Improved control of clear water underground pumping system for demand side management at an interconnected South African goldmine

A. Meyer

22840176

Dissertation submitted in fulfilment of the requirements for the degree Master of Engineering in Electrical and Electronic Engineering at the Potchefstroom Campus of the North-West University

Supervisor: Mr. W Kukard

November 2016

DECLARATION OF AUTHORSHIP

I, **Anton Meyer**, declare that this thesis titled, "**Improved control of clear water underground pumping system for demand side management at an interconnected South African goldmine**" and the work presented in it are my own.

I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ______________________________

2016/12/05

Date: _________________________________

ABSTRACT

Title: Improved control of clear water underground pumping system for demand side management at an interconnected South African goldmine

Author: Anton Meyer

Promoter: Warren Kukard

Key words: DSM, automated, underground pumping system, multi-shaft

Deep level clear water pumping at gold mines accounts for nearly 30 % of a mine's total electricity consumption. Demand side management (DSM) initiatives for various deep level water pumping systems have been implemented throughout South Africa for more than a decade which contributed to the reduction of the demand for the national electrical utility, Eskom. Therefore many DSM load shifting projects at South African mines have been implemented, but most of the solutions were on single shaft pumping systems.

To date, no successful fully automated load shifting project has been implemented on an intricate interconnected underground gold mine pumping system with several shafts. This paper presents work done to optimise an automated pumping control system on a mine and comparing it to manual load shifting results.

The mine studied consisted of three shafts and pump stations at six interlinked levels. Total power demand peaks at 16 MW on weekdays. A simulation of the mine's pumping system has been done by iterating pumping times to find optimal dam levels throughout the day in order to increase electricity cost savings in Eskom peak times. Data was collected from the mine in order to generate an effective water and energy balance to validate the simulation. The simulation consisted of a control strategy which focused on each level individually without inputs from other levels. The simulation model had a 91% accuracy for the maximum amount of load that can be shifted. Previous studies indicated that an automated load shifting system resulted in more electricity cost saving for mines.

This paper illustrates that with semi-automated load shifting a higher electricity cost saving potential is possible than with manual load shifting. Semi-automated load shifting had a 78% increased cost saving in summer and a 5.5% increase in winter when compared to manual load shifting results. The evening peak load shifting amount for semi-automated load shifting increased by 38% in summer and 0.11% in winter when compared to manual load shifting. The most efficient point to operate the mine’s pumping system, in order to gain the maximum possible electricity cost saving with load shifting has been indicated by a controller.

Increased electricity cost savings for the mine also means that pressure will be relieved on Eskom’s distribution system due to a reduction in peak demand electricity usage.

SAMEVATTING

Titel:	Verbeterde beheer van ‘n helder water ondergrondse pomp stelsel vir DSM by 'n inter-verbine Suid-Afrikaanse goudmyn
Outeur:	Anton Meyer
Promoter:	Warren Kukard
Sleutelwoorde:	DSM, outomatiese, ondergrondse pomp stelsel, multi-skag

Diep helder water pompe in myne is verantwoordelik vir byna 30% van die totale elektrisiteitsverbruik van ‘n myn. Demand side Management (DSM) inisiatiewe vir verskeie diep ondergrondse water pomp stelsels is in Suid-Afrika geïmplementeer vir meer as 'n dekade. Dit het bygedra tot die vermindering van die vraag na elektrisiteit van die nasionale elektriese krag voorsienner, Eskom. Daar is verskeie DSM projekte in Suid-Afrikaanse myne wat in werking gestel is, maar die meeste van die oplossings is op enkel skag pomp stelsels ge-implimenteer.

Tot op hede is daar geen suksesvolle outomatiese elektrisiteit verskuiwings projekte geïmplementeer, op 'n inter-verbinde ondergrondse goudmyn met verskeie skagte nie. Hierdie studie gaan te werk om 'n outomatiese pomp beheer stelsel te optimaliseer op 'n myn en dit te vergelyk met nie-outomatiese elektrisiteit verskuiwings resultate.

Die bestudeerde myn betsaan uit drie skagte met ses verbinde ondergrondse pompstasies. Die totale krag verbuik van die myn is 16 MW vir weeksdae. Die simulasie van die myn se pomp stelsel is gedoen, deur die pompe te laat pomp op optimale tydperke. Dit is gedoen om optimale damvlakke deur die hele dag te hê om kostebesparings in Eskom spitstye te verhoog. Data is ingesamel vir die myn om ten einde ‘n effektiewe water en energie balans vir die myn te hê. Die simulasie bestaan uit 'n beheerstrategie wat fokus op elke pompstasie vlak individueel sonder insette van ander vlakke. Vorige studies het aangedui dat 'n outomatiese pomp las verskuiwings stelsel gevolg het tot ‘n groter elektrisiteit kostebesparing vir myne.

Hierdie studie illustreer dat met semi-outomatiese pomp las verskuiwings, 'n hoër besparings koste van elektrisiteit moontlik is, as met 'n nie-outomatiese krag verskuiwing stelsel. Semi-outomatiese las verskuiwing het 'n 78% toename in kostebesparing gehad in die somer en 'n toename van 5,5% in die winter wanneer dit vergelyk word met die nie-ouomatiese las verskuiwing resultate. Die aand spitslas verskuiwing vir semi-outomatiese las verskuiwing het met 38% in die somer en 0,11% in die winter verhoog wanneer dit vergelyk word met die nie-outomatiese las verskuiwing. Die mees doeltreffende punt om die myn se pomp stelsel te beheer was ook ondersoek, om ten einde die maksimum moontlike elektrisiteit kostebesparing met maksimum las verskuiwing te kry deur ‘n beheerder te gebruik.

Verhoogde elektrisiteit kostebesparings vir die myn beteken ook dat die druk verlig sal word op Eskom se elektrisiteit verspreidingstelsel. Dit is te danke aan 'n afname in die piek verbruik vraag na elektrisiteit.

ACKNOWLEDGEMENTS

I would firstly and most importantly want to thank our Heavenly Father for the talents He has given me.

Secondly I would like to thank my thesis advisor Mr. Warren Kukard of the School of Electrical and Electronic Engineering at the North-West University, for his willingness to assist.

I would also like to thank my family, friends and BBEnergy for their moral and technical support throughout this study.

ABBREVIATIONS

DME	Department of Minerals and Energy
#	Shaft
NUMSA	The National Union of Metalworkers of South Africa
TOU	Time of use
NERSA	National Energy Regulator of South Africa
M & V	Independent Measurement and Verification
DSM	Demand Side Management
EE	Energy Efficiency
IDM	Integrated Demand Management
ESCo	Energy Services Company
Eskom	Electricity Supply Commission
CM	Chamber of Mines of South Africa
MW_E	Mega Watt Electrical
c/kWh	Cent per Kilowatt Hour
MVA	Mega Volt Ampere
REMS	Real Time Energy Management System
kW	Kilo Watt
GWh	Gigawatt Hour
PRV's	Pressure reducing valves
3CPFS	Three Chamber Pipe Feeder System

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION AND BACKGROUND

In this chapter a brief background about the current electricity demand situation in South Africa will be discussed. Furthermore the problem investigated will be stated, as well as the objectives and the contribution of the study. Lastly the layout of research followed in the present study will be given.

1.1 Introduction

South Africa's economy is largely dependent on the energy intensive mining and processing industries. The mining sector contributes approximately 50% of all foreign exchange earnings, with a total income in excess of ZAR330 billion annually to the country [1]. Historically electricity tariffs in South Africa have been very low [2], giving South Africa a competitive market in mineral extraction [3], leading to an increased electric consumption with little incentive for energy efficiency, placing continued pressure on the national energy grid. Due to energy being taken for granted in South Africa [4], the gross domestic product (GDP) is higher than other nations.

In 2016, the National Energy Regulator of South Africa (NERSA) granted Eskom (a state owned electricity supplier) a tariff increase of 9.4% [5]. This increase is coherent with the annual 8% [6] increase, granted to Eskom between 2013 and 2018, placing the commercial and industrial sectors under strain leading to energy efficient initiatives.

The implementation of these energy efficient initiatives [3], contributed to the stability of the network. It also encouraged the implementation of energy efficient technologies due to the potential cost savings for the consumer.

1.2 Investigated Deep Level Hard Rock Mine

The investigated mine is a deep level gold mine, with existing underground clear water pumping installations. The mine has three interconnected shafts that form part of the investigation, namely Shaft one, Shaft two and Shaft four. The combined rated pumping capacity is 52 MW_E. These pumps (individually rated up to 2.1 MW) pump hot clear mine water out of the mine through a common shaft, which is in turn fed for cooling at the refrigeration plant.

This master's thesis will implement an improved automated sequencing control system that will optimize the operation of six sets of underground clear water pumping stations in relation to fourteen large warm water dams (dam sizes range between 1.3 and 3 ML (Mega Litres). These shafts are linked underground, with water being pumped to the surface through only one of the three shafts. Water from Shaft one is pumped underground to Shaft two and from there pumped underground to Shaft four, where it is pumped to the surface. Individual manual load shifting attempts are currently implemented at the shafts. The electricity shifting, is part of a global energy neutral project at the mine. This project shifts electricity consumption to less-expensive time of use periods which form part of a Mega-flex tariff structure.

1.3 Problem Statement

Individual manual load shifting attempts are currently being issued at each shaft to shift energy consumption during Eskom's peak period to off-peak periods. This project undertakes load shifting across all three shafts simultaneously, optimising the operation for maximum load shifting potential and increasing the global energy efficiency of the mine.

1.4 Aims and Objectives

- The present study, will concentrate on a dewatering scheme of a deep level mine with three interconnected shafts. The primary objective of the study is to reduce the energy consumption during peak electricity time periods and comparing automated and manual controlled water pumping systems. This will be done by shifting electricity consumption to standard and off-peak times, which will save on electricity tariff costs.

- The secondary objective of this study is to develop an improved automated pump controller to maximise electricity cost savings in deep level mines with multiple shafts.

The hypothesis for this study is that when using a controller, larger cost savings and load shifted will be obtained, when compared to manual load shifting

1.5 Methodology

- Obtain mine baseline data to find existing average water flow rates between warm water dams of Shaft one, Shaft two and Shaft four
- Obtain baseline data of pump power consumptions for Shaft one, Shaft two and Shaft four
- Implementation of manual load shifting on warm water dam pumps for the integrated Shaft one, Shaft two and Shaft four
- Determine dam levels and sizes
- Generate an overall system flow sheet to show where each shaft is pumping into the other and what times
- Create a model for the exciting flow sheet
- Validate the flow sheet using actual and modeled data
- Solve the model for minimum electricity consumption by optimizing pumping times to ensure that all three shafts are working in synchronization to reduce warm dam levels to the minimum before peak hours

- Develop a control strategy using dam levels and flow rates to optimize pump utilization between peak times (morning and night peak times according to the TOU tariff structure)
- Implementation of automatic load shifting on Shaft one, Shaft two and Shaft four
- Make conclusions and recommendations on results found from water utilization
- Risk analysis for pump automation

1.6 Motivation for this study

- ➢ Eskom's electricity supply constraints during evening peak time
- ➢ Mines are obligated to increase electric efficiency by reducing electricity consumption without decreasing production
- ➢ Independent manual load-shifting takes place at each individual shaft, thus opening the possibility to enable multi-shaft integrated automated load shifting
- ➢ No successful studies have been done on automating underground integrated systems

1.7 Study Contribution

- Determining the effectiveness of multi-shaft integrated automatic load shifting against single shaft manual load shifting
- Investigating the effectiveness of early morning load shifting
- Different control strategies will be implemented and investigated to see what their effect will be on financial savings
- Many single mine shaft pump load shift studies have been successfully completed in South Africa. This study develops a new methodology from study's done on single shafts and integrates them into a new improved control strategy for an integrated multi-shaft

1.8 Work Plan

Layout of research followed in the present study

Chapter 1 – General Introduction

- Provides a background of the project
- Discusses the problem and states how the problem is going to be resolved through research

Chapter 2 – Literature Survey

- A detailed study will be done on previous studies regarding demand side management and load shifting
- The study will show the importance of the current study and why it should be investigated in detail

Chapter 3 – Investigational Procedure

- Procedure followed to obtain the mine layout, operational methods and baseline data for the de-watering pumps

Chapter 4 – Simulation Model and controllers

- The development of the pumping model and controller will be shown in this chapter. The inputs and outputs of the model will be presented.

Chapter 5 – Results and discussion

- The outcomes will be shown and results for the aims and objectives will be discussed.
- Modelled data results will also be shown in this section

Chapter 6 – Conclusion and Recommendations

- A conclusion will be made regarding semi-automated and manual load shifting in interconnected underground mines. Recommendations for future research will be discussed.

CHAPTER 2: LITERATURE SURVEY

In this chapter a complete literature survey will be discussed, showing the importance and uniqueness of the current thesis. The chapter gives a broad overview of South Africa's growing electricity demand with solutions to the current energy crisis. The impact and importance of load shifting will also be discussed.

2.1 Background on South African Energy Consumption

The Witwatersrand area in South Africa is a gold producing region promoted by an ideal geological formation [7], this is shown in Figure 2-1. Various mining companies are named in this figure, including AngloGold Ashanti, Goldfields and Sibanye. These form part of 35 large-scale gold mines operating currently in South Africa [8], advocating the optimisation of load shifting.

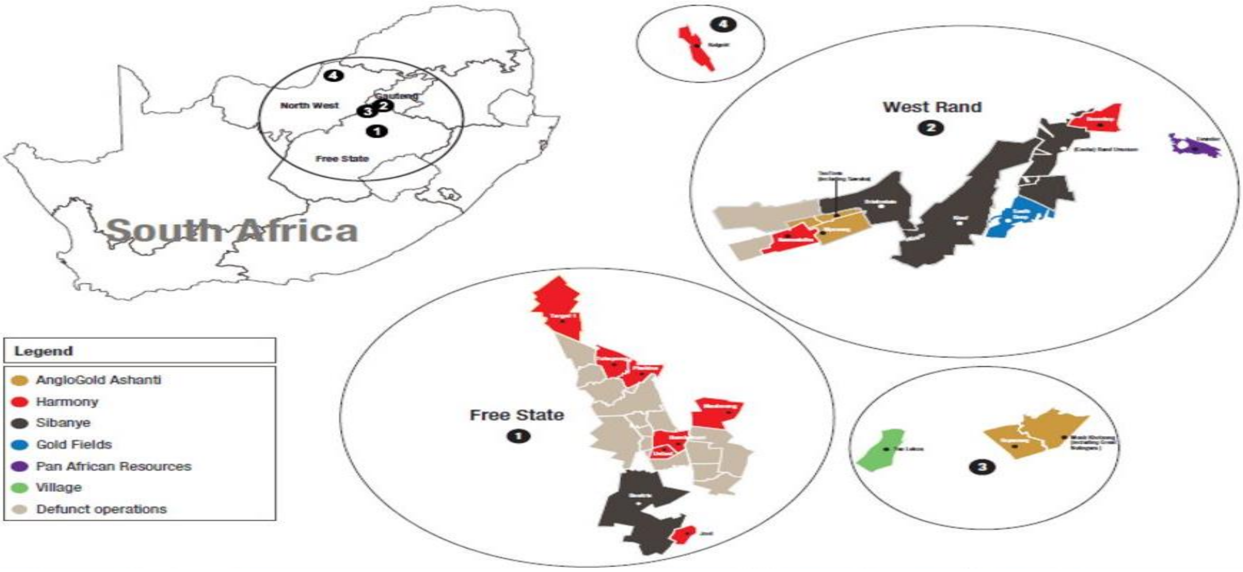


Figure 2-1: Location and Geology of South African Gold Mines [7]

2.1.1 The National Energy Regulator of South Africa (NERSA)

NERSA is an energy regulatory authority with a mandate to regulate electricity, petroleum pipelines and piped-gas industries. The electricity industry in South Africa is regulated by the Electricity Regulation Act [9] of 2006. The Act states: [10] "To establish a national regulatory framework for the electricity supply industry; to make the National Energy Regulator the custodian and enforcer of the national electricity regulatory framework; to provide for licences and registration as the manner in which generation, transmission, distribution, reticulation, trading and the import and export of electricity are regulated; to regulate the reticulation of electricity by municipalities; and to provide for matters connected therewith."

2.1.2 The Chamber of Mines of South Africa (CM)

The CM consist of 69 members across the mining industry with a vision to support and promote the South Africa mining industry. The chamber aids and promotes their interests by providing advisory input and strategic support [7].

The hike of 9.4% [9] in the electricity tariff granted by NERSA to Eskom had strong opposition from the chamber of Mines. They [7] disputed that the hike may lead to 40 000 jobs being lost, in the mining sector.

2.1.3 Electricity Sources and Consumption

Approximately 43% of the total African electricity is generated by Eskom [11]. According to [12] the South African government fully owns Eskom’s generation, transmission distribution and the Eskom Enterprise. Eskom provides most peak and base load capacity for the different South African energy consumers as shown in Figure 2-4.

Eskom has also recently been subjected to load shedding, due to insufficient supply for the demand of electricity required. This is primarily due to peak periods and continuous growth of customers, demanding electricity [10].

In Figure 2-2 there are two lines which represent South Africa’s typical daily load profiles; the brown line indicating winter load profiles and the orange line summer load profiles. During the winter, two peak periods are evident. One being in the morning and the other in the evening. This is due to Eskom’s production complications at the mentioned times; peak demand outweighs the power utilities generating capacity especially during maintenance at power stations. The winter daily profile is almost 4 000 MW higher than the summer day profile, endorsing load shedding by Eskom during winter.

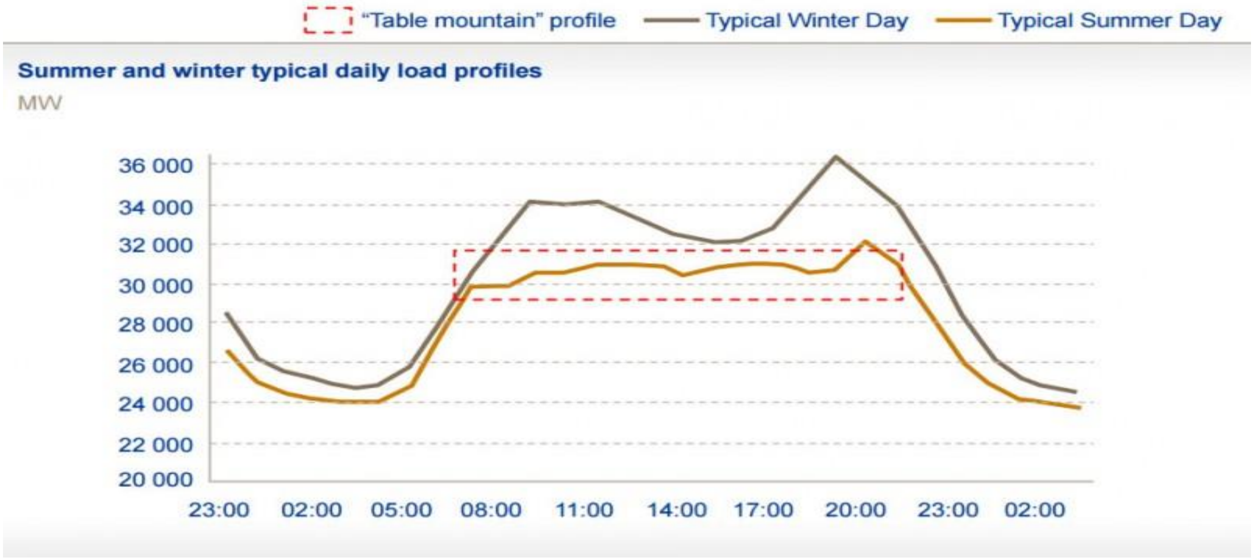


Figure 2-2: Typical Summer and Winter Daily Load Profile [13]

Figure 2-3 was obtained in a NUMSA Statement, representing Eskom's tariff price increases. Prices have been gradually increasing from the year 2006 until the present year (2016), but forecasts stipulated in [14] show that price increases will only continue. This emphasizes the need to save energy in South Africa to reduce the entire energy consumption profile. According C. Smythe [15] to the increasing price of electricity have contributed in the drive to save energy.

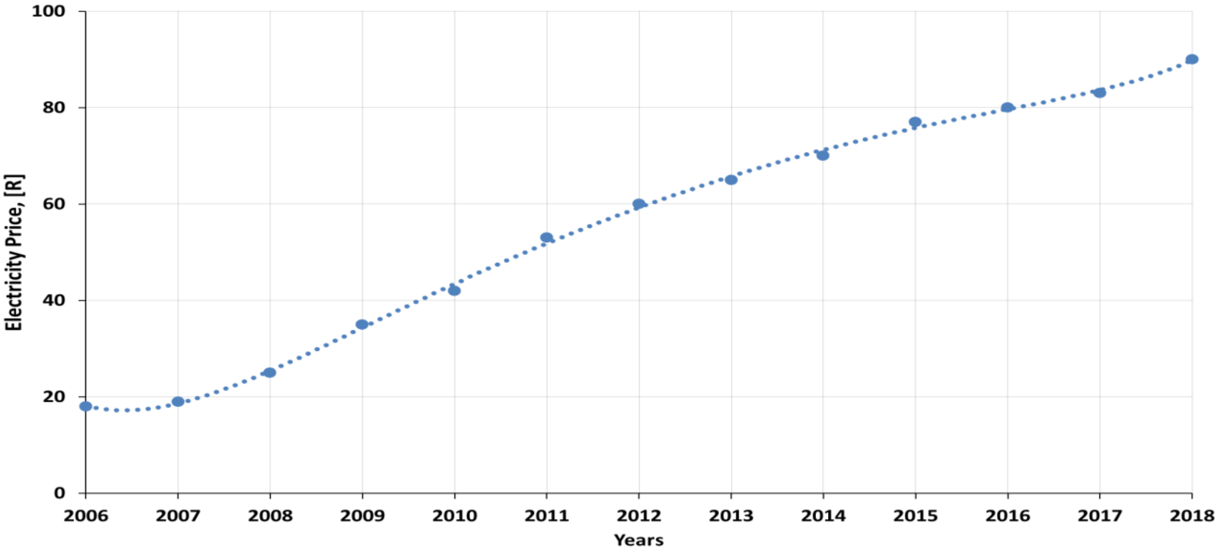


Figure 2-3: South African Electricity Price Increase [14]

South Africa has three dominating energy consumers, evident in the pie chart illustrated below (Figure 2-4). From Figure 2-4 it is evident that three major consumers account for more than 75% of the electricity produced by Eskom. The three major consumers are a combination between mining, industrial and municipal consumers. It is important for South Africa to increase energy efficiency in all three sectors to reduce electrical energy load on Eskom.

The mining sector is the third largest consumer in South Africa with 10% of the total energy generated being consumed by mines. Gold and platinum mines are the largest sectors of the mining industry in South Africa in terms of investment, revenue and employment.

Gold mining has had a steady decline in gold production over the last 30 years, this may be a result of operating expenditure increasing due to mine's increasing in depth [6]. This resulted in a fourfold energy increase from 1970 to 2001. In a survey conducted by [14] on electricity cost for mines it was reported that electricity cost comprised 5.37% of the total operational expenditure for the mine.

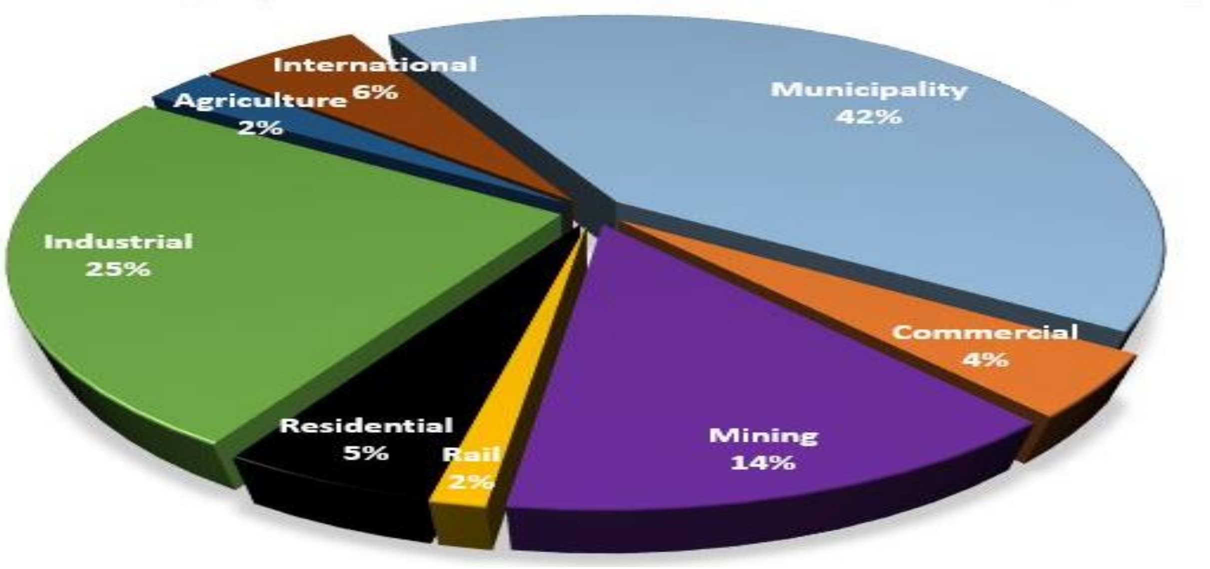


Figure 2-4: South Africa's Electricity Sections Powered by Eskom [16]

Within the South African mining industry, the gold mining subdivision is the largest energy consumer, consuming 47% of all energy supplied to mines. Platinum consumes 33% and 20% is consumed by all the other mine types [17].

Due to the mining sector being one of the three largest electricity consumers, it will be analysed and further investigated in the current thesis. Figure 2-5 gives a schematic break down of energy consumption of a typical South African gold mine. Energy consumption is split almost equally between compressors, pumping stations, ventilation, refrigeration and hoisting. South Africa has many deep mines that employ a cascading pumping system [18], which is very energy intensive. Pumping ranks as one of the largest electricity consumers at 14%.

Figure 2-5 illustrates that an integrated system is formed with the individual consumers in the mine, meaning that if you save energy in one area of a deep level gold mine it has a domino effect on energy savings in other areas.

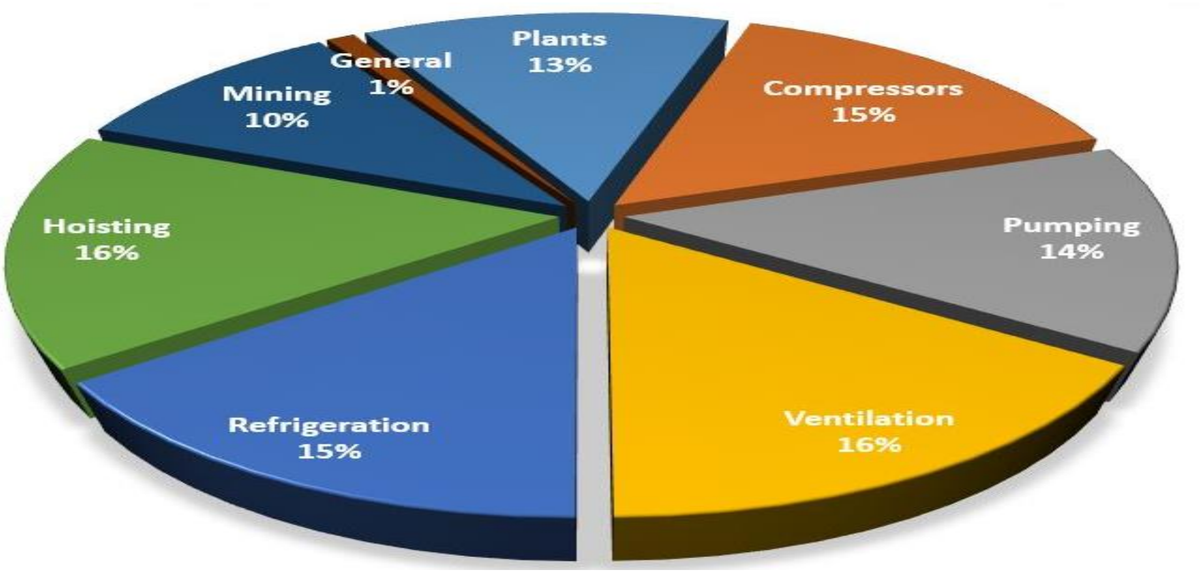


Figure 2-5: Gold Mine Largest Electricity Consumers [19]

Pumping water is required for deep mines (gold), because they need to dewater the mine in order to prevent flooding. If water is not pumped from one underground dam to the next, it will result in the initial dam to overflow, resulting in flooding. Water usage is paramount for deep-water mines because it is used for cooling, sweeping and drilling [20]. Additional underground fissure water also needs to be pumped out [18]. Clearwater pumping in deep level underground gold mines consist of pumping and refrigeration adding to a total electrical consumption of up to 35% for the entire gold-mine [21]. The total integrated water recirculation system can consume up to 42% [22] of the total electrical consumption for the mine.

2.1.4 Demand Side Management

DSM is generally aimed at electricity usage and can be described as a pattern change of energy consumed. DSM initially started in 1973 during the oil crisis in the Unites states of America [23].

South Africa’s electricity shortages relied on DSM projects as a short term solution. The purpose of DSM projects is to offer significant reductions in peak-time electricity. According to M. van Eldik [24] DSM has economic, environmental and social advantages, for example, financial savings, lower environmental impact (coal and water) and job creation

A variable tariff structure was introduced to South African mines and process plants, with large consumers compensated for reducing energy consumption in peak times. This was introduced due to the recent equalization of generation capacity to demand of electricity in South Africa [18]. Eskom also offers a DSM Profitable Partnership Program which offers financial assistance to energy saving projects.

Table 2-1: DSM saving potential rankings adapted from [25]

Industry	Rank	% of total Electricity used	DSM potential Rank	GWh saved
Iron and Steel	**1**	22.91	**2**	2 289
Precious and non-ferrous metals	**2**	16.55	**10**	184
Gold mining	**3**	15.36	**1**	2 311
Chemicals	**4**	12.54	**4**	1 370
Wood and wood products	**5**	8.18	**3**	1 458
Platinum mining	**6**	6.13	**5**	927
Non-metallic minerals	**7**	5.02	**8**	524
Rest of man	**8**	4.12	**7**	542
Food, beverages and Tobacco	**9**	3.20	**6**	605
Coal mining	**10**	2.52	**9**	381
Copper mining	**11**	0.88	**11**	133
Rest of mining	**12**	0.80	**12**	121
Diamond mining	**13**	0.60	**13**	91
Textile, cloth and leather	**14**	0.38	**14**	67
Iron ore mining	**15**	0.32	**15**	48

Industry	Rank	% of total Electricity used	DSM potential Rank	GWh saved
Rest of basic metals	**16**	0.18	**18**	13
Chrome mining	**17**	0.16	**16**	24
Manganese mining	**18**	0.13	**17**	19
Asbestos mining	**19**	0.02	**19**	3

Table 2-1 compares the most significant industries for DSM in South Africa. The largest sector is iron and steel with the lowest being asbestos mining. The industries referred to is the mining and industrial sectors collectively. With mention to DSM projects rank, gold mining has the biggest opportunity for energy savings and secondly iron and steel and thirdly wood and wood products division. Gold mining consumes 15.36% of the overall electricity produced by Eskom for industries as stipulated in Table 2-1, DSM projects has saved electricity in gold mining which accumulated to 2 311GWh. Also from the table above many potential DSM project exist in the industrial sectors [26]. For DSM projects Gold mining has a payback period of 2.4 years [26].

Four funding mechanisms by Eskom exist for the commercial and industrial sector. They are the ESCo model, performance contracting, standard offer and standard product.

2.1.5 Eskom's Tariff Structure

In this study gold mines are focused on, most of the mines in South Africa uses the Mega Flex tariff structure [20], this is due to large gold mines easily reaching in excess of 5 MVA [27]. The urban mega flex tariff consists of a service charge, admin charge, network charge, (active) energy charge: non-time of use, (active) energy charge: time of use, reactive energy charge and electrification and rural subsidy. All these accumulate to a total cost for the large consumers. This tariff is more expensive in peak period than in no-peak periods.

2.1.6 Time of Use Periods

The time of use (TOU) is an initiative from Eskom, which will ensure that South Africa's resources are more efficiently utilized to keep electricity prices more from exponentially increasing. This type of initiative will assist with reducing the necessity of building additional power stations, due to less coal that needs to be burned. This will lead to environmental benefits (less carbon dioxide will be emitted) by burning less coal to generate electricity [28].

Figure 2-6 below shows Eskom's TOU periods. The image on the left-hand hand side is for low demand seasons (summer) which is from 1 September to 31 May annually, further the image on the right-hand side is for high demand seasons (winter) which is from 1 June to 31 August annually. The red, yellow and green segments in Figure 2-6 symbolize peak, standard and off-peak periods respectively. The figure differs for public holidays where weekdays are treated as Sundays or Saturdays [29]. Peak hours are when South Africa's energy system has the greatest pressure due to maximum demand from consumers. This time is from 7-10 pm and from 6 – 8 pm daily.

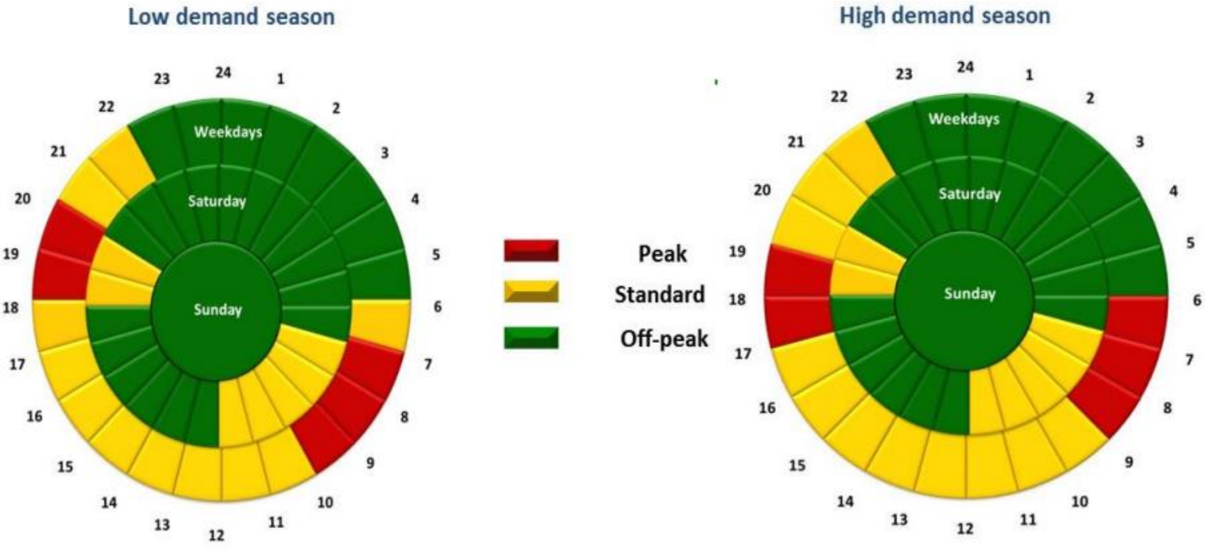


Figure 2-6: Low and high demand TOU periods [29]

Peak periods are more expensive than standard and off-peak periods due to Eskom being demanded to operate peaking power stations which are more expensive. Peak power stations are only used during emergencies and high electricity demand periods. During normal standard and off-peak hours, Eskom only run baseload and mid-merit power stations which are the most economical to operate [28].

Electricity is thus more expensive to purchase during the winter due to the higher energy peaks in winter as shown in Figure 2-2. In Table 2-2 the effect of season change on six projects cost saving is demonstrated. The average for winter (high demand) and summer (low demand) savings is 16.4% and 5.0% respectively. Thus giving an increase of 11.4% during the change of seasons.

Table 2-2: Difference in tariff prices for low demand and high demand seasons [30]

Mine	Installed Capacity, [MW]	Monthly Operational Cost Before DSM. [R]		Evening Load Shift Potential , [MW]	Average Monthly Cost Savings Due to DSM (Actual), [R]			
		Low Demand Season	High Demand Season		Low Demand Season	% Saving	High Demand Season	% Saving
Kopanang	26.0	341 811	626 942	4.5	16 971	5	103 812	17
Elandsrand	27.2	642 961	1 196 637	3.5	14 556	2	102 137	9
Bambanani	23.8	714 061	1 398 010	7.0	32 407	5	160 263	11
Masimong 4#	18.8	237 218	430 104	4.0	20 405	9	111 964	26
Harmony 3#	24.2	318 309	605 802	3.8	15 651	5	72 801	12
Mponeng	47.2	984 241	1 878 697	11.0	46 641	5	448 971	24
Average	**27.9**	**539 767**	**1 022 699**	**5.6**	**24 439**	**5**	**166 658**	**16.4**

As seen in Table 2-2, the average cost saving of the DSM implementation on the six mines is more or less 5% for low demand season of the monthly operational cost before DSM and 16% for high demand season.

Different options exist for DSM implementation. These options are energy efficiency, load shifting and peak clipping and are illustrated in Figure 2-7, Figure 2-8 and Figure 2-9 below.

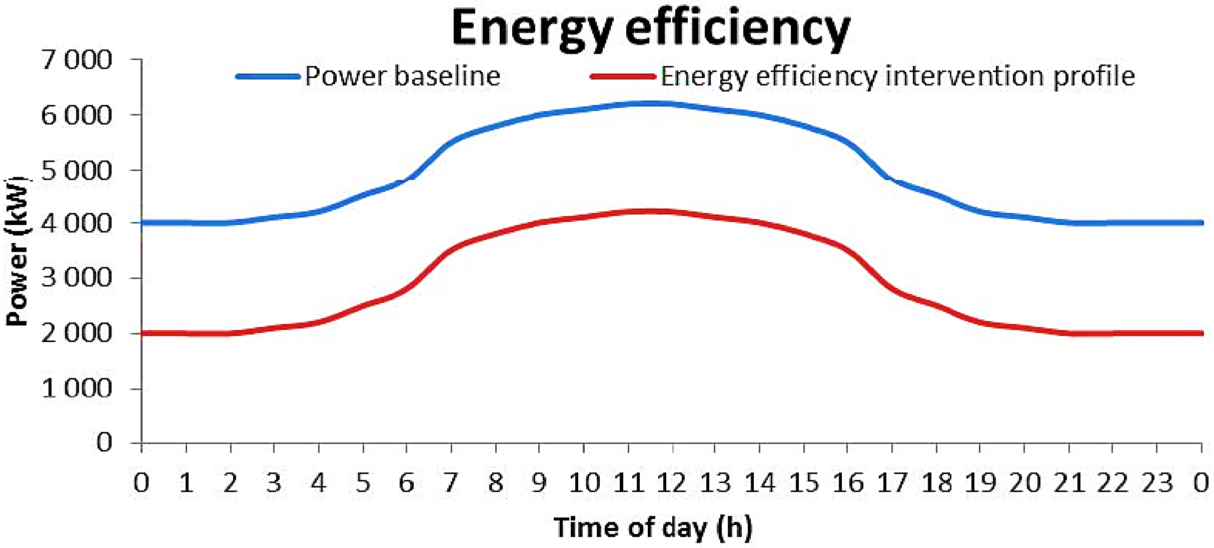


Figure 2-7: Energy efficiency adapted from [31]

Energy efficiency is illustrated in Figure 2-7, the blue line represents the original power baseline of the electricity consumed. The primary objective of this strategy is reducing the power consumption curve, while keeping the same throughput on a daily base. Thus an electricity saving is obtained throughout the day in peak, non-peak and standard time periods. The daily energy consumption will be reduced by utilising this strategy, compared to the original baseline.

According to [32], mining systems could be optimized or a process' efficiency be increased in reducing the power baseline. Energy efficiency can be well-defined as a contrast [33] due to on the one side, production output needs to be increased and on the other side the mining industry needs to reduce energy consumption.

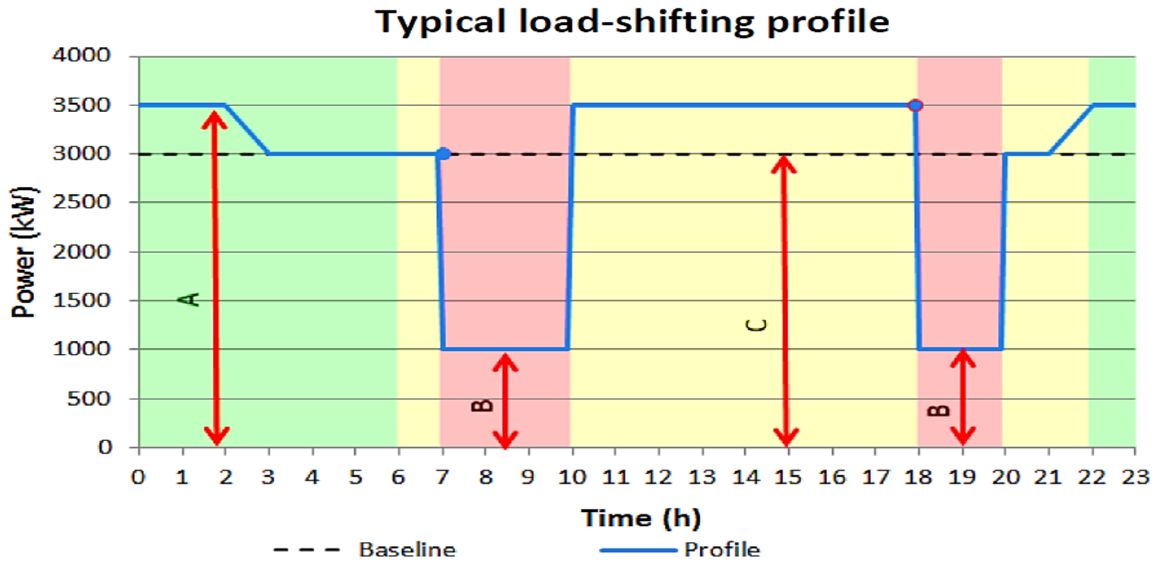


Figure 2-8: Load shift adapted from [32]

A typical load shift strategy is illustrated in Figure 2-8, the black line (C) represents the original power baseline of the electricity consumer and the blue line the proposed load shifting strategy. The principle of this approach is ideally to eliminate electricity consumption during peak hours and to shift the electricity consumed to non-peak and standard times. In the above example, power is shifted to non-peak times. Total daily energy consumption will remain unchanged while employing this strategy [31]. This will result in cost savings, due to the peak periods being avoided and non-peak periods being harnessed.

Load shifting constraints [32] consist firstly of, pumps installed capacity cannot be larger than (line A) in Figure 2-8, secondly the minimum amount of pumps specified by the mines to run in peak time and thirdly the baseline is the maximum amount of load that can be shifted

According to M. Den Boef [34] the electrical load profile consists of a dynamic or controllable part and a static or base-load part. The static part can be described by (B) in Figure 2-8. This load cannot be shifted due to the base load including fundamental electricity consumption in key areas, like production.

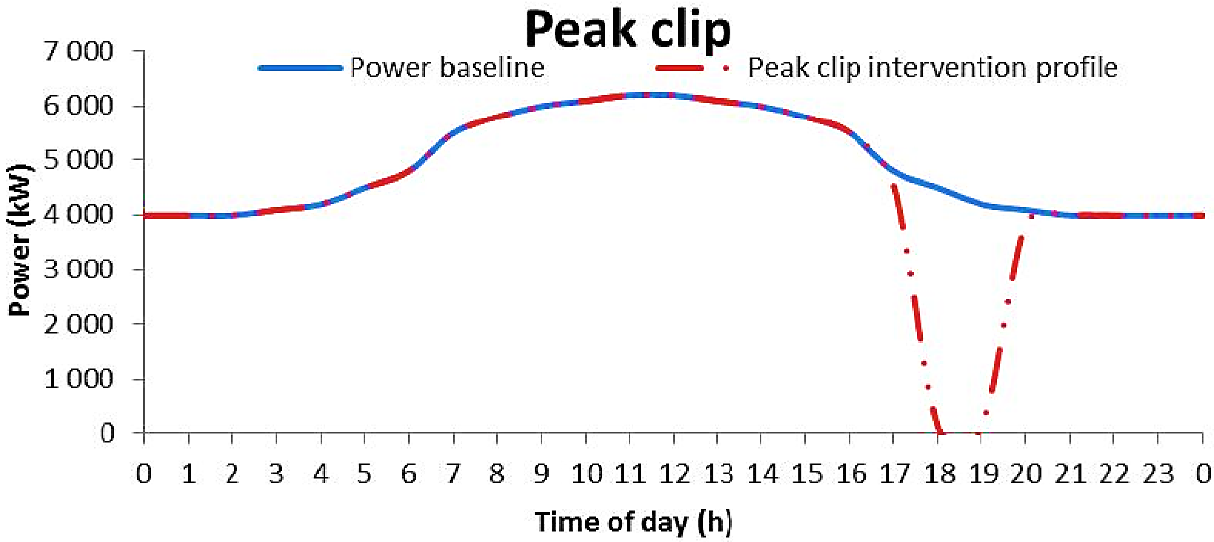


Figure 2-9: Peak clip adapted from [31]

A peak clip strategy is illustrated in Figure 2-9, the blue line represents the original power baseline of the electricity consumer and the red line demonstrates peak clip intervention profile. This strategy may lead to lost production, as no provision is made during the day to compensate for the strategy [31]. Total daily energy consumption will reduce with this strategy.

2.1.7 Gold Mine Layout

South Africa is home to some of the deepest mines in the world reaching depths in excess of 3800m. At these depths, underground temperatures of 70°C can be reached at the rock face. As a result, it is crucial to understand the ventilation and cooling systems on mines to ensure safe operation environments are met for people underground [32].

One of the functions of chilled water in the mining sector is it is used as a cooling medium for deep level mines. Figure 2-10 shows a typical mine water recirculation system. The recirculation system consists of cooling, distribution and de-watering systems. The water distribution system works with gravity to feed the mine with cold water from the refrigeration system. When the cold water used as cooling medium is pumped by large de-watering pumps to surface, it is defined as the dewatering system. [32]. This forms a closed loop, as warm water pumped by the dewatering system is fed to the refrigeration system where it is cooled and recycled back to the mine.

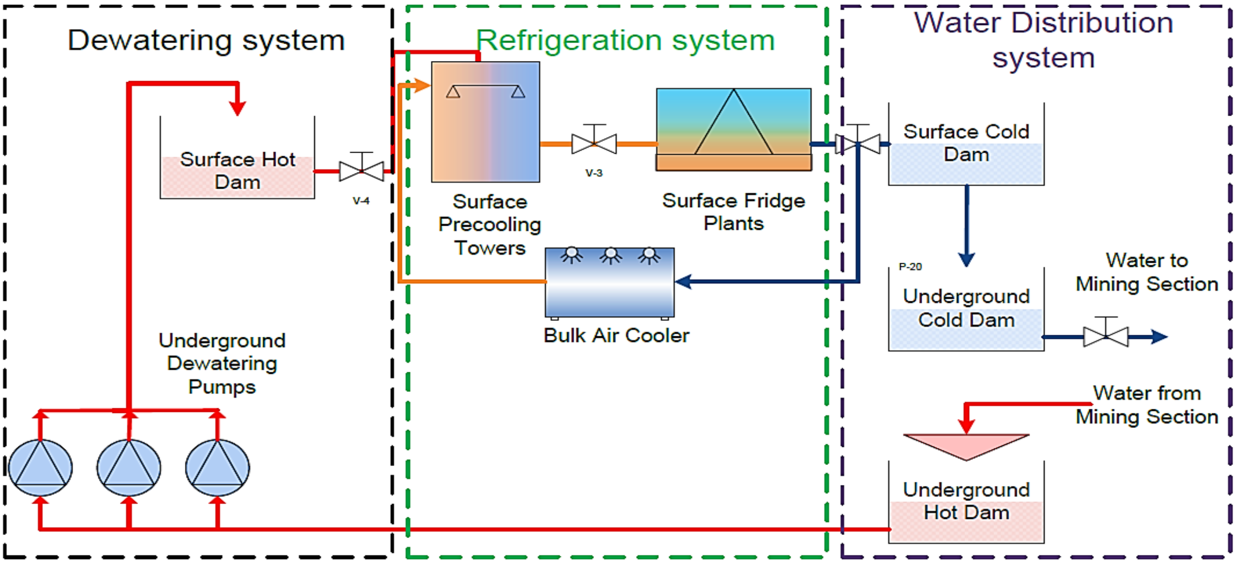


Figure 2-10: Mine water reticulation cycle [32]

Reduction of pumping and cooling needs, results in water and energy savings.

2.1.7.1 Manual Underground de-watering Pumping Systems

In Figure 2-11 the demand profile during different mining shifts is given. Three shifts can be distinguished namely morning, afternoon and night shift. It is important to keep these shift in consideration when doing load shifting to maintain a high production availability [32].

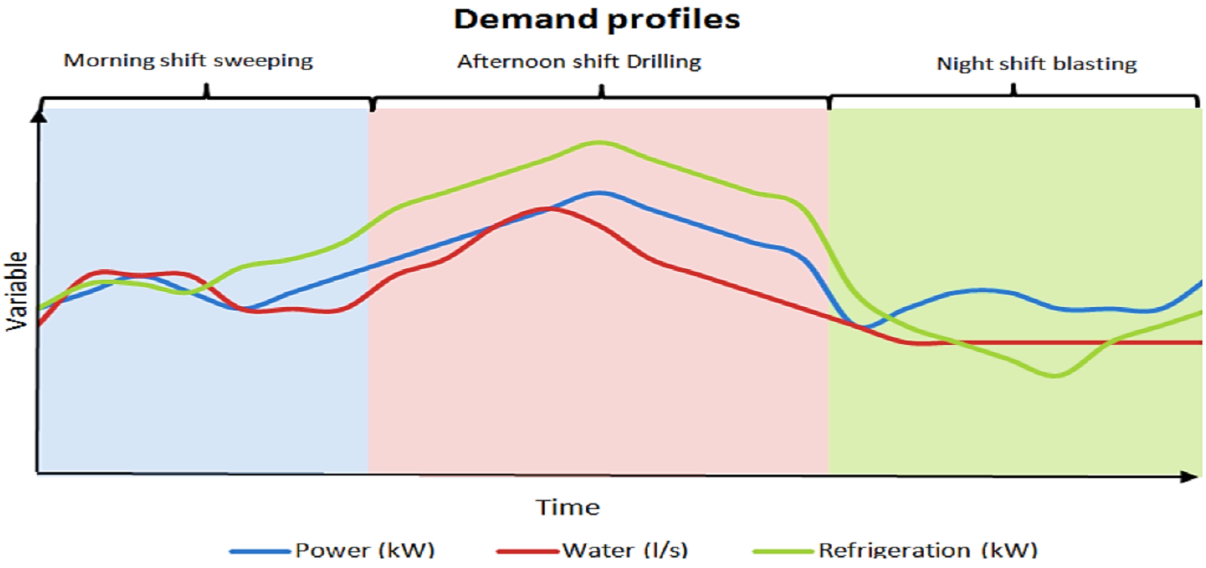


Figure 2-11: Morning, afternoon and night shift mining schedules [32]

2.1.7.2 Automated Underground de-watering Pumping Systems

The information in Table 2-3 shows the advantages and disadvantages between automated and manual pumping in deep level underground mining systems. The automated pumping systems have many advantages when compared to the manual pumping systems. Therefore automated pumping is becoming more evident in the mining environment. In a study done by J. Van Der Bijl [35] energy and simulation predictions have proved to be within 10% accurate with the actual measured values.

Table 2-3: Comparison between manual and automated pumping systems

Pumping Type	Advantages	Disadvantages	Source
Manual Pumping		Delay in opening discharge valve causes damage	**Pelzer,** [25]
		Inappropriate pump cycling	**Pelzer,** [25]
		Inefficient capitalization of cheaper off-peak time	**Pelzer,** [25]
		Inaccurate pump data logging	**Pelzer,** [25]
Automated Pumping	Occasional control (human input) actions		**Pelzer,** [25]
	Enhanced safety		**Vosloo,** [20]
	Improved energy management		**Vosloo,** [20]
	Pump condition monitoring		**Vosloo,** [20]
	Labour cost saving		**Vosloo,** [20] **and De Kock,** [30]
		Additional infrastructure required	**Pelzer,** [25]
		Expensive	**Pelzer,** [25]
		High Level maintenance	**Pelzer,** [25]
		Will not control suitably in an emergency position	**Pelzer,** [25]

2.1.8 Previous Issues with DSM Projects

In a previous study conducted by J.P. Steyl [36] many DSM projects which were implemented had poor sustainability. This poor sustainability was due to manual intervention by control room operators.

2.1.9 Alternative DSM Project

2.1.9.1 Pressure Reducing Valve's

A study done by A. Botha [37] was done on Pressure reducing valve (PRV) stations at Kopanang gold mine. Figure 2-12 below shows the average water flow from 39 Level dam together with production water supply pressure. When the test pressure is reduced from 12 bar to 8 bar, a reduction in chilled water flow of 100 L/s is evident. A daily chilled water flow reduction, results in a saving of 9.6 MWh electrical energy [37].

To calculate the PRV electricity saving in Eskom peak hours, the amount of time that the water takes to reach the hot water mine dewatering pumps from the production areas need to be calculated. This should be done to see the exact impact on peak time electricity savings due to the delay in the water cycle. The water cycle implies to the time it takes from when chilled water is used for mining until it reaches the de-watering pumps.

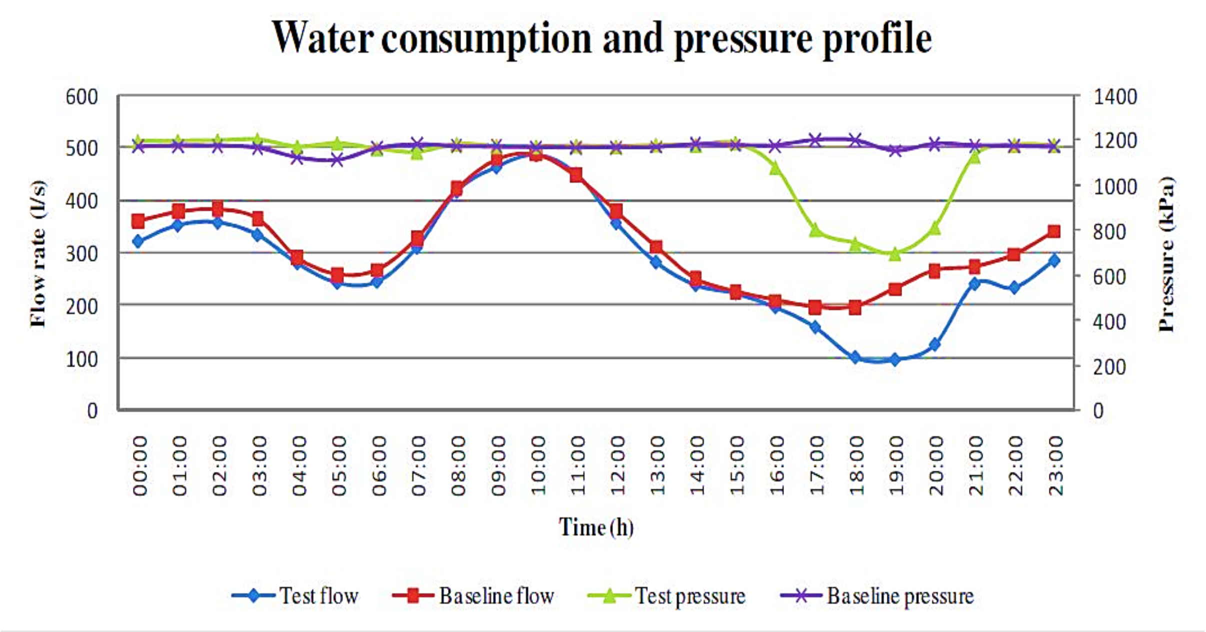


Figure 2-12: Results of pressure reducing valves adapted from [37]

In Figure 2-13 the effect of the PRV‘s is evident on the electrical demand profile. The PRV valves show savings only during Eskom of peak time periods. The reason for this is that A. Botha [37] already had a Load shifting project running, therefore during peak hours no savings could be claimed for the PRV’s, only for the load shifting project [37]. A. Botha [37] calculated an annual cost saving amount of R513 700 which is based on twenty two (22) average workdays per month.

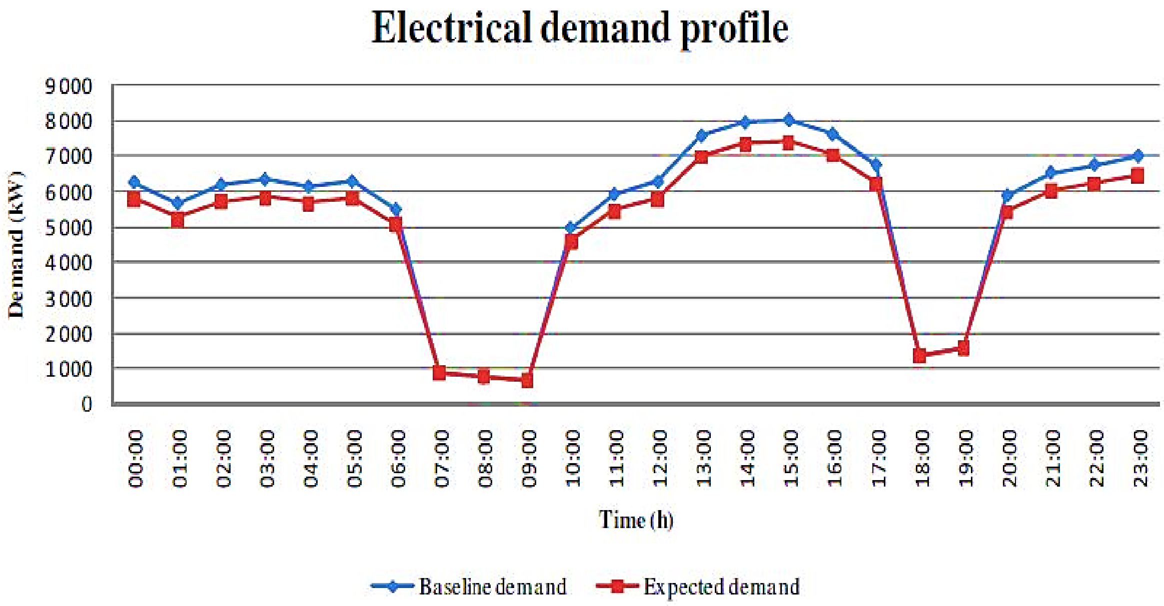


Figure 2-13: Electrical impact of the PRV's at Kopanang adapted from [37]

Note that if the Load shifting was not done on the mine, the PRV’s would have had a much bigger saving. Because then the PRV’s would have saved electricity during peak Eskom hours.

2.1.10 Alternative to Pump Pumping Stations

J.C. Vosloo [20] concluded that electricity dewatering systems can reach as high as 190% by using alternative systems including 3-CPS and turbine pumps, which are alternative energy sources.

2.1.10.1 Three Chamber Pipe Feeder System (3CPFS)

The 3CPFS uses a fundamental U-tube effect as indicated in Figure 2-14. This effect leads to water recirculation in mines that are more energy efficient than conventional[1] dewatering pumping systems. The efficiency of a 3CPFS is estimated to be 98% [38].

The U-tube effect of the 3CPFS operates by using incoming chilled water from higher up in the mine to displace hot used water out of the mine. The displacement is done due to the 3CPFS being a pressure exchange system that connects a high-pressure system (chilled water) to a low-pressure system (hot water) [38].

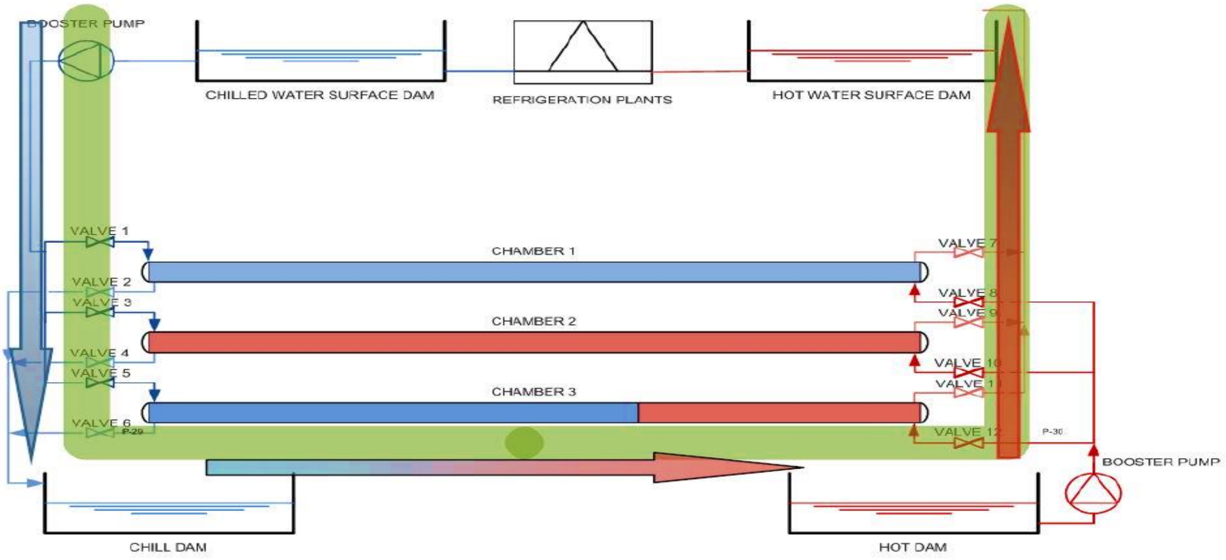


Figure 2-14: U-tube schematic effect of 3CPFS adapted from [38]

2.2 Previous Studies Done on Load Shifting Projects

Energy savings can be reached by integrating or replacing old technologies with new technologies while also using the best energy practices. According to the World Summit on Sustainable Development [39], energy savings lead to cost savings and environmental benefits.

It is challenging to determine the expected savings for the implementation of DSM interventions on a water reticulation system of a mine. The reason is that each mine has its own unique way of mining, meaning that they have different water recirculation systems, layouts and operational

---

[1] Conventional pumping system – electrically driven pumping systems

procedures. Mining can be unpredictable due to unscheduled repairs and maintenance of mining equipment [32].

Due to the above mentioned reasons, it can be difficult to calculate the exact savings of DSM interventions. It is therefore important to review previous studies and develop an estimation of potential savings and problems that may be encountered when installing and operating DSM interventions [32].

2.2.1 First Review - Optimization of single and multi-shaft operations

In a study done by N. Oosthuizen [40] which specifically focused on deep-level gold mines found that essential production processes will not be affected by DSM projects. The research done by [40], focussed on the optimization of both a single shaft and a mine consisting of multiple shafts. Two Simulations were done, the first simulation (X) was for each individual shaft to transfer used water to the surface, without the shafts pumping to each other. The second simulation (Y) simulated interconnected pumping between shafts to one common surface point.

Table 2-4: Consumption, adapted power consumption adapted from [40]

Shaft	Average power usage Simulation X (kW)	Average power usage Simulation Y (kW)	Power difference between X and Y
Mine Shaft A	15 167.57	7 192.26	52.58%
Mine Shaft C	13 098.56	17 687.24	-25.94%
Mine Shaft D	11 980.09	14 115.83	-15.13%
Mine Shaft E	6 478.25	6 570.73	-1.41%
Total simulated power	**46 724.46**	**45 566.07**	**-2.48%**

From Table 2-4 the total simulated power saving, simulation X resulted in an average of 1.2 MW (2.48%) less average power usage than simulation Y over a period of five weekdays.

2.2.2 Second Review – Critical review of manual and automated single shaft DSM projects

R. Pelzer, RP. Richter, M. Kleingeld and J. van Rensburg [21] used data from six mines where DSM projects were implemented, three of these mines were automated and the other three manual interventions. Figure 2-15 is a representation of the design for one of the six mines, which are a single shaft mines. The other five mines had a similar layout.

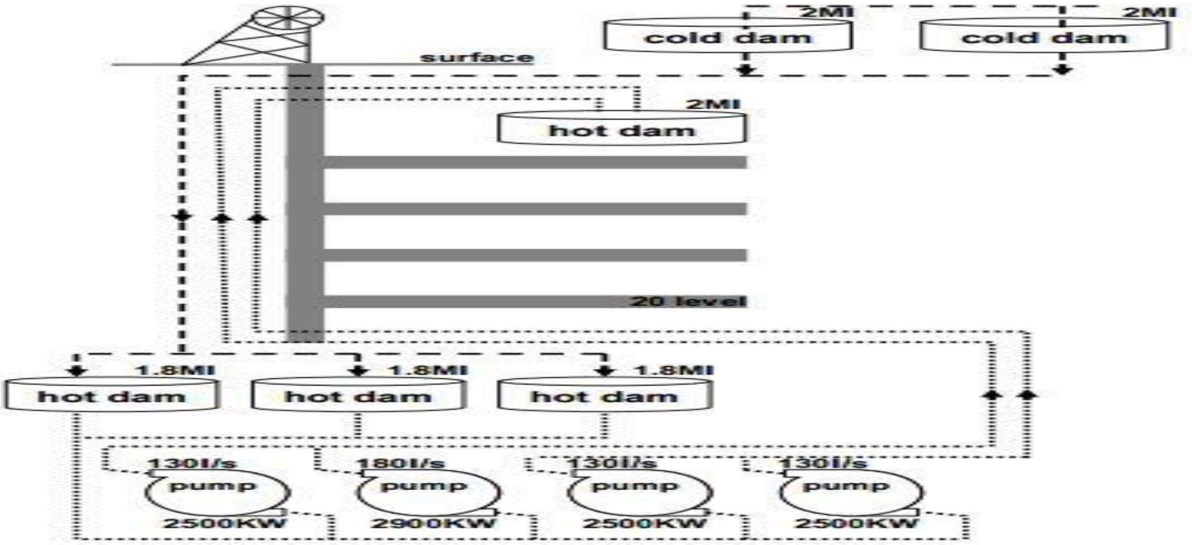


Figure 2-15: Amandelbult 2# layout adapted from [21]

Table 2-5: Automated and manual control prediction accuracy adapted from [21]

	AUTOMATED CONTROL		**MANUAL CONTROL**	
	Project name	% Difference simulated vs. actual	Project name	% Difference simulated vs. actual
Project 1	Amandelbult 2#	2.4	Tau Tona	34.7
Project 2	Masimong 4#	1.2	Beatrix 1,2 &3#	33.8
Project 3	Beatrix 4#	8.3	South Deep	51.2
Average		**4.0**		**39.9**

Table 2-5 has two main columns namely automated and manual control. Automated control had a 4.0% difference for the simulated versus actual data and the manual control had a 39.9% increase for predicted automated load shifting. The data above were based on evening load shift [21].

The study [21] concluded a 36% improvement in savings when clear water pumping systems were changed from manual to automatic for mines with a layout similar to Figure 2-15.

R.P. Richter [25] found that automated systems performance are 40% more efficient than manual load shift DSM projects (Table 2-6). Automated systems, in the long run, are justified due to higher implementation costs that manual load shifting present.

Table 2-6: Comparison between results of simulated and actual load shifting [25]

	Contractual load shifting value (MW)	**Manual load shifting (MW)**	**Predicted automated load shifting (MW)**	**Difference in load shifting (MW)**	**Av. difference between manual and automated load shifting (%)**
Tau Tona	5.50	7.96	12.20	4.24	34.7
Beatrix 1,2 & 3#	6.00	4.04	6.10	2.06	33.8
South Deep	6.00	3.80	7.80	4.00	51.2
Total/Av.	17.50	15.80	26.10	10.30	40.0

2.2.3 Third Review – modelled automated multiple-shaft loadshifting

S. Thein [41] did a study on an integrated underground water recirculation system at Beatrix mine after it was identified as a potential candidate for DSM implementation (Figure 2-16). The study assumed that multiple-shaft pumping systems will have a similar impact to single shaft pumping systems, only larger. To calculate the total possible load shift potential, the entire systems power baselines was added together. Simulation using rems, without physical results automated load shifting results.

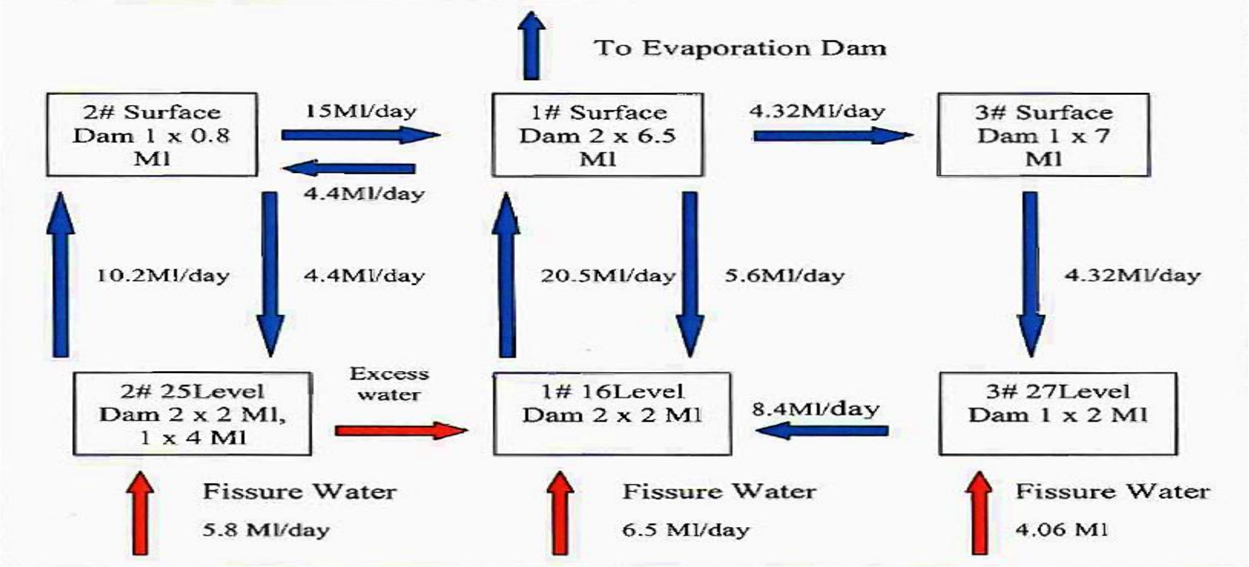


Figure 2-16: Beatrix interconnected underground water system [41]

According to R.P. Richter [25] the project on Beatrix 1, 2 and 3# has insufficient infrastructure that prevents fully automated control. The Beatrix interconnected pumping system is also presented in Figure 2-17.

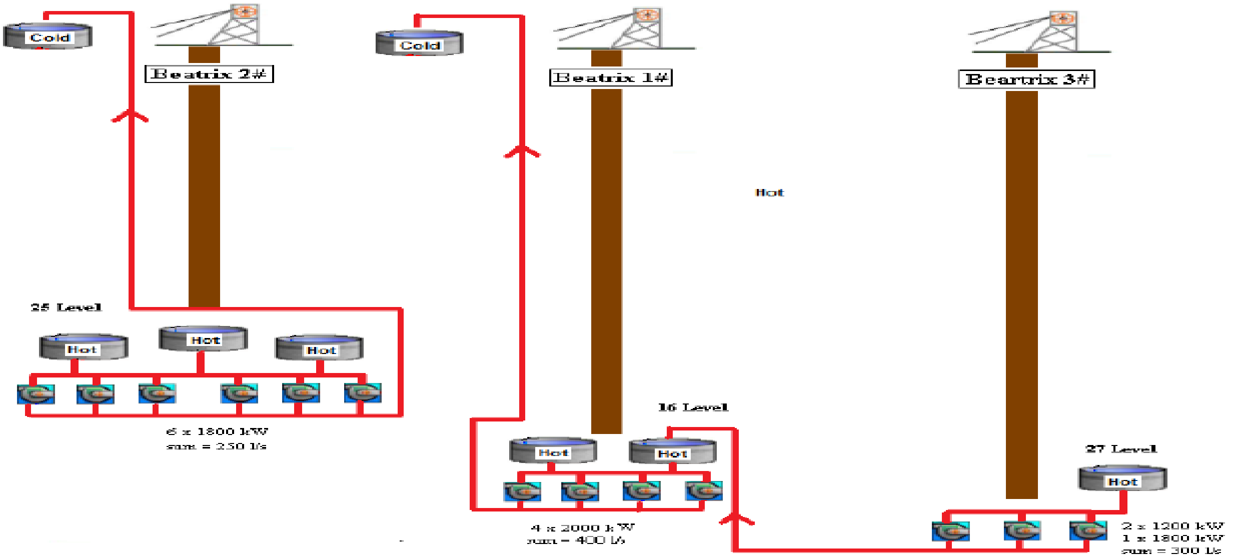


Figure 2-17: Beatrix 1, 2 and 3 Shaft system layout [25]

The simulated target, proposed target to Eskom and average performance was 6.10 MW, 6.00 MW and 4.00 MW respectively. The project had a lifetime of 17 months and the underperformance of the project was because of an increased amount of water to be pumped and the manual pumping interventions (human errors) [25].

2.2.4 Fourth Study – Baseline energy shifting modelling

In a study done by A.P. van Niekerk [32], it stated the importance to study a mines operative procedure to optimize a water recirculation system. The data presented in Figure 2-18 shows a correlation in the savings potential and power demand. The blue bullets represent the previous load shifting projects that were conducted on mines. A linear trend line is also evident on the figure below which can be used to estimate the potential savings that a load shifting project can yield. This estimation still has a large error but it can show the feasibility of a potential project if a more detailed savings figure is needed a simulation package should be used.

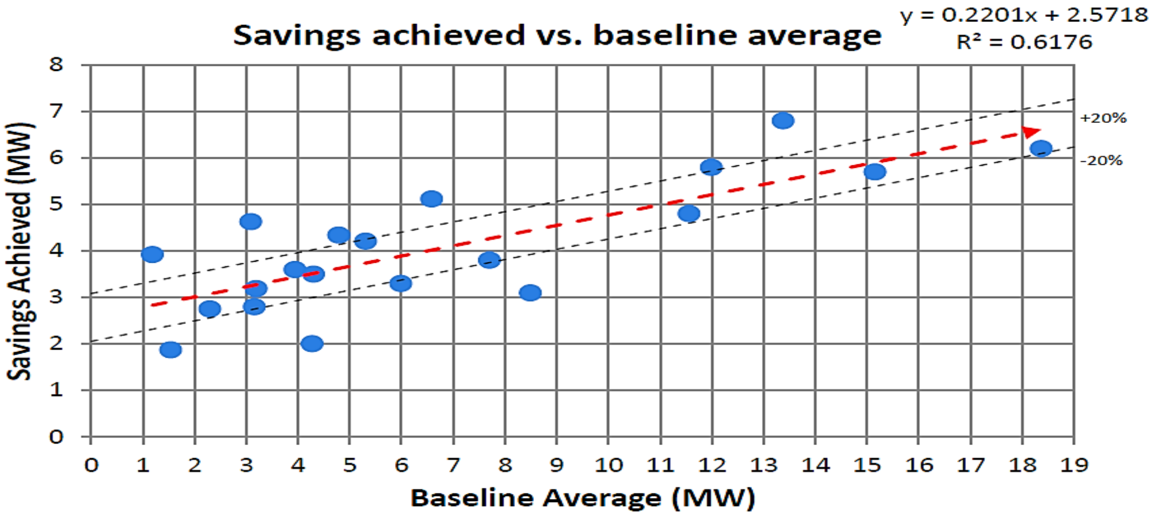


Figure 2-18: Historic project load shifting data [32]

2.2.5 Pump monitoring

2.2.5.1 Tas Online

Tas online PumpMonitor® system measures lifetime and real-time pump efficiencies. The system can predict the most effective time to replace or maintaining pumps.

The information gathered from the system may also be used for load shifting project. This will show which pump has the highest efficiency, therefore during Eskom peak time the pump can be used instead of other less efficient pumps. This system is not a real time energy management system but can be used for energy management.

2.2.5.2 SCADA [20]

Supervisory control and data acquisition (SCADA), is a centralized system which monitors and controls systems or components from a remote computer. This system shows real time values, which can be seen by operators.

2.3 Conclusion

From literature numerous studies have been done on demand side management, more specifically de-watering pump load shifting studies. Most of the literature examined, concentrated on single shaft, pump de-watering systems. Few studies have been done on larger multiple-shaft mining systems. The studies that has been done on multiple shaft load shifting were only modelled data, which may differ significantly from actual automated load shifting results. This reason together with South Africa's electricity demand shortage and electricity price increases happening each year, it is important to do studies on these kind of projects, due to the magnitude of the de-watering systems of multiple shaft pumping systems.

This study will focus on the load shifting of a large scale de-watering pumping system, which has already fully been equipped to go fully automated.

CHAPTER 3: INVESTIGATIONAL PROCEDURE

This chapter presents the possibility for Demand Side Management at the deep level hard rock mine. Steps taken to determine the potential of the (DSM) project with detailed layout drawings and discussions will be shown.

3.1 Chapter Introduction

The multiple shaft deep level mine, which was deemed suitable for the investigation is studied in detail. Layouts of the shafts, pumps, capacitances and pump-sizes together with infrastructures to automate the pumps will be presented.

Baselines will be shown, before and after the implementation of the automated pumping system at the investigated deep level hard rock mine. The baselines will display the pumping demand usages for weekdays, Saturdays and Sundays in kW electrical.

The feasibility of fully automated pumping will be discussed after comparing it with manual load shifting, semi-automated load shifting and a simulation. This will be done to ensure that the interconnected underground pumping system can be safely and effectively automated. The results between manual, semi-automated and automated load shifting will then be discussed together with all of the problems that were realized and how it were overcome.

Furthermore, the chapter will conclude if it's better to do load shifting in the morning or in the evening for the investigated gold mine. This will be tested with manual data and simulated values. Benefits will be shown for Eskom and the investigated mine. Saturday potential load shifting will also be discussed between standard and off peak as from the literature review in Figure 2-6.

From the literature study conducted, it was concluded that pumping is one of the major electricity consumers of deep level mines as presented in Figure 2-5. It was then determined that the DSM potential had to be checked to see if load shifting will be a viable possibility for the interconnected system.

The Mega flex system was also determined to be the pricing structure of mines by Eskom from literature. Load shifting possibilities will be done mainly on Weekdays but possibilities will also be discussed on Saturdays to load shift on standard times. Sundays will be used to do preparation for morning load shifting on the beginning of weekdays, thus Mondays.

3.2 Steps Taken to Determine the Potential for the DSM Study

3.2.1 Gold Mine Layout Overview

Firstly, the layout of the de-watering system of the examined deep level mine was studied. The system layout of Shaft one (1#), Shaft two (2#) and Shaft four (4#) is presented in Figure 3-1.

The three shafts, each have their own mining activities and are up to 3 km deep. This information was obtained from detailed mine drawings. Each shaft has its own personnel and mining structure. This makes it more difficult to communicate between shaft personnel, to effectively run large scale load shifting projects. Each shaft has its own control room which consist of multiple people, which operate morning, afternoon and evenings shifts. The three shafts also have a combined control room (Central control room) which oversees more technical information and manages energy projects.

The three shafts have de-watering pump systems which has a combined total design capacity of 52 MW_E (Mega Watt electrical). The combined electrical power consumption for the existing clear water pump installations will peak at about 10.8 MW_E with the annual average load over 24 hours being 9.5 MW_E.

The mine's de-watering system layout is very complex due to the mine having numerous interconnected shafts. The three shafts shown in Figure 3-1 forms a closed water system, these three shafts combined, forms the multiple shaft mine investigated in this thesis. This means Shaft one pump it’s used hot mining water from Transfer Level to 35 Level, through Shaft two 24 Level to Shaft four 24 Level where it is pumped to surface together with mining water from Shaft four, 38 Level. This used hot water is then re-cycled and re-used as cold water at the three shafts.

The mining levels described in this study is where de-watering pump stations are located. Each pumping station has its own personnel operating and maintaining it.

Due to pressure increasing dramatically with height, more than one pumping station is used per Shaft when pumping vertically. This is due to the design capacities of the pumps and pumping columns.

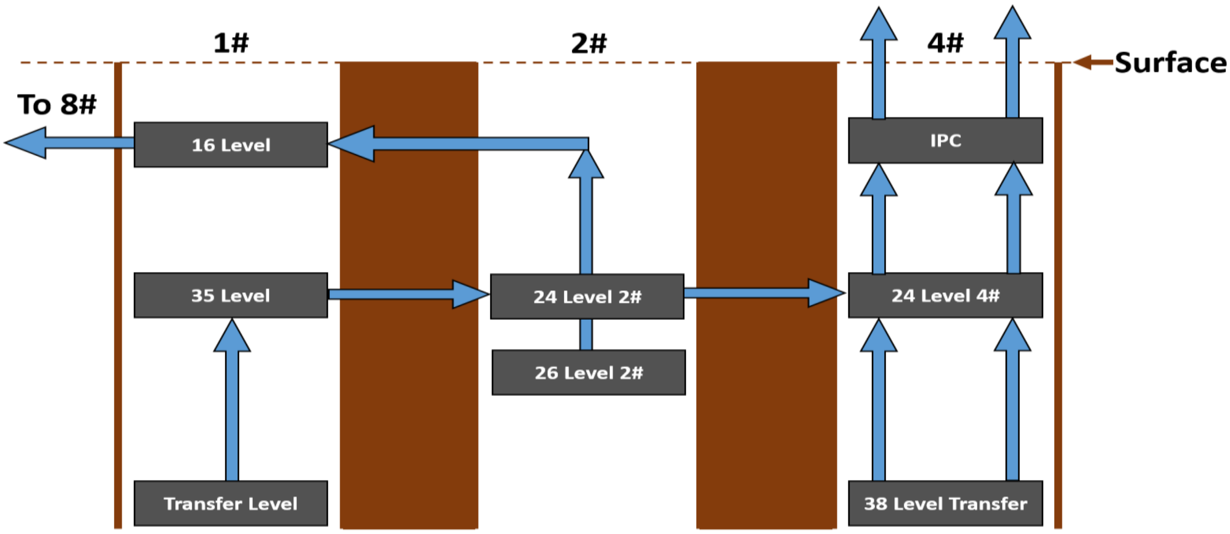


Figure 3-1: Layout overview of the investigated deep level hard rock mine system

The blue arrows in Figure 3-1 signify the direction of water flow from the de-watering pumps. Each arrow also demonstrates a pumping column. The maximum amount of pumps that may be started per column is two. If this amount is exceeded the column may attain structural damage. The water in the columns is used mining water which needs to be pumped to surface to be refrigerated and re-used. More than one pump may be started per column when the mine gives the necessary permission to do so.

Before the load shifting project was started, the procedure that was used to pump the water through the system was, the central control room has a SCADA system which has an interface showing all the different conditions underground. The SCADA has all the data that is necessary to control the pumps underground. This data include pump running feedback, trip feedback and dam levels. The operator in the central control room then uses his/her own discretion to start and stop pumps depending on the dam levels in the system. When they have decided on the necessary action to be taken on the pumps they call the shaft control room. The shaft control room calls underground to the desired pumping station, where the preferred pump will be started or stopped depending on the hot water dam level, by the pump personnel. When this system of stopping and starting is followed long lag times can be obtained due to communication errors between operators. It is also important to know that al the operators from the top to bottom can use their own discretion when a pump needs to stop or start. The detailed mine layout is shown in Figure 3-2, which show all the pumping stations with pumps and capacitances.

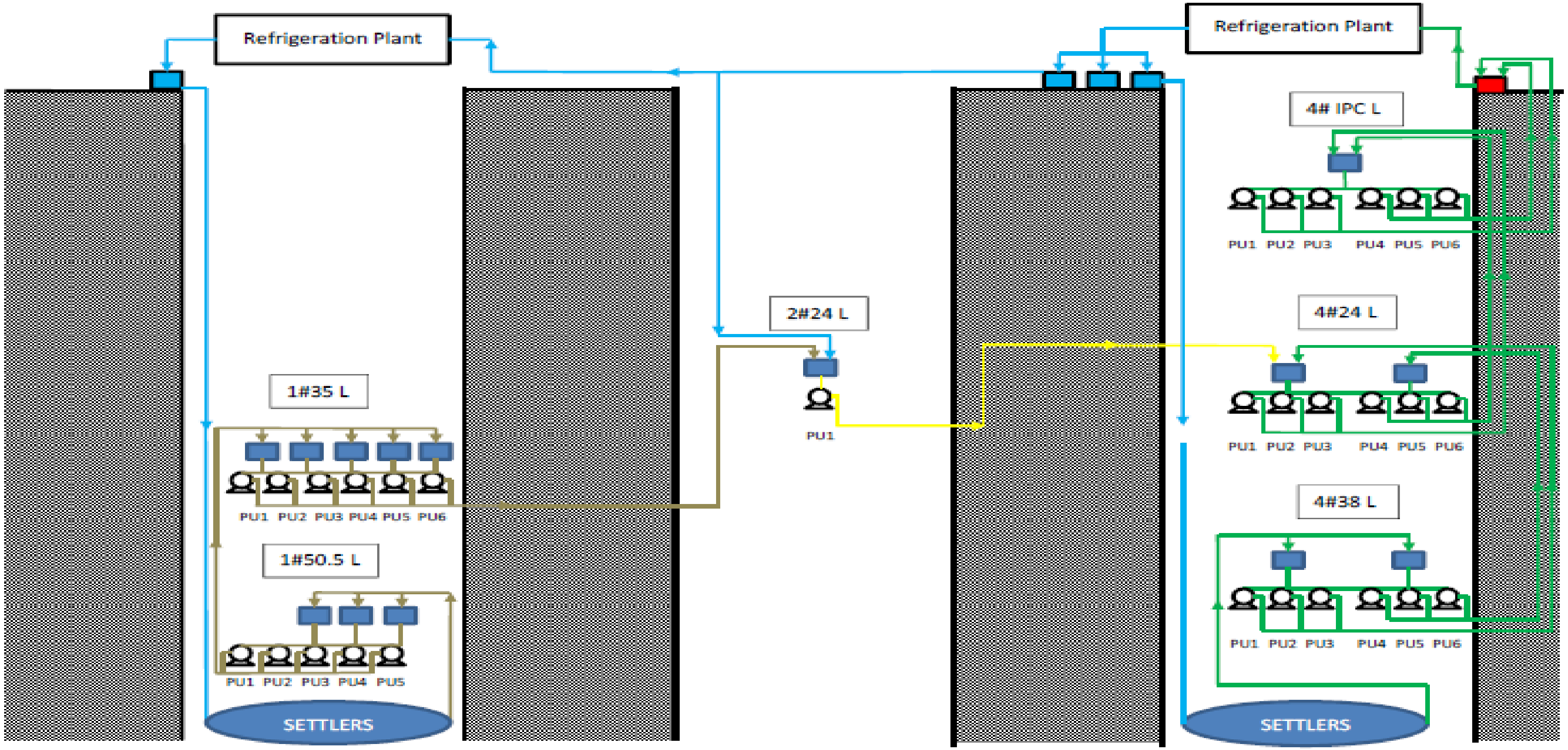


Figure 3-2: Detailed layout of the investigated deep level hard rock mine system

3.2.1.1 Hot Dam System

Hot water used in Shaft one and Shaft four accumulates in the hot dam on the surface of Shaft four, which is indicated by the red block. Water accumulates in the hot water dam at the end of the water cycle, through the pumping of the de-watering pumps.

3.2.1.2 Settler System

When the cold water is used for mining purposes in Shaft one and Shaft four, it settles in the settlers. Once the water reaches the settlers it has already been mixed with dust and other pollutants due to mining operations. The settler's separate the water from the mud with the use of inoculants. From here the clean water, depending on the settler's efficiency, is pumped to the Shaft four surface hot dam.

3.2.1.3 De-watering Pump System

The de-watering pumps are shown in detail on Figure 3-2. Table 3-1 shows each pumps rated power, flow rate and pump efficiency. This detail is used in the pumping model, described further down in the following section. Table 3-1 shows all the de-watering pumps in the pumping system, including the rated power, flow rate and pump efficiency.

Table 3-1: Goldmine de-watering pumps rated capacity

Pump Description	Power Rated, [kW]	Flow Rate, [L/s]	Pump Efficiency ,[%]	Pump Description	Power Rated, [kW]	Flow Rate, [L/s]	Pump Efficiency, [%]
Shaft one, 50 Level pump 1	1 850	152	-	**Shaft four, 38 Level pump 5**	1 850	135	-
Shaft one, 50 Level pump 2	1 850	146	101	**Shaft four, 38 Level pump 6**	1 850	152	-
Shaft one, 50 Level pump 3	1 850	146	120	**Shaft four, 24 Level pump 1**	2 100	158	96
Shaft one, 50 Level pump 4	2 450	200	107	**Shaft four, 24 Level pump 2**	2 100	146	91
Shaft one, 50 Level pump 5	2 450	223	-	**Shaft four, 24 Level pump 3**	2 100	162	93
Shaft one, 35 Level pump 1	1 850	196	69	**Shaft four, 24 Level pump 4**	2 100	149	89
Shaft one, 35 Level pump 2	1 850	187	74	**Shaft four, 24 Level pump 5**	2 100	167	90
Shaft one, 35 Level pump 3	1 850	137	72	**Shaft four, 24 Level pump 6**	2 100	160	-

Pump Description	Power Rated, [kW]	Flow Rate, [L/s]	Pump Efficiency ,[%]	Pump Description	Power Rated, [kW]	Flow Rate, [L/s]	Pump Efficiency, [%]
Shaft one, 35 Level pump 4	1 850	180	80	**Shaft four, IPC Level Pump 1**	2 100	144	93
Shaft two, 24 Level pump 1	75	290	-	**Shaft four, IPC Level pump 2**	2 100	124	96
Shaft four, 38 Level pump 1	1 850	146	79	**Shaft four, IPC Level pump 3**	2 100	131	94
Shaft four, 38 Level pump 2	1 850	135	76	**Shaft four, IPC Level pump 4**	2 100	175	93
Shaft four, 38 Level pump 3	1 850	108	76	**Shaft four, IPC Level pump 5**	2 100	167	92
Shaft four, 38 Level pump 4	1 850	118	70	**Shaft four, IPC Level pump 6**	2 100	155	-

From Table 3-1 it can be realised that the rated power of the Shaft four pumps on IPC and 24 Level, are all 2.1 MW. Shaft four 38 Level and Shaft one 35 Level has 1.85 MW rated pumps. The smallest pump is on Shaft two 24 Level due to horizontal pumping. Two of the biggest pumps are found on Shaft one Transfer Level, which are 2.45 MW. The other three pumps on this level have a rated capacity of 1.85 MW.

3.2.2 Mine Over-all Baseline Profile

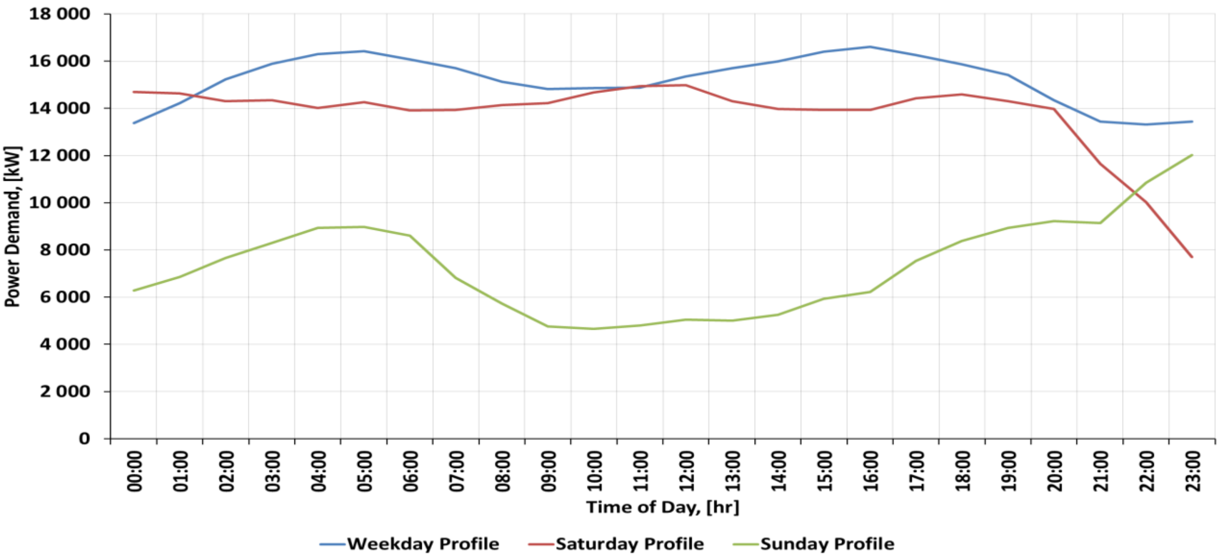


Figure 3-3: Gold-mine total de-watering pump system baseline

Figure 3-3 shows the average total pumping electricity demand baseline for weekdays, Saturdays and Sundays for the investigated hard rock mine. The baseline was calculated for a time period of six months before the implementation of any manual load shifting.

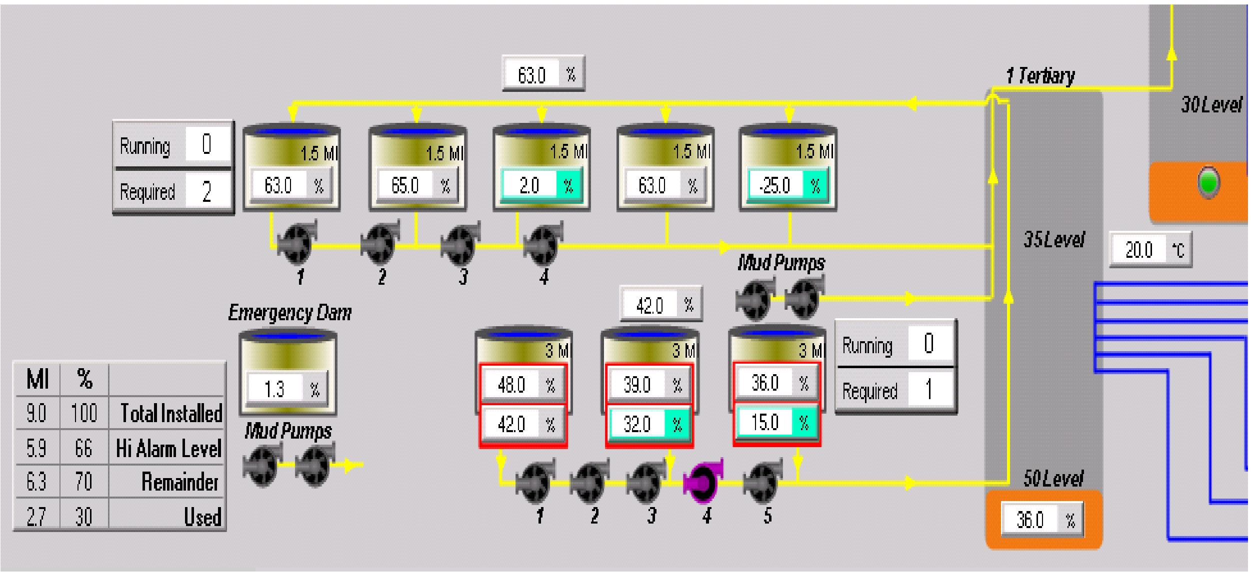
Three sets of data are represented by the three lines in the above graph. The blue line shows the weekday power consumption for the three shafts combined. High power consumption is reached throughout the weekday, with high power demand between the expensive Eskom peak hours (6am until 10am and from 5pm and 8pm). The times mentioned are between the earlier peak time in winter and the later peak time in summer as displayed in Figure 2-6. This is when Eskom has the highest electricity tariffs. The power demand in standard and off-peak is also very high for weekdays. Saturday has a very high electricity baseline, thus showing the possibility to shift electricity from standard to off-peak times. The reason for the high demand is that most of the Saturdays on the studied mine are on-Saturdays (working days) meaning that normal mining is present. Sundays consist only of off-peak time, meaning that it is not necessary to do load shifting from an economical point of view. Sundays are used to ensure that the mine has low dam levels on Mondays, by minimising the dam levels as much as possible in off-peak times.

The form of the weekend baseline is based on the control room operators, mining conditions such as water usage, dam cleaning and pump maintenance. The maximum electricity demand for weekdays, Saturdays and Sundays are 16 600, 15 000 and 12 000 kW respectively. When comparing Figure 3-3 with Figure 2-6 and Figure 2-8, the possibility to do load shifting gets very respectable.

3.2.3 Shaft one Detailed Layout, Baseline and Capacitance

Figure 3-4 shows the five dams with an average dam level above the five dams, this is the dam level that is used to decide whether a pump needs to be stopped or started. The tertiary shaft on Figure 3-4 is where 35 Level and Transfer Level is situated. The running and required block situated next to the five dams is the controller that was developed. The controller and the operation thereof will be discussed in the following sections.

3.2.3.1 Shaft one Detailed Pumping Layout



Ml	%	
9.0	100	Total Installed
5.9	66	Hi Alarm Level
6.3	70	Remainder
2.7	30	Used

Figure 3-4: Shaft one detailed schematic representation from mine's SCADA

3.2.3.2 Shaft one Pumping Baseline

Shaft one consists of three major pumping levels, namely 16 Level, 35 Level and Transfer Level. Hot mining water used for mining purposes on Shaft one goes down to the settler dams just above the hot water dams on the Tertiary shaft. After the water has reached the settler dams it is fed to transfer level, from where it is pumped out as mentioned above through Shaft one 35 Level to Shaft two 24 Level.

The mine consist of many more additional shafts than the three mentioned in this thesis. Some of these shafts are also interconnected with the three shafts (of this study), but the water of the other shafts doesn't form part of the closed loop studied in this study. Due to almost all of the shafts being interconnected water is pumped through Shaft one 16 Level from Shaft two 26 Level. The water pumped through Shaft one 16 Level is not used in the water balance between Shaft one, two and four because it is purely pumped through Shaft one to Shaft eight. Chilled water used for mining in this Shaft (Shaft one) is fed through a gravity fed cascade system. The chilled water is cooled at Shaft four's surface refrigeration plant and then distributed with pumping columns on surface to one shaft. This refrigerated water is then used for mining.

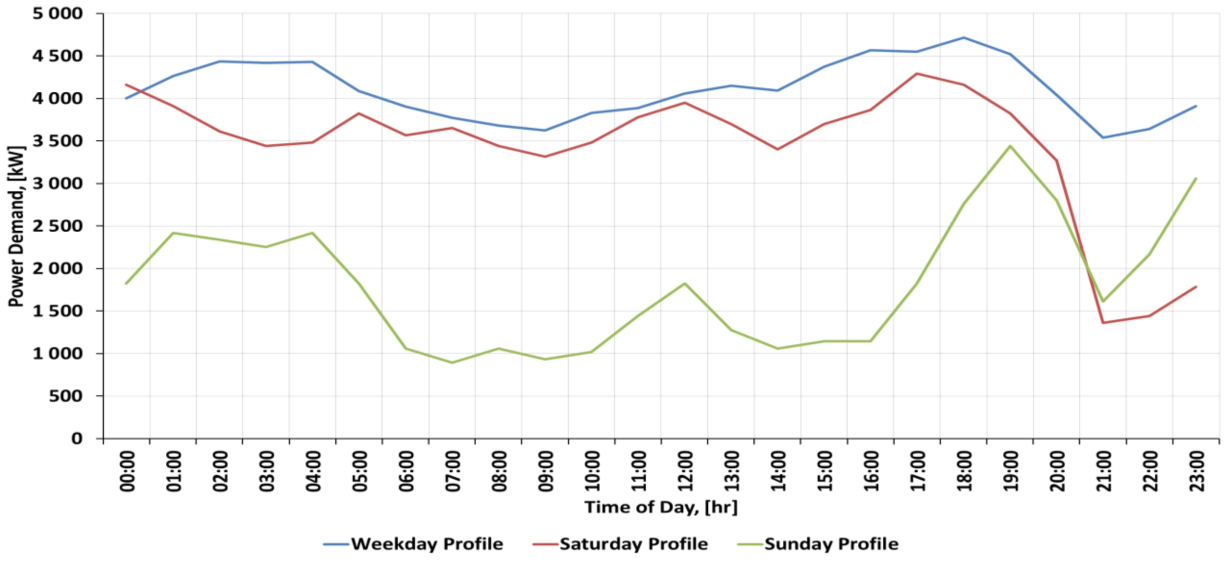


Figure 3-5: Shaft one total de-watering pump system baseline

The maximum power demand for weekdays, Saturdays and Sundays from Figure 3-5 are 4 700, 4 300 and 3 400 kW respectively. Weekdays have the largest electricity demand thus, Shaft one has a large potential for cost effective load-shifting. Saturdays also have a possibility for load shifting in standard times from 7:00-12:00 and 18:00-20:00, for winter and summer. It is evident from Figure 3-5 that the power profile of Saturday drops at 20:00 due to Sunday not being a mining day, thus less water needs to be pumped out.

3.2.3.3 Shaft one Capacitance

The capacitance on 35 Level is divided between five hot water dams that are each 1.5 ML in size. Only three dams are used, and the other two dams are used as backups. Thus the combined size of water capacitance on 35 Level is 4.5 ML.

Transfer Level (50.5) has three dams with only one being used at a specified time. This level is at the bottom of the sub-shaft. Due to this being the lowest level two backup dams exist to prevent potential flooding due to electrical or communication shortages. The combined capacity of this level is 3 ML.

3.2.4 Shaft two Detailed Layout, Pumping Baseline and Capacitance

3.2.4.1 Detailed Pumping Layout

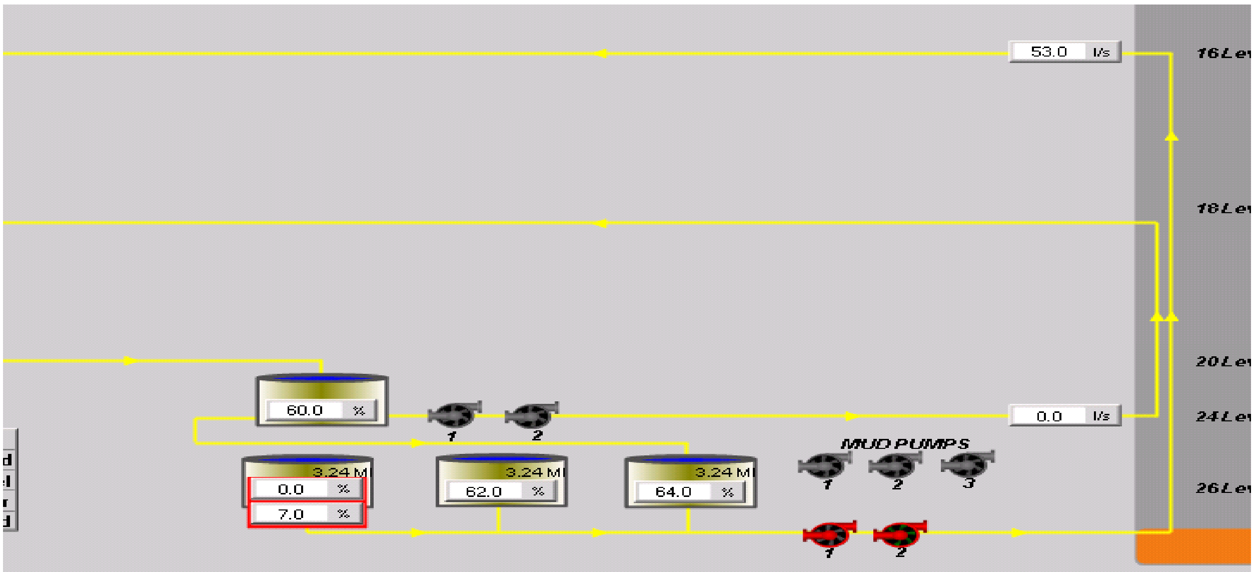


Figure 3-6: Shaft two detailed schematic representation from mine's SCADA

3.2.4.2 Shaft two Pumping Baseline

Shaft two has two key pumping levels, namely 24 and 26 Level. Mining water (chilled water used for mining) from Shaft two collects on 26 Level and is then pumped through Shaft one 16 Level to Shaft eight. Figure 3-6 shows the detailed schematic representation of 26 Level. 26 Level is the deepest pumping station on Shaft two. Used mine water from Shaft one 35 and Transfer Level passes through Shaft two to Shaft four. It can be concluded that Shaft two's water down is not in the water balance, when calculating the potential for load shifting.

Shaft two uses dolomite water mixed with small quantities of refrigeration water for cooling purposes, this is only when the dolomite water is not cold enough and thus it is not used in the closed water cycle. This water is also fed through a cascade dolomite dam system underground.

The chilled water of Shaft one and Shaft four is also delivered through a cascading dam system. The reason for the cascade systems is to reduce pressure as the mine gets deeper. The water from Shaft one 35 Level is pumped horizontally through Shaft two 24 Level to Shaft four 24 Level. This is the reason for the low pumping electricity consumption for Shaft two as indicated and mentioned in Figure 3-7. There are two multi-stage pumps on 24 Level (one pump serves as a back-up pump), which are controlled according to the dam level by ultrasonic and pressure sensors. Only one pump can be used at time. When the level reaches 70% a pump will start and when it reaches 40% the pump will stop automatically. A maximum of one multistage pump is allowed to operate on this level. The pump can deliver up 290 L/s depending on the water composition. When the water has a lot of mud (settler dams not working properly) the flow will reduce radically.

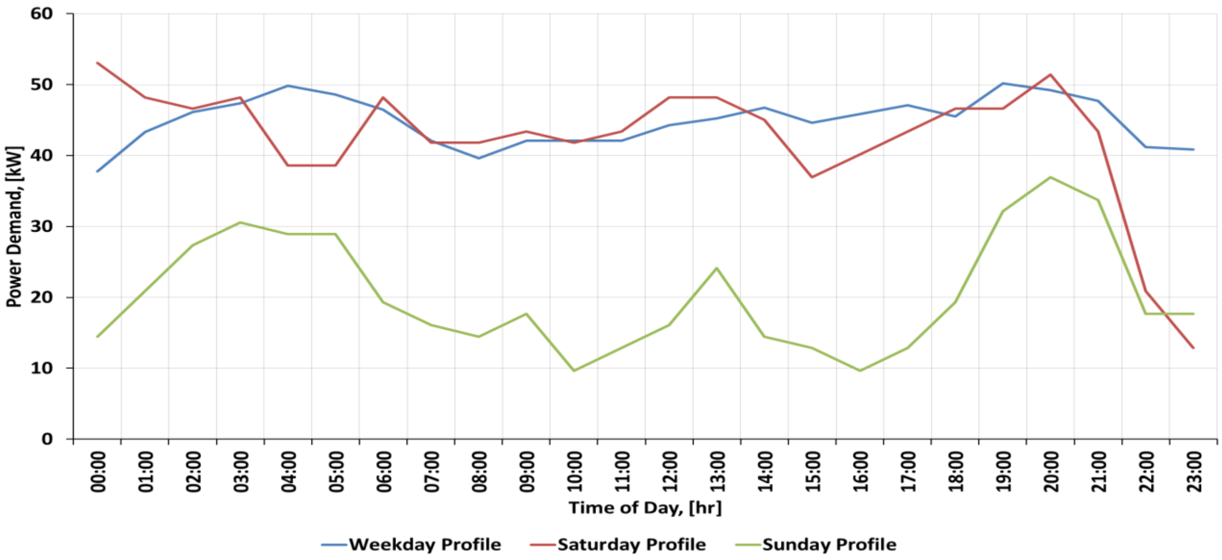


Figure 3-7: Shaft two total de-watering pump system baseline

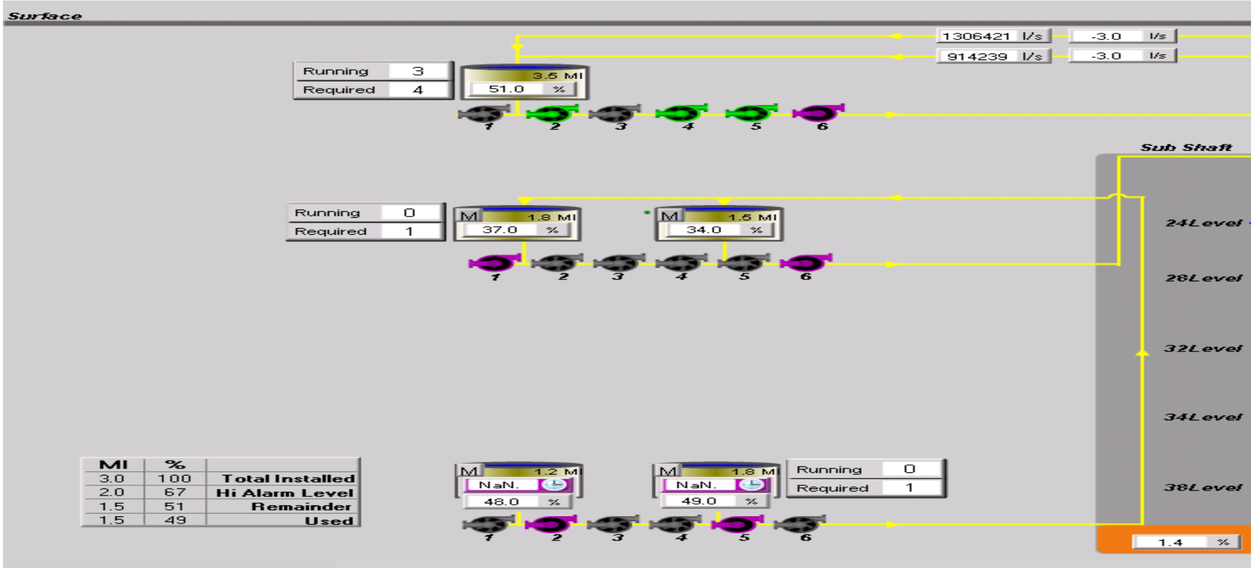
The maximum electricity demand for weekdays, Saturdays and Sundays are 50, 53 and 37 kW respectively.

3.2.4.3 Shaft two Capacitance

The capacitance of the Shaft two dam is unknown. This dam is a flooded haulage (old mining Level) which receives water from Shaft one 35 Level. The time it takes to reach water to flow from Shaft one 35 Level to Shaft two 24 Level is more or less 40 min as obtained from mine data. The data used presented when an effect was obtained on the Shaft two dam by starting a pump on Shaft one 35 Level, without running a pump on Shaft two 24 Level. Due to shaft two's limited dam size and limited information, it makes it very difficult to simulate this type of system.

3.2.5 Shaft four Detailed Layout, Pumping Baseline and Capacitance

3.2.5.1 Detailed Pumping Layout



Running 3
Required 4

Running 0
Required 1

Running 0
Required 1

Ml	%	
3.0	100	Total Installed
2.0	67	Hi Alarm Level
1.5	51	Remainder
1.5	49	Used

Figure 3-8: Shaft four detailed schematic representation from mine's SCADA

3.2.5.2 Shaft four Pumping Baseline

The schematic representation of Shaft four is showed in Figure 3-8. The shaft has three primary pumping stations on the following levels, namely the intermediate pumping chamber (IPC Level), 24 Level and 38 Level. IPC Level pumping station is the upper-most pumping station, with 24 Level pumping station beneath it. 38 Level pumping station is below 24 Level, refer to Figure 3-8. The pumping station on Shaft four 24 Level receives water from Shaft four 38 Level and Shaft two 24 Level. 38 Level is not the lowest pumping station on Shaft four. There is also a pumping station below 38 Level, but it is not part of the automated pumping system layout in this thesis. IPC Level pumps water to the hot surface dam as shown in Figure 3-2 in the detailed representation of the mine. It is important to ensure that the surface dams always have enough water for the fridge plant on Shaft four to work efficiently.

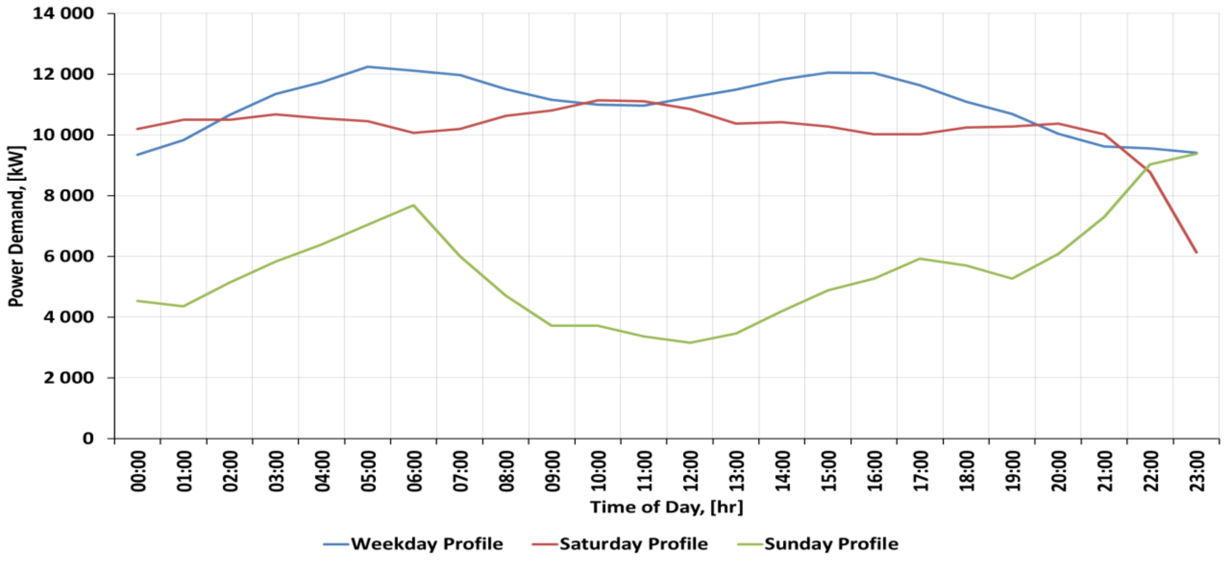


Figure 3-9: Shaft four total de-watering pump system baseline

The maximum electricity demand for weekdays, Saturdays and Sundays from Figure 3-9 are 12 200, 11 100 and 9 378 kW respectively. The averages for the electricity consumption on Saturdays and weekdays are much more than that on Sundays. The reason for the high maximum on Sunday evening between 22 and 23 pm is the mining preparation for the start of weekdays.

3.2.5.3 4# Capacitance

38 Level has two dams, which are interconnected with a pipe (balanced dams). Thus forming a single capacitance of 3 ML. 38 Level has no backup dam due to it not being the lowest level. The lowest level on Shaft four is 42 Level, which is also called the Transfer Level. 24 Level has two dams which are connected and their combined capacity is 3.3 ML. One dam receives water from Shaft two 24 Level and the other dam receives water from 38 Level pumping station. IPC Level has one dam, which has a 3.5 ML capacity.

3.2.6 Shaft one, two and four electricity consumption summary

Table 3-2 contains the pumping power summary throughout weekdays, for all the shafts. The two columns shows the peak morning and evening power usage. From here it can be seen that Shaft four has the largest power usage of all the shafts. Both for morning and evening, the reason is that this shaft, pumps al the water out of the mine that goes down in Shaft one and four. When doing manual load shifting it will be important to focus on Shaft four because this is where the largest potential will be for cost savings and load shifting. Shaft one is the second largest power consumer and shaft two the third largest power consumer. It is of great importance to find the optimal balance between the three shafts, to increase cost savings and power shifted. This will be done by the simulation presented later in this study.

Table 3-2: Shaft one, two and four power consumption summary

Shaft number	Peak morning electricity, [MW]	Peak evening electricity, [MW]
Shaft one	4.0	4.7
Shaft two	0.04	0.05
Shaft four	11.5	11.0

3.3 Beneficiaries of the Load Shifting Project

3.3.1 Eskom

Eskom is only concerned by the evening peak load shifting for weekdays, due to this being the time of day when most customers of Eskom uses electricity. This is shown in Figure 2-2 from the literature survey.

3.3.2 Investigated deep level hard rock mine

The mine is concerned by the morning and evening peak times. Shifting electricity demand out of peak times into off-peak and standard times, will benefit them greatly with regard to cost savings.

3.3.3 Price Tariffs used

The pricing structure showed in Figure 3-10 and Figure 3-11 gives electricity tariffs for low (summer) and high (winter) demand season respectively. In low-demand season the maximum price for weekdays is in peak time which accumulates to 97 c/kWh, compared to 278 c/kWh in the high-demand season. This is more or less three times more in winter, the reason can be seen in Figure 2-2 with Eskom’s generation capability refer back to the literature review. Thus it is much more profitable for Esco’s to do DSM load shifting projects in winter. Therefore when doing predictions on the viability of projects winter and summer Mega flex price tariffs needs to be taken into account.

Summer is from September to May and winter is from June to August. Saturdays and Sundays still have the same times for standard and off-peak but have slightly increased prices from summer to winter. Saturday load shifting will be more profitable for the mine but not for Eskom due to Eskom having fewer constraints during Weekends. The difference in winter and summer between standard and off-peak times are R0.37/kWh and R0.22/kWh. The impact on the proposed mine will analyzed later in this chapter.

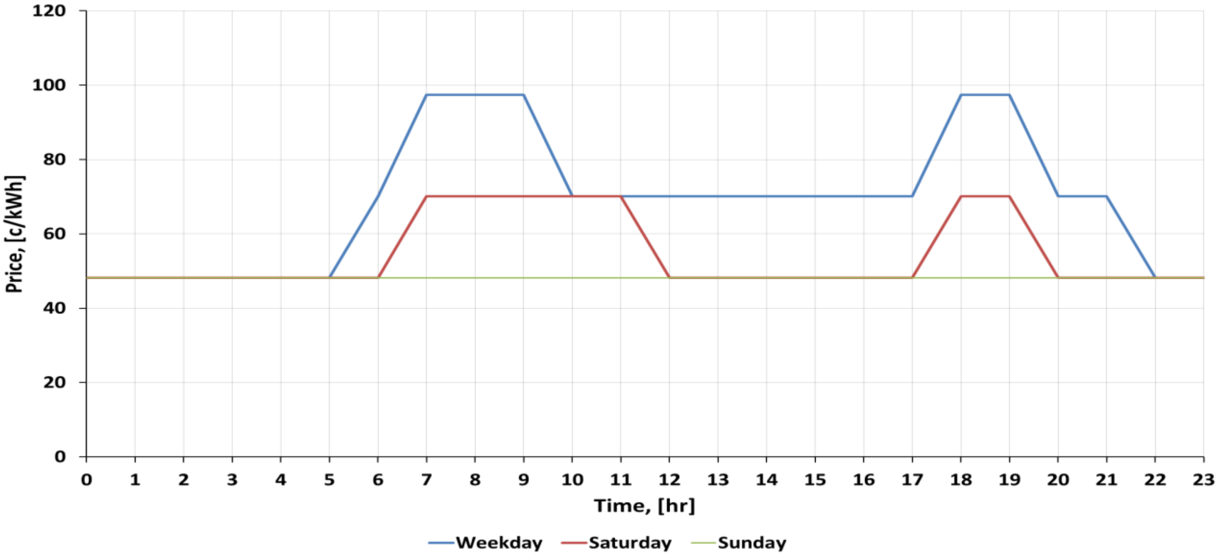


Figure 3-10: Mega flex price tariffs for low-demand season

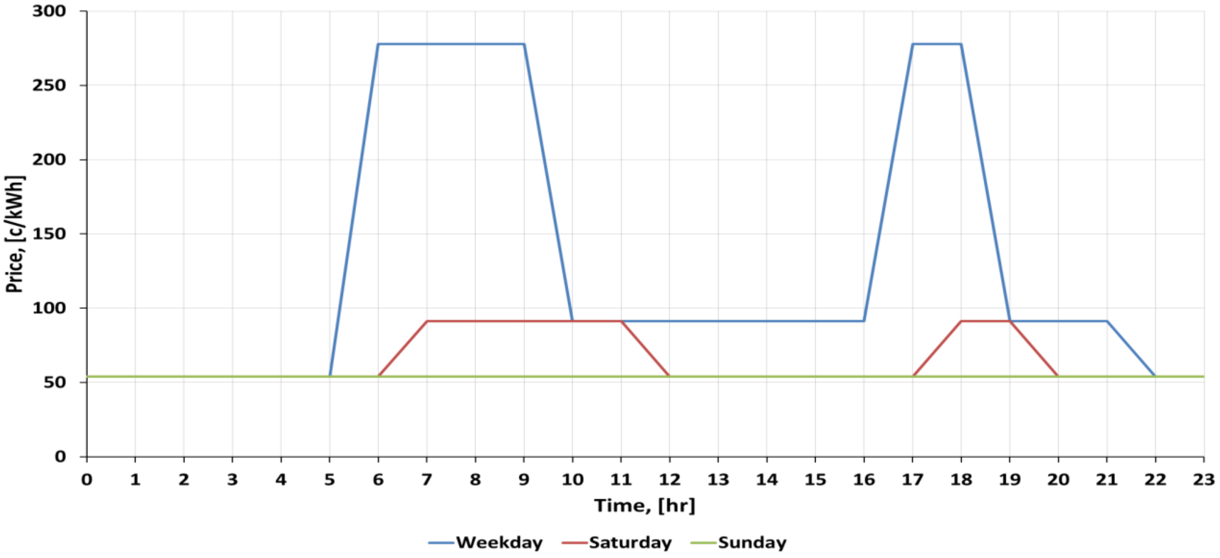


Figure 3-11: Mega flex price tariffs for high-demand season

From Figure 3-10 and Figure 3-11, the best pumping times can clearly be realised for summer and winter. The best pumping times by the mine for the energy producer Eskom will be in standard and off-peak for Weekdays. The best pumping times for the mine to gain as much possible cost benefit will be to pump according to the following schedule:

3.3.4 How to Load Shift According to the Mega-Flex Tariff on Weekdays:

In winter and summer pump the maximum possible amount of water out of capacitances during off-peak and standard times, refer back to Figure 2-6.

3.3.4.1 How to Load Shift According to the Mega-Flex Tariff on Weekends:

Pumps should be operated only in of peak times if possible on Saturdays and Sundays to electricity being more affordable in off-peak periods. In winter and summer, there is a difference of R0.37 and R0.22 in cost between standard and off-peak. This is an increase of 60% for the two change in two seasons. This means a much larger saving will be obtained by the client which is the mine in winter weekends than in summer weekends. This is only a small saving compared to Weekdays when the peak time rand value rises from R0.97 to R2.78. This is a 287% increase which shows why it is so profitable to run a load shift project in winter.

The Mega-flex tariff increase every year, this is important when calculating the cost saving and payback period.

3.4 Saving Calculations and verification

The measured parameters used in calculating the cost savings in the next chapter was:

Obtain the running status of each pump on each respective mining level. Only the running status was monitored for the calculations. The running status data, which are compiled of discrete values of zero’s and ones was used. Discrete 5 minute data were averaged half hourly, thus obtaining a value which represents in proportion the amount of time the specific pump was in operation. The data are obtained from a data server used by the mine.

Values from the running statuses were in the form of 0, 0.166, 0.333, 0.5, 0.666, 0.833 and 1. Running status averaged data are backward facing data meaning data shown next to x (hours) time, is wat happened from x-25 min to time x for 5min data. When calculating the error for 5 min data there are six samples (x-25, x-20, x-15, x-10, x-5, and x), thus the maximum error in the data can be 1/6 of a half hour. An example is shown in Table 3-3 below:

Table 3-3: Data error determination

Time	Pump running feedback
16:05	1
16:10	1
16:15	0
16:20	1
16:25	1
16:30	1

From Table 3-3 the error would be the zero next to 16:15. The reason for this is data that were not processed correctly because the large pumps underground doesn't switch off and on in 5 minutes. This may happen, but very seldom when a pump is tested for some reason.

Average pump running times was calculated to be 204 minutes, thus the maximum error expected would be 5minutes interval/ 204 minute = 2.45%.

Data validation was done the following:

- Ensuring the correct data files were checked for each pump on the different levels
- Ensuring data stay between zeros and ones.
- When pumps were changed ensure that the running statuses reflected zero for the specified time interval.
- Obtain pump efficiencies see attached in the Appendix
- Obtain pump sizes in MW electrical
- The results obtained for the manual load shifting was measured against Eskom measurement and verification team. The adjusted baseline, actual power usage and power impact were all below 1% error from each other for a seven month period.

3.5 Steps taken to calculate the load shifted

Draw up a baseline, which consists of data for six months, before the load shifting project started. Data for the baseline was obtained from pump running feedbacks, efficiencies and pump sizes in MW electrical on Shaft one, Shaft two and Shaft four.

- The baseline together with the model developed which includes dam capacities, pumping, water flows and other variables was used to generate the potential savings this study could achieve.

- Actual daily savings are calculated by using an adjusted baseline. The adjusted baseline takes into consideration the total energy consumed over a daily period. Thus the normal baseline as described in the previous paragraph is multiplied by a ratio, consisting of the total amount of actual energy consumed per day and the total amount of energy from the normal baseline. After the ratio is multiplied with the normal baseline, the adjusted baseline is obtained. The adjusted baseline will always keep the same shape as the normal baseline, but will have different energy usage for the day. This means that the original baseline in Figure 3-3 will move upwards or downwards based on energy consumption for the specified day. The ratio above is justified by noting that the load shifting project is energy neutral, meaning that energy is shifted through a different time of use periods.

3.6 Financial section

The total cost of the project was R 27 000 000 for the implementation of all the parts to fully automate the de-watering system. The funding of this project were done by Eskom. Eskom payed a certain amount per megawatt shifted out of evening peak time.

3.7 Manual Load Shifting

Central control room starts and stops the pumps according to dam levels by calling shaft control rooms which in turn calls the pump operators underground.

3.8 Semi-automated Load Shifting

Consists of the central control room personnel following a strict schedule and remotely stopping the pumps and starting them from surface. This has to be done before the fully automated system is implemented.

3.9 Risk Assessment

Table 3-4 shows the risk assessment that was done for this study. This had to be done two show how different situations will be handled when going from a manual operated system to a fully automated pumping system.

Table 3-4: Risk Assessment

Hazard Identification		
Potential Hazards What if?	**Current controls in place**	**Additional recommended control**
Normal operational breakdowns, if running in auto. For example a balance disk replacement.	If for any reason the required operational conditions cannot be complied with, normal operation will prevail - override to manual operation and normal lockout procedure. Pump operator stops the pump and notify central control.	Flag on surface SCADA when the underground operator has switched over to local (manual) control. Flag to clear when pump is in auto. Control room operator to phone to ask reason for local (manual) control.
Communication and control system failure between decision engine, control and plant (communication failure from surface)	Alarm in central control and initiate the call-out procedure if necessary. Notify the pump operator telephonically. The schedule with the next 10 operations will be written to the PLC in set intervals. When communication fails the PLC can carry on with these 10 instructions until communication is restored. For more information refer to the approved FDS.	None, because call-out procedure has been followed. Notify relevant shaft personnel.

Hazard Identification

Potential Hazards What if?	**Current controls in place**	**Additional recommended control**
Communication loss between instrument(s) and the PLC, or between PLCs	Audio visual alarm to warn operator of communication loss	Pump operator to phone central control room with more information. Alarm in central control, control room operator to phone pump operator when nothing is heard from pump operator. Initiate call-out procedure if necessary.
Power failure	Normal call-out procedure to be followed. Program must operate fail safe, when power is restored all parameters must be scanned and default operation must commence	None, because call-out procedure has been followed. Notify relevant shaft personnel.
Automation of plant	None (new system)	1 Start-up alarms to be installed both audible and visual to warn operators of pumps that start automatically - refer to the approved FDS 2 Notices to be placed at all equipment warning that machinery stop and start automatically 3 Lockout procedure to be followed correctly

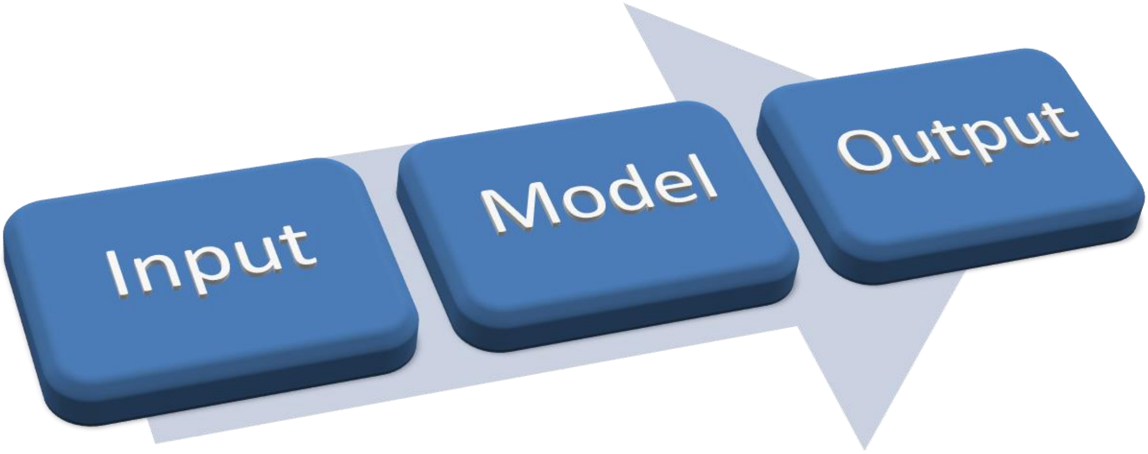
Hazard Identification

Potential Hazards What if?	**Current controls in place**	**Additional recommended control**
Flooding of shaft	Shaft specific emergency flooding procedure in place	Control room operator to start more pumps, or the pump operator can override the pumps to manual to enable the starting of additional pumps in case of emergency.
	Emergency capacity for lowest dams: maximum dam level of 66%	PLC to start maximum pumps at high level of 66%
	All other dams: Maximum dam level of 80%	PLC to start maximum pumps at high level of 80%
	Downstream dam control: control room operators manually prevent downstream dam from overflowing by monitoring dam levels	Alarm on downstream level, current level and central control room. If necessary, the system to be put in manual and central control room operators to take over control.
Bursting of column	Surge relief valves installed on all pump out columns. Annual pipe wall thickness testing	Third party to inspect surge relief valves on a quarterly basis, wall thickness annually
	On 1# Transfer: Never run more than 1 large pump or 2 small pumps at the same time	Keep to the set maximum dam levels. On orders from the control room, the pump operator may start 1 large

Hazard Identification

Potential Hazards What if?	**Current controls in place**	**Additional recommended control**
		and 1 small pumps on local control.
	On all other levels: Never run more than 2 pumps per column	Keep to the set maximum dam levels
Damage to electrical infrastructure when more than one pumps start at the same time on the same feeder	Incorporate a 5 minute interval between starting pumps and a 2 minute interval between stopping pumps in auto control	Control room and pump operators to be trained in the new pumping system and the operation thereof.

CHAPTER 4: SIMULATION MODEL AND CONTROLLERS



In this the chapter the model and controller used for load shifting will be discussed.

4.1 Simulation Model Overview

The simulation model in this section was used to model the underground clear water pumping system. The model used various inputs to calculate outputs from where a schedule was developed.

4.1.1 Model Input

Historical data was used for the flow from surface to underground for Shaft one and Shaft four. The flows used was an average of five months before the implementation of the projects. Values were obtained from the surface flowmeters, where the chilled water goes underground from the fridge plants. The schematic representation of the flows discussed are shown below in the Figure 4-1 to Figure 4-3.

The fissure water calculated were obtained by using the increase/decrease in dam level when no mining water flowed into the dam and no pumps were pumping out of the dam. Thus dam size and amount of time the dam level increased/decreased, were used to calculate the fissure water. The amount of fissure water calculated where neglect-ably small. The model still has the option to include the fissure water.

Other inputs used in the simulation were:

- The minimum and maximum amount of pumps that can be used on one single time. This input is constrained with the amount of pumping columns on each pumping level
- The average amount of litres pumped per second for each pump on every level
- Average power consumed per pump on each level
- The minimum and maximum dam levels for each level, this values is determined by the mine. Minimum levels should be such that the pumps doesn't pump mud. Maximum levels should ensure that when there is a power shortage, that the dams doesn't over flow on the lowest level of the mines
- Total power usage of all the pumps for an average of five months

The values used for this specific model were obtained from Taz reports which contains all the detailed information per pump.

4.1.1.1 Shaft one chilled water flow underground

Figure 4-1 displays the average chilled water flow baseline for 5 months. This water is used for mining on Shaft one and collects on Transfer level Shaft one.

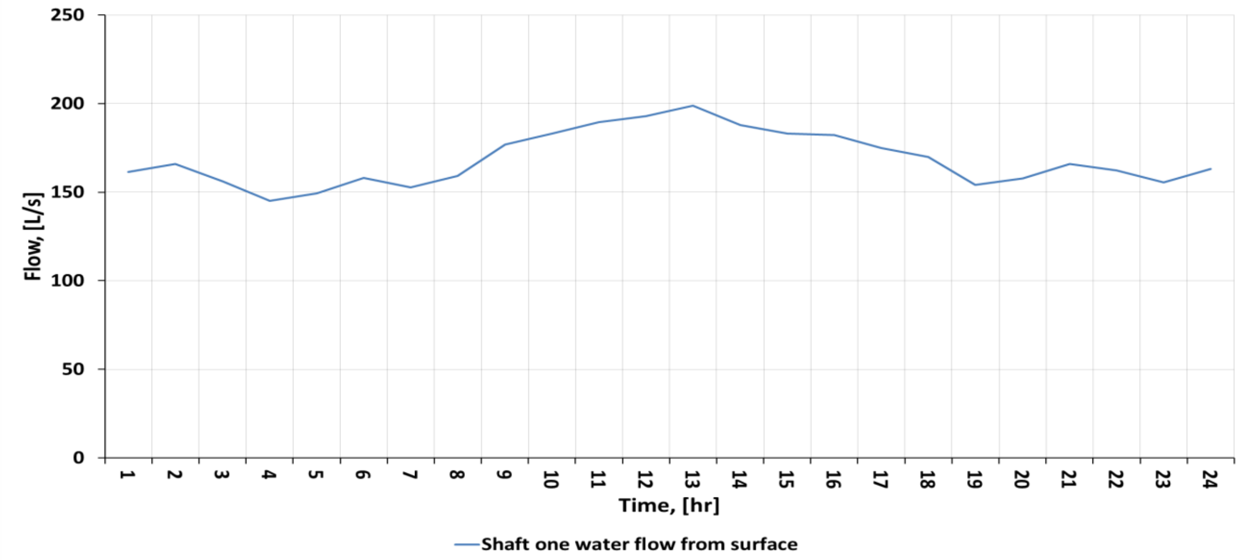


Figure 4-1: Shaft one flow from surface to underground

The flow input for this dam is obtained from Figure 4-1. The flow has a two hour delay due to the water first being used by the mine and then flowing and settling down to Transfer level. The model takes this into effect, the amount of water in 35 Level and all the other levels.

4.1.1.2 Shaft four Parameters

Figure 4-2, displays the average chilled water flow baseline for 5 months. This water is used for mining on Shaft four and collects on 38 Level. The model follows the same procedure and constraints as in Shaft one. Fissure water on Shaft four is also left out of the model due to it being minimal.

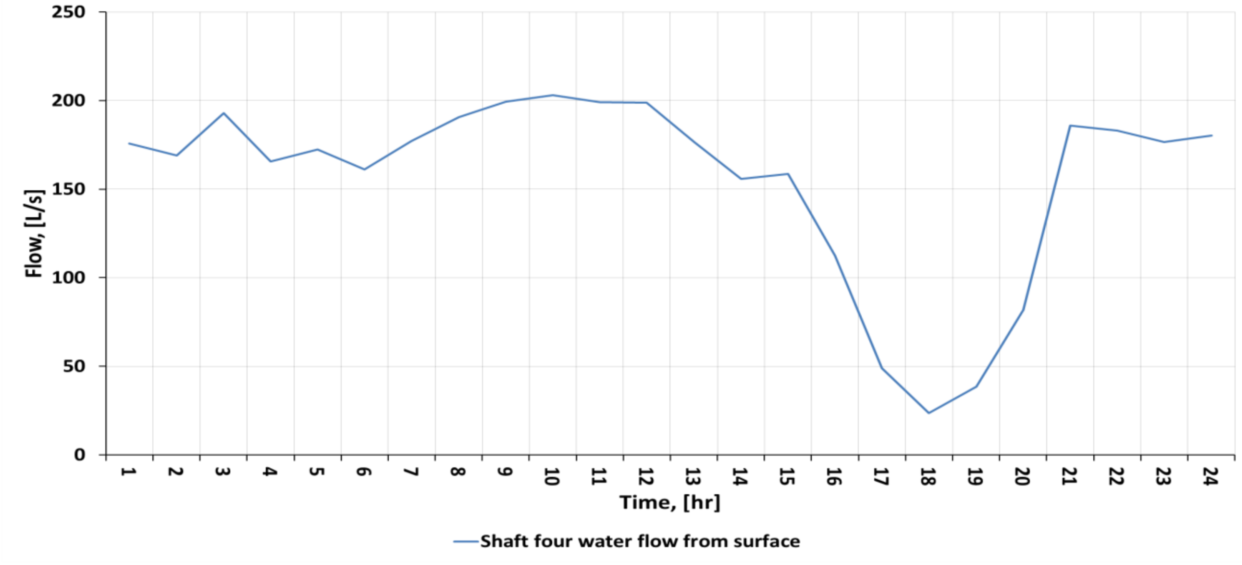


Figure 4-2: Shaft four flow from surface to underground

4.1.1.3 Shaft two Parameters

Figure 4-3, displays the average chilled water flow baseline for 5 months. This water is used for mining on Shaft two and collects on 26 level. This water is not used in the optimising pumping model.

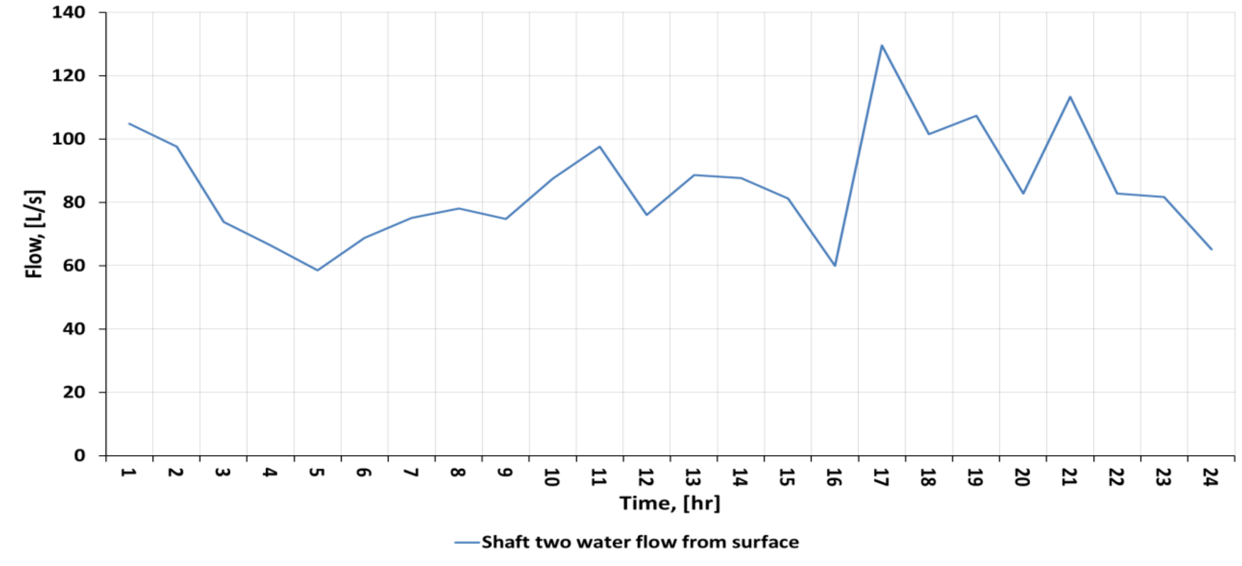


Figure 4-3: Shaft two flow from surface to underground

4.1.2 Model calculations

The algorithm in the model uses the inputs from the previous section to generate outputs. The algorithm iterates and solves to use minimum power consumption during evening peak times. Morning peak power usages is also minimized but not as much as in evening peak, due to this study being Eskom funded (Eskom fund evening peak load shifting). Standard times are constrained by the algorithm to equal the baseline. The maximum amount of pumping is done in the off-peak times. Other constraints used in the algorithm is the maximum amount of pumps on each level, maximum and minimum dam level, inflows and outflows for each dam on each level, Shaft four surface water dam constraints and the total energy usage of the baseline must be the same as the new pumping profile simulated by the algorithm. The model uses a complex solver program due to all of the constraints that needs to be calculated.

4.1.3 Model output

4.1.4 Baseline and optimised baseline

Figure 4-4, shows the simulation results for the baseline and optimised baseline. The baseline (red line) is the same as the weekday baseline presented in Figure 3-3. The optimised baseline (blue line) is an improved representation from the algorithm which include the most cost effective pumping times, whilst remaining in the mines parameters as discussed in the previous chapter. According to the simulation model the following maximum values can be obtained in the evening peak and morning peak. Evening peak is 12.7 MW and morning peak is 4.3 MW, this is for the most cost effective pumping schedule.

In Figure 4-4 the pumping power is minimised in the following order, from highest to lowest namely off-peak, standard and peak time. It is also evident from the figure that morning peak is not reduce as much as evening peak, due to Eskom funding evening peak projects.

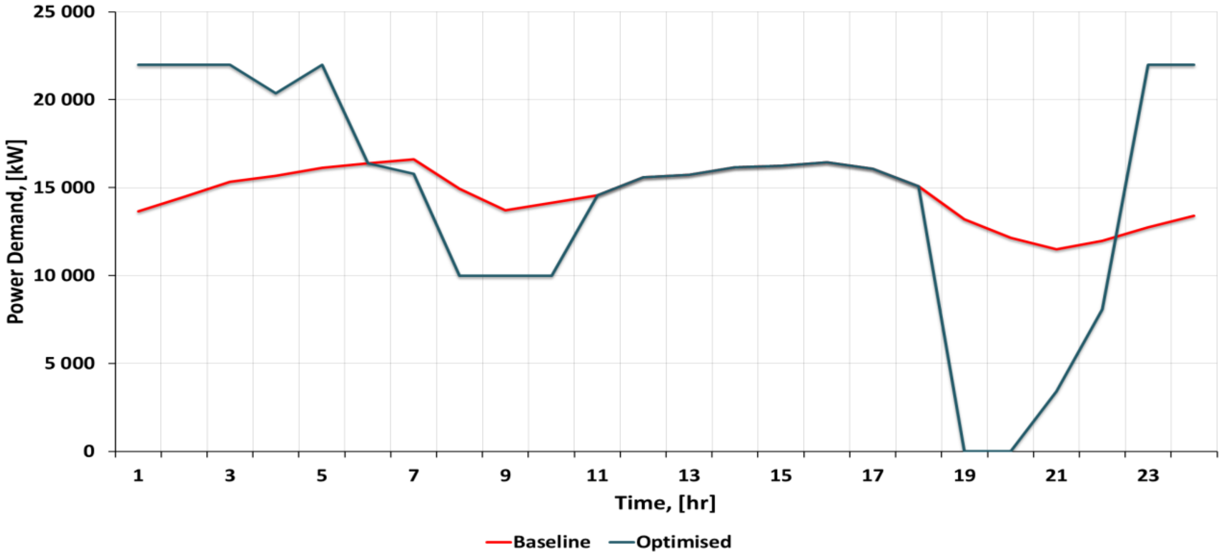


Figure 4-4: Simulation results for the inter-connected mine

4.1.5 Optimal energy usage per shaft

The pumping model gives the following optimal pumping times for each individual level, the energy usage is optimized to satisfy the input constraints.

4.1.5.1 Shaft one

Figure 4-5 has the proposed optimised power usage against time for Shaft one, 35 Level and Transfer Level. It is evident form Figure 4-5 that the modelled power usage from Transfer and 35 Level is the highest in non-peak time and the lowest in peak times. Both levels on Shaft one have about the same energy usages over time, due to Shaft one only having to pump out its own water. Unlike Shaft four which also has to pump Shaft one's water to surface. This pumping profile will also ensure that the hot water dams on Shaft one won't overflow and that the correct amount of de-watering pumps will run.

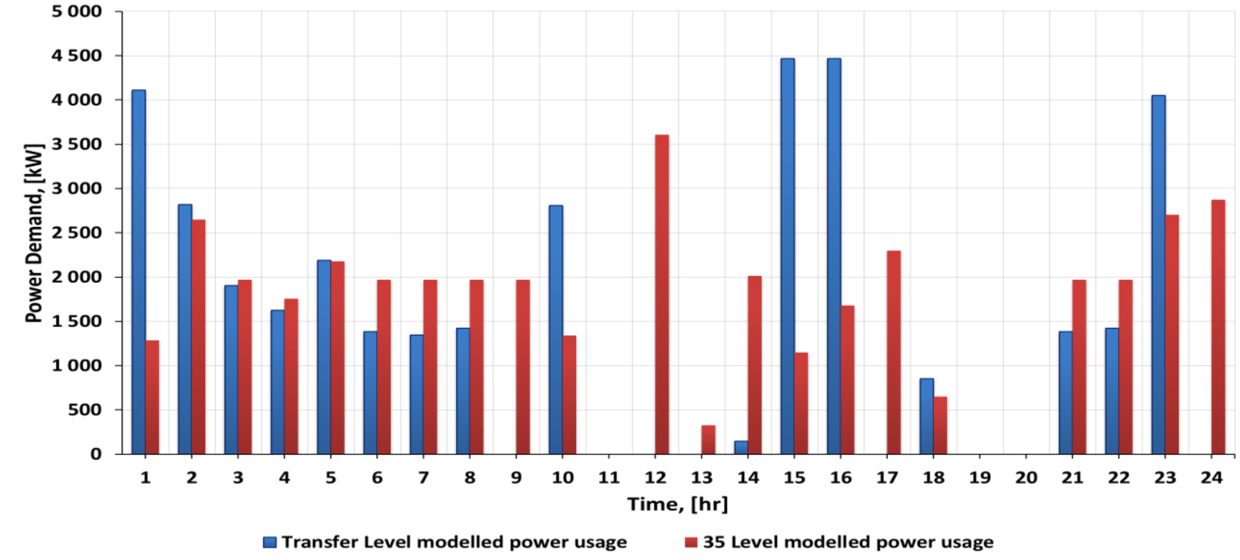


Figure 4-5: Simulation results for Shaft one

4.1.5.2 Shaft two

Figure 4-6 shows the proposed optimised power usage against time for Shaft two. The pumping on this level is almost constant at 75 kW, which is the rated power of the pumps. Evening peak time power usage by the pump is minimal. The reason for the horizontal pump to pump the whole day is that the capacity of the dam on Shaft two 24 Level is small.

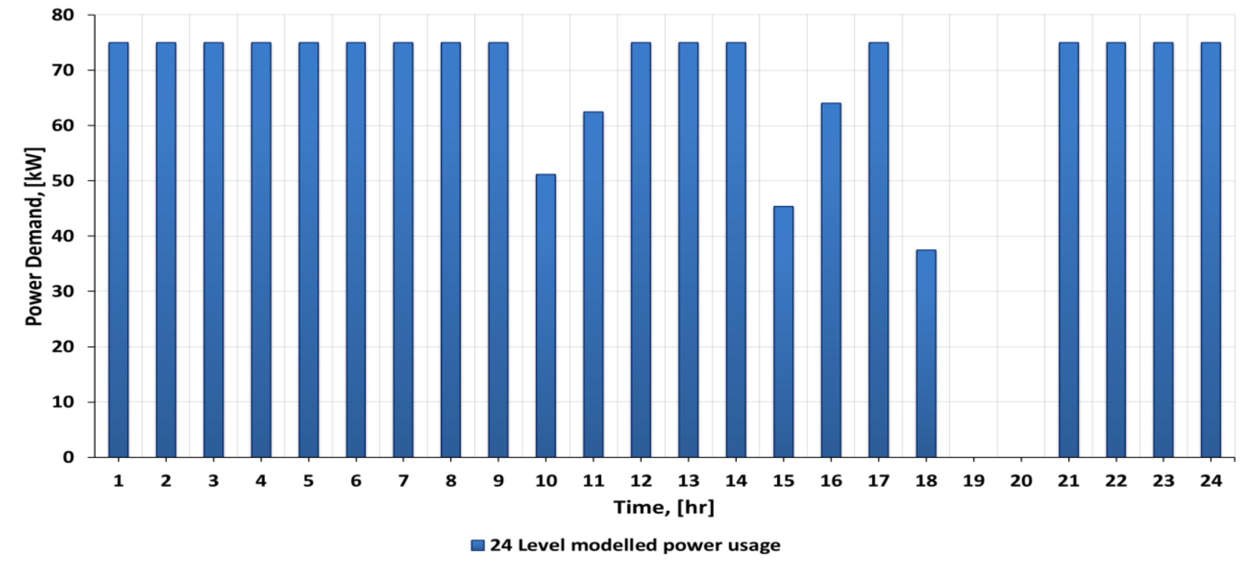


Figure 4-6: Simulation results for two shaft

4.1.5.3 Shaft four

Figure 4-7 shows the proposed optimised power usage against time for Shaft four, 38, 24 and IPC Level. Shaft four 38 Level has the lowest power usage with a peak of almost 4 000kW. Shaft four 24 Level and IPC Level has the largest power usages with a peak of 8 000kW. The reason for the large difference is that 24 Level receives both the water from Shaft one and 38 Level Four shaft. Evening peak has the lowest power consumption.

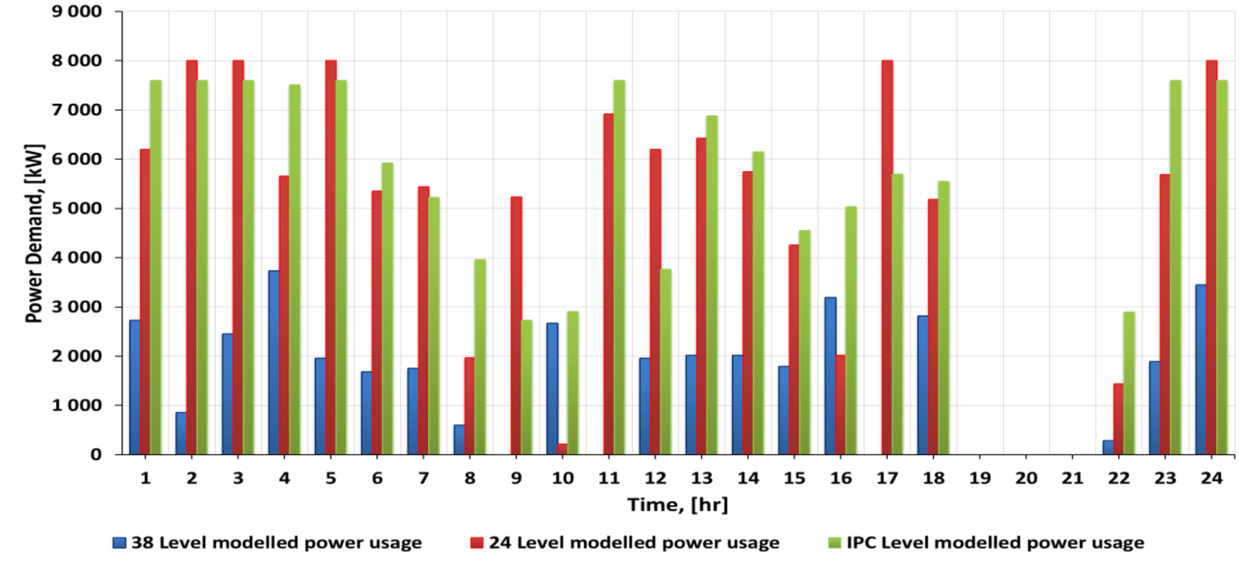


Figure 4-7: Simulation results for four shaft

4.1.6 Optimal amount of pumps to run according to the model

The optimal amount of pumps to run according to the simulation model, for each shaft with the most cost effective pumping is:

4.1.6.1 Shaft one optimal amount of pumps

4.1.6.1.1 Shaft one Transfer Level

Figure 4-8, displays the amount of pumps and respective dam levels due to the pumping, calculated by the model. The amount of pumps on Transfer level ranges between zero and two. The constraints on the dam levels ranges between 40% and 90%. The average amount of pumps will be imitated in the control philosophy that will be described later in this section for Transfer Level. Also the amount of pumps running in peak times will always be as small as possible due to the model. The amount of pumps is dependent on all the dam levels in the system. The average amount of pumps that needs to run through the day is 0.68.

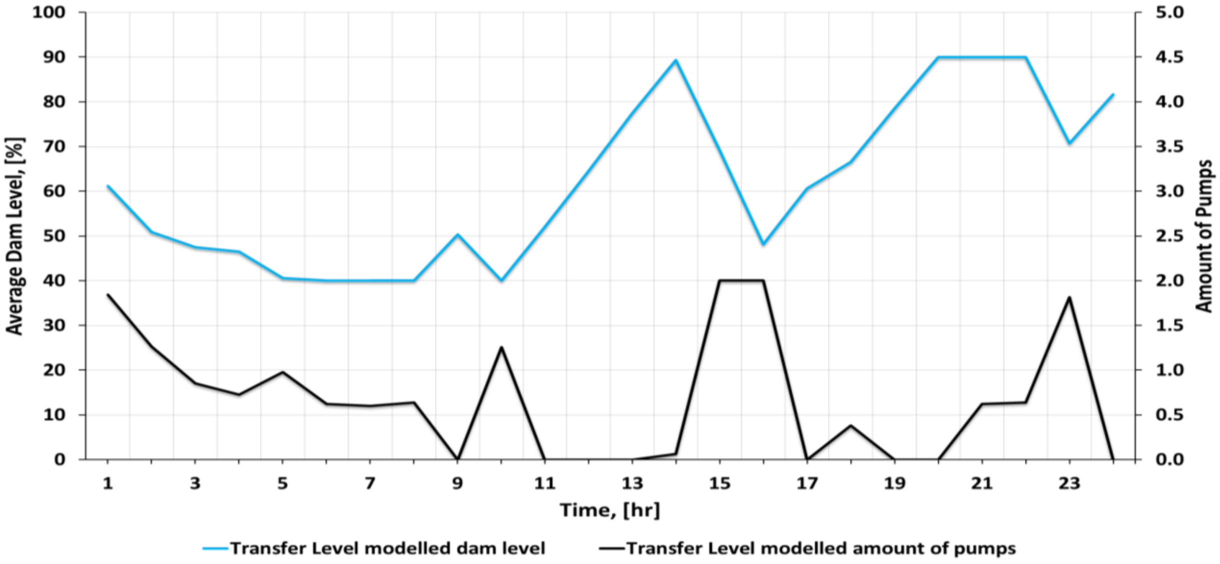


Figure 4-8: Transfer Level optimal amount of pumps and dam level

4.1.6.1.2 Shaft one 35 Level

From Figure 4-9 the average amount of pumps on this level ranges between zero and three pumps, with 1.3 pumps running on average through the day.

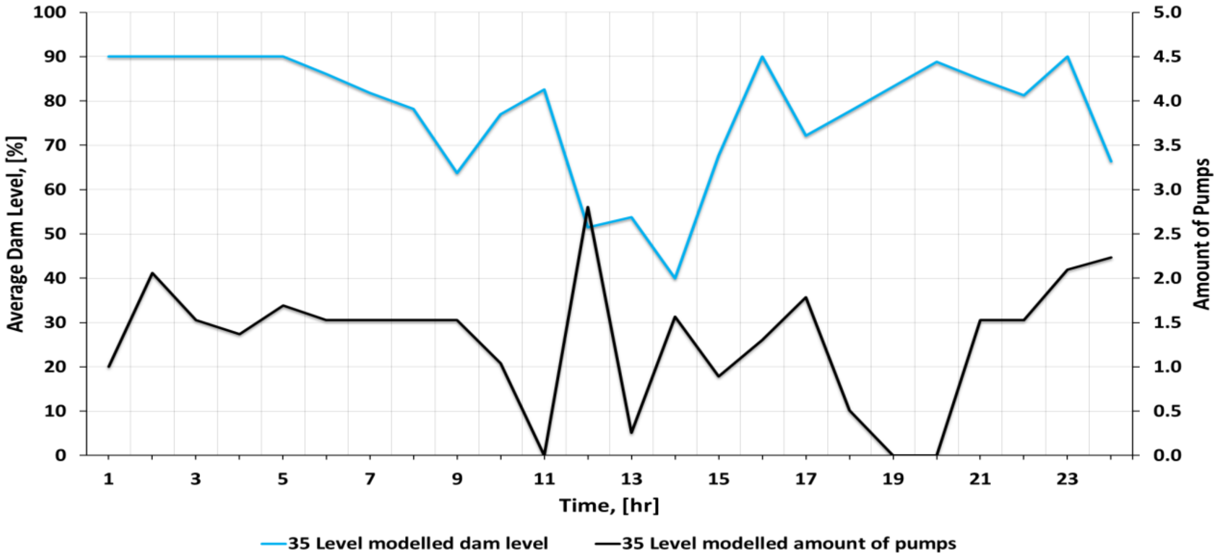


Figure 4-9: 35 Level optimal amount of pumps and dam level

4.1.6.2 Shaft two optimal amount of pumps

4.1.6.2.1 Shaft two 24 Level

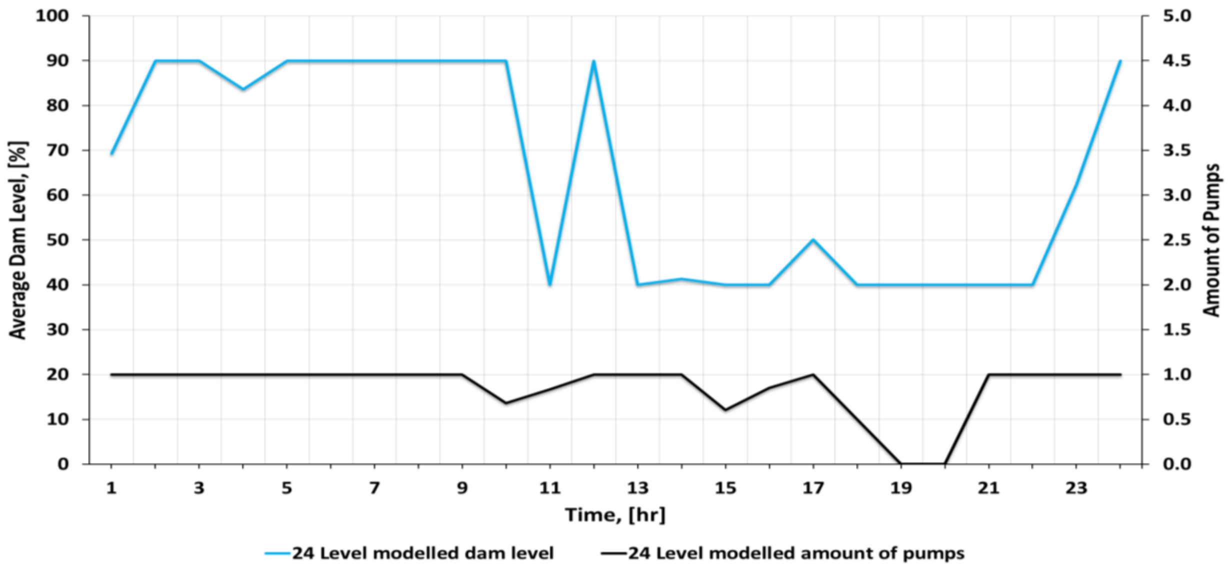


Figure 4-10: 24 Level optimal amount of pumps and dam level

From Figure 4-10 the amount of pumps that needs to run on this level is almost constantly one for the entire day, except for Eskom peak time when the amount of pumps is zero. The reason for this large amount of pumping required by the horizontal pump is to ensure that the dams are prepped on Shaft one, when load has to be shifted. It is important to maximise the pumping on all the levels in the mine throughout the day, to capitalise on load shifting and cost savings.

The simulation also ensures that pumps run to their maximum potential without stopping and starting constantly, this will reduce a pumps lifetime when they are stopped and started. The model solves to run constant amount of pumps instead of pumping out batch volumes of water, which will lead to a lot of stopping and starting of the pumps.

4.1.6.3 Shaft four optimal amount of pumps

4.1.6.3.1 Shaft four 38 Level

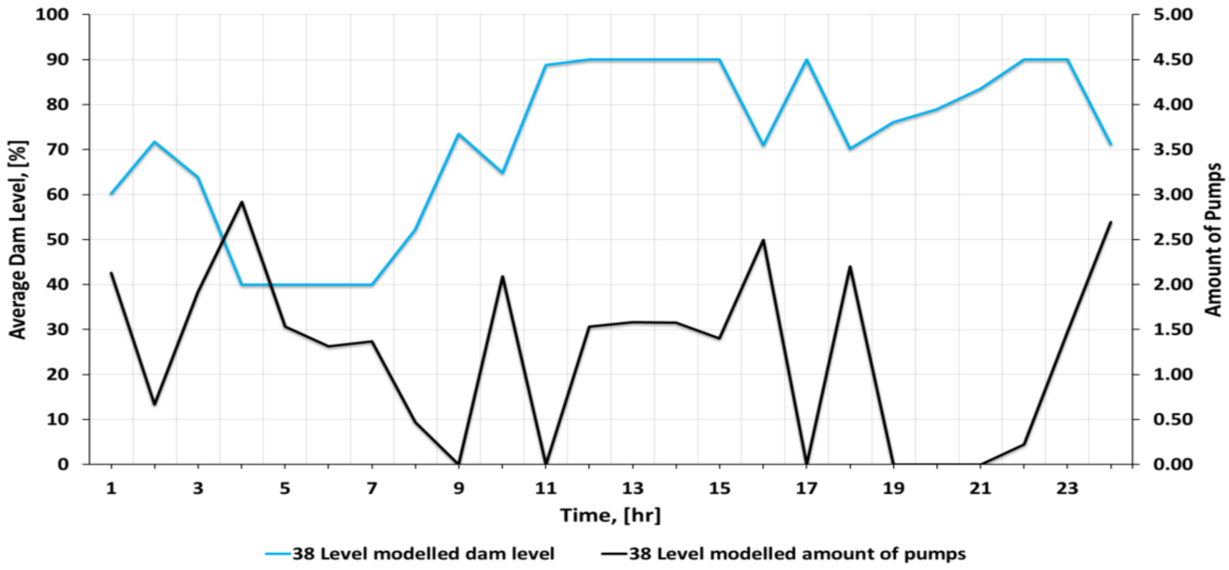


Figure 4-11: 38 Level optimal amount of pumps and dam level

4.1.6.3.2 Shaft four 24 Level

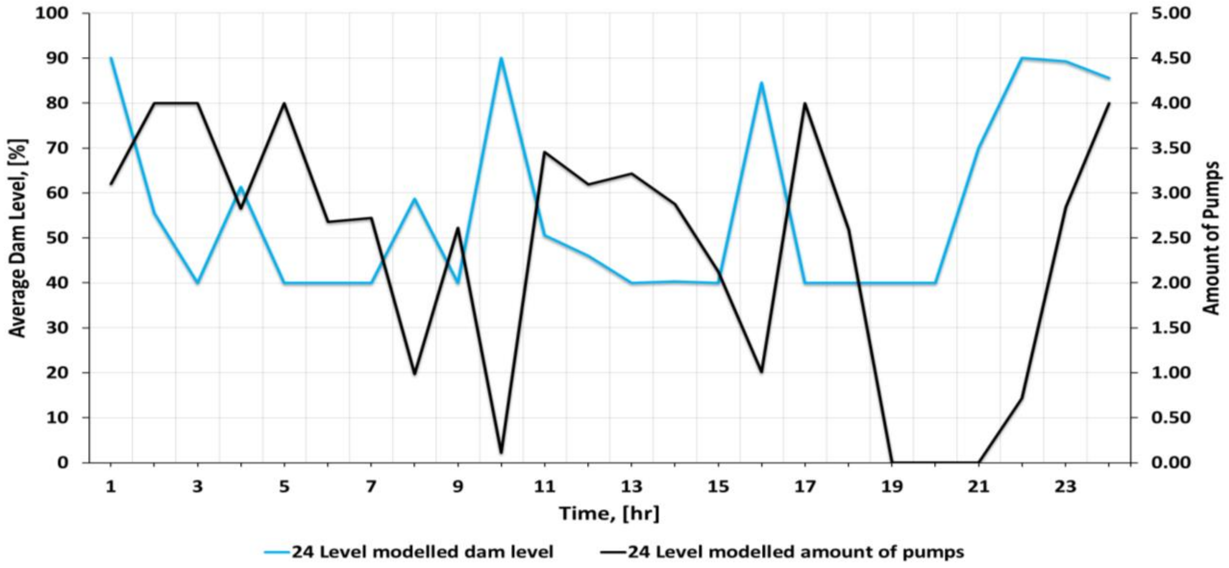


Figure 4-12: 24 Level optimal amount of pumps and dam level

4.1.6.3.3 Shaft four IPC Level

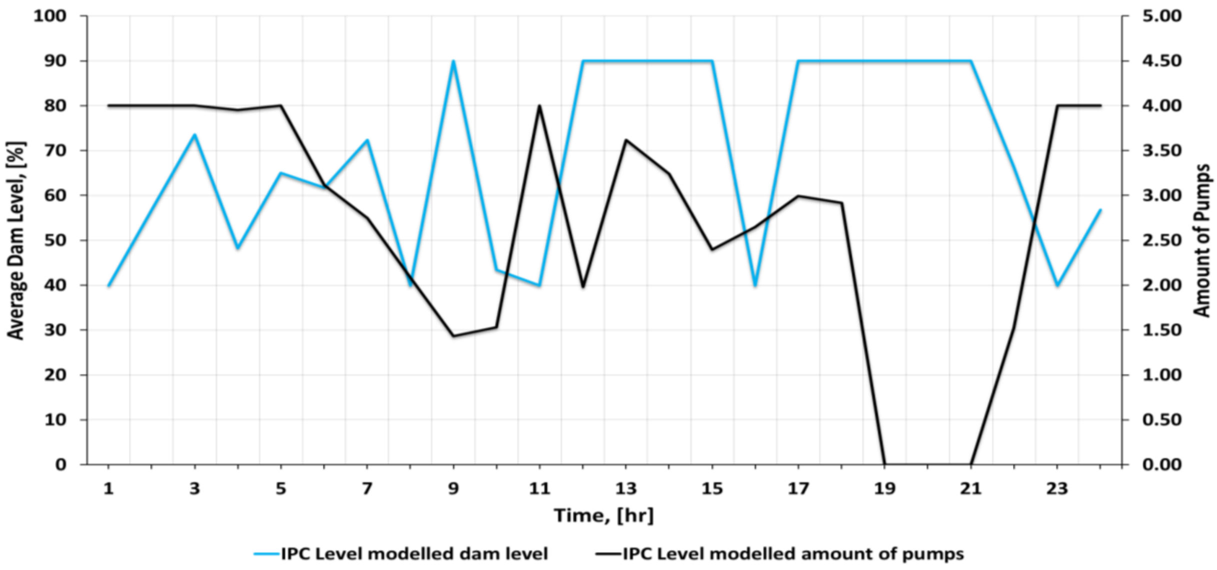


Figure 4-13: IPC Level optimal amount of pumps and dam level

Figure 4-8 to Figure 4-13, displays the amount of pumps and dam levels calculated by the model. The amount of pumps on these level ranges between zero and four. The constraints on the dam levels ranges between 40% and 90%.

4.1.6.4 Summary of baseline and optimised baseline

Table 4-1 shows the results of the simulation model, which indicates the average amount of pumps need to run throughout the day per pumping station. This is to ensure maximum load shifting potential. The controller that was developed used the data in Figure 4-8 to Figure 4-13 to obtain the best results.

Table 4-1: Shaft one, two and four Electricity consumption Summary

Shaft, Level	Average Power for 24 hours, [MW]	Average amount of pumps for 24 hours
1# Transfer	1.52	0.68
1# 35 Level	1.68	1.30

Shaft, Level	**Average Power for 24 hours, [MW]**	**Average amount of pumps for 24 hours**
2# 24 Level	0.06	0.85
4# 38 Level	1.58	1.23
4# 24 Level	4.75	2.37
4# IPC Level	5.08	2.67
Sum	14.67	8.44

4.1.7 Controllers

4.1.7.1 Controller 1

The controller focusses on each individual level with no inputs from the other levels. The parameters of the controller were obtained from the model by taking the average number of pumps that needs to operate during peak, standard and off-peak intervals. The schedule however only operates during weekdays. Alternative schedules are followed during weekends. The controller have built in lag times to ensure pumps are not started simultaneously. Pumps are also selected according to efficiency and running times.

4.1.7.1.1 35 Level Shaft one

The pumping setup is shown in Figure 4-14 below.

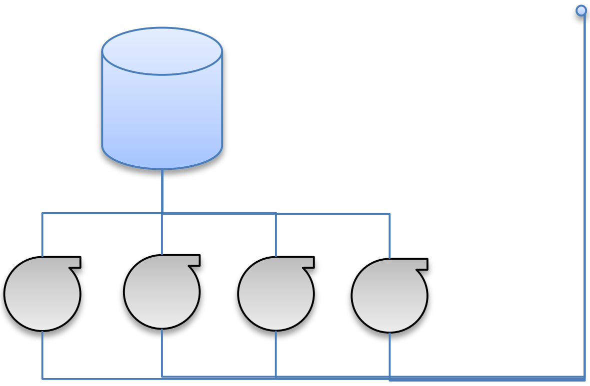


Figure 4-14: Controller Layout at 35 Level

One controller to be used for this level. There are two main columns in Table 4-2, one for Eskom's peak time and one for all other times. There are four pumps and a maximum of only two can run on the same time.

Table 4-2: 35 Level Peak and Non-Peak Time Table

Peak Time Controller			Non-Peak Time Controller		
#Pumps	**Dam level to start pump#**	**Dam level to stop pump#**	**#Pumps**	**Dam level to start pump#**	**Dam level to stop pump#**
0		< 70%	**0**		< 30%
1	80%	70%	**1**	40%	30%
2	90%	80%	**2**	50%	40%

Table 4-2, shows the peak and non-peak controller. The controller uses a gradient to realise whether the dam level is going up or down. When the dam level is 40% during non-peak hours and the level is steadily increasing, then one pump will start on 50%. When the level reaches 60% the gradient will change due to the level of the dam getting lower. When the level reaches 50% one pump of the two will switch of. On 40% there will be no pumps running. The aim of this controller is to keep the dam level as low as possible during non-peak, to ensure capacity when load is shifted.

Figure 4-15 shows the performance of controller 1 on 35 level 1#. The controller is followed by the control room operators almost exactly until 11:50. The reason for this deviation is the dam that is being fed by the pumps on 35 level is full (2# 24 level). The same problem occurs between 15:00 and 16:00 when 2# 24 level is full. When the dam reached 35 percent the operators also deviated from the schedule. The reason for this was that mud was being pumped due to the dams being dirty and full of mud. It is important to clean the dams regularly.

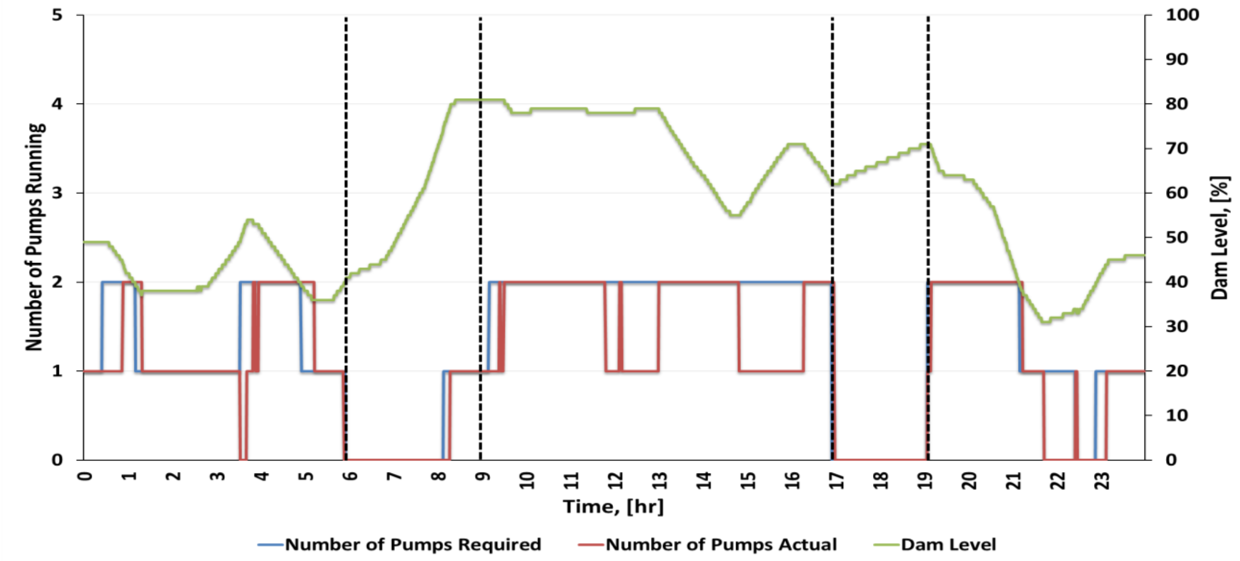


Figure 4-15: Controller Results at Shaft one, 35 Level

4.1.7.1.2 Transfer Level Shaft one

The pumping setup is shown in Figure 4-16 below.

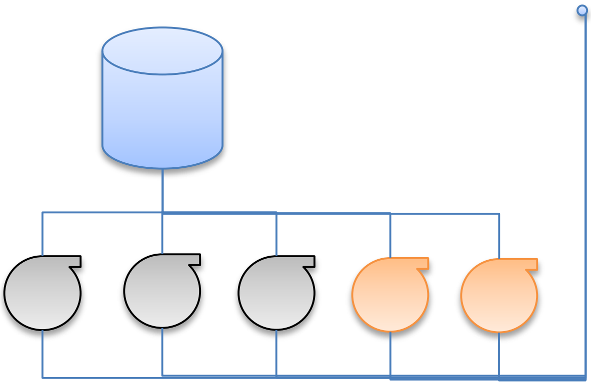


Figure 4-16: Controller Layout at Transfer Level

Two controllers are to be used for this level. The reason for that is the different sizes of electrical motor and pump. Pumps 1-3 are smaller pumps, while pumps 4 and 5 are larger pumps. Because there is only one column, only one large pump or two smaller pumps are allowed to run at any single given time.

Table 4-3: Transfer Level Peak and Non-Peak Time Table Small Pumps (1-3)

Peak Time Controller			Non-Peak Time Controller		
#Pumps	**Dam level to start pump#**	**Dam level to stop pump#**	**#Pumps**	**Dam level to start pump#**	**Dam level to stop pump#**
0		< 70%	**0**		< 30%; > 80%
1	80%	70%	**1**	40%	30%
2	90%	80%	**2**	50%	40%

When the dam level is between 40% and 80% and in Peak time only use small pumps. When the dam is fuller than 80% use one of the larger pumps (3-5).

Figure 4-17 show the result when control room operators did not follow the schedule. This happens when they are too busy. It is evident from Figure 4-17 how the controller operates in peak hours.

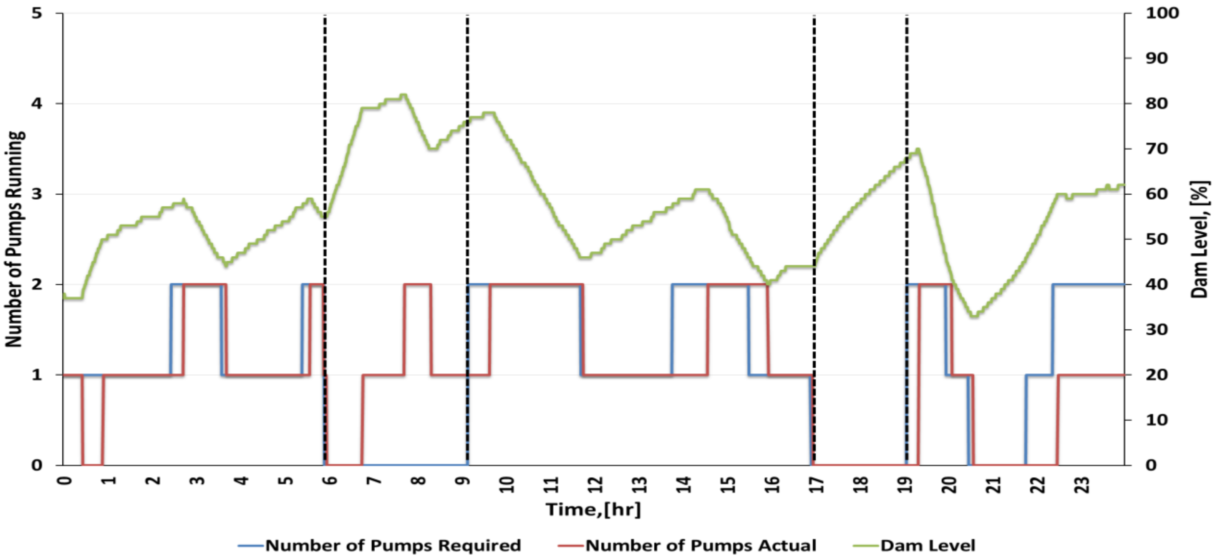


Figure 4-17: Controller Results at Shaft one, Transfer Level

4.1.7.1.3 38, 24 and IPC Level Shaft four

Each pumping station's setup is shown in Figure 4-18 below.

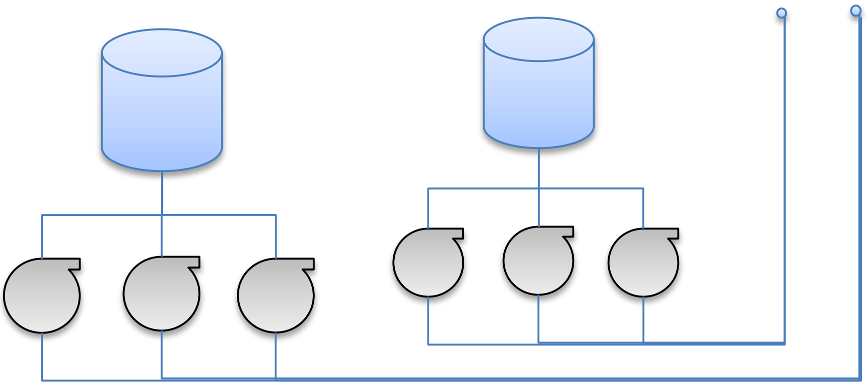


Figure 4-18: Controller Layout at Shaft four

Two identical controllers will be used for this level, one for each column. There are two tables per controller, one for Eskom's evening peak time and one for all other times.

Table 4-4: Shaft four Peak and Non-Peak Time Table

Peak Time Controller			**Non-Peak Time Controller**		
#Pumps	**Dam level to start pump#**	**Dam level to stop pump#**	**#Pumps**	**Dam level to start pump#**	**Dam level to stop pump#**
0		< 70%	**0**		< 30%
1	80%	70%	**1**	40%	30%
2	90%	80%	**2**	50%	40%

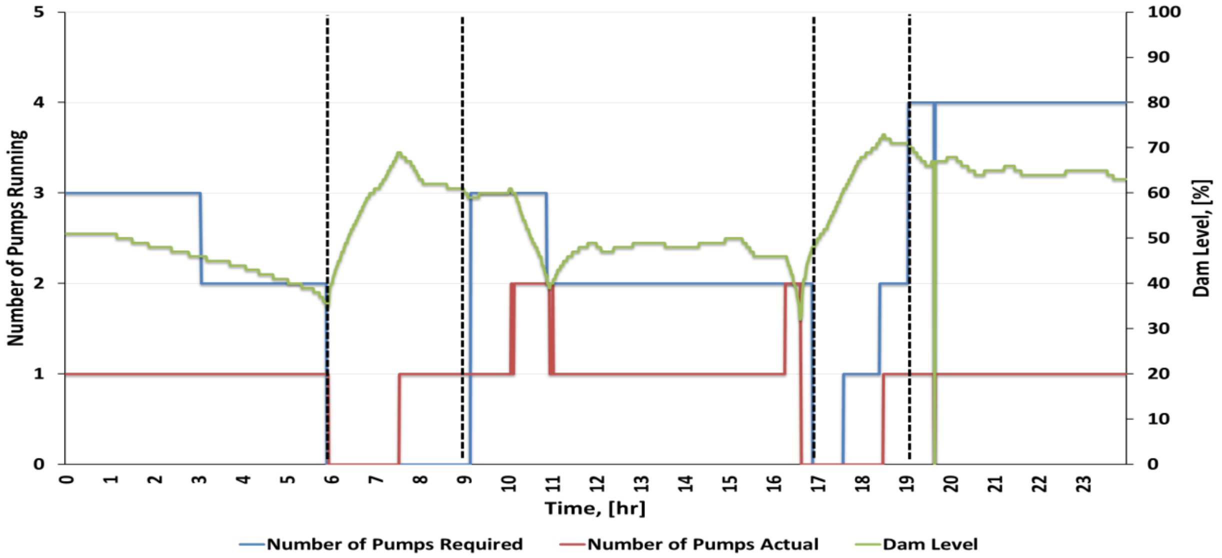


Figure 4-19: Controller Results at 38 Level, Shaft four

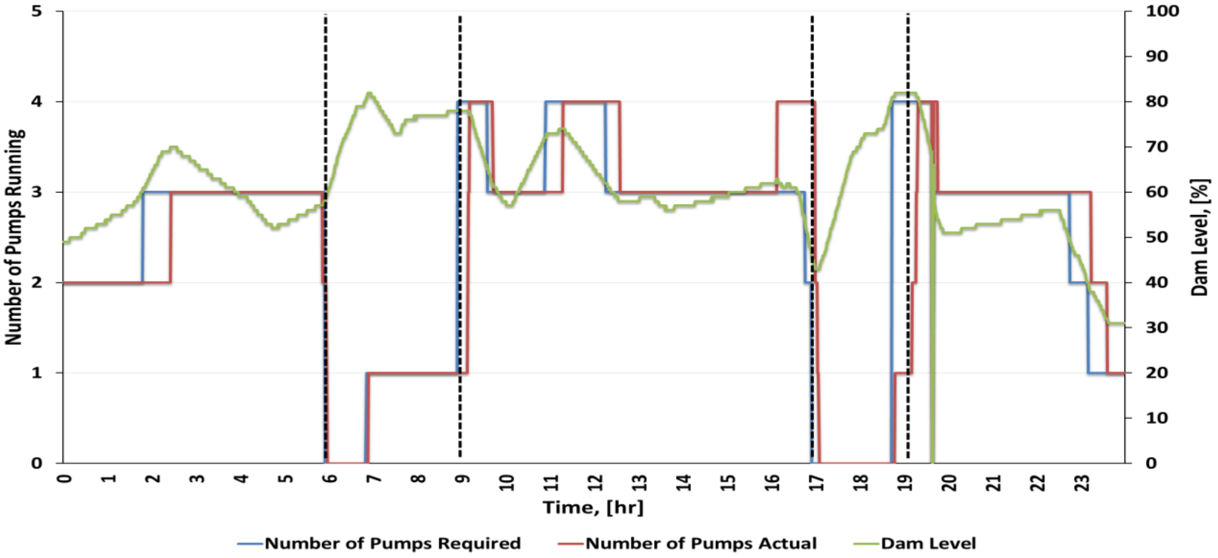


Figure 4-20: Controller Results at 24 Level, Shaft four

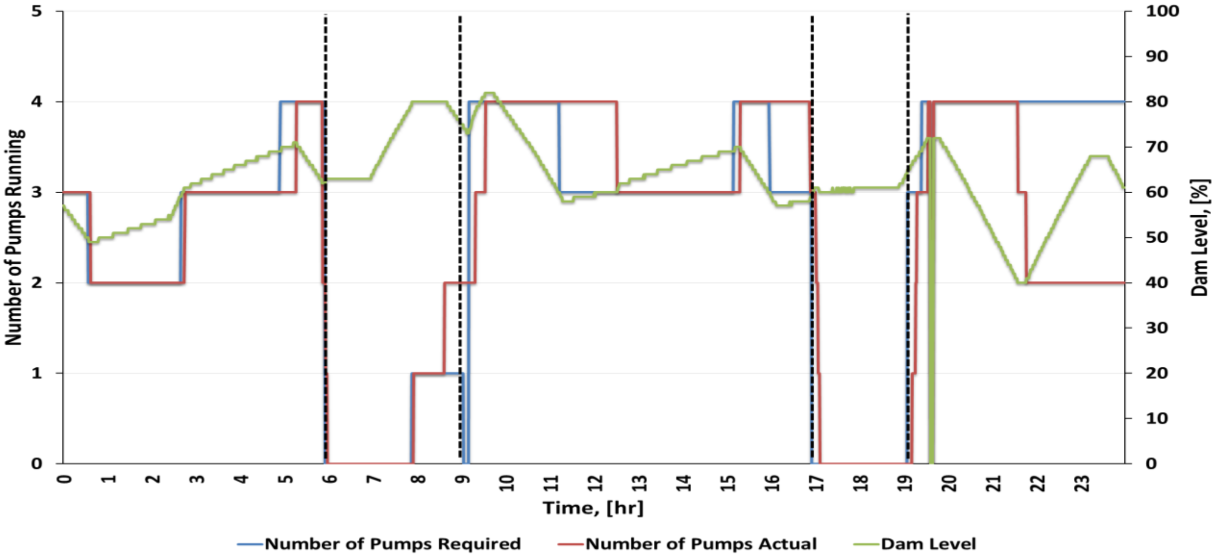


Figure 4-21: Controller Results at IPC Level Shaft four

The scheduler where followed very accurately in Figure 4-20 and Figure 4-21. In Figure 4-19 the schedule were not followed. This due to the operators not being used to running the amount of pumps as suggested by the controller.

4.1.7.2 Summary on Controller 1

The controller was developed based on the simulation data and the mines input. The mine opted for this control strategy of the dams looking only at its own level for safety reasons, which includes communication losses between mining levels. This controller can be used when all the capacitances have enough capacity, with enough pumps to efficiently pump water out of the mine.

The limitations are when the mine changes its operation procedures and one of the capacitances doesn't have enough capacity. During the course of this study the mine changed its operation and one of the dam sizes were reduced. It was too risky for the controller to only look at its own dam therefore controller 2 was develop.

4.1.7.3 Controller 2

The second controller is currently being programmed on the interconnected system. This controller will monitor others levels and its own level before starting or stopping pumps. The method will be, Shaft two 24 Level's dam will be monitored by Shaft one Transfer Level and Shaft one 35 Level. Shaft four's surface dams will be monitored by Shaft four 38, 24 and IPC Level. This type of controller is also supported more by literature.

4.2 Fully automated Load Shifting

The pumps are exclusively controlled by a programmable logic controller (PLC) which is operated by a set schedule according to time and dam level.

Although the fully automated system is equipped to go into the automated operation there are still obstacles to overcome to implement it safely namely:

- Workers needs to be informed and trained before continuing with the fully automated mode, due to pumps that starts automatically.

- The flooded haulage on Shaft 2 has a decreased capacity due to a build-up of mud. This leads to random pumping intervals of Shaft one, 35 Level pumping station.

CHAPTER 5: RESULTS AND DISCUSSION

This chapter gives the results of manual and semi-automated load shifted and cost savings

5.1 Monthly Actual Cost savings

In Figure 5-1, the maximum actual electricity demand is 325 235 kW compared to 287 743 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 108 662 kW and 196 888 kW respectively for January 2016. January 2016 had one public holiday.

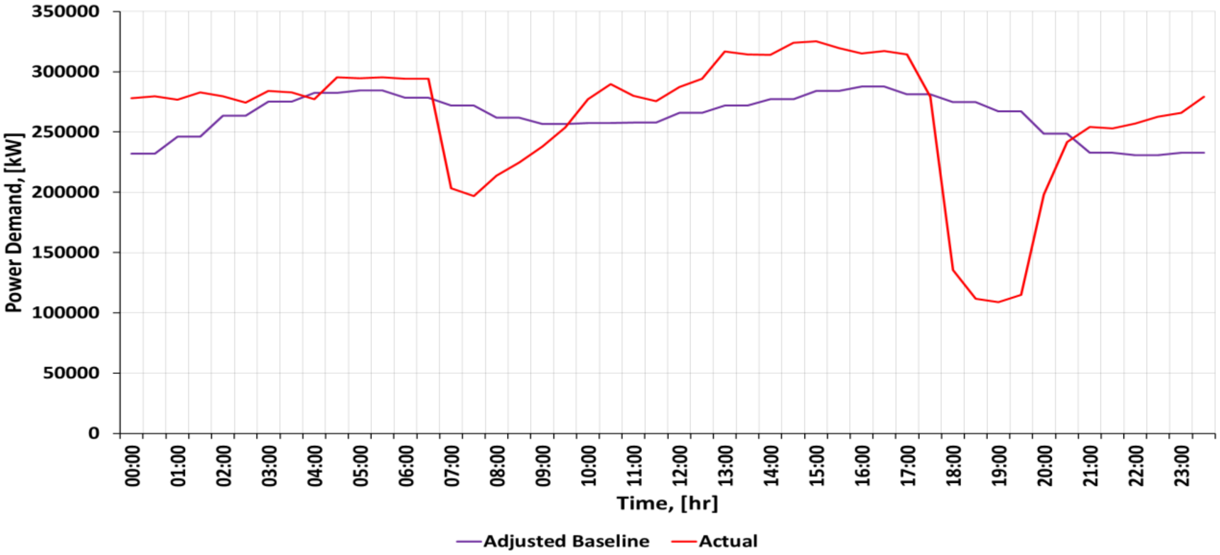


Figure 5-1: January 2016 Actual and Adjusted Baseline

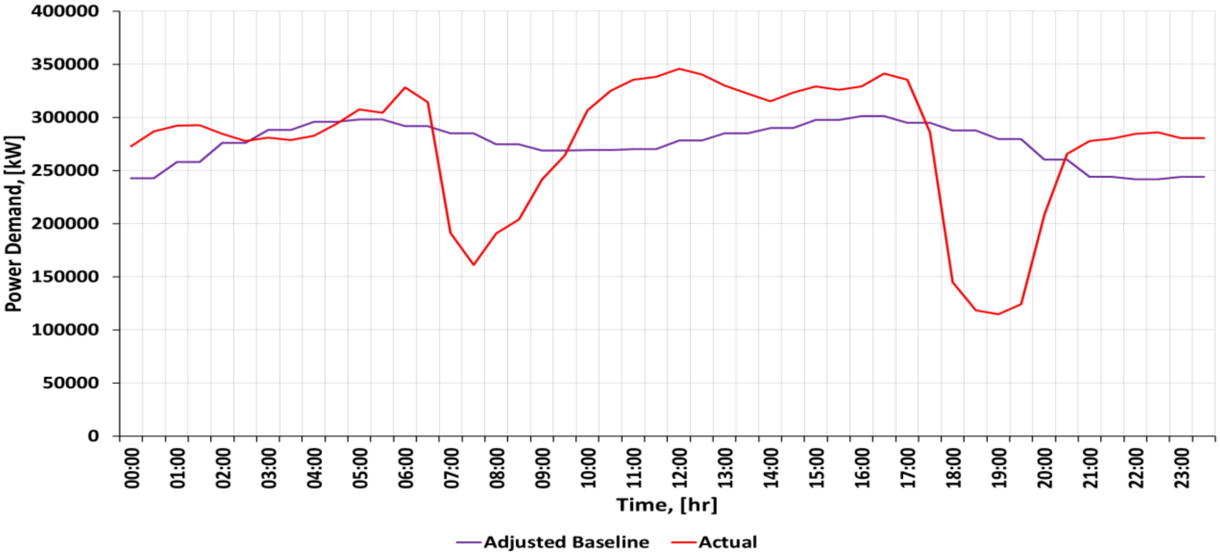


Figure 5-2: February 2016 Actual and Adjusted Baseline

In Figure 5-2, the maximum actual electricity demand is 345 844 kW compared to 301 420 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 161 390 kW and 114 569 kW respectively for February 2016. February 2016 had no public holiday.

In Figure 5-3, the maximum actual electricity demand is 371 751 kW compared to 300 151 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 143 328 kW and 122 007 kW respectively for March 2016. March 2016 had three public holidays.

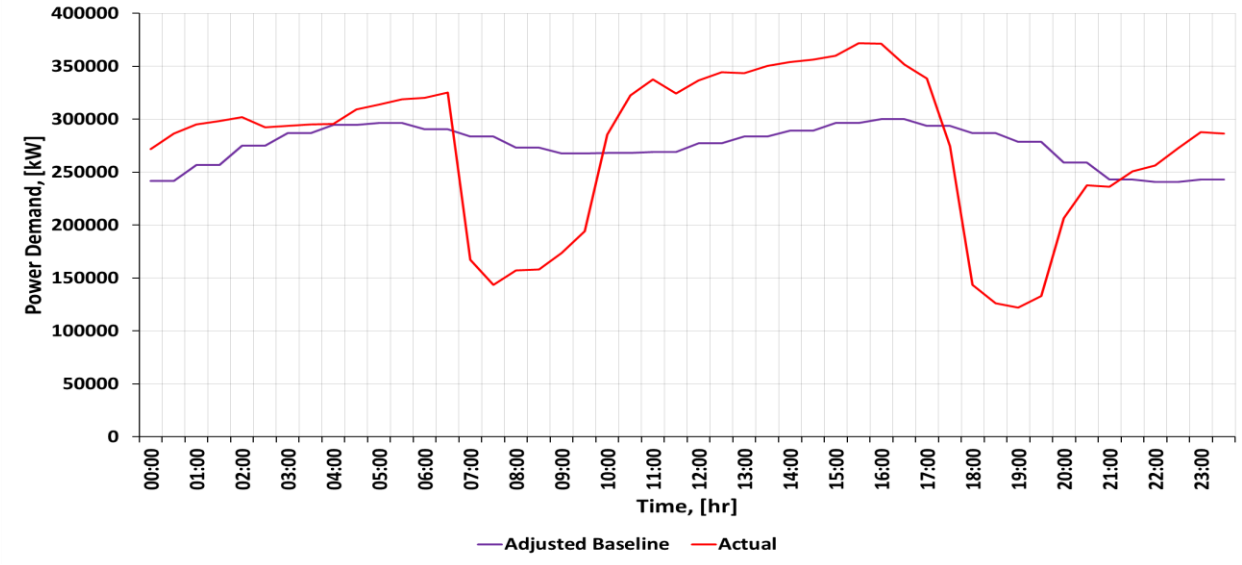


Figure 5-3: March 2016 Actual and Adjusted Baseline

In Figure 5-4, the maximum actual electricity demand is 356 115 kW compared to 278 979 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 135 773 kW and 111 428 kW respectively for April 2016. April 2016 had one public holiday.

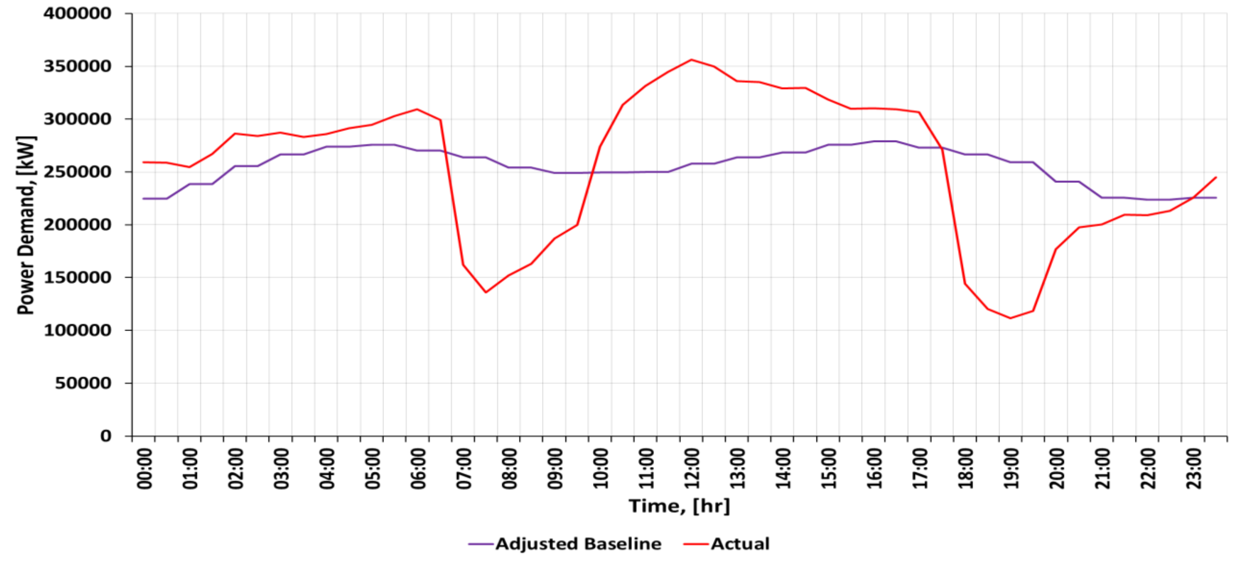


Figure 5-4: April 2016 Actual and Adjusted Baseline

In Figure 5-5, the maximum actual electricity demand is 259 087 kW compared to 221 688 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 92310 kW and 93 493 kW respectively for May 2016. May 2016 had two public holidays and nine condonable days.

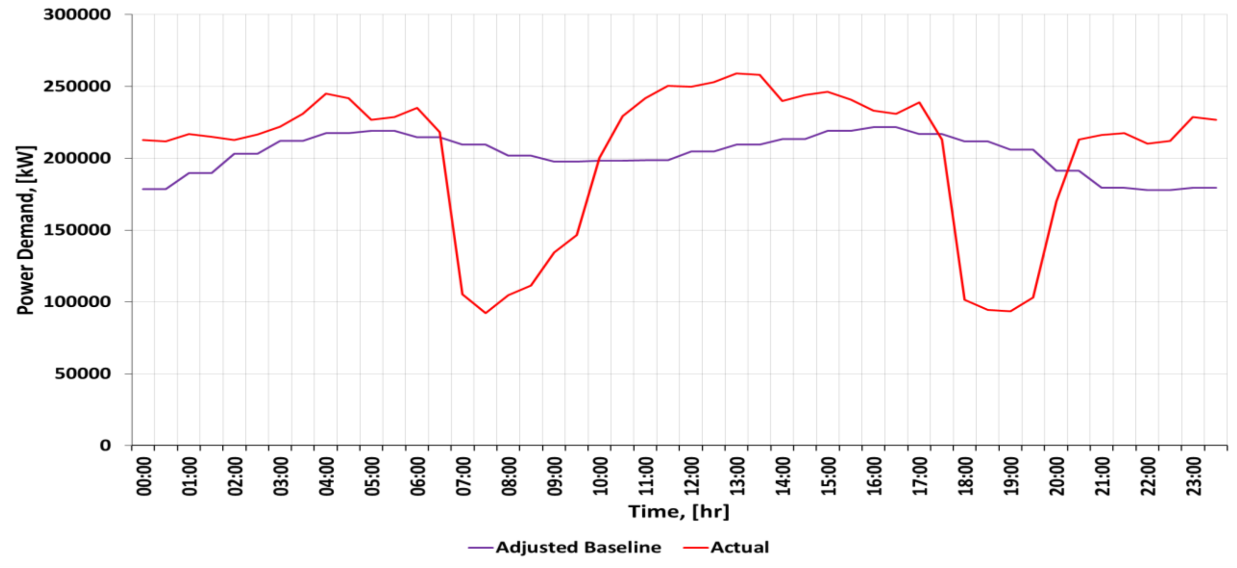


Figure 5-5: May 2016 Actual and Adjusted Baseline

In Figure 5-6, the maximum actual electricity demand is 356 710 kW compared to 272 841 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 124 900 kW and 72 902 kW respectively for June 2016. June 2016 had one public holiday and three condonable days.

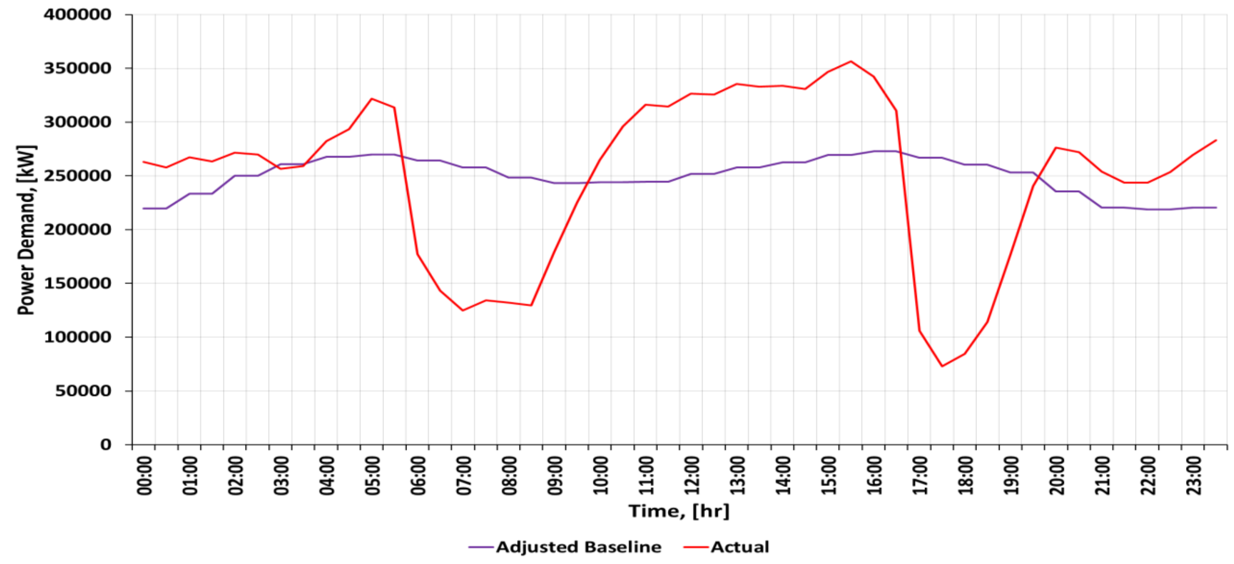


Figure 5-6: June 2016 Actual and Adjusted Baseline

In Figure 5-7, the maximum actual electricity demand is 338 371 kW compared to 265 673 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 81 108 kW and 60 470 kW respectively for July 2016. July 2016 had zero public holidays. This was the winter month with the highest cost savings and megawatt shifted. The reason for this is that off-peak and standard times were utilised efficiently.

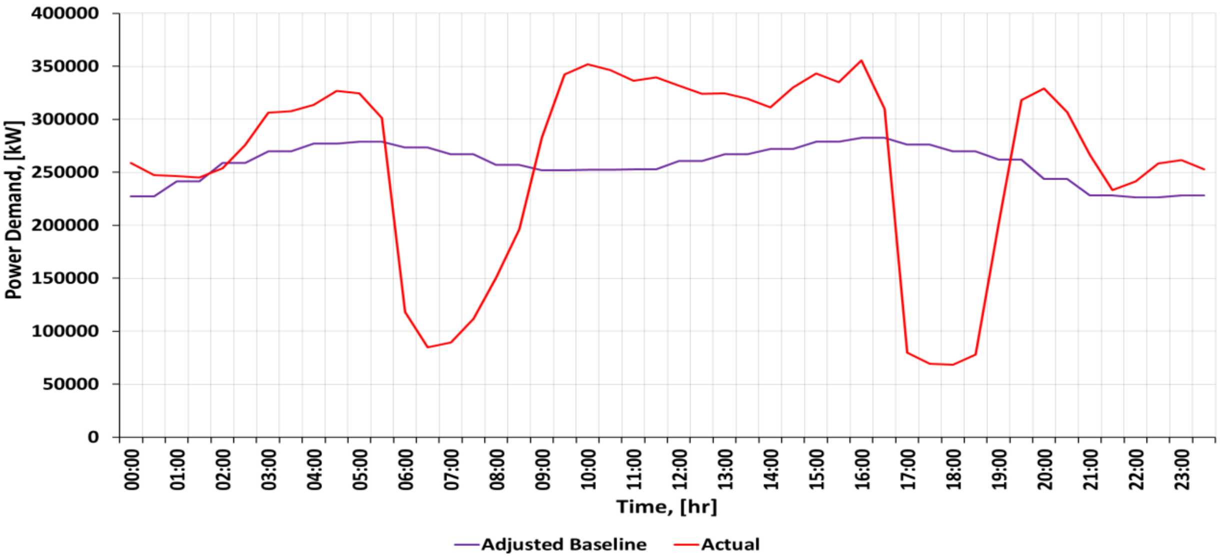


Figure 5-7: July 2016 Actual and Adjusted Baseline

In Figure 5-8, the maximum actual electricity demand is 387 968 kW compared to 291 003 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 105 464 kW and 65 921 kW respectively for August 2016. August 2016 had two public holidays.

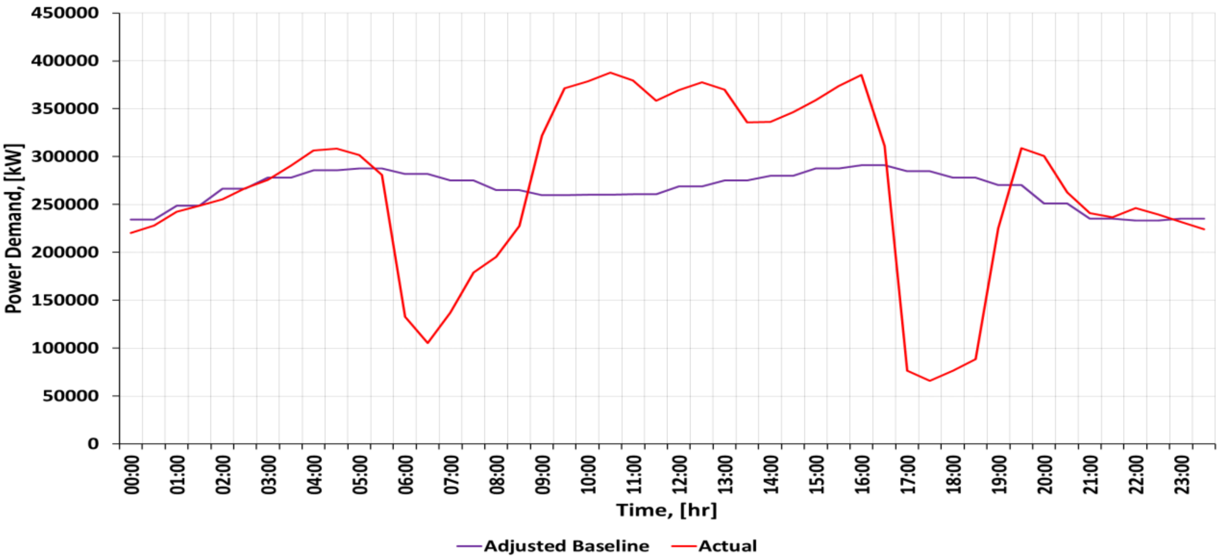


Figure 5-8: August 2016 Actual and Adjusted Baseline

In Figure 5-9, the maximum actual electricity demand is 440 452 kW compared to 332 162 kW for the adjusted baseline. The minimum electricity demand for morning and evening peak is 63 793 kW and 58 427 kW respectively for September 2016. September 2016 had two public holidays. This was the summer month with the highest cost savings and megawatt shifted. The reason for this is that off-peak and standard times were utilised efficiently.

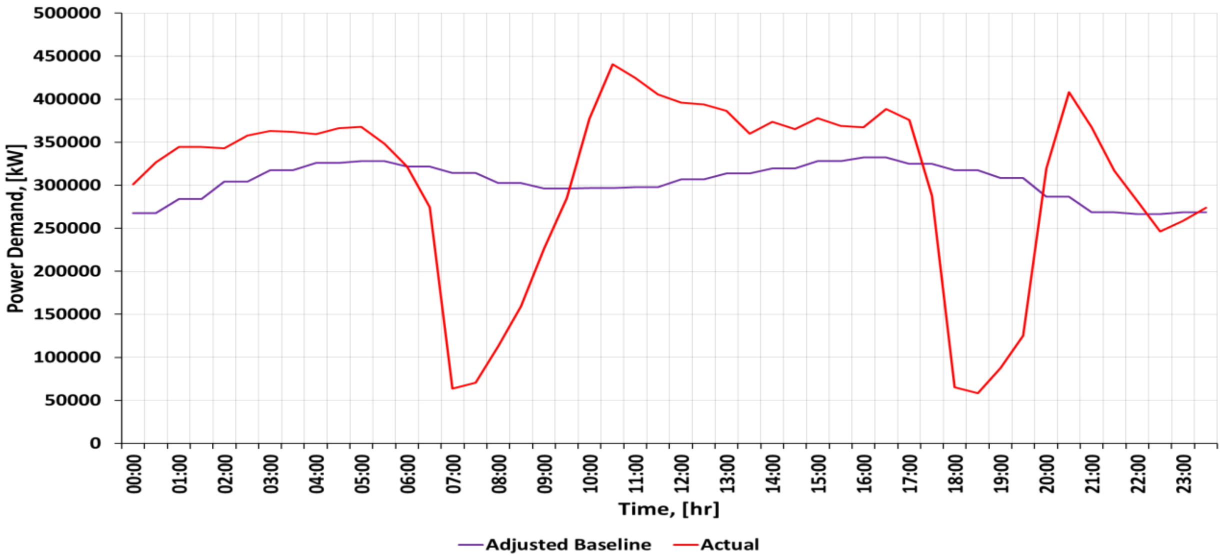


Figure 5-9: September 2016 Actual and Adjusted Baseline

5.1.1 Summary of load shifted and cost savings

The accumulated cost saving in Table 5-1 ranges from January 2016 to September 2016. Load shifting has been done on every weekday of the 9 month period (except on condonable days). The table below takes the average of the weekdays for every month shown below. Cost savings are calculated for the full day. The sum is then taken of the weekdays to calculate the monthly cost savings. The actual average MW shifted is calculated only for evening peak. Thus the cost saving included morning and evening load shifting and all the other time off use periods.

From Table 5-1 the best load shifting results for summer and winter was September and July 2016 respectively.

Table 5-1: Results of load shifted and cost savings

	Actual MW Shifted (Evening Peak)	Monthly Cost Saving, [R]
2016		
Jan	7.67	145 544
Feb	7.53	159 603
Mar	7.57	198 412
Apr	6.96	179 384
May	7.90	176 267
Jun	9.41	1 376 799
Jul	9.10	1 514 201
Aug	9.73	1 391 559
Sep	10.39	305 604

Table 5-1 gives energy cost savings for the manual load shifting period without a schedule, from January 2016 to June 2016 which amounts to R 2 236 009. The period in which the schedule was followed is from July 2016 to September 2016 which accumulated to R 3 211 364.

Furthermore, from Table 5-1 winter months are represented by blue blocks and summer by green, this is directly related to the tariffs in Figure 2-2 and Figure 2-6. Average savings for a winter and summer month is R1 427 519 and R 194 136 respectively. Thus a large sum of money is saved in winter compared to summer. This leads to an 86% increase in financial savings for winter months.

When comparing September 2016 which was a semi-automated month to the other summer months which was only manual. An increase from manual (average R 171 842) to semi-automated load shifting (R 305 604) leads to a 78% increase when following a schedule. For winter months an increase from R 1 376 799 to R 1 452 880 were realized, this is an increase of 5.5%. The cost saving summary is shown in Table 5-2.

Table 5-2: Cost Saving (whole day) Summary

	Manual Load shifting Cost Savings, [R]	Semi-Automated Load shifting Cost Savings, [R]	Increase, [%]
Summer	171 842	305 604	78
Winter	1 376 799	1 452 880	5.5

Table 5-3 shows the amount of load shifted in Eskom evening peak times for manual and semi-automated load shifting.

Table 5-3: Evening Peak Load Shifted Summary

	Manual Load shifting, [MW]	Semi-Automated Load shifting, [MW]	Increase, [%]
Summer	7.53	10.4	38
Winter	9.41	9.42	0.11

When comparing Table 5-2 with Table 5-3 semi atomated load shifting had a higher success rate than manual load shfiting, in both daily cost savings and evening peak load shifted. Athough the evening peak load shifted had only a small increase in winter it lead to a significant amount a money saved (R 76 081).

By using the equation from literature in Figure 2-18:

$$y = 0.2201x + 2.5718$$

$$R^2 = 0.6176$$

Saving results that can be achieved according to literature is 5.92 MW. The current project reached 8.47 during the period of the study. Thus the project savings results can lower or higher, due to the coefficient of determination being 0.6176.

The simulation model in the previous section was calculated to be 12.7 MW divided by the maximum obtained Megawatt obtained from load shifting which is 14 MW. This a 91% accuracy for the model for the maximum amount of load shifting that can be obtained.

5.2 Good Versus Bad Load shifting

5.2.1 Good Load Shifting Summer

Figure 5-10 displays a good load shifting performance both for the investigated mine and for Eskom. The load shifted, has an Eskom evening performance 11.78 MW with a daily cost saving of R 19 963 for the mine. The reason for this big financial cost saving is the load shifting in morning and evening peak. Also the off-peak and standard times were used equally and effectively to do the preparation for the peak load shifting. The day selected for this graph was in summer. The Adjusted baseline is also presented in Figure 5-10, meaning the total kWh of the actual graph equals the adjusted baseline kWh. Maximum energy demand peaks at 21 000 kW in standard time.

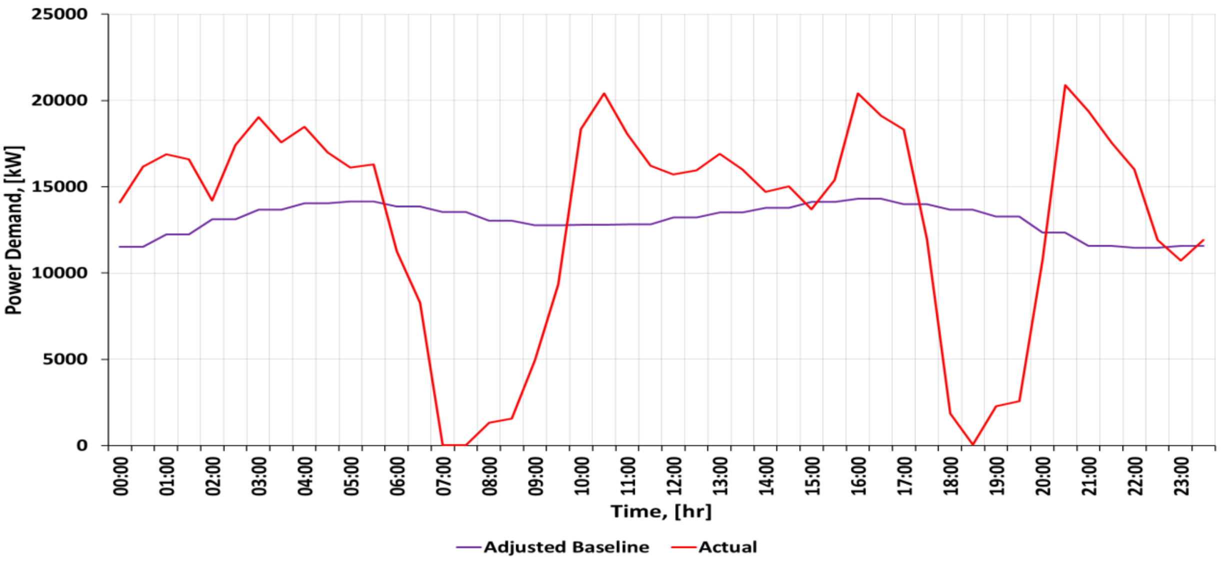


Figure 5-10: Example of good load shifting practice in summer

5.2.2 Bad Load Shifting Summer

Figure 5-11 displays a bad and good load shifting performance for the investigated mine and Eskom respectively. The load shifted, has an Eskom evening performance 12.57 MW with a daily cost saving of R 5 274 for the mine. The reason for this small financial cost saving, is that no load were shifted in the morning. Also the off-peak and standard times were used equally and effectively to do the preparation for the peak load shifting. The day selected for this graph was in summer. The Adjusted baseline is also presented in Figure 5-11, meaning the total kWh of the actual graph equals the adjusted baseline kWh. Maximum power demand peaks at 23 000 kW in standard time. The reason for the bad load shifting may also be when referring back to literature the unpredictability due to unscheduled repairs and maintenance of mining equipment.

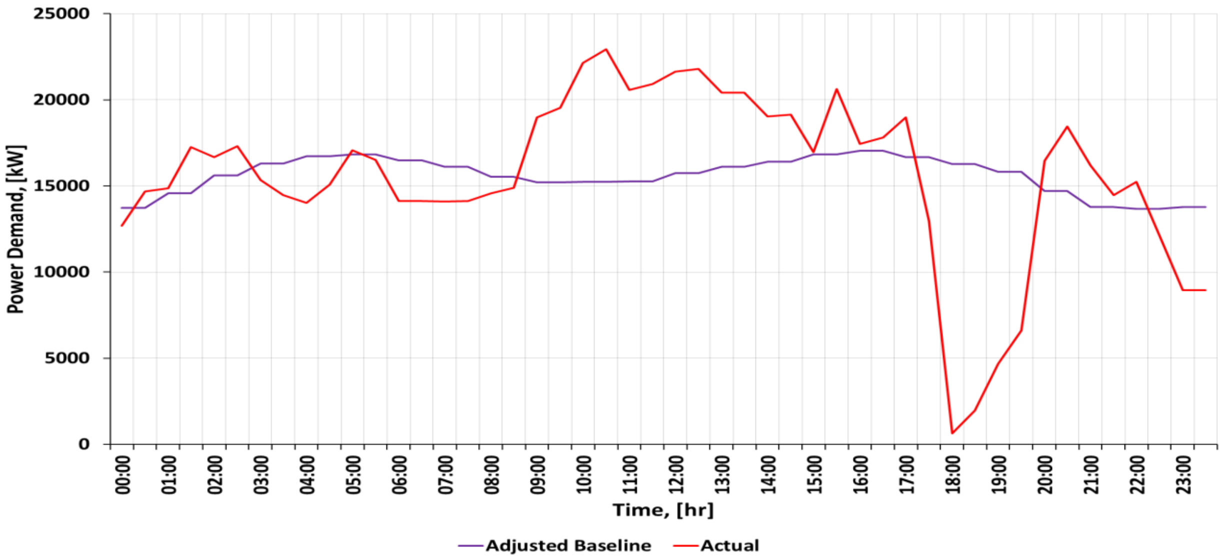


Figure 5-11: Example of bad load shifting practice in summer

5.2.3 Conclusion between good and bad load shifting for summer

When comparing Figure 5-10 and Figure 5-11, the adjusted baseline of Figure 5-11 is above the normal baseline. The adjusted baseline in Figure 5-11 is below the normal baseline. This means that more power was used in Figure 5-11, this is a reason for this poor cost saving. The two figures follow on each other, Figure 5-10 is a day before Figure 5-11. The reason for the high power usage in Figure 5-11 is because the evening off-peak time in Figure 5-10 were not used effectively, to pump out as much water as possible to surface.

Conclusions that can be made from Figure 5-10 and Figure 5-11 is that fully automated pumping systems should be investigated by universities and other institutions. The reason for this assumption is that fully automated systems will follow the trend shown in Figure 5-10 more accurately than in Figure 5-11. The two graphs appearances are basically similar but for Eskom Figure 5-10 and Figure 5-11 has an 11.78 MW and 12.57 MW evening peak load shifted respectively. Thus Eskom will benefit significantly in both situations.

This shows the importance of this study when implementing a load shifting project on an integrated shaft mine.

Fully automated load shifting should not be bonded only to the peak Eskom performance but also the rand value cost saving that can be achieved.

5.3 Load shifting problems

- Financial savings on labour reduction when automating a mines pumping system were not investigated. This was due to the investigated mine not wanting to reduce workers jobs, due to possible union problems and strikes.

- Electricity feeders to the pumps are sometimes overloaded due to the start-up power of the large de-watering pumps. This happens when a large amount of pumps are started at a single time in the mine.

- Pump out or pipe columns are occasionally overloaded by operators due to lack in concentration.

- Fully automated load shifting is very difficult to run effectively. Before the mine decides to go fully automated they firstly need to run the controller with human input. This human input have a lot of problems when trying to get the amount of pumps running which the controller suggests. This has been the main problem for this study to go to fully automated. Currently controller 2 is in operation due to controller 1 that has proven to be insufficient for the multiple-shaft mine.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

The dissertation will be concluded in this chapter. Recommendations for additional studies are also presented in this chapter.

6.1 Conclusions

The importance of the optimisation of load shifting in multiple shaft mines is supported by the fact that South Africa has 35 large-scale gold mines in operation currently.

This study developed a control philosophy by using a simulation model to optimize the power usage and to maximize the cost saving for an interconnected underground pumping system. This was done by physically implementing the control philosophy in the selected mine.

One of the main advantages of implementing a controller is the reduction in lag time between control room operator and underground pump operator. The other advantage of a controller is that the control room operator doesn't need to use his own discretion. Results obtained in this study were for manual, semi-automated and fully automated de-watering pump load shifting.

The study reduce the energy consumption during peak electricity time periods and increases cost savings. Semi-automated load shifting had a 78% increased cost saving in summer and a 5.5% increase in winter when compared to manual load shifting results. The evening peak load shifting amount for semi-automated load shifting increased by 38% in summer and 0.11% in winter when compared to manual load shifting. This is a large saving for both Eskom and the mine that was studied. Semi-automated load shifting greatly improved on load shifting results by decreasing lag times and showing the operator which pumps to start and stop with the use of a controller.

- Morning load shifting was also successfully implemented in this project. This leads to a larger cost saving for the client. When doing morning load shifting it is important not to increase dam levels beyond the point where it will have an influence on evening peak load shifting.

- Load shifting projects needs to pump as much water as possible in off-peak time in winter and in summer. With winter being the most profitable when not pumping in standard and peak times

- Multiple shaft load shifting is very difficult to maintain due to the large amount of instrumentation maintenance, constant changing of mining methods, water quality, pump maintenance and new workers. Also when comparing single shaft with multiple-shaft load shifting. Multiple shaft load shifting has the potential to have knock on effects, this will happen when communication is lost between hardware. This effect can take longer to eliminate than in single shaft pumping system due to the system being so complex.

- Controller 1 had good results when looking only at Shaft four. The reason was that this shaft has enough pumping power and capacitances to effectively pump out all the water to surface. Thus Controller 1 which only looks at its own dam level, may be effective for single shaft load shifting. Controller 1 resulted in an increase in cost saving and load shifted (semi-automated), compared to manual load shifting. Due to it constantly reminding the control room operators to stop and start pumps throughout the day.
- Controller 2 which uses other inputs from other levels will be more appropriate for multiple-shaft load shifting due to all the variances that may occur.
- The more efficient the system the more effective the load shifting project will be. Thus when other energy efficiency project are done during a load shifting period the load shifting project will gain in savings, due to dams that will have less water.
- When doing load shifting it is important to manage the pump profile throughout the day to maximize cost savings.
- The simulation model had a 91% accuracy for the maximum amount of load that can be shifted.
- In this thesis the fully automated results were not obtained. The reason is that the mine firstly needs to check if the controller is sufficient to control six pumping levels without any problems. Controller 1 was found to be insufficient in going fully automated but functioned well in semi-automated mode to remind control room operators.

6.2 Recommendations

- This Master’s Degree could be used as a cornerstone for other mine shafts in South Africa or globally to act as a guideline in how automation for integrated mine shafts could be done

- Universities can research alternative financial calculations programs to run an equation to iterate to ultimately optimise the mines pumping system which has small capacitance and varying capacitance. This program also has to constantly update according to when the changes takes effect in the mine.

- Energy efficiency project can also have positive results on load shifting baseline by minimizing the actual energy results in of peak time due to lower water inflow rates into capacitance.

- Obtain physical fully automated results for inter-connected mining shafts

7 BIBLIOGRAPHY

[1] “The Role of Mining in the South African Economy.” [Online]. Available: http://www.sablog.kpmg.co.za/2013/12/role-mining-south-african-economy/. [Accessed: 14-Apr-2016].

[2] R. C. W. Webbeer-Youngman, “An integrated approach towards the optimization of ventilation, air cooling and pumping requirements for hot mines/RCW Webber-Youngman,” 2005.

[3] P. MLAMO-NGCUKA, “Draft Energy Efficiency Strategy of the Republic of South Africa,” 2004.

[4] A. J. Schutte, “Demand-side energy management of a cascade mine surface refrigeration system/AJ Schutte,” 2007.

[5] “Why Nersa granted Eskom 9.4% tariff hike.” [Online]. Available: http://www.fin24.com/Economy/Eskom/why-nersa-granted-eskom-94-tariff-hike-20160301. [Accessed: 14-Apr-2016].

[6] W. Schoeman, “The integrated effect of DSM on mine chilled water systems,” 2014.

[7] “GOLD.” [Online]. Available: http://www.chamberofmines.org.za/sa-mining/gold. [Accessed: 25-Apr-2016].

[8] “Mineral resources.” [Online]. Available: http://www.gov.za/about-sa/minerals. [Accessed: 14-Apr-2016].

[9] “Welcome to the National Energy Regulator of South Africa.” [Online]. Available: http://www.nersa.org.za/. [Accessed: 25-Apr-2016].

[10] “ELECTRICITY REGULATION ACT 4 OF 2006.” [Online]. Available: http://www.nersa.org.za/Admin/Document/Editor/file/Electricity/Legislation/Acts/Electricity%20Regulation%202006(%20Act%20No%20%204%20of%202006)%20as%20amended%20by%20the%20Electricity%20Regulation%20Amendment%20Act2007(%20Act%20No%20%2028%20of%202007).pdf. [Accessed: 25-Apr-2016].

[11] R. Inglesi-Lotz and J. N. Blignaut, “South Africa’s electricity consumption: A sectoral decomposition analysis,” *Applied Energy*, vol. 88, no. 12, pp. 4779–4784, 2011.

[12] “Eskom Overview.” [Online]. Available: http://www.dpe.gov.za/soc/Pages/Eskom.aspx. [Accessed: 14-Apr-2016].

[13] “So where did load-shedding go?” [Online]. Available: http://lowvelder.co.za/302742/so-where-did-load-shedding-go/. [Accessed: 25-Apr-2016].

[14] “NUMSA Statement on Eskom ‘s Selective Re-opener of the third Multi-Year Price Determination (MYPD3).” [Online]. Available: http://www.numsa.org.za/article/numsa-statement-on-eskom-s-selective-re-opener-of-the-third-multi-year-price-determination-

mypd3/. [Accessed: 25-Apr-2016].

[15] C. Smythe, “An investigation into the efficiency and embodied energy of electric motors for use in pumping,” 2011.

[16] “Improving operations.” [Online]. Available: http://integratedreport.eskom.co.za/bec-operations.php. [Accessed: 22-Nov-2016].

[17] “The Energy Efficiency series Towards an energy efficient mining sector.” [Online]. Available: http://www.eskom.co.za/sites/idm/Documents/121040ESKD_Mining_Brochure_paths.pdf. [Accessed: 28-Apr-2016].

[18] C. Cilliers, L. van der Zee, and M. Kleingeld, “Cost savings on mine dewatering pumps by reducing preparation-and comeback loads,” in *Industrial and Commercial Use of Energy (ICUE), 2014 International Conference on the*, 2014, pp. 1–8.

[19] S. Africa, “Draft Energy Efficiency Strategy of the Republic of South Africa,” 2004.

[20] J. C. Vosloo, “A new minimum cost model for water reticulation systems on deep,” *Detail*, 2007.

[21] R. Pelzer, R. Richter, M. Kleingeld, and J. van Rensburg, “Performance comparison between manual and automated DSM pumping projects,” *ICUE, Cape Town*, pp. 10–12, 2009.

[22] J. Vosloo, L. Liebenberg, and D. Velleman, “Case study: Energy savings for a deep-mine water reticulation system,” *Applied energy*, vol. 92, pp. 328–335, 2012.

[23] R. Pelzer, E. Mathews, D. Le Roux, and M. Kleingeld, “A new approach to ensure successful implementation of sustainable demand side management (DSM) in South African mines,” *Energy*, vol. 33, no. 8, pp. 1254–1263, 2008.

[24] M. Van Eldik, “An investigation into the DSM and energy efficiency potential of a modular underground air cooling unit applied in the South African mining industry/Martin van Eldik,” 2006.

[25] R. P. Richter, “Comparison between automated and manual DSM pumping projects/RP Richter,” 2008.

[26] A. Hughes, M. Howells, A. Trikam, A. Kenny, and D. Van Es, “A study of demand side management potential in South African industries,” *Wood and wood products*, vol. 5, pp. 8–18, 2006.

[27] “Eskom Holdings Limited Integrated Report 2010.” [Online]. Available: http://financialresults.co.za/2010/eskom_ar2010/025.html. [Accessed: 28-Apr-2016].

[28] Eskom, “Eskom Introduction.” [Online]. Available: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Eskom%20Booklet.pdf. [Accessed: 23-Nov-2016].

[29] "Eskom." [Online]. Available: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/WhatsNew/Documents/ScheduleStdPrices2015_16_27Feb2015.pdf. [Accessed: 28-Apr-2016].

[30] N. C. J. M. De Kock, "Researching the long-term impact of load management projects on South African mines/Nicolaas Cornelius Jacobus Marthinus de Kock," 2006.

[31] W. F. Van Niekerk, "The value of simulation models for mine DSM projects/WF van Niekerk.," 2012.

[32] A. P. Van Niekerk, "Implementing DSM interventions on water reticulation systems of marginal deep level mines/Adriaan Petrus van Niekerk," 2014.

[33] S. Govender, "Energy Saving Mechanisms in the Mining Industry: A Case Study of Switching Off Non-essential Power," 2008.

[34] M. Den Boef, "Assessment of the national DSM potential in mine underground services/M. den Boef," 2003.

[35] J. Van der Bijl, "The simulation, verification and application of an underground pumping system/Johan van der Bijl," 2005.

[36] J. P. Steyl, "An automated solution to facilitate sustainable DSM in the mining environment/JP Steyl," 2008.

[37] A. Botha, "Optimising the demand of a mine water reticulation system to reduce electricity consumption," 2010.

[38] I. Mulder, "Potential savings when re-instating mine DSM projects," 2012.

[39] "World Energy Outlook 2015." [Online]. Available: https://www.iea.org/. [Accessed: 05-Dec-2016].

[40] N. L. Oosthuizen, "Optimum water distribution between pumping stations of multiple mine shafts," 2012.

[41] S. Thein, "Demand side management on an intricate multi-shaft pumping system from a single point of control," 2007.