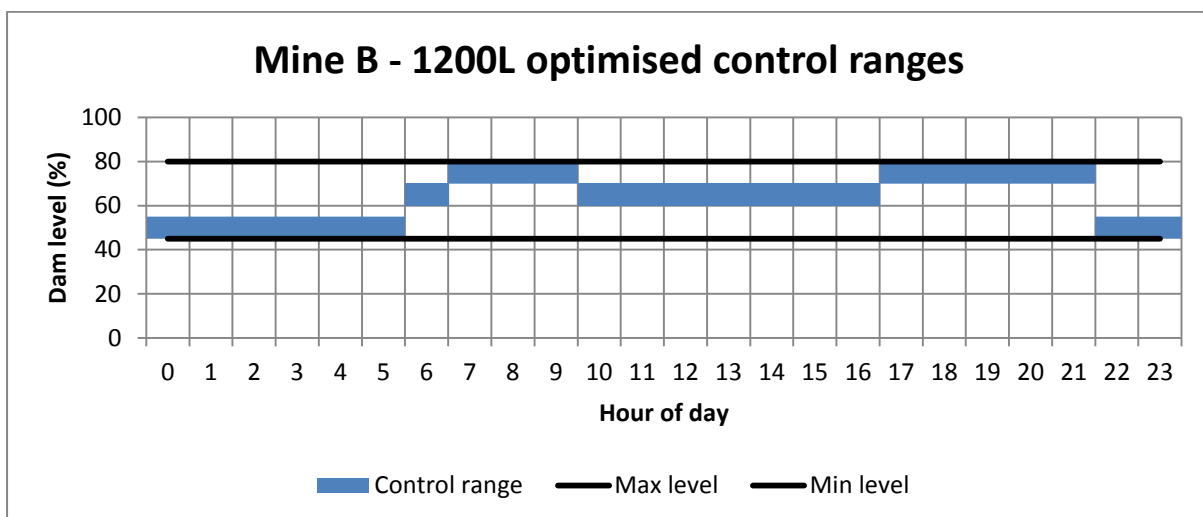


Figure 70: Mine B – 1200L optimised control ranges

4.3.2.4 WATER REDUCTION

Due to downscaling and low water usage by the mine, water reduction through valve control was not considered for Mine B. As no water reduction was done, the optional re-optimisation step in the methodology discussed in Chapter 3 was not needed.

4.3.3 VERIFICATION OF METHODOLOGY

To verify the control range optimisation method on Mine B, simulations consisting of the total dewatering system had to be done. Two scenarios were simulated to prove the

methodology before the actual implementation. Figure 71 shows a screenshot of the simulation platform used to recreate the following two scenarios:

1. Pre-optimised control range.
2. Optimised control range.

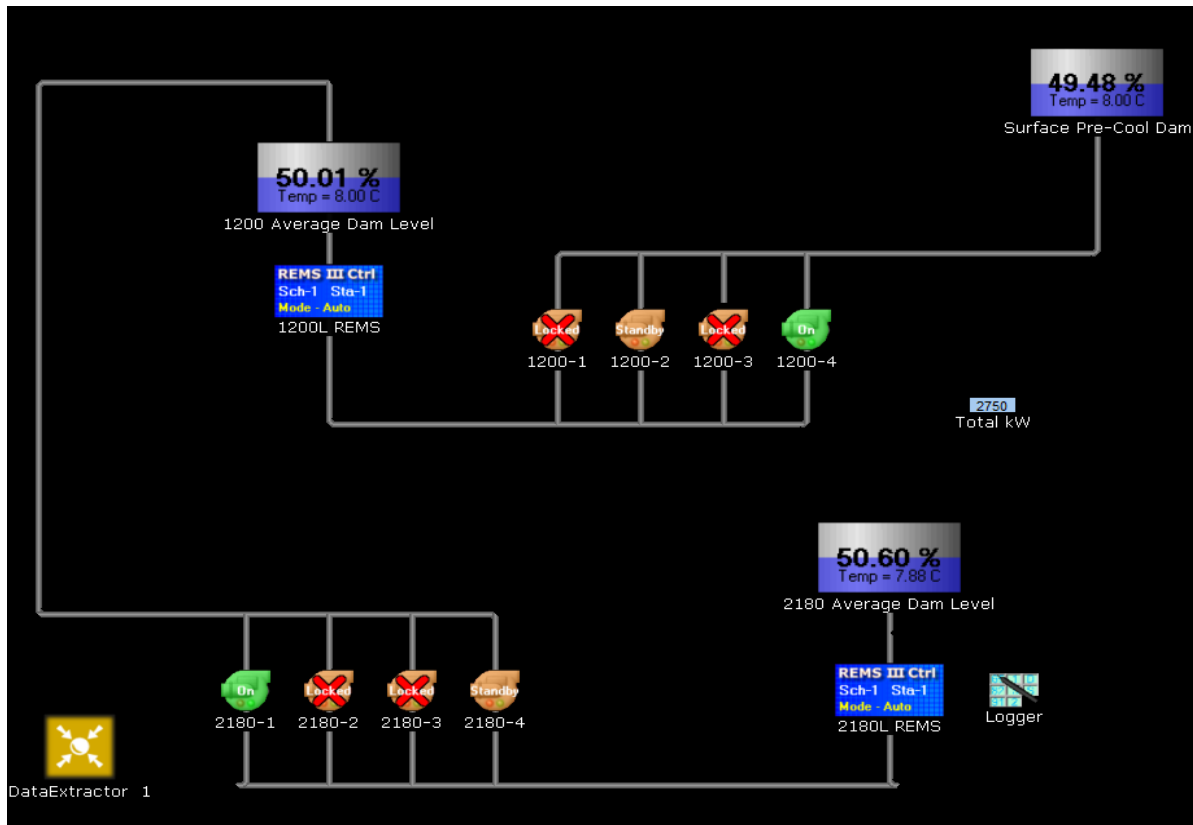


Figure 71: Mine B - Simulation platform screenshot

4.3.3.1 SIMULATION OF PRE-OPTIMISED CONTROL RANGE

Using the present control philosophy towards load shifting for Mine B, a simulation platform was built in order to match the present electrical energy usage of the dewatering system. Figure 72 shows a representation of Mine B's control range location used for all upstream dams throughout a 24-hour period. The actual power profile as calculated from data retrieved from Mine B is compared to the obtained simulated profile and is displayed in Figure 73.

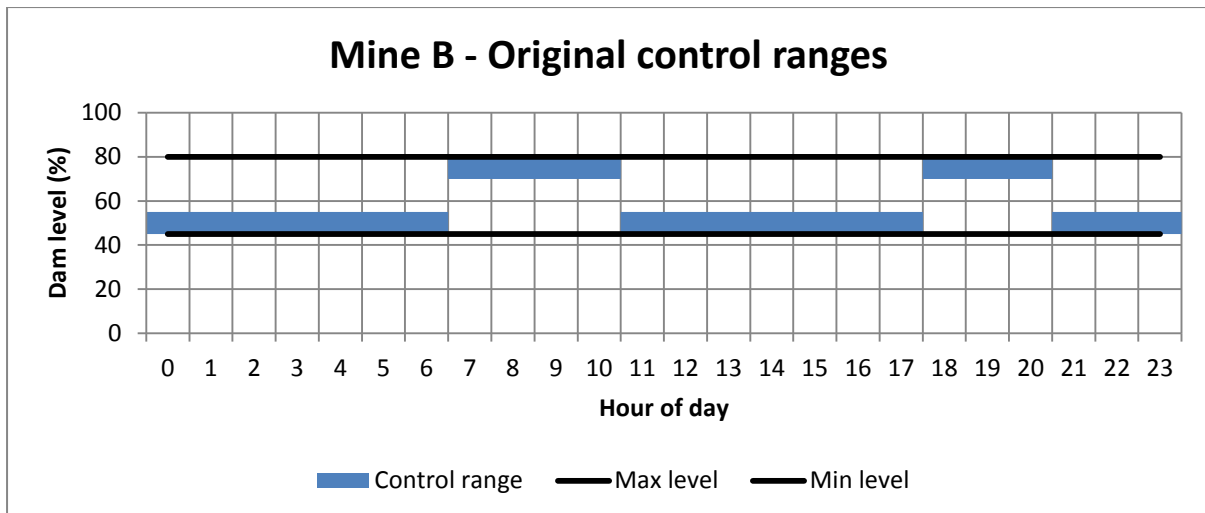


Figure 72: Mine B - Original control ranges

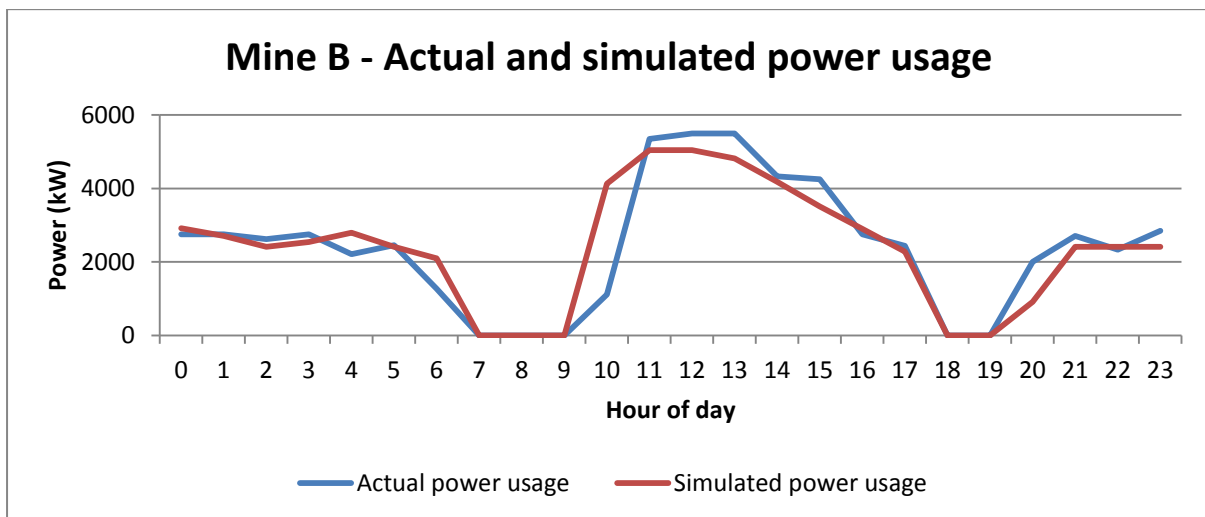


Figure 73: Mine B - Actual and simulated power usage

4.3.3.2 SIMULATION OF OPTIMISED CONTROL RANGE

The simulation platform used to obtain the true-to-actual power profile shown in Section 4.3.3.1 was reprogrammed with the optimised control ranges for Mine B as calculated in Section 4.3.2.3. Similarly to Mine A, a surface dam at Mine B with a minimum allowable level of 25% had to be taken into account when reprogramming of the simulation was done.

The simulation yielded the results shown in Figure 74. Figure 74 and Table 20 show that a substantial shift of electrical energy from standard to off-peak TOU is possible on Mine B. A simulated **8.09 MWh** was shifted from standard to off-peak TOU with an average annual

financial saving of **R434,831.07** (2013 Megaflex tariffs calculations in Appendix C; Profile data in Appendix A).

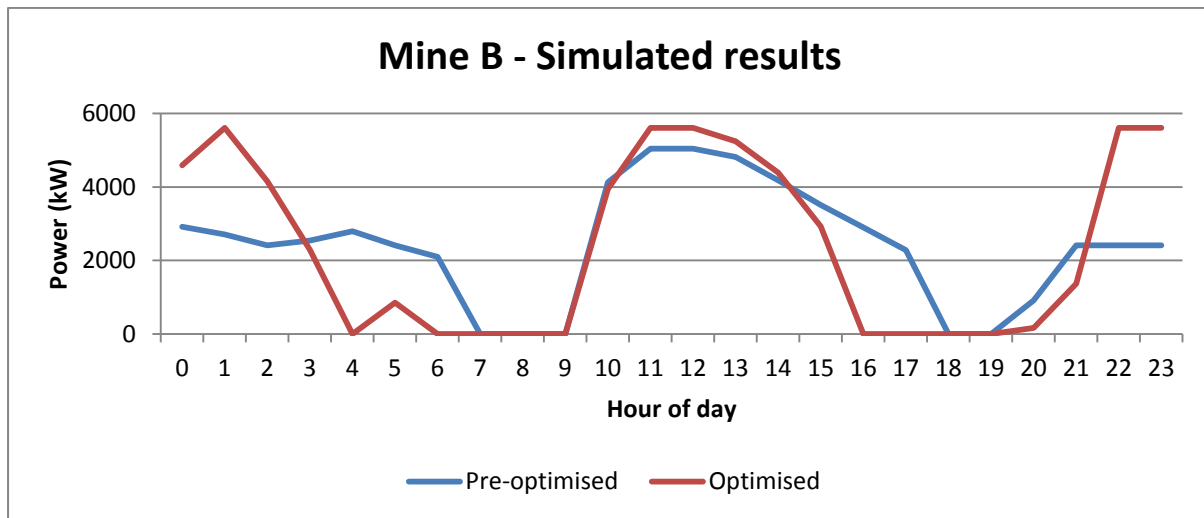


Figure 74: Mine B - Simulated results

Table 20: Mine B - Simulated TOU analysis

TOU	Pre-optimised		Optimised	
	Average power (kW)	Energy usage (kWh)	Average power (kW)	Energy usage (kWh)
Off-peak	2 577.60	20 620.81	3 588.32	28 706.56
Standard	3 393.51	37 328.58	2 658.44	29 242.83
Peak	0.00	0.00	0.00	0.00
Total	5 971.11	57 949.39	6 247.76	57 949.39

4.3.4 IMPLEMENTATION

4.3.4.1 CONTROL RANGE OPTIMISATION

With confirmation of substantial financial savings through simulated results of Mine B, implementation can commence. Optimised control ranges were programmed into Mine B's REMS-P software and the following results were obtained.

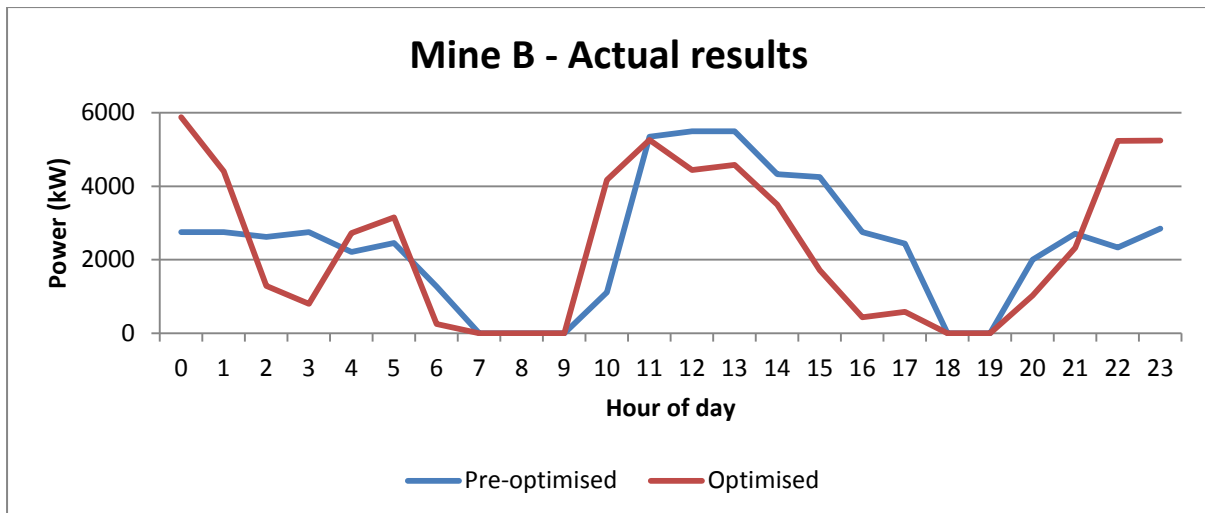


Figure 75: Mine B - Actual results

Table 21: Mine B – Actual TOU analysis

TOU	Pre-optimised		Optimised	
	Average power (kW)	Energy usage (kWh)	Average power (kW)	Energy usage (kWh)
Off-peak	2 590.62	20 724.99	3 592.04	28 736.32
Standard	3 384.04	37 224.40	2 572.64	28 298.99
Peak	0.00	0.00	0.00	0.00
Total	5 974.66	57 949.39	6 164.68	57 035.31

Again a considerable reduction in standard TOU electrical energy usage is visible on Figure 75 and Table 21. **8.93 MWh** was shifted from standard to off-peak TOU and will result in an average annual financial saving of **R579,394.27** (2013 Megaflex tariffs calculations in Appendix C).

4.3.5 RESULT VERIFICATION

By comparing actual results with simulated results for control range optimisation with no water reduction, an error of **10.4%** was found. This error was calculated on the amount of energy moved from standard to off-peak TOU for both the actual and simulated results. The comparison of actual results with simulated results for Mine B is presented in Figure 76 through a 24-hour power usage profile.

Through the comparison it is clear that between the hours of 00:00 and 07:00 there is a great difference between the actual and simulated results. There may be various reasons

4.4 SUMMARY

Two case studies were used to test the methodology described in Chapter 3. Simulations were first carried out to ensure an acceptable financial saving would be realised after which the method was implemented.

Case Study 1 was done on Mine A and returned a reduction in PL and CL that equates to an annual financial saving of **R1,096,056.65**. Mine B was used as Case Study 2. A reduction in standard TOU which led to PL and CL reduction was also found and showed an annual financial saving of **R579,394.27**.

Through these case studies the methodology was verified and substantial financial savings were obtained.

5 CONCLUSION AND RECOMMENDATIONS



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¹⁸ Discover Spring Texas, "How to Save Money on your Electric Bills," Discover Spring Texas, 12 October 2009. [Online]. Available: <http://discoverspringtexas.com/2009/10/12/how-to-save-money-on-your-electric-bills/>. [Accessed 5 September 2013].

5.1 CONCLUSION

Electrical energy and its uses within South African industrial environments are paramount to the financial and socio-economic development of the country. This leads to high electrical energy consumption by gold mines in South Africa, and particularly by large underground dewatering pumps. With this high usage of electricity comes ever-increasing problems that lead to the inevitable outstripping of demand over supply if no action is taken.

Research on the different aspects of gold mine water reticulation systems was done. It was found that water is used for various purposes on a mine that include cooling, drilling and cleaning. The supply of service water to each level on a mine can be regulated via valve control and introduces opportunities for electrical energy savings. Used service water accumulates in underground dams together with underground fissure water and need to be pumped to surface to start the reticulation cycle again.

Studies previously done on the water reticulation system towards energy and cost savings showed that load-shifting strategies have been implemented on dewatering pumps. Introduction of these projects greatly lowered the strain on the supply side (Eskom) and realised financial savings for the client due to the use of TOU tariff structures. Optimised water supply strategies have also been implemented to reduce overall electrical energy usage on mines. Pressure set-point valve control on water supply columns feeding mining levels has shown that a decrease in dewatering is possible and therefore a reduction in electrical energy was achieved.

As tariffs as well as electrical energy demand increased, a need for further reduction was required on the demand side. Due to preparation- and comeback loads resulting from load shifting on dewatering pumps, the high demand within standard TOU hours before and after peak TOU hours was becoming more apparent. This was shown to be an increasing problem over the following years due to essential development of the country that induced an increase in electrical energy demand.

The solution to decrease standard TOU electrical energy usage via decreasing preparation- and comeback loads on mine dewatering pumps was identified. The design of a method that could be implemented on any current dewatering pump load-shifting strategies was discussed and formulated. This method makes use of pump control through optimised control ranges that upstream underground dams have to adhere to. An optional step in the

method is to implement a water supply optimisation strategy through valve control that in effect reduces water flow to underground dams and promotes a further optimised control range.

The method was tested on two South African gold mines (Mine A and Mine B) through simulations and actual implementation. The results obtained showed an electrical energy shift of **21.61 MWh** from standard to off-peak TOU for Mine A and **8.93 MWh** for Mine B. This equates to an average annual financial saving of **R1,096,056.65** and **R579,394.27** respectively.

It is concluded that by implementing this study's designed method, substantial electrical energy shifts from standard to off-peak TOU is achievable by reducing preparation- and comebacks loads of mine dewatering pumps. The main objective of this study, being an increase in financial saving over present systems, was thus achieved.

5.2 RECOMMENDATIONS FOR FURTHER STUDY

Throughout this study various limiting factors regarding the performance of said method were identified. As the method is designed around immediate factors included in the dewatering pump system further optimisation may be achieved by addressing the following:

- Increasing dam storage capacity.
- Installing high-efficiency dewatering pumps.
- Reducing fissure water.

Integrating surface pumping- and cooling schedules with dewatering schedules may also be investigated to reduce the need for pumping to surface at certain times of the day. This was a limiting factor found during Case Study 1.

The effect of reducing water as an optional part of the methodology could only be simulated and not tested fully due to time constraints. It is recommended that after implementation on Mine A, further studies are conducted to verify this step.

As the goal of this study was to reduce preparation- and comeback loads and in effect optimise load-shifting implementations on mine dewatering pumps, a similar method may be

developed for other load-shifting environments. Cement mills, gold ore mills and mine fridge plants are but a few additional systems where load shifting is utilised. All of these systems contain storage capacity of some sort. Further development of this study's method towards a generic model providing for a broader range of industries may yield desirable results.

6 BIBLIOGRAPHY

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APPENDIX A

Table 22: Example of processed data

Time of day (hh:mm)	Example 1 (kW)	Example 2 (kW)	Example 3 (kW)
00:00	13 519	17 957	3 183
01:00	10 242	18 001	3 279
02:00	9 899	18 223	3 267
03:00	7 893	18 242	3 241
04:00	7 995	18 538	3 283
05:00	8 935	18 308	3 380
06:00	8 465	18 188	3 237
07:00	150	15 000	3 602
08:00	130	15 129	3 840
09:00	491	14 128	4 225
10:00	13 757	13 641	3 991
11:00	13 629	12 854	3 879
12:00	12 509	12 467	3 343
13:00	14 216	12 043	3 320
14:00	14 216	12 070	3 077
15:00	14 216	11 655	3 167
16:00	13 043	11 836	3 125
17:00	8 242	12 203	3 518
18:00	101	12 458	4 013
19:00	256	12 496	4 008
20:00	13 990	13 086	3 634
21:00	13 990	13 555	3 671
22:00	13 586	14 509	3 423
23:00	14 393	16 523	3 326

Table 23: Mine A – Dewatering pump data

Time of day (hh:mm)	Power (kW)
00:00	11 978.6
01:00	11 658.9
02:00	10 530.2
03:00	7 991.6
04:00	5 767.4
05:00	4 431.0
06:00	4 530.3
07:00	16.3
08:00	16.2
09:00	53.3
10:00	5 455.6
11:00	10 025.2
12:00	12 651.0
13:00	14 022.3
14:00	13 835.1
15:00	13 154.1
16:00	11 926.5
17:00	10 647.3
18:00	101.7
19:00	15.2
20:00	4 663.6
21:00	7 437.3
22:00	10 013.8
23:00	11 349.1

Table 24: Mine A - Simulated optimised results

Time of day (hh:mm)	Pre-optimised (kW)	Optimised (kW)
00:00	11 496.3	12 250.0
01:00	7 816.3	11 911.0
02:00	8 344.6	12 250.0
03:00	9 896.7	13 628.7
04:00	7 435.8	11 956.2
05:00	8 379.0	12 001.4
06:00	4 817.7	6 506.6
07:00	0.0	0.0
08:00	0.0	0.0
09:00	0.0	0.0
10:00	3 653.5	4 649.9
11:00	12 190.0	10 057.7
12:00	13 723.3	12 250.0
13:00	12 350.0	12 001.4
14:00	11 515.8	11 202.6
15:00	13 600.8	11 596.7
16:00	11 947.5	11 415.9
17:00	7 571.9	79.1
18:00	0.0	0.0
19:00	0.0	0.0
20:00	3 320.2	0.0
21:00	10 984.6	1 310.1
22:00	13 147.5	14 159.8
23:00	11 387.5	14 351.9

Table 25: Mine A - Simulated optimised results with water reduction

Time of day (hh:mm)	Pre-optimised (kW)	Further optimised (kW)
00:00	11 496.3	11 899.7
01:00	7 816.3	11 888.4
02:00	8 344.6	12 803.7
03:00	9 896.7	13 244.4
04:00	7 435.8	11 820.6
05:00	8 379.0	11 978.8
06:00	4 817.7	1 884.5
07:00	0.0	0.0
08:00	0.0	0.0
09:00	0.0	0.0
10:00	3 653.5	3 361.7
11:00	12 190.0	9 402.3
12:00	13 723.3	13 278.3
13:00	12 350.0	11 363.3
14:00	11 515.8	10 952.6
15:00	13 600.8	10 930.0
16:00	11 947.5	6 998.8
17:00	7 571.9	0.0
18:00	0.0	0.0
19:00	0.0	0.0
20:00	3 320.2	113.0
21:00	10 984.6	636.7
22:00	13 147.5	14 471.9
23:00	11 387.5	13 888.6

Table 26: Mine A - Actual results

Time of day (hh:mm)	Actual pre-optimised (kW)	Actual optimised (kW)
00:00	11 978.6	12 891.3
01:00	11 658.9	12 000.4
02:00	10 530.2	12 517.2
03:00	7 991.6	11 289.1
04:00	5 767.4	12 119.9
05:00	4 431.0	10 455.4
06:00	4 530.3	6 101.9
07:00	16.3	29.7
08:00	16.2	74.0
09:00	53.3	745.9
10:00	5 455.6	6 640.1
11:00	10 025.2	10 521.7
12:00	12 651.0	11 905.8
13:00	14 022.3	12 354.0
14:00	13 835.1	11 797.8
15:00	13 154.1	10 700.9
16:00	11 926.5	9 416.0
17:00	10 647.3	272.1
18:00	101.7	260.9
19:00	15.2	0.0
20:00	4 663.6	2 759.3
21:00	7 437.3	3 199.3
22:00	10 013.8	11 260.2
23:00	11 349.1	12 958.7

Table 27: Mine B – Dewatering pump data

Time of day (hh:mm)	Power (kW)
00:00	2750.0
01:00	2750.0
02:00	2625.0
03:00	2750.0
04:00	2208.3
05:00	2458.3
06:00	1275.0
07:00	0.0
08:00	0.0
09:00	0.0
10:00	1116.1
11:00	5350.0
12:00	5500.0
13:00	5500.0
14:00	4333.3
15:00	4250.0
16:00	2750.0
17:00	2441.7
18:00	0.0
19:00	0.0
20:00	2000.0
21:00	2708.3
22:00	2333.3
23:00	2850.0

Table 28: Mine B - Simulated optimised results

Time of day (hh:mm)	Pre-optimised (kW)	Optimised (kW)
00:00	2920.8	4590.8
01:00	2706.2	5606.4
02:00	2413.6	4152.0
03:00	2545.3	2291.3
04:00	2794.0	0.0
05:00	2413.6	853.2
06:00	2099.1	0.0
07:00	0.0	0.0
08:00	0.0	0.0
09:00	0.0	0.0
10:00	4125.1	3948.9
11:00	5046.7	5606.4
12:00	5046.7	5606.4
13:00	4815.1	5240.8
14:00	4181.2	4387.6
15:00	3510.8	2925.1
16:00	2896.4	0.0
17:00	2282.0	0.0
18:00	0.0	0.0
19:00	0.0	0.0
20:00	911.8	162.5
21:00	2413.6	1365.0
22:00	2413.6	5606.4
23:00	2413.6	5606.4

Table 29: Mine B - Actual optimised results

Time of day (hh:mm)	Pre-optimised (kW)	Optimised (kW)
00:00	2750.0	5876.1
01:00	2750.0	4405.1
02:00	2625.0	1288.1
03:00	2750.0	803.1
04:00	2208.3	2728.9
05:00	2458.3	3148.8
06:00	1275.0	248.1
07:00	0.0	0.0
08:00	0.0	0.0
09:00	0.0	0.0
10:00	1116.1	4169.7
11:00	5350.0	5263.8
12:00	5500.0	4440.1
13:00	5500.0	4583.2
14:00	4333.3	3501.8
15:00	4250.0	1717.5
16:00	2750.0	435.7
17:00	2441.7	585.2
18:00	0.0	0.0
19:00	0.0	0.0
20:00	2000.0	1025.7
21:00	2708.3	2328.2
22:00	2333.3	5238.4
23:00	2850.0	5247.9

APPENDIX B

MINE A – CONTROL RANGE LIMIT CALCULATIONS

25L

$$\text{Lowerbound}_1 = \text{AbsMin} \quad (\text{Equation 6})$$

$$\text{Lowerbound}_1 = 40 \%$$

$$\text{Upperbound}_1 = \text{AbsMin} + \text{CR} \quad (\text{Equation 7})$$

$$\text{AbsMin} = 40 \%$$

$$\text{CR} = 5 \%$$

$$\text{Upperbound}_1 = 45 \%$$

$$\text{PreparationLevel}_2 = \text{AbsMax} - \left(\left(\frac{\text{PeakVol}_1}{\text{Cap}} \right) \times 100 \right) \quad (\text{Equation 8})$$

$$\text{AbsMax} = 80 \%$$

$$\text{PeakVol}_1 = 106 \text{ l/s} \times 3600 \times 3$$

$$\text{PeakVol}_1 = 1144800 \text{ l}$$

$$\text{Cap} = 7000000 \text{ l}$$

$$\text{PreparationLevel}_2 = 63.54 \%$$

$$\text{Upperbound}_2 = \text{PreparationLevel}_2 \quad (\text{Table 7})$$

$$\text{Upperbound}_2 = 63.54 \%$$

$$\text{Lowerbound}_2 = \text{PreparationLevel}_2 - \text{CR} \quad (\text{Table 7})$$

$$\text{Lowerbound}_2 = 58.54 \%$$

$$\text{Upperbound}_3 = \text{AbsMax} \quad (\text{Equation 9})$$

$$\text{Upperbound}_3 = 80 \%$$

$$\text{Lowerbound}_3 = \text{AbsMax} - \text{CR} \quad (\text{Equation 10})$$

$$\text{Lowerbound}_3 = 75 \%$$

$$\text{PreparationLevel}_4 = \text{AbsMax} - \left(\left(\frac{\text{PeakVol}_2}{\text{Cap}} \right) \times 100 \right) \quad (\text{Equation 11})$$

$$\text{AbsMax} = 80 \%$$

$$\text{PeakVol}_2 = 116 \text{ l/s} \times 3600 \times 3$$

$$\text{PeakVol}_2 = 1252800 \text{ l}$$

$$\text{Cap} = 7000000 \text{ l}$$

$$\text{PreparationLevel}_4 = 62 \%$$

$$\begin{aligned} \text{Upperbound}_4 &= \text{PreparationLevel}_4 && \text{(Table 8)} \\ \text{Upperbound}_4 &= 62 \% \end{aligned}$$

$$\begin{aligned} \text{Lowerbound}_4 &= \text{Upperbound}_4 - CR && \text{(Equation 12)} \\ \text{Lowerbound}_4 &= 57 \% \end{aligned}$$

$$\begin{aligned} \text{Upperbound}_5 &= \text{Upperbound}_3 && \text{(Equation 13)} \\ \text{Upperbound}_5 &= 80 \% \end{aligned}$$

$$\begin{aligned} \text{Lowerbound}_5 &= \text{Lowerbound}_3 && \text{(Equation 14)} \\ \text{Lowerbound}_5 &= 75 \% \end{aligned}$$

$$\begin{aligned} \text{ReducedVolume} &= (\text{FlowReduction} \times 3600) \times \text{Duration} && \text{(Equation 15)} \\ \text{FlowReduction} &= 20.6 \text{ l/s} \\ \text{Duration} &= 10 \text{ hours} \\ \text{ReducedVolume} &= 742.7 \text{ kl} \end{aligned}$$

$$\begin{aligned} \text{OverallFlowReduction} &= \left(\frac{\text{ReducedVolume}}{3600} \right) / 24 && \text{(Equation 16)} \\ \text{OverallFlowReduction} &= 8.6 \text{ l/s} \end{aligned}$$

$$\begin{aligned} \text{PeakVolRed}_1 &= \left(\frac{\text{ReducedVolume}}{24} \right) \times t_1 && \text{(Equation 17)} \\ \text{PeakVolRed}_1 &= 92837.5 \text{ l} \\ t_1 &= 3 \text{ hours} \end{aligned}$$

(Mine A requested peak TOU to start at 17:00)

$$\begin{aligned} \text{PeakVolRed}_2 &= \left(\frac{\text{ReducedVolume}}{24} \right) \times t_2 && \text{(Equation 18)} \\ \text{PeakVolRed}_2 &= 92837.5 \text{ l} \\ t_2 &= 3 \text{ hours} \end{aligned}$$

$$\begin{aligned} \text{PreparationLevel}_{2-2} &= \text{PreparationLevel}_2 + \left(\frac{\text{PeakVolRed}_1}{Cap} \right) \times 100 && \text{(Equation 18)} \\ \text{PreparationLevel}_{2-2} &= 64.87 \% \end{aligned}$$

$$\begin{aligned} \text{PreparationLevel}_{4-2} &= \text{PreparationLevel}_4 + \left(\frac{\text{PeakVolRed}_2}{Cap} \right) \times 100 && \text{(Equation 20)} \\ \text{PreparationLevel}_{4-2} &= 63.32 \% \end{aligned}$$

$$\begin{aligned} \text{Upperbound}_{2-2} &= \text{PreparationLevel}_{2-2} && \text{(Table 7)} \\ \text{Upperbound}_2 &= 64.87 \% \end{aligned}$$

$$\text{Lowerbound}_{2-2} = \text{PreparationLevel}_{2-2} - CR \quad (\text{Table 7})$$

$$\text{Lowerbound}_{2-2} = 59.86 \%$$

$$\text{Upperbound}_{4-2} = \text{PreparationLevel}_{4-2} \quad (\text{Table 8})$$

$$\text{Upperbound}_{4-2} = 63.32 \%$$

$$\text{Lowerbound}_{4-2} = \text{Upperbound}_{4-2} - CR \quad (\text{Equation 12})$$

$$\text{Lowerbound}_{4-2} = 58.3 \%$$

21L

$$\text{Lowerbound}_1 = \text{AbsMin} \quad (\text{Equation 6})$$

$$\text{Lowerbound}_1 = 40 \%$$

$$\text{Upperbound}_1 = \text{AbsMin} + CR \quad (\text{Equation 7})$$

$$\text{AbsMin} = 40 \%$$

$$CR = 10 \%$$

$$\text{Upperbound}_1 = 50 \%$$

$$\text{PreparationLevel}_2 = \text{AbsMax} - \left(\frac{\text{PeakVol}_1}{\text{Cap}} \right) \times 100 \quad (\text{Equation 8})$$

$$\text{AbsMax} = 80 \%$$

$$\text{PeakVol}_1 = 0 \text{ l/s} \times 3600 \times 3$$

$$\text{PeakVol}_1 = 0 \text{ l}$$

$$\text{Cap} = 6000000 \text{ l}$$

$$\text{PreparationLevel}_2 = 80 \%$$

$$\text{Upperbound}_2 = \text{AbsMax} - CR \quad (\text{Table 7})$$

$$\text{Upperbound}_2 = 70 \%$$

$$\text{Lowerbound}_2 = \text{AbsMax} - 2CR \quad (\text{Table 7})$$

$$\text{Lowerbound}_2 = 60 \%$$

$$\text{Upperbound}_3 = \text{AbsMax} \quad (\text{Equation 9})$$

$$\text{Upperbound}_3 = 80 \%$$

$$\text{Lowerbound}_3 = \text{AbsMax} - CR \quad (\text{Equation 10})$$

$$\text{Lowerbound}_3 = 70 \%$$

$$\text{PreparationLevel}_4 = \text{AbsMax} - \left(\frac{\text{PeakVol}_2}{\text{Cap}} \right) \times 100 \quad (\text{Equation 11})$$

$$\text{AbsMax} = 80 \%$$

$$PeakVol_2 = 0 \text{ l/s} \times 3600 \times 3$$

$$PeakVol_2 = 0 \text{ l}$$

$$Cap = 7000000 \text{ l}$$

$$PreparationLevel_4 = 80 \%$$

$$Upperbound_4 = AbsMax - CR \quad (\text{Table 8})$$

$$Upperbound_4 = 70 \%$$

$$Lowerbound_4 = Upperbound_4 - CR \quad (\text{Equation 12})$$

$$Lowerbound_4 = 60 \%$$

$$Upperbound_5 = Upperbound_3 \quad (\text{Equation 13})$$

$$Upperbound_5 = 80 \%$$

$$Lowerbound_5 = Lowerbound_3 \quad (\text{Equation 14})$$

$$Lowerbound_5 = 70 \%$$

5L

$$Lowerbound_1 = AbsMin \quad (\text{Equation 6})$$

$$Lowerbound_1 = 40 \%$$

$$Upperbound_1 = AbsMin + CR \quad (\text{Equation 7})$$

$$AbsMin = 40 \%$$

$$CR = 10 \%$$

$$Upperbound_1 = 50 \%$$

$$PreparationLevel_2 = AbsMax - \left(\left(\frac{PeakVol_1}{Cap} \right) \times 100 \right) \quad (\text{Equation 8})$$

$$AbsMax = 80 \%$$

$$PeakVol_1 = 5 \text{ l/s} \times 3600 \times 3$$

$$PeakVol_1 = 5400 \text{ l}$$

$$Cap = 3000000 \text{ l}$$

$$PreparationLevel_2 = 78.2 \%$$

$$Upperbound_2 = AbsMax - CR \quad (\text{Table 7})$$

$$Upperbound_2 = 70 \%$$

$$Lowerbound_2 = AbsMax - 2CR \quad (\text{Table 7})$$

$$Lowerbound_2 = 60 \%$$

$$Upperbound_3 = AbsMax \quad (\text{Equation 9})$$

$$Upperbound_3 = 80 \%$$

$$\text{Lowerbound}_3 = \text{AbsMax} - \text{CR} \quad (\text{Equation 10})$$

$$\text{Lowerbound}_3 = 70 \%$$

$$\text{PreparationLevel}_4 = \text{AbsMax} - \left(\frac{\text{PeakVol}_2}{\text{Cap}} \right) \times 100 \quad (\text{Equation 11})$$

$$\text{AbsMax} = 80 \%$$

$$\text{PeakVol}_2 = 5 \text{ l/s} \times 3600 \times 3$$

$$\text{PeakVol}_2 = 5400 \text{ l}$$

$$\text{Cap} = 3000000 \text{ l}$$

$$\text{PreparationLevel}_4 = 78.2 \%$$

$$\text{Upperbound}_4 = \text{AbsMax} - \text{CR} \quad (\text{Table 8})$$

$$\text{Upperbound}_4 = 70 \%$$

$$\text{Lowerbound}_4 = \text{Upperbound}_4 - \text{CR} \quad (\text{Equation 12})$$

$$\text{Lowerbound}_4 = 60 \%$$

$$\text{Upperbound}_5 = \text{Upperbound}_3 \quad (\text{Equation 13})$$

$$\text{Upperbound}_5 = 80 \%$$

$$\text{Lowerbound}_5 = \text{Lowerbound}_3 \quad (\text{Equation 14})$$

$$\text{Lowerbound}_5 = 70 \%$$

MINE B – CONTROL RANGE LIMIT CALCULATIONS

2180L

$$\text{Lowerbound}_1 = \text{AbsMin} \quad (\text{Equation 6})$$

$$\text{Lowerbound}_1 = 45 \%$$

$$\text{Upperbound}_1 = \text{AbsMin} + \text{CR} \quad (\text{Equation 7})$$

$$\text{AbsMin} = 45 \%$$

$$\text{CR} = 10 \%$$

$$\text{Upperbound}_1 = 55 \%$$

$$\text{PreparationLevel}_2 = \text{AbsMax} - \left(\frac{\text{PeakVol}_1}{\text{Cap}} \right) \times 100 \quad (\text{Equation 8})$$

$$\text{AbsMax} = 80 \%$$

$$\text{PeakVol}_1 = 70 \text{ l/s} \times 3600 \times 3$$

$$\text{PeakVol}_1 = 756000 \text{ l}$$

$$Cap = 5000000 \text{ l}$$

$$PreparationLevel_2 = 64.88 \%$$

$$Upperbound_2 = PreparationLevel_2 \quad (\text{Table 7})$$

$$Upperbound_2 = 64.88 \%$$

$$Lowerbound_2 = PreparationLevel_2 - CR \quad (\text{Table 7})$$

$$Lowerbound_2 = 54.88 \%$$

$$Upperbound_3 = AbsMax \quad (\text{Equation 9})$$

$$Upperbound_3 = 80 \%$$

$$Lowerbound_3 = AbsMax - CR \quad (\text{Equation 10})$$

$$Lowerbound_3 = 70 \%$$

$$PreparationLevel_4 = AbsMax - \left(\frac{PeakVol_2}{Cap} \right) \times 100 \quad (\text{Equation 11})$$

$$AbsMax = 80 \%$$

$$PeakVol_2 = 70 \text{ l/s} \times 3600 \times 3$$

$$PeakVol_2 = 756000 \text{ l}$$

$$Cap = 5000000 \text{ l}$$

$$PreparationLevel_4 = 64.88 \%$$

$$Upperbound_4 = PreparationLevel_4 \quad (\text{Table 8})$$

$$Upperbound_4 = 64.88 \%$$

$$Lowerbound_4 = Upperbound_4 - CR \quad (\text{Equation 12})$$

$$Lowerbound_4 = 54.16 \%$$

$$Upperbound_5 = Upperbound_3 \quad (\text{Equation 13})$$

$$Upperbound_5 = 80 \%$$

$$Lowerbound_5 = Lowerbound_3 \quad (\text{Equation 14})$$

$$Lowerbound_5 = 70 \%$$

1200L

$$Lowerbound_1 = AbsMin \quad (\text{Equation 6})$$

$$Lowerbound_1 = 45 \%$$

$$Upperbound_1 = AbsMin + CR \quad (\text{Equation 7})$$

$$AbsMin = 45 \%$$

$$CR = 10 \%$$

$$Upperbound_1 = 55 \%$$

$$PreparationLevel_2 = AbsMax - \left(\left(\frac{PeakVol_1}{Cap} \right) \times 100 \right) \quad (\text{Equation 8})$$

$$AbsMax = 80 \%$$

$$PeakVol_1 = 0 \text{ l/s} \times 3600 \times 3$$

$$PeakVol_1 = 0 \text{ l}$$

$$Cap = 1500000 \text{ l}$$

$$PreparationLevel_2 = 80 \%$$

$$Upperbound_2 = AbsMax - CR \quad (\text{Table 7})$$

$$Upperbound_2 = 70 \%$$

$$Lowerbound_2 = AbsMax - 2CR \quad (\text{Table 7})$$

$$Lowerbound_2 = 60 \%$$

$$Upperbound_3 = AbsMax \quad (\text{Equation 9})$$

$$Upperbound_3 = 80 \%$$

$$Lowerbound_3 = AbsMax - CR \quad (\text{Equation 10})$$

$$Lowerbound_3 = 70 \%$$

$$PreparationLevel_4 = AbsMax - \left(\left(\frac{PeakVol_2}{Cap} \right) \times 100 \right) \quad (\text{Equation 11})$$

$$AbsMax = 80 \%$$

$$PeakVol_2 = 0 \text{ l/s} \times 3600 \times 3$$

$$PeakVol_2 = 0 \text{ l}$$

$$Cap = 1500000 \text{ l}$$

$$PreparationLevel_4 = 80 \%$$

$$Upperbound_4 = AbsMax - CR \quad (\text{Table 8})$$

$$Upperbound_4 = 70 \%$$

$$Lowerbound_4 = Upperbound_4 - CR \quad (\text{Equation 12})$$

$$Lowerbound_4 = 60 \%$$

$$Upperbound_5 = Upperbound_3 \quad (\text{Equation 13})$$

$$Upperbound_5 = 80 \%$$

$$Lowerbound_5 = Lowerbound_3 \quad (\text{Equation 14})$$

$$Lowerbound_5 = 70 \%$$

APPENDIX C

Mine A - Simulated results - Winter					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11496	12250
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7816	11911
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8345	12250
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	9897	13629
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7436	11956
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8379	12001
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4818	6507
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	3654	4650
11:00	R _{standard}	R _{standard}	R _{off-peak}	12190	10058
12:00	R _{standard}	R _{standard}	R _{off-peak}	13723	12250
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	12350	12001
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	11516	11203
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13601	11597
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11948	11416
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	7572	79
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	3320	0
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	10985	1310
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	13148	14160
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11388	14352

Tariff:	R _{off-peak}	R 0.37
	R _{standard}	R 0.67
	R _{peak}	R 2.23

Cost saving:	Weekday	R 7 571.07
	Saturday	R 802.85
	Sunday	R 0.00

Total winter saving:	R 463 898.25
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Mine A - Simulated results - Summer					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11496	12250
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7816	11911
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8345	12250
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	9897	13629
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7436	11956
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8379	12001
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4818	6507
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	3654	4650
11:00	R _{standard}	R _{standard}	R _{off-peak}	12190	10058
12:00	R _{standard}	R _{standard}	R _{off-peak}	13723	12250
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	12350	12001
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	11516	11203
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13601	11597
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11948	11416
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	7572	79
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	3320	0
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	10985	1310
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	13148	14160
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11388	14352

Tariff:	R _{off-peak}	R 0.32
	R _{standard}	R 0.50
	R _{peak}	R 0.73

Cost saving:	Weekday	R 4 502.78
	Saturday	R 477.48
	Sunday	R 0.00

Total winter saving:	R 919 655.28
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Mine A - Simulated results (with water reduction) - Winter					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11496	11900
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7816	11888
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8345	12804
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	9897	13244
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7436	11821
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8379	11979
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4818	1885
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	3654	3362
11:00	R _{standard}	R _{standard}	R _{off-peak}	12190	9402
12:00	R _{standard}	R _{standard}	R _{off-peak}	13723	13278
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	12350	11363
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	11516	10953
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13601	10930
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11948	6999
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	7572	0
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	3320	113
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	10985	637
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	13148	14472
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11388	13889

Tariff:	R _{off-peak}	R 0.37
	R _{standard}	R 0.67
	R _{peak}	R 2.23

Cost saving:	Weekday	R 15 938.34
	Saturday	R 5 713.58
	Sunday	R 4 629.08

Total winter saving:	R 1 080 412.08
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Mine A - Simulated results (with water reduction) - Summer					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11496	11900
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7816	11888
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8345	12804
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	9897	13244
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7436	11821
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	8379	11979
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4818	1885
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	3654	3362
11:00	R _{standard}	R _{standard}	R _{off-peak}	12190	9402
12:00	R _{standard}	R _{standard}	R _{off-peak}	13723	13278
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	12350	11363
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	11516	10953
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13601	10930
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11948	6999
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	7572	0
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	3320	113
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	10985	637
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	13148	14472
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11388	13889

Tariff:	R _{off-peak}	R 0.32
	R _{standard}	R 0.50
	R _{peak}	R 0.73

Cost saving:	Weekday	R 10 727.08
	Saturday	R 4 646.05
	Sunday	R 4 001.06

Total winter saving:	R 2 491 299.81
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Mine A - Actual results - Winter					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11979	12666
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11659	11971
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	10530	12208
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7992	11640
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	5767	11713
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	4431	10438
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4530	7358
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	16	340
08:00	R _{peak}	R _{standard}	R _{off-peak}	16	48
09:00	R _{peak}	R _{standard}	R _{off-peak}	53	484
10:00	R _{standard}	R _{standard}	R _{off-peak}	5456	5845
11:00	R _{standard}	R _{standard}	R _{off-peak}	10025	10444
12:00	R _{standard}	R _{standard}	R _{off-peak}	12651	11899
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	14022	12099
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	13835	11374
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13154	11001
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11927	8974
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	10647	207
18:00	R _{peak}	R _{standard}	R _{off-peak}	102	169
19:00	R _{peak}	R _{standard}	R _{off-peak}	15	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	4664	2731
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	7437	4807
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	10014	10829
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11349	12393

Tariff:	R _{off-peak}	R 0.37
	R _{standard}	R 0.67
	R _{peak}	R 2.23

Cost saving:	Weekday	R 5 321.66
	Saturday	R 55.90
	Sunday	R 231.37

Total winter saving:	R 322 746.83
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Mine A - Actual results - Summer					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11979	12666
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11659	11971
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	10530	12208
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	7992	11640
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	5767	11713
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	4431	10438
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	4530	7358
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	16	340
08:00	R _{peak}	R _{standard}	R _{off-peak}	16	48
09:00	R _{peak}	R _{standard}	R _{off-peak}	53	484
10:00	R _{standard}	R _{standard}	R _{off-peak}	5456	5845
11:00	R _{standard}	R _{standard}	R _{off-peak}	10025	10444
12:00	R _{standard}	R _{standard}	R _{off-peak}	12651	11899
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	14022	12099
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	13835	11374
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	13154	11001
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	11927	8974
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	10647	207
18:00	R _{peak}	R _{standard}	R _{off-peak}	102	169
19:00	R _{peak}	R _{standard}	R _{off-peak}	15	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	4664	2731
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	7437	4807
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	10014	10829
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	11349	12393

Tariff:	R _{off-peak}	R 0.32
	R _{standard}	R 0.50
	R _{peak}	R 0.73

Cost saving:	Weekday	R 3 807.43
	Saturday	R 95.62
	Sunday	R 199.98

Total winter saving:	R 773 309.82
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Mine B - Simulated results - Winter					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2921	4591
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2706	5606
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	4152
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2545	2291
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2794	0
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	853
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	2099	0
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	4125	3949
11:00	R _{standard}	R _{standard}	R _{off-peak}	5047	5606
12:00	R _{standard}	R _{standard}	R _{off-peak}	5047	5606
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	4815	5241
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	4181	4388
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	3511	2925
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	2896	0
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	2282	0
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	912	163
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	2414	1365
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	5606
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	5606

Tariff:	R _{off-peak}	R 0.37
	R _{standard}	R 0.67
	R _{peak}	R 2.23

Cost saving:	Weekday	R 2 487.99
	Saturday	-R 290.22
	Sunday	R 0.00

Total winter saving:	R 145 796.58
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Mine B - Simulated results - Summer					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2921	4591
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2706	5606
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	4152
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2545	2291
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2794	0
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	853
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	2099	0
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	4125	3949
11:00	R _{standard}	R _{standard}	R _{off-peak}	5047	5606
12:00	R _{standard}	R _{standard}	R _{off-peak}	5047	5606
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	4815	5241
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	4181	4388
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	3511	2925
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	2896	0
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	2282	0
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	912	163
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	2414	1365
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	5606
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2414	5606

Tariff:	R _{off-peak}	R 0.32
	R _{standard}	R 0.50
	R _{peak}	R 0.73

Cost saving:	Weekday	R 1 479.69
	Saturday	-R 172.60
	Sunday	R 0.00

Total winter saving:	R 289 034.49
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Mine B - Actual results - Winter					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	5876
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	4405
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2625	1288
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	803
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2208	2729
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2458	3149
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	1275	248
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	1116	4170
11:00	R _{standard}	R _{standard}	R _{off-peak}	5350	5264
12:00	R _{standard}	R _{standard}	R _{off-peak}	5500	4440
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	5500	4583
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	4333	3502
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	4250	1718
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	2750	436
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	2442	585
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	2000	1026
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	2708	2328
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2333	5238
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2850	5248

Tariff:	R _{off-peak}	R 0.37
	R _{standard}	R 0.67
	R _{peak}	R 2.23

Cost saving:	Weekday	R 3 080.54
	Saturday	-R 252.75
	Sunday	R 334.19

Total winter saving:	R 185 809.39
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Mine B - Actual results - Summer					
Time of day	Weekdays	Saturdays	Sundays	Pre-opt	Post-opt
00:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	5876
01:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	4405
02:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2625	1288
03:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2750	803
04:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2208	2729
05:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2458	3149
06:00	R _{standard}	R _{off-peak}	R _{off-peak}	1275	248
07:00	R _{peak}	R _{off-peak}	R _{off-peak}	0	0
08:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
09:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
10:00	R _{standard}	R _{standard}	R _{off-peak}	1116	4170
11:00	R _{standard}	R _{standard}	R _{off-peak}	5350	5264
12:00	R _{standard}	R _{standard}	R _{off-peak}	5500	4440
13:00	R _{standard}	R _{off-peak}	R _{off-peak}	5500	4583
14:00	R _{standard}	R _{off-peak}	R _{off-peak}	4333	3502
15:00	R _{standard}	R _{off-peak}	R _{off-peak}	4250	1718
16:00	R _{standard}	R _{off-peak}	R _{off-peak}	2750	436
17:00	R _{standard}	R _{off-peak}	R _{off-peak}	2442	585
18:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
19:00	R _{peak}	R _{standard}	R _{off-peak}	0	0
20:00	R _{standard}	R _{off-peak}	R _{off-peak}	2000	1026
21:00	R _{standard}	R _{off-peak}	R _{off-peak}	2708	2328
22:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2333	5238
23:00	R _{off-peak}	R _{off-peak}	R _{off-peak}	2850	5248

Tariff:	R _{off-peak}	R 0.32
	R _{standard}	R 0.50
	R _{peak}	R 0.73

Cost saving:	Weekday	R 1 922.20
	Saturday	-R 60.22
	Sunday	R 288.85

Total winter saving:	R 393 584.87
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