ENERGY COST OPTIMISATION OF A COMPLEX MINE PUMPING SYSTEM

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ABSTRACT

The purpose of this study was to do an energy cost optimisation on a specific complex mine pumping system by means of load shift. A Real-Time Energy Management System (REMS) was installed on the mine and the pumps were controlled according to certain constraints. The results that were obtained were very satisfactory.

This project was undertaken on Elandsrand Mine and was a part of Eskom's Demand Side Management (DSM) initiative. Eskom fully finances these load shifting projects to encourage Energy Savings Companies (ESCOs) to undertake load shift projects in order to reduce the national peak demand profile.

The project entailed doing a detailed investigation of the mine's pumping system. The pumping system was analysed and simulated according to specific constraints that were specified by the mine. After the simulation was completed, an optimisation on this simulation was done and the pumping system was fully automated to react to the changing electricity tariff. This automation led to a successful load-shifting project.

Load shift means that the demand, during peak periods, is decreased. This is done by moving the energy requirement to another time of day when the demand and therefore the cost is less. However, the total energy used for the day remains the same.

Load shift decreases the energy demand during the peak periods and at the same time generate savings for the relevant energy user. The average load shift that was obtained for the 5 months (June – November 2004) was 3.66 MW. This load shift has resulted in an average monthly cost saving for the mine of R60 000.

This project showed that with the necessary historical data and expertise, a load shifting project, and therefore a cost optimisation project, can be successfully implemented on a mine's pumping system. This method can also be successfully applied to other electrical components on the mine

SAMEVATTING

Die doel van hierdie studie was om 'n energiekosteoptimeering van 'n spesifieke myn se waterpompstelsels te doen deur lasskuif toe te pas. 'n "Real-Time Energy Management System" (REMS) is op die myn geinstaleer, en die pompe is beheer onderhewig aan sekere veranderlikes. Die resultate wat uit die studie verkry is, was bevredigend.

Hierdie projek was gedoen op Elandsrand myn en was deel van Eskom se Demand Side Managment "DSM" inisiatief. Eskom befonds hierdie las skuif projekte ten volle om "Energy Savings Companies (ESCOs)" aan te spoor om las skuif projekte te implimenteer en sodoende die nationale piek behoefte te verlaag.

Die projek behels die detail studie van die myn se waterpompstelsel. Die pompstelsel was geanaliseer en volgens spesifieke beperkings, wat deur die myn voorgelê is, gesimuleer. Na 'n suksesvolle simulasie is die model verder geoptimeer en is dit ten volle geautomatiseer om te reageer op die veranderende tariewe. Hierdie automatiseering het gelei tot 'n suksesvolle las skuif projek.

Lasskuif beteken dat die energie behoefte tydens piek tye verlaag word. Dit word moontlik gemaak deur die energie gebruik tydens piektyd na 'n ander tyd van die dag te skuif wanneer die behoefte laer en dus ook goedkoper is. Die totale daaglikse energie wat vebruik word, bly egter dieselfde. Lasskuif verminder die energiebehoefte tydens piek tye en terselfde tyd genereer dit elektriese kostebesparings vir betrokke energie gebruiker. Die gemiddelde las skuif wat behaal is vir die afgelope 5 maande (Junie – November 2004) was 3,66 MW. Hierdie las skuif het 'n gemiddelde maandlikse koste besparing van R60 000 vir die myn meegebring.

Die uitkoms van hierdie projek was dat met die nodige historiese data en ondervinding, 'n suksesvolle lasskuifprojek, en dus ook 'n kosteoptimeringsprojek, suksesvol geimplementeer kan word op 'n myn se waterpompstelsel. Hierdie metode kan ook suksesvol toegepas word op enige ander elektriese komponente op die myn.

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Finally, all thanks to my Creator without whom none of this would have been possible. Thank you Lord, for your endless blessing.

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ABBREVIATIONS

ESCO	Energy Service Company
Eskom	Electricity Supply Commission
DSM	Demand Side Management
HVAC	Heating Ventilation and Air Conditioning
PLC	Programmable Logic Controller
REMS	Real-time Energy Management System
RTP	Real Time Pricing
SCADA	Supervisory Control and Data Acquisition

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1. BACKGROUND

This chapter presents the background of the current energy situation in South Africa and its purpose is to generate the necessary knowledge to ensure the successful understanding of the ever-growing electricity demand, the peak electricity demand problem, different pricing structures and the current electricity situation existing on South African mines.

1.1 Introduction

The mining sector is one of South Africa's strongest financial resources. At the moment this industry struggles due to the low gold price. Mining, along with agriculture, trade and manufacturing, is South Africa's biggest electricity consumer[1] In 1996 mining consumed 23% of all electric power generated by Eskom[2] [3] This amounts to approximately R3 billion of electricity per annum used in the mining industry.

1.2 Ever-growing electricity demand

This ever-growing demand for electricity gives rise to a number of problems which have led South African electricity suppliers to invest in studies that would shed some light on ways to lessen the demand of the large energy users. One of the studies that was conducted in 1996 by Lane [4] revealed the following:

A 27% peak load reduction can be achieved on a typical South African deep level mine. This peak load reduction can be achieved by introducing an optimised scheduling of electricity usage on all systems on the mine such as pumps, winders, fridge plants, compressors, etc.

If it is assumed that these peak load reductions can be realised, the potential savings which could be realised if an optimising energy usage schedule system were implemented, could be calculated.

Looking at a typical deep gold mine's electricity bill, one will see that 30% of the cost is due to energy used during peak electricity billing hours [5] . This figure is so high not because more electricity is used during those hours but because a unit of electricity used at this time can cost up to 6 times as much as the average unit price. See pricing tariffs in Table 2 on p8.

Assuming that 30% of the electricity bill of the mine is due to the peak hour electricity demand, it implies that an 8% reduction can be achieved on the total electricity bill of a mine when this optimised schedule for the electrical systems, as suggested by Lane, is implemented.

1.3 Peak electricity demand problem

A couple of years ago electricity suppliers in South Africa realised the magnitude of the electricity crisis and have since then tried a number of options to find a successful load shifting program, but without much success.

After intense investigation, Eskom realised that electricity demand follows certain trends that are governed by the following parameters: [5]

Time of the day: There are two main peaks during a normal day. The first is in the morning between 07:00 and 10:00. The second is in the afternoon between 18:00 and 20:00.

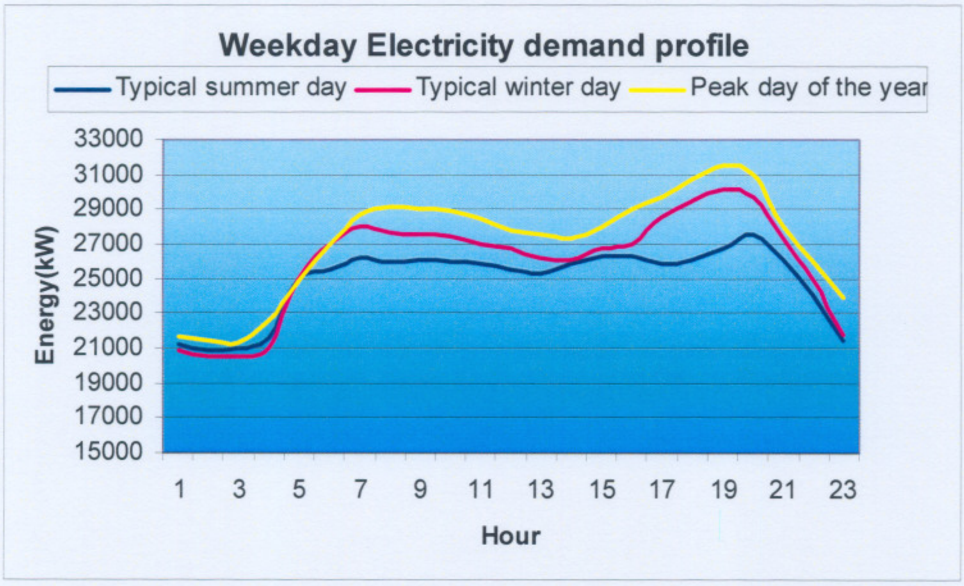

Figure 1: Weekday electricity demand profile

Season of the year: The time of year also plays an important role in the electricity demand curve. The total electricity demand rises in the Winter due to additional electricity that is required for heaters, geysers, etc. This is especially evident in the commercial sector. The difference between the maximum peak demand and the average demand is higher in the Winter than in the Summer. Figure 2 shows the curve of a typical year's average energy profile, where the peak in winter during June to August is of the order of 37 GWh.

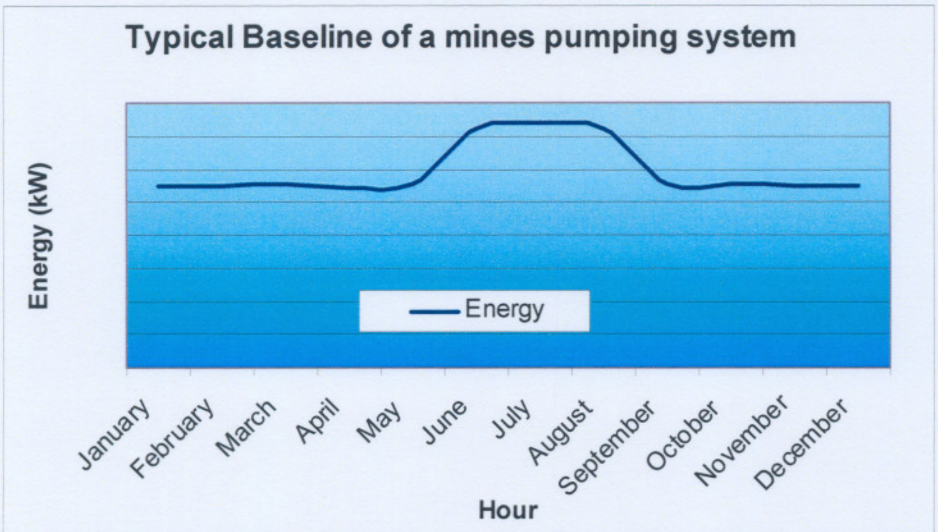

Figure 2: Weekday electricity demand profile

Type of day: The type of day is another factor that strongly influences the electricity demand curve. The different types of days are identified as Weekdays, Saturdays, Sundays or Public Holidays. A Public Holiday is often categorised under either a Saturday or a Sunday.

The two peaks found every day as mentioned in Figure 1 are more prominent on weekdays than on Saturdays, Sundays. Figure 3 shows a representation of the difference in each daily profile. No values are inserted into the figure due to the fact that the profile is the prominent factor and not the values as such.

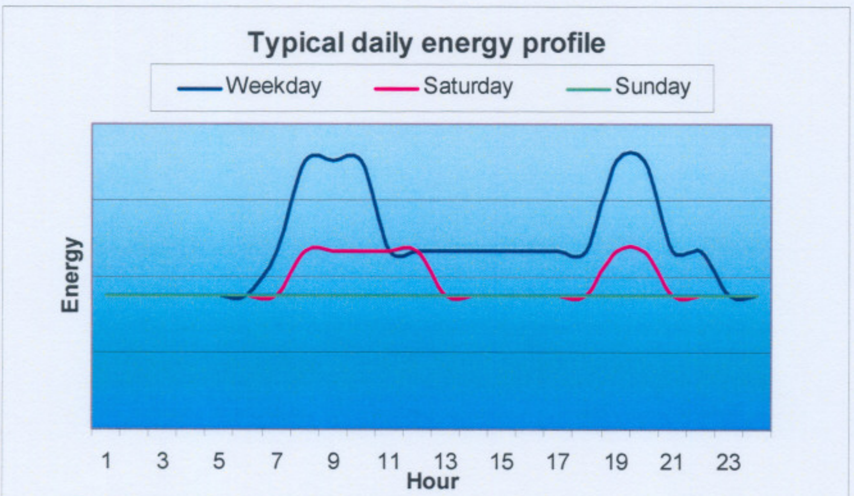

Figure 3: Energy profile for specific day

A typical demand profile for a typical weekday is illustrated in Figure 3. As one can see, the peak period during the day is in the mornings between 07:00 and 10:00 and in the evenings between 18:00 and 20:00. According to Eskom the two-hour peak in the evenings is the most critical. They have therefore concentrated on finding a solution to reducing the evening peak.

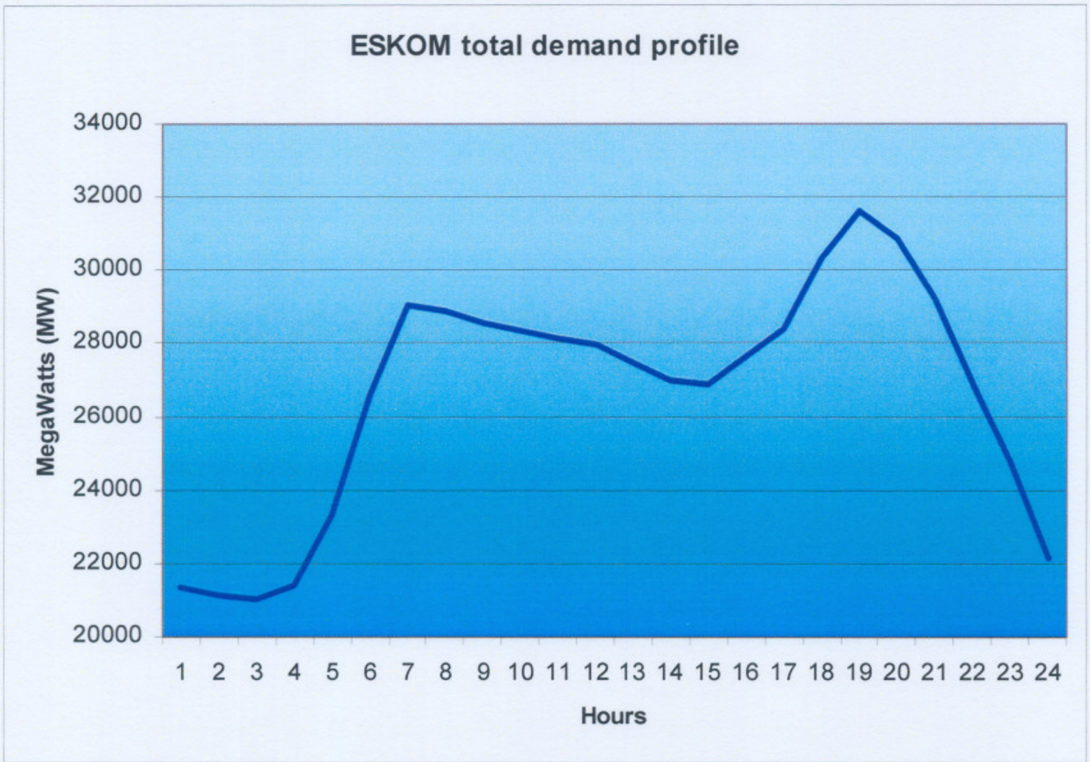

Figure 4: Typical daily energy demand profile

1.4 Implementation of variable pricing structure

An example of previous attempts to establish a successful load-shifting program was the implementation of variable pricing structures. This was done to try and coax the consumers to use electricity during the off peak periods when the tariffs are much lower than in the more expensive peak periods [6] .

Let us first investigate the Real-Time Pricing structure [7] . The complete workings and conditions as per supplier of Eskom's Real-Time Pricing billing system can be seen in reference [8] . The following is a short summary of how the Real-Time Pricing (RTP) billing system works:

First of all, a Base Load is agreed upon between the electricity user and the supplier. This base load is based on the historical pump data for this specific mine for the past year. The base load is set up to serve as a guideline from where the load shift and savings calculations can be done. This Base Load is a 24-hour profile of the expected MW of electricity to be used during each hour of the day.

To start with, the user is billed for this Base Load profile on a fixed c/kWh tariff. This fixed c/kWh differs for seasons and day types. The tariff is higher for the Winter months, which are June, July and August. For the Summer months, September to May, the tariffs are a bit lower. The same applies to the day types. The tariff rates are the highest for weekdays, lower for Saturdays and the lowest for Sundays.

The RTP price profile is updated every day and is issued the previous day. This profile consists of two 24-hour profiles listed as follows: (1) Above Profile, (2) Below Profile. A typical example of such an RTP price is shown in the following table.

Hour	RTP below	RTP above
00:00	5.40	8.41
01:00	5.01	8.02
02:00	4.80	7.81
03:00	4.80	7.81
04:00	4.80	7.81
05:00	6.72	9.73
06:00	6.90	9.90
07:00	8.75	11.76
08:00	9.63	12.64
09:00	9.77	12.78
10:00	7.08	10.08
11:00	7.76	10.76
12:00	72.85	81.25
13:00	14.30	17.31
14:00	11.97	14.97
15:00	11.94	14.95
16:00	72.85	88.97
17:00	6.20	9.20
18:00	9.74	12.74
19:00	72.85	92.84
20:00	14.40	17.40
21:00	6.16	9.17
22:00	8.58	11.58
23:00	6.72	9.73

Table 1: RTP above and below hourly prices

In figure 5 the monthly energy profile is compared with the base load to do certain calculations.

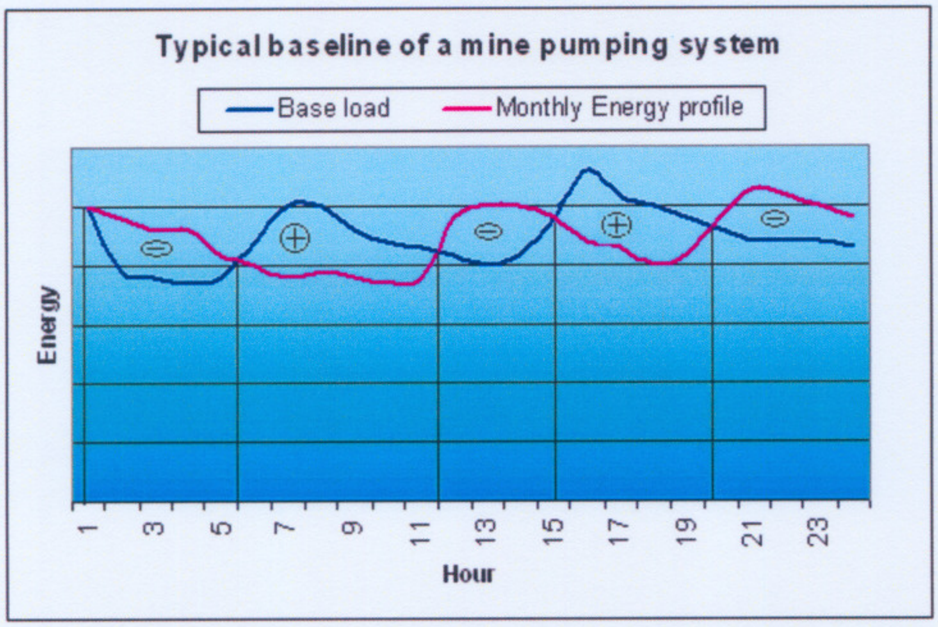

Figure 5: Comparing the Base Load with energy profile

The user is billed for the deviation from the agreed Base Load. Whenever the real demand exceeds the Base Load, the difference is billed according to the RTP Above hourly prices as shown in Table 1 and discussed in reference[9] .

Whenever the real demand is lower than the agreed Base Load, the user's bill is debited according to the price of that deviation according to the RTP Below profile shown in Table 1 and discussed in reference [9] .

Let's look at MegaFlex pricing. The complete workings and conditions as per supplier of Eskom's MegaFlex billing system can be seen as reference [11] . See Table 2 and 3 for a short summary of how the MegaFlex billing system works.

MegaFlex is a much less complicated tariff structure than is the case for RTP, and today more and more industries are going over to MegaFlex because of its simplicity. MegaFlex is widely known by the following table.

Defined Time Periods:	Weekday	Saturday	Sunday
Peak	07:00 - 10:00 18:00 - 20:00	N/A	N/A
Standard	06:00 - 07:00 10:00 - 18:00 20:00 - 22:00	07:00 - 12:00 18:00 - 20:00	N/A
OffPeak	22:00 - 06:00	12:00 - 18:00 20:00 - 07:00	Whole day

Table 2: MegaFlex – Demand Time Periods

The MegaFlex system divides the time of the week into 3 periods. These are 1) peak, 2) standard, and 3) off-peak times. Electricity is then priced according to these periods. In peak time, electricity is most expensive and in off-peak periods the cheapest.

MegaFlex also differentiates between demand seasons and they are 1) High-demand season, which is June to August, and 2) Low-demand season, which is September to May. In table 3 the exact prices for each period can be seen.

High-demand season (June - August)		Low-demand season (September - May)
50.44c + VAT = 57.50c/kWh	Peak	15.45c + VAT = 17.61c/kWh
14.56c + VAT = 16.59c/kWh	Standard	10.23c + VAT = 11.66c/kWh
8.63c + VAT = 9.84c/kWh	Off-peak	7.72c + VAT = 8.80c/kWh

Table 3: MegaFlex – Demand tariffs

1.5 The mining situation

South African gold mines are in a financial crisis and some of them are threatening to close down. Every time the Rand gold price drops, it has a negative impact on the mining industry. If mines are forced to close down, Eskom would lose some of their biggest customers. It will therefore be beneficial for both Eskom and the mine to be more energy-smart and to reduce their operating costs.

South Africa's gold and platinum mines consumed 26.0 GWh of all electricity generated in South Africa in the year 2000 [2] . The average electricity cost in this year was 10 c/kWh. This means that the total amount paid for electricity by gold and platinum mines was R2.6 billion. 65% of all these gold and platinum mines are deep mines. Millions could have been saved in electrical cost during 2000 just by applying optimised scheduling of electrical systems on deep mines in South Africa.

Due to the growth of the industrial and mining sectors' demand for power and the forecast rise in electricity costs, we can assume that this estimated potential saving will grow in the following years. This anticipated rise in electricity demand is the main reason for a drastic solution having to be found for the problematic peak period situation. The load during the peak periods had to be shifted to the less critical off-peak periods and by so doing the energy cost is also optimised.

2. OBJECTIVES AND PROBLEM STATEMENT

The need, contribution and the value of this study are presented in this chapter. The importance of load shift and the methods of achieving this using DSM are discussed in detail. The important role that ESCOsplay in the load shifting process is also discussed.

2.1 Importance of load shift

High peak demands prove to be a big problem for electricity suppliers such as Eskom. Electricity suppliers sought a way to level out the demand curve. This is where the term 'load shift' was born.

To shift load means to lower the electricity demand during peak demand hours and to rather 'shift' that demand to a time when the global electricity demand is lower. Thus their mission was not to urge electricity users to use less electricity, but rather to use electricity at specific times.

Figure 6 shows a typical energy profile of a mine *BEFORE* implementation of an automatic control system. As one can see, the demand during the morning and evening peaks is quite high when compared with the rest of the day. These loads can easily be shifted to another time when the demand and price are much lower.

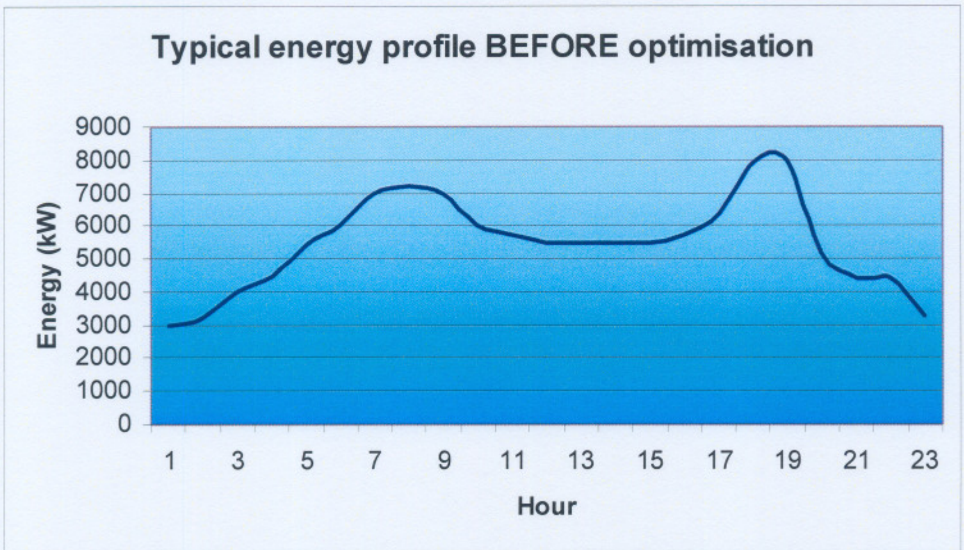

Figure 6: Energy profile BEFORE implementation of control system

Figure 7 shows an ideal energy profile that would to be realised AFTER an automatic control system was implemented on the mine. The same amount of energy is used in both these energy profiles, therefore the total sum of the energy underneath the curve will still be the same.

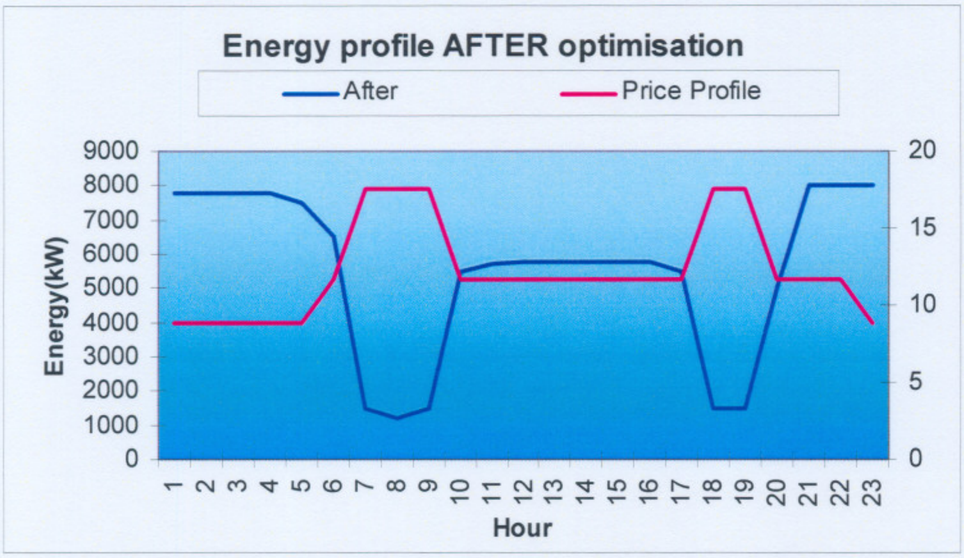

Figure 7: Energy profile AFTER implementation of control system

The maximum electric power capacity of Eskom is governed by the maximum demand of their clients. At the moment Eskom's off-peak capacity is well within demand, it is only during the peak periods that the problems arise.

When the maximum demand passes a certain point, the need to build a new power plant will arise. This would require capital input, which would mean a rise in the electricity cost to the commercial and industrial market. Eskom would like to postpone this for as long as possible and search instead for alternative solutions.

To level out the demand profile as shown in Figure 6 and Figure 7, would be beneficial to both Eskom and the mine. For the mine this directly implies electricity cost savings and financial benefits. For Eskom the peak period demand decreases.

During the low demand hours all excess power generated cannot be saved, therefore power plant sections are shut down to cut these losses. During the high demand hours these power plant sections, which were shut down in low demand hours, must be powered up again to meet the peak period demands. This whole process is repeated twice a day because of the two peaks.

Levelling out the demand profile would consequently result in less shut-downs and start-ups, cutting start-up and shut-down costs.

The implementation of these pricing structures did not realise the load shift that Eskom expected, because the introduction of the pricing structures does not shift load. Load is only shifted when the companies, where these structures are present, react to this change in hourly prices. Therefore a more drastic solution had to be found. Eskom introduced the DSM program.

2.2 Demand Side Management (DSM)

As mentioned in paragraph 2.1, Eskom has tried a number of different strategies in an endeavour to coax the consumer to use energy during the off-peak periods rather than during the peak periods, but with no great success. They therefore had to implement a more drastic and reliable program to ensure that the energy consumers reacted to these tariff structures.

They came up with a program called DSM. DSM is not a tariff structure but a program to motivate energy users to use energy during the right periods. This is achieved with the help of ESCOsto shift the amount of load that is promised by the ESCOs to Eskom. DSM can be applied for any tariff structure like RTP, MegaFlex or Nightsave.

Of all the programs that Eskom has implemented in the last couple of years, this concept appears to be the better option. The reason for this is that load shift for a specific mine is contractually bound. If the promised load is not delivered, the relevant ESCOs are responsible for the penalties[11] . This action ensures that the required load will be shifted and Eskom can rely on this figure when doing future planning.

Eskom fully funds these DSM projects and sponsors these ESCOs that initiate a successful response to pricing structures. At the moment there are only a few ESCOs capable of running a DSM project of this magnitude. HVAC International is one of the leaders in this field, with a simulation package called Real-Time Energy Management System (REMS).

2.3 The purpose of Energy Service Companies (ESCOs)

By definition an ESCO (Energy Service Company) is a company that develops, installs and finances projects designed to improve the energy efficiency and maintenance costs for facilities over a seven to ten year time period.

The ESCO industry is two decades old. Its beginnings can be traced to the oil crisis in the late 1970s, which created an opportunity to make a business out of reducing the growing energy bills of companies. Currently the ESCO industry in North America facilitates $2 billion annual investment in energy efficiency [12] .

The success of a DSM project depends directly on the responsible ESCO. After the ESCO has done their research on the specific mine, a contract between the ESCO and Eskom is signed. In this contract the number of Megawatts (MW) that will be shifted during the peak period, is stipulated.

After the contract has been signed the ESCO takes full responsibility for ensuring that the promised load is shifted [13] . If, for any non-condonable reason the load has not been shifted, the ESCO will be liable to pay penalties. Condonable reasons are things that the ESCO has no control over, things like pump breakdowns, column bursts or malfunctioning valves, etc.

As ESCOs help to realise Eskom's vision to shift load, they qualify for part of the funding provided as mentioned above. To govern the relationship between the ESCOs and Eskom, Eskom laid down the following conditions for ESCOs to comply with before they qualify for the agreed funding:

(1). The ESCO is responsible for identifying, implementing and maintaining projects.

(2). Eskom will fund the capital to cover any equipment cost and implementation. This capital input is of the order of R1.5 million per peak MW load shifted.

(3). The client, the ESCO and Eskom will share in the savings achieved as a result of the load shifting.

(4). An independent party will verify the total load shifted and electricity savings realised.

2.4 Existing systems

Due to the huge financial benefits that can be realised in the industry, and by Eskom who make the funds available for such a project, a number of ESCOs and systems were developed to try and save electricity.

In spite of this motivation, none of these systems satisfy the need of the typical consulting engineer for integrated, efficient and accurate simulation, and no system that combines the following was developed [15] [16] [17] .

(1). Automated scheduling of electrical components of pumping and cooling systems.
(2). Real-time responsive schedule that reacts to changes in live data.
(3). Automated control of electrical equipment in accordance with calculated schedule.

There are products and systems that claim to save money in *City water distribution systems*. Many other products and systems are focused on HVAC (Heating, Ventilation and Air Conditioning). Some of these systems are discussed in the following section: *U.S. Patent No.6366889 by Zalloom [18]* and *U.S. Pat. No. 6178362 by Woolard et al [19]*

These patents claim the ability to optimise energy cost in HVAC systems in mines, buildings and industries. These products enable the users to analyse energy consumption trends. The goal of this software is to help the user determine operating errors, equipment faults and billing errors. Both systems, as with many others, have extensive Internet-based communication capabilities to connect the user to real-time data.

The shortcomings in these two systems, and other similar systems, are as follows:

(1). They do not eliminate human operation and therefore do not qualify as fully automated systems.

(2). These are not continuous optimising tools. After extensive information input, a once-off optimisation is done and an answer is given.

(3). This software does not have the capability to self ascertain the information needed for the optimisation.

(4). This software does not do active automated control in accordance with the optimised schedule calculated.

The following patent, *U.S. Pat. No. 5963458 by Cascia et al [20]*, follows a real-time low-level control approach. With this approach a controller is used to control an electrical component. This electrical component can be part of any cooling, heating or hoisting system.

In the patent by *Cascia* a digital controller is used to control the different electrical components. An optimal set point is calculated by the controller for the component and controlled according to this. All this is done in real-time. Following this strategy the controller optimises the energy consumption of the components for that specific point in time.

The shortcomings in this system and others like it are as follows:

(1). This system only optimises for a single electrical component. Therefore optimising for an integrated network of components in parallel systems is not possible.

(2). As control is performed via individual controllers, a single human interface that gives access to the control platform is not possible.

(3). This approach seeks to optimise power usage. As such it strives to save electricity rather than to shift load.

The following patent *U.S. Pat. No. 6178393 Irvin et al [21]* is to optimise the total energy cost of integrated components and/or systems and to serve as a measurement tool to aid in reporting. This patent is focused on the control of constant and variable speed pumps. In short this system takes into account the real-time operating cost for each pump and calculates the optimum combination of pumps that should be running and, if applicable, at what speed. This schedule is passed to a human controller who is responsible for the execution thereof.

The shortcomings in this system and others like it are as follows:

(1). This system only takes into account the immediate cost, not what the cost in the near future will be. This implies that this system is unable to optimise for a period of time but only for an instant in time.

(2). This system does not have the ability to automatically control equipment, but relies on a human operator to execute the optimised schedule.

IST Otokom PTY (Ltd) [22] is a South African company that provides systems that can be used to achieve automated energy readings in the industrial environment. This data is logged into a database and is available to the user via their ecWinTM software. This system does not focus on control at all and cannot therefore directly be used for load shifting.

The following 3 software packages that are discussed are focused on the *distribution of city water*. These packages claim to minimise the electricity costs of the city water distribution system. Because these systems are designed for city water distribution it is crucial to emphasise the differences between a city water distribution and mine water pumping systems. The differences are as follows:

(1). City water reservoirs are much larger than the reservoirs used in mine applications. The smaller the reservoir the faster its percentage level will change. Thus, a system that intends to control a system containing a smaller reservoir must be capable of faster reaction and control. Another result of a fast changing % dam level is that it could result in pump cycling.

(2). The bill for city water distribution is much higher than that for mine water pumping. As a result of this the cost of this software is very high in comparison to the savings it could realise in the mining set-up.

The first city water distribution software package that is discussed is *H2ONET Scheduler[23]* . This system is developed for the city water distribution market. Its focus is to calculate optimised operation schedules for water pumps for maximum performance and energy saving. This system can also be used to optimise the design of a city water distribution network. The operation schedule is calculated on a daily basis. This system is capable of taking into account hydraulic operational constraints such as pressure, velocity, head loss and desired tank trajectory curves.

The second city water distribution software package that is discussed is *MISER-PS [24]* . This application is used to calculate day-to-day pump operational schedules to optimise electricity cost and efficiency. It can also be used to plan emergency procedures in the event of pump failure.

The schedule is calculated in half-hour intervals and contains an on-off status for all the pumps taken into account. The operator can specify constraint limits like the number of pumps running simultaneously, flow parameters and reservoir levels.

Thirdly, *Derceto 3.0 [25]* is focused on larger water distribution networks. It aims to deliver a certain demand of water to certain points. With on-line data collection capabilities, it finds the cheapest water source and delivers the water to points where it is needed. The water is distributed via a pump system that is automatically controlled. This whole process is optimised in real-time to minimise the operating cost.

This is the only application that schedules pumps for minimal electricity cost in real-time. This application is very flexible and can be applied to a wide range of fields but it needs a specialist to install and maintain it and costs of the order of US $500 000 per installation.

A product that enables commercial and industrial systems to respond to real-time pricing is *RTP Control^{TM} by Honeywell Inc [9]* . It was tested and verified in a case study at the Marriott Marquis Hotel in New York. This system has the right load shifting approach but is does so by thermal energy storing. This system can therefore not be used in the controlling of systems which include components like pumps and/or electric motors.

2.5 The need for Real-Time Energy Managing System (REMS)

In section 2.1 and 1.3 the benefits that can be gained from shifting load were discussed. In Section 1.5 the huge potential that can be gained when load shifting is applied to the mining industry were discussed.

In section 2.4 a number of already existing systems that help to shift load in some way were discussed. The advantages, drawbacks and field of application of all these systems were highlighted.

Taking all this into account, it can be concluded that there is a need for a system that answers the following requirements:

(1). A system that can be used to shift load.

(2). This load shifting must be realised through the scheduling of electrical components such as water pumps, valves and cooling plants. This schedule must be continuously calculated, taking into account real-time data.

(3). The system must be capable of controlling these electrical components automatically in accordance with the calculated schedule.

(4). The system must be developed in such a way that it can be applied in a wide range of industrial applications.

(5). The system must incorporate all series of operating constraints as not to schedule and control components outside safety and operating regulations.

(6). A system that is completely reliable and stable.

(7). A system that can act upon real-time data such as unforeseen changes in the controlled environment.

(8). A systems that can self ascertain the information needed to complete the task for which it is designed.

(9). A system that can keep track of its own performance in terms of load shifted and the savings that are realised.

2.6 Problem Statement

South African gold mines are in a financial crisis due to the low gold price value in Rand and the high cost of mining to transform gold into a valuable product. Therefore, the need to minimise operational cost is very important so that profit can be increased. Large financial benefits can actually be realised if energy usage is optimised.

Optimising energy does not necessarily mean using less energy, but rather using the electricity at the right time of day. This procedure is not as simple and easy as it sounds because of the fact that there are so many factors influencing the use of electrical equipment such as production, safety, mining rules and regulations, etc.

In this thesis the author has studied the hot water pumping system of Elandsrand Mine and designed and implemented an automatic control system. By doing so the energy cost for this specific mine was optimised.

3. WATER PUMPING SYSTEMS IN DEEP MINES

This chapter explains the important role that water plays in a mine. A typical water cycle is discussed to ensure that the reader understands the different uses of the mine water such as cooling, mining operations and general uses.

3.1 Introduction

Due to the fact that underground rock faces release a lot of heat, mines in South Africa have great difficulty in keeping working conditions in the mine within comfortable limits. Many ways to achieve this have already been investigated.

None of the conventional cooling methods that are available on the market can be applied to the mining industry. Take for instance gas cooling. Due to the fact that gas is so highly flammable and the risk of explosions and fires so high, it is not worth even considering this option.

Another cooling method that is familiar to us all is the air conditioning principle. The air in the room is extracted into the air conditioner, cooled down and this cold air is then blown back into the room. The cold air mixes with the warmer air in the room from where this slightly colder air again enters the air conditioner. This process will strive to keep the air inside the room at the specified temperature. This whole system can be seen as a control volume. The heat that is extracted from the warm air is blown into the atmosphere, outside the control volume.

The air conditioning principle will not work as well in the mine as it does in a closed room due to the fact that the area that needs to be cooled is too big and the rock face where the heat comes from is far too extensive for an air conditioner to cool down. Therefore another plan had to be made.

3.2 Water on the mine

In paragraph 2.1 the different options have been looked at, but the best option, taking cost and reliability into account, is using fridge plants. Fridge plants make use of water as a cooling medium, therefore a lot of water is required. The inlet water temperature of the fridge plant water is of the order of 20°C, the plant then cools this water down to temperatures below 5°C.

This water is then used in the Bulk Air Coolers (BAC) to cool down the air that is blown down the mine and into the shafts. Some of this water is directly transferred to lower levels in the mine were it is used for mining purposes such as drilling and dust prevention, and also for cooling purposes in the cooling cars and spot coolers.

After all this water has been used for whatever purpose, it then flows down the stopes and into settlers. Settlers are conical dams used to remove mud from water as it flows from the mine workings. The mode of operation is as follows:

Muddy water flows in pipes in the direction of the settler. The water flows past a gel that binds with the mud particles in the water, causing the mud to sink to the bottom. For this reaction to work, the PH of the water must be controlled at 8.5, an alkaline solution.

This water with the heavy mud now flows into the intake well. This is a vertical pipe in the middle of the settler, with the bottom end submerged about 2 metres under the water in the settler. The purpose of this is to confine the turbulent inlet water flow in the inlet well, while the mud sinks to the bottom of the settler. This arrangement allows the water around the intake well to lie still, thus preventing the mud from being in suspension because of water movement.

The clean water is then removed from the top of the settler by means of a channel that flows to the clear water dams.

The separated water is then pumped to the surface via the different pump stations where it is again used in the fridge plant as a cooling medium. If there is too much mud in the bottom part of the settler, a valve is opened and the mud is drained off.

3.3 Typical mine water cycle

The mine receives external water from Rand Water whenever the total volume of cycle water is too low. The mine pays for this water and as a result it is more economical for them to re-use the water.

After the cold water from the fridge plants has been used in the mine for cooling purposes, the warm water flows down the stopes and through the settlers. From here the warm water is pumped from the settlers into a dam using transfer pumps. These 100 kW transfer pumps are small compared to the 2000 kW pumps used to pump water to other levels and therefore are not included in the simulation. From here water is pumped to different pump stations on different levels, ending up in the surface hot water dam, which again supplies the surface fridge plant. From here the water cycle starts all over again.

3.4 Clear water pumping system

Pumping in a typical mine accounts for almost 30% of the total energy usage in a mine. It is therefore feasible to do a detailed survey on the potential load shift on the clear water pumping system of a specific mine.

The clear water pumping system is by far the most complex and important control system on the mine. This is because it is such a sensitive process. If problems occur with the control of the clear water pumping system, dam levels can be exceeded and possible floods could occur. This puts the life of workers in danger.

If no water can be pumped to the surface, it is only a matter of time before the fridge plant dam will have no water and the cooling process will be unable to continue. Working conditions will become unbearable and productivity will decrease.

This load shifting can be achieved by using a proposed control system. The control will have to be done by a specifically designed control system that is able to incorporate the many constraints found within the clear water pumping system.

The physical properties of a clear water pumping system determine the load shifting potential that could theoretically be achieved. These properties include flows, pump capacities, dam sizes, etc. The most important of these is the dam sizes. Dams are used to buffer workload. The bigger the dam, the more workload can be buffered and thus be moved, resulting in load being shifted.

Keeping the pumping system in balance by switching a number of pumps on at each level, resulting in the flow rate of the in- and the outlet of the specific dam being equal, would have been much simpler. But the problem arises when one wants to switch the pumps off during expensive, high demand periods to save on electricity costs. By doing this, water accumulates and dam levels get critical. The smaller the ranges of the minimum and maximum dam levels, the more critical the situation.

After the water has accumulated in a specific dam, the pump capabilities start playing an important role. If the pumps are not capable of shifting the water within a certain time, a snowball effect begins and the problem will only get bigger and more critical. For this reason a simulation and optimisation package is necessary to achieve the energy cost optimisation of a complex mine pumping system.

4. SIMULATION AND OPTIMISATION MODELS

The mine's pumping system is so complex, that before the automatic control system can be implemented on the mine, it should first be simulated in a virtual environment to determine whether the control stays within the control specifications. This is done by means of a simulation model. After successful simulation of the system, further optimisation can be done with the help of an optimisation model. This chapter explains in detail how the simulation and optimisation operates.

4.1 Introduction

A water pumping system consists of a number of variables that vary over time for each day. The most important variable in a mine water pumping system is surely the amount of water going down the mine. At some mines this variable is more critical than at others. This is because some mines are linked with nearby mines and their water ends up in the local pumping system.

The changing water volume has a direct impact on the energy usage of the pumping system. If the water volume increases, more pumping needs to be done and therefore the energy usage and energy costs will increase.

Due to this scenario, a fixed pumping schedule for each day is not possible. Thus it is important to simulate the entire pumping system, and by using the simulation model controlling pump schedules at a specific point in time.

4.2 Simulation model

When building the simulation model for the mine operations, each and every element in the mining process has to be simulated in exact detail. For each element a mathematical model must be built which accurately represents that specific component. The model for the component is verified to ensure that it reacts in exactly the same way as the real component on the mine.

The simulation model uses mathematical equations to model the pumping system of the mine as accurately as possible. Each component is specified individually so that component models link input values to the basic variables in the system. This is based on the simplified fundamental principles combined with correlation coefficients derived from discrete empirical data [26] .

The simulation model is built up out of modular mathematical models. Each model represents a different component of the pumping system. These models are developed with the goal of portraying the effect that this specific component will have on the systems as a whole.

All the simulated components are combined into one integration model which represents the integrated operation of the complete mine. The full control system is then integrated with this to arrive at a "real life" simulation of the mine.

Now the fully integrated dynamic system and control model for the mine is extensively verified with detailed measured data. The necessary update of the integrated model is done until perfect verification proves to the client that a successful computer model of the mine has been achieved.

Using the different models and combining them into a simulation model, any mine pumping system can be built, no matter how complex. It is not the goal of this study to simulate the intricate workings of the different components and this was therefore not coded into these models.

Each mathematical model was developed with a standard interface. This was done to enable the models to exchange data, based on a set standard. The data that is conveyed between these models include flows, temperatures, status, etc. According to the data obtained from the different models, the next step in the control strategy can be determined.

The models were all linked and run on a simulation platform called REMS Viewer that is built on the principles as described above. The function of the Viewer is to control the extracted information from the mathematical models and represent it in a usable format to the user.

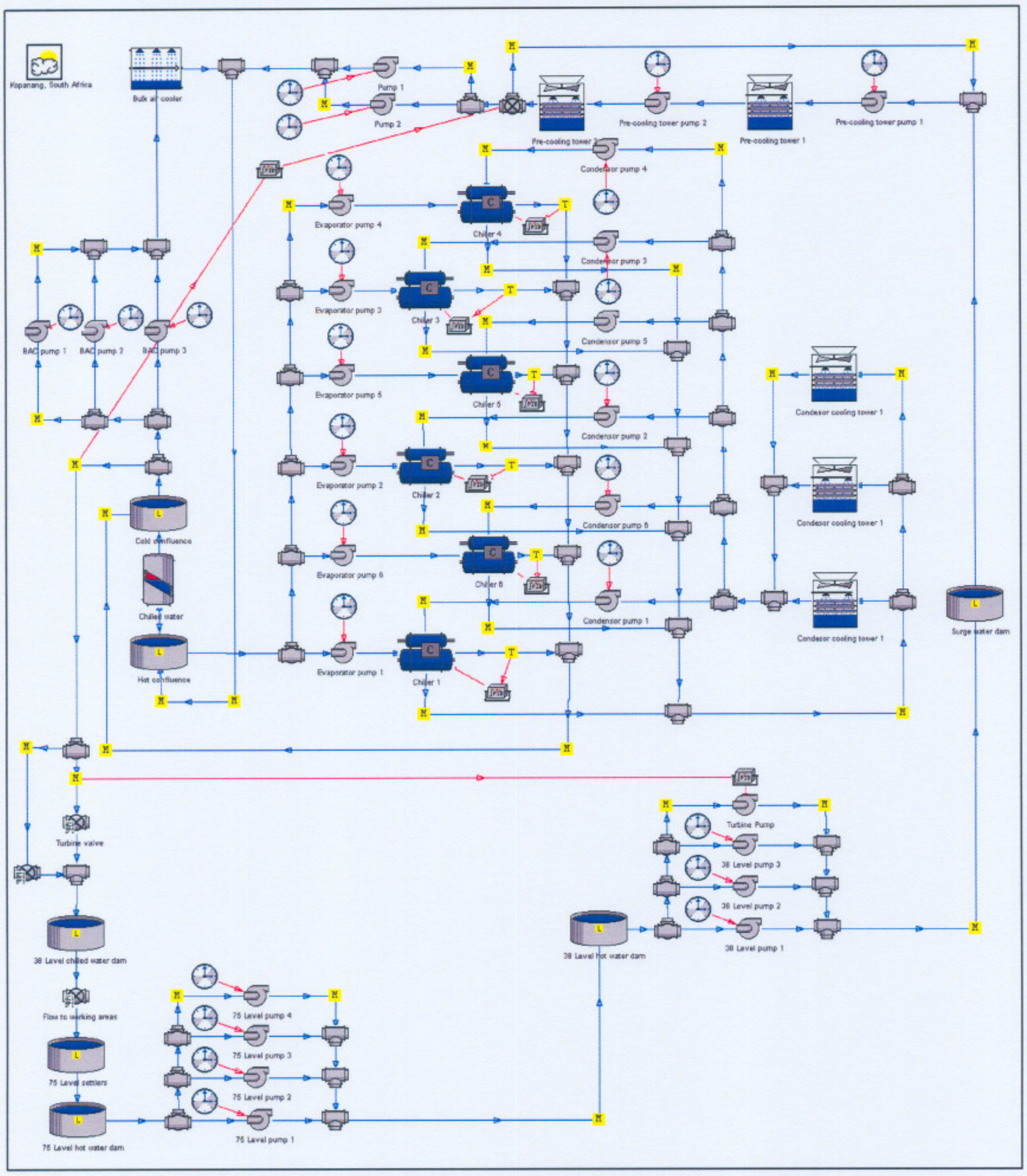

Figure 8: **Schematic representation of a typical water cycle simulation**

Figure 8 shows the water cycle simulation. This figure gives the visual representation of the water system and flow information. The information or data is carried by the viewer to and from the relevant mathematical model.

A fully component-based model allows simulation of a wide range of operating conditions. Each model calculates the energy consumption of each component. The correlation coefficients for a specific make and model of equipment can be derived by using measurements or manufacturer's data sheets.

A simple time constant approach is used to simulate dynamic effects. The user is responsible for supplying the time constants. The approach is as follows:

$$\tau \frac{d\varphi}{dt} = Function$$

(model input parameters), with τ the time constant of the model and φ one of the output parameters of the model [27] [28] . The relevant psychometric relationships are employed in all models dealing with the pumping system.

The simulation model makes provision for integral, proportional, derivative, on/off and step controllers. These controllers are used in many control applications. With these controllers any measurable condition can be controlled from a sensor. Water flow rates, dam levels and electricity consumption of the system are controllable variables.

Controller output at each step is only dependent on the previous step values. This considerably reduces the complexity of the solution algorithm. From a system point of view, this implies that the controller acts like a controller that has a sampling rate corresponding to the system integration time step size.

There are also energy management systems included in the simulation tool. By using these simulation tools, the components can be controlled more energy-efficiently to reduce system energy consumption. The simulation tool provides a series of energy management strategies.

Building a simulation of a specific system enables us to test any control system that is developed for that specific system and to determine whether the control strategy that is followed keeps all the constraints within the specified regions. The true value of this lies in the fact that when the control system that is tested fails, the results thereof exist only in the simulated world. This concept was fully utilised in this particular case study.

Surely the most valuable aspect of a simulation is the fact that it can predict future statuses. Simulations can also be used to predict the future status of a system. A simulation that is built to simulate a system can start with either real-world system status as start values or with values that are specified by the user. The simulation can then be run at faster-than-real-time to reach a simulated system condition or status of the system. This principle was also used in this study.

The simulation model has to be completely stable as this simulation model is going to be used in the control strategy. A simulation model that, under certain conditions and input values, does not arrive at an answer, will not work for this application. If the simulation model does not arrive at an answer for whatever reason, these problems can be solved in a simulation model environment where the implications are not critical.

The mathematical models were therefore created in such a way that a solution is always reached. All recursive and loop functions are created in such a way that they stop after a number of cycles are completed. This can lead to a certain amount of inaccuracy, but the error made is small compared to the duration that the simulation is run for. This will become evident in paragraph 7.1 where the verification of the simulation model is discussed.

4.3 Optimisation model

After the simulation model was used to simulate all the selected electrical components of the pumping system, this simulation must be optimised. This optimisation is done with the help of an optimisation model. This optimisation model schedules the selected electrical equipment for an optimised result taking energy usage into account.

It takes into account all the factors that influence the control strategy, such as the price tariff profile, operational constraints and real-time data such as dam water levels, pump-, valve- and chiller statuses. It calculates the optimised schedule for all the selected electrical equipment that contain pumps statuses, valve fractions, chiller set points and chiller statuses.

The completed simulation of the systems creates the opportunity to build an optimisation engine. The heart of the optimisation engine is the system simulation upon which a component scheduler is built. The output of the component scheduler is an operation schedule for every controllable component in the system.

This operation schedule consists of on/off, open/close and set point instructions for every controllable component in the system for the next 24 hours. These set points and constraints are specified by the responsible person on the mine. Controllable components can be pumps, valves, fridge plants, etc. The controllable components in this case study are electric pumps on each level and the bypass valve on 73 level that regulates the water to 71 and 75 level dams.

4.4 Optimisation using the simulation model

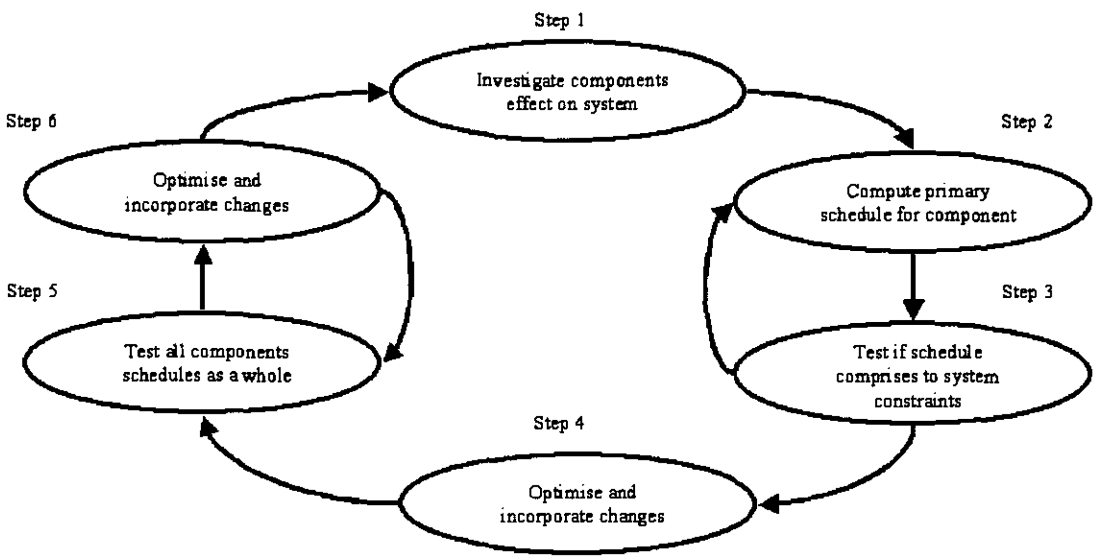

Figure 9: Optimisation cycle

Figure 9 shows the optimisation cycle that is used for the component scheduling and control. During steps one, two and three the components and their operation schedules are handled individually. The system and the complete operation schedule are handled as a whole in steps four to five.

The first step of the optimisation uses the simulation model of the system. Each component is simulated separately to investigate the effect its operation will have on the system. This information is used in the following steps.

Information on the effect that each component will have on the system is known by now. This information is then used to compute a primary schedule for each component individually. Optimising each component individually results in successful optimisation of the system as a whole. This is done during step two of the optimisation cycle. This schedule is computed to realise the most ideal future for the system.

An ideal future for the system is where the electricity cost is the lowest. This is calculated by finding the electricity usage by running a simulation of the system. The cost is then calculated as follows:

$$\textit{Energy cost} = kWh * R$$

Where ***kWh*** is the amount of energy used and ***R*** is the energy unit price for the specific hour.

Step three in the optimisation cycle will test the schedules that have been calculated for the individual components against the system constraints set by the mine. System constraints include maximum and minimum dam levels, max number of pumps running in conjunction, etc. If any constraint is broken the cycle will go back to step two where the schedule will be altered to remedy the problem and compute a new schedule that is within the constraint boundaries.

The test procedure is done by running the simulation while the component schedule is applied. The start values for the simulation are the real-world system statuses. The simulation is then run at faster-than-real-time speed. This gives an almost immediate prediction of the effect the tested schedule will have on the system. If the result is not as expected, changes can be made and another simulation test run can be done.

Optimisation is done during step four. After the schedules for the individual components have been calculated, they are put together. At this point the system will alter the schedules of each component to make sure all the schedules work together. Conflicting actions are eliminated.

During step five all the schedules are put together and again tested in the simulation model. All the operation constraints as given by the operators are tested and confirmed. If any of these should be violated, the optimisation cycle will go back to step four where the schedules will be altered to remedy the problem.

If the schedules are within the specified region and no constraints are violated, the optimisation cycle is successfully completed, and the calculated schedules are used in the simulation model.

5. SOFTWARE CONTROL PHILOSOPHY

This chapter describes the detail of the control philosophy according to which the water pumping system on the mine is controlled. These control philosophies are nothing other than variables, specified by a responsible person on the mine, within which the system must be controlled. These variables range from minimum and maximum dam levels, changing tariff structure, safety regulations and the maximum number of pumps.

5.1 Introduction

As can be seen from the problem statement, the main aim of this study is to implement an energy cost optimisation project on a mine[29] . This project will include the controlling of specific electrical components according to certain variables. The most important variable is surely the changing price tariff structure[30] [31] .

Due to the fact that the unit price tariff directly reflects the demand periods, the load will be shifted if the electrical components are controlled according to these tariff structures.

The other control variables with which the system must comply are the system variables. These variables differ from mine to mine and are provided by the responsible person on the mine. These variables can be anything from minimum or maximum dam levels, pump and column capabilities as well as pump start-up procedures.

5.2 Important variables

The pumping system must be controlled according to certain variables to ensure the success of an energy cost optimisation project on the clear water pumping system.

First of all one should understand the price tariff structure before any savings can be generated. The different price tariffs are discussed in detail in paragraph 1.4. For the purpose of this study we will concentrate on the MegaFlex tariff structure as a control criterion, because the mine that this survey was conducted on, is billed according to the MegaFlex pricing structure. The defined time periods and cost of each period are clearly shown in Table 2 and Table 3.

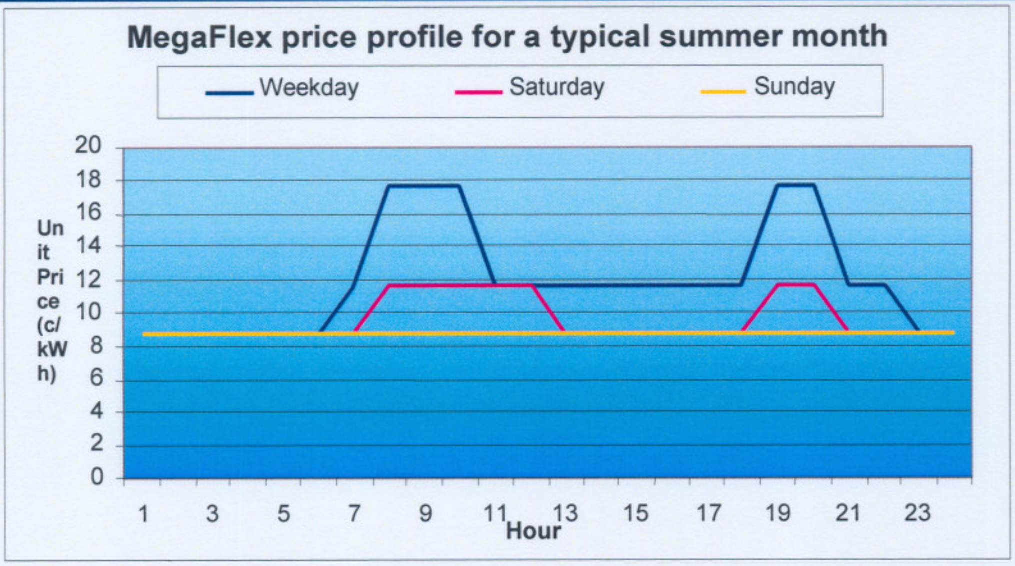

Figure 10: MegaFlex price tariff structure – Summer month

Figure 10 shows the unit price profile for a typical Summer month. Summer months are from September to May. The savings that are generated during these months are not as big as those made in the Winter months because of the hourly rate being significantly smaller than during the Winter months.

The Winter month unit price is in fact much higher than is the case for the Summer months and it is during these months that the enormous electricity cost savings can be achieved. The Winter months, according to Eskom billing tariffs, are June, July and August.

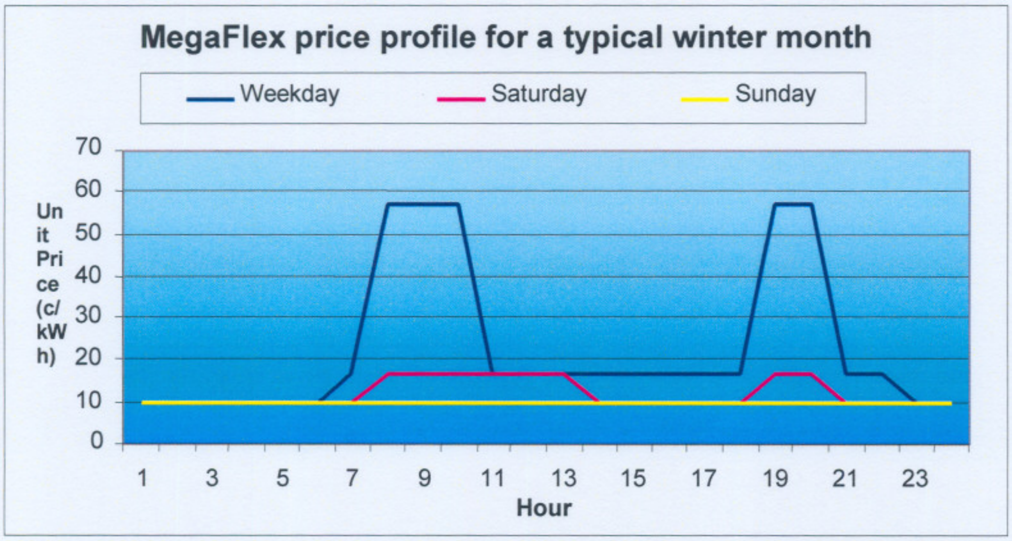

Figure 11: MegaFlex price tariff structure – Winter month

The blue line in Figure 11 is the most important, because it represents the weekday tariff. Weekdays contribute 85% of the weekly tariff price.

After a detailed investigation is done on the mine's pumping system, a result, namely the baseline, is the end product. From this baseline the detailed assumptions can be made and the calculations done.

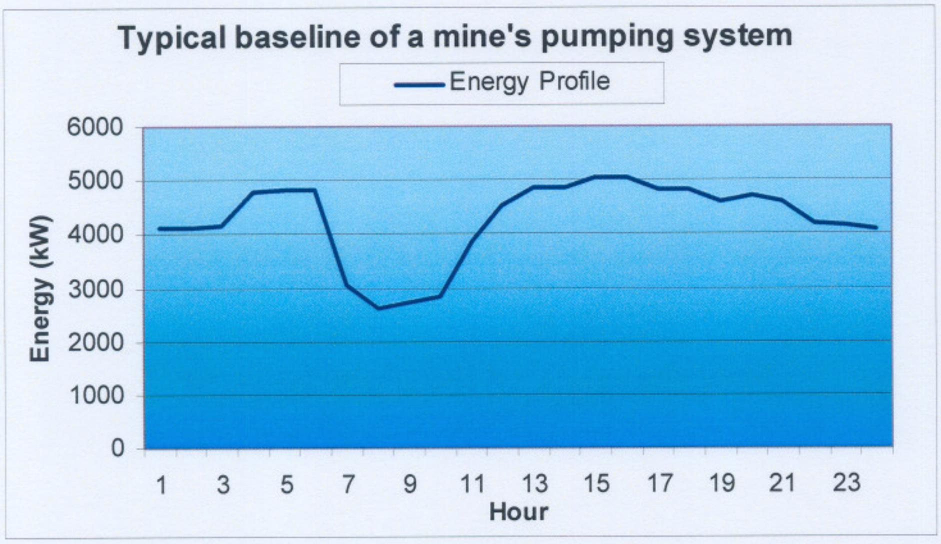

Figure 12: Typical baseline of a mine

Figure 12 shows a typical baseline of Masimong mine's pumping system. From this specific mine's baseline one can assume that there is approximately 4.5 MW potential load present that can be shifted.

Only by using a simulation program can one determine what percentage of this potential can in fact be realised. As mentioned in paragraph 4.2, a simulation model will be used to consider the different constraints that will have an effect on the load shift and simulate an optimised result. These constraints could be dam capacities, pump capabilities or maximum demand control.

5.3 Control strategy

The control strategy behind REMS is as follows: REMS use SCADA tags to obtain information on pump statuses, pump availabilities, valve statuses and dam levels. REMS incorporates the values of these tags into the model and then does a simulation and optimisation according to the variables that are specified for each dam, pump, valve, etc. The result of this simulation is a suggestion as to the number of pumps that should be running at that particular point in time at a specific pump station.

The SCADA system is the backbone of the whole control system on the mine and sends instructions, that are given by the control operator, to the PLCs. These PLCs are connected to pumps, valves and dam level indicators. The PLCs register the value of each tag, and send these values to the SCADA were they are displayed on a screen for the control operator to see.

If the control operator changes the value of any of these tags on the SCADA, the SCADA will alert the PLCs and the PLCs will execute the change.

REMS connect onto the SCADA and replace the decision making of the control operator, with a result from the optimiser. REMS then alert the SCADA to change certain tags. The PLCs receive this message and ensure that it is executed.

Each controller on each level looks at an upstream and a downstream dam as shown in Figure 13. The downstream dam has the control privilege and therefore its constraints are the deciding factor in the decision making process.

Therefore, if the downstream dam is near its maximum dam level constraint, the controller will switch off the pumps that supply this dam with water. This has a backward effect and the next controller upstream should compensate and notice that less water is going out of the downstream dam and he should therefore also switch off pumps when the dam level reaches a certain critical value.

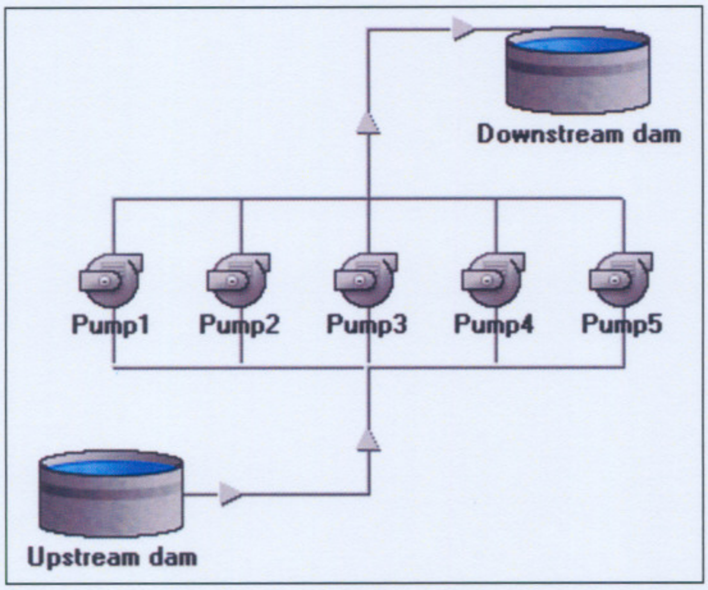

Figure 13: Upstream and downstream dam representation

The control ranges and system constraints are set up in such a way that safety factors are also taken into consideration. These safety factors are things like dam level controls that are set a few percent lower than the extreme maximum of the specific dam.

Looking at the dams at the bottom of the mine, for instance, it will be seen that if these dams flood, many workers' lives will be endangered. Therefore the maximum of these dams is 100%, but with a safety factor built in the mine wants to keep these dams below 80%. 80% is therefore already a dangerous situation for the mine if anything like a malfunctioning level indicator or a power failure should occur.

Therefore it is specified that this specific dam should be kept below 70%. An error field of 10% is built into the control strategy should anything happen with the control systems. Possible problems that may occur are a loss of communication with the SCADA, pump breakdowns, column bursts, etc. If any of these problems occur during a critical time when dam levels are high, the results will be catastrophic. Therefore REMS control the pumps without compromising the safety and control specifications set in the mining industry [32] [33] .

Another important control strategy that is built into the control system is to prevent columns from bursting. This is likely to occur when the pressure in the column is too high due to the amount of water that is pumped through it. Therefore it is specified that only a given number of pumps be allowed to pump simultaneously. This will ensure that the mean time between failures for columns will be extended.

Pump start-up and shut-down procedures are also processes that are very important in enhancing the life of the pump. Before a pump is started up there are a certain procedures that need to be executed. These inspections happen automatically with the help of PLCs, but the control system must give these PLCs enough time to complete the whole start-up procedure. Therefore a pump start-up lack time is also part of the control strategy. The value of this start-up lack time differs with each mine, depending on the start-up procedure that is programmed into the PLCs.

Now the specific system constraints and parameters for each controller will be stipulated.

6. ELANDSRAND CASE STUDY

The purpose of this study was to do an energy cost optimisation on a complex mine pumping system. To prove that this is possible, REMS had to be installed on an active mine's pumping system. Elandsrand Mine was identified as a candidate mine for this survey. It was implemented and full control of the hot water pumping system compliant with the changing tariff structure was achieved. This chapter fully describes the Elandsrand pumping layout and how REMS was installed and set-up on the mine.

6.1 Detailed investigation on Elandsrand Mine

Elandsrand Mine, situated 10 km South-West of Carltonville, is one of the flagship mines in the Harmony Group.

During the 2003 financial year, Elandsrand Mine milled 1,33 million tons of ore. With an average gold recovery of 6.18 g/ton [34] , Elandsrand has produced 8,228 kg of gold during the 2003 financial year.

During 2004 Elandsrand has milled 1,3 million tons of ore. With an average gold recovery of 5.98 g/ton [34] , this adds up to an annual gold production of 7,790 kg for 2004.

Water plays a major role in the mining process. Mining operations cannot commence without an adequate water supply. Most of the water on Elandsrand Mine is actually used for cooling purposes, to cool down the stopes and shafts through various processes. The mine is 3,300 metres deep and 22 ML of water is pumped daily from these levels to the surface. The average amount of energy needed to pump all this water to the surface is 26 MW/day.

During peak times Elandsrand uses an average of 7.8 MW of energy. By implementing REMS on the clear water pumping system, 3 MW of this peak time load can be shifted to another part of the day when the global energy demand is much lower and energy is therefore also much cheaper. The detailed electricity breakdown structure of the mine is shown in the figure below.

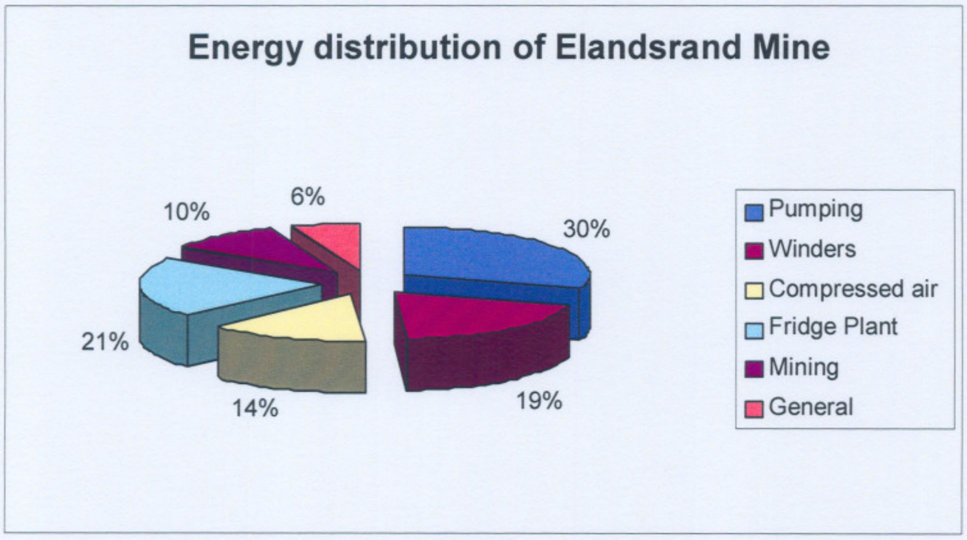

Figure 14: Energy distribution

Elandsrand Mine was identified as a possible candidate on which to do an energy cost optimisation in June 2003. Pump data was obtained from the mine and a detailed investigation was launched. This data had to be processed to obtain a baseline and from there determine the potential load shift that can be realised on Elandsrand Mine during peak periods.

After a detailed investigation on Elandsrand Mine was launched and historical data of the mine investigated, a baseline was obtained for each Weekdays, Saturdays and Sundays. With the help of these baselines the potential load shift on the pumping system was obtained.

In Figure 15 one can see the baseline for a typical weekday of Elandsrand pumping system. This baseline represents the average amount of energy that was used over the past couple of months, and one can assume that they will use the same amount of electricity during the next couple of months.

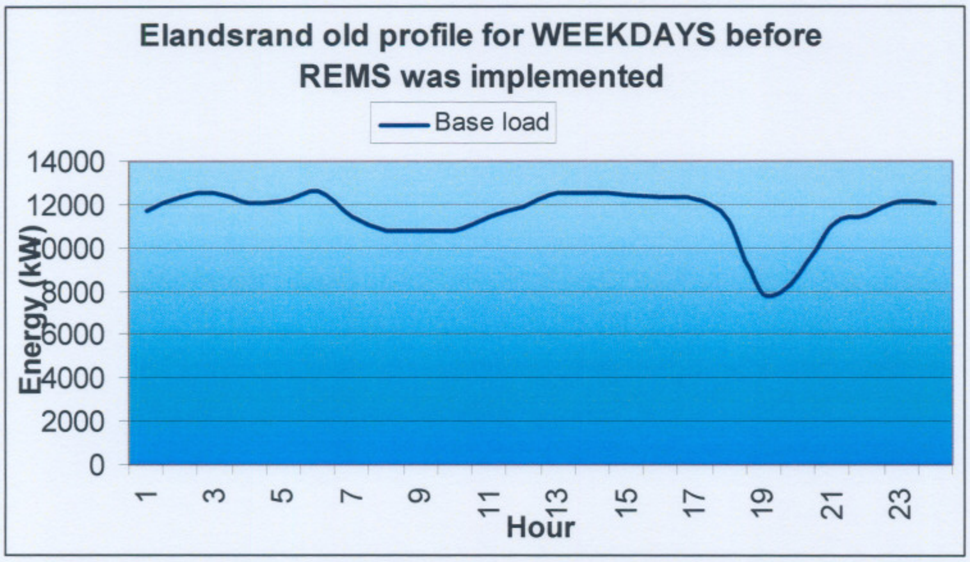

Figure 15: Elandsrand Baseline for Weekdays

Figure 16 and 17 represent a typical baseline for a Saturday and Sunday. These baselines are then use to calculate the load shift during Saturdays and Sundays.

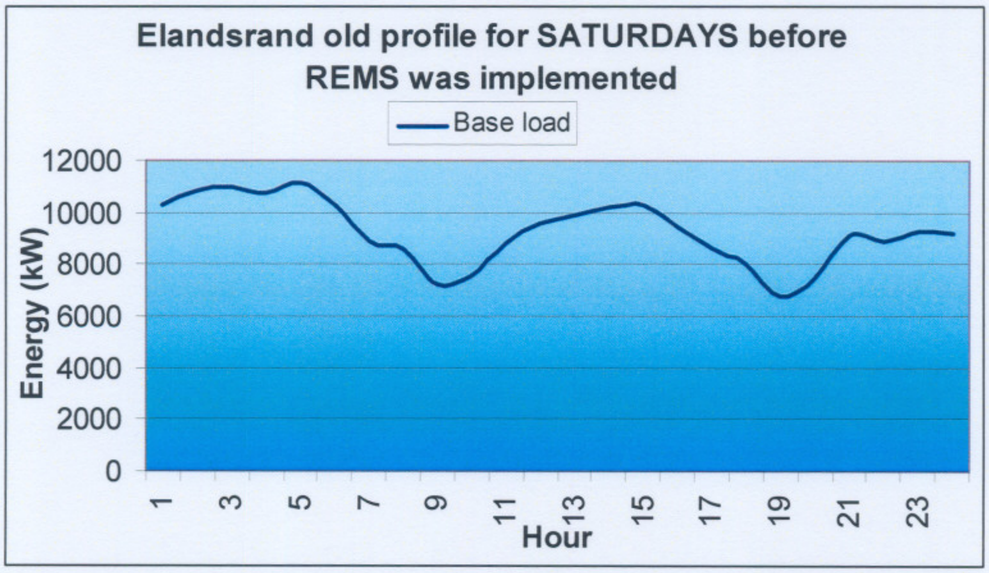

Figure 16: Elandsrand Baseline for Saturdays

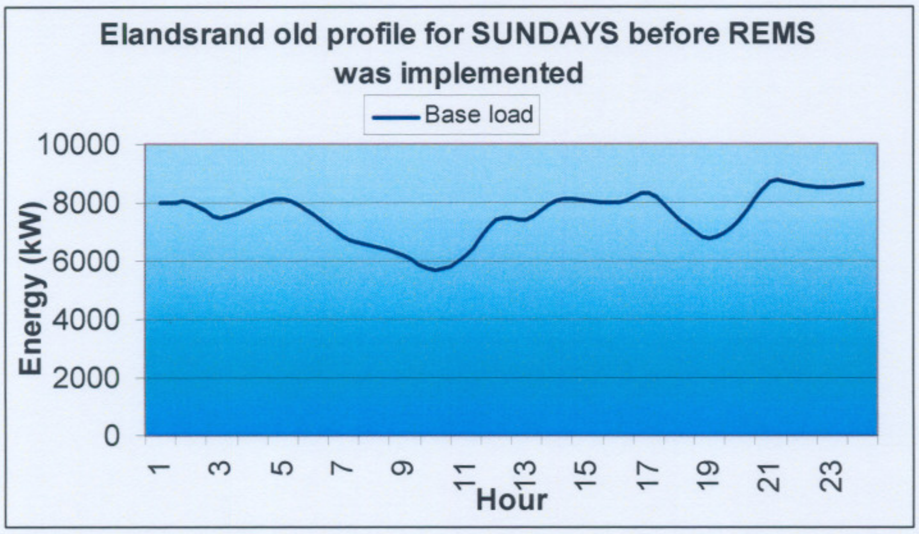

Figure 17: Elandsrand Baseline for Sundays

If one looks at the curves in Figure 15, 16 and 17 a couple of conclusions can be drawn. During the time that this data was obtained, Elandsrand was on a Real-Time Pricing structure (RTP), where the evening peak, between 18:00 and 20:00 was very highly priced, and the morning peak was not that critical. One can see, therefore, that the mine tried to minimise the electricity usage during the evening peak, but could not manage to shift the full load.

From the curve one can see that a possible 7.8 MW load shift potential is available, and only during the simulation will one be able to determine what part of this potential load shift can be realised. Possible factors that will have an effect on this load shift are things like dam capacities, pump and column capabilities, etc.

The reason for making this statement is as follows: If the dam capacity is not capable of accommodating all the water that will flow into it during the two-hour peak period, some pumps will need to run and the full amount of load will not be shifted.

If, for instance, the dam capacity is sufficient to hold all the water that flows into the dam for two hours, then no pumps will need to operate and the full load can be shifted.

The other factor is pump capabilities. The pump capability must be large enough to transfer all this accumulated water before the next peak period, otherwise it won't be possible to shift this load constantly every day.

6.2 Elandsrand clear water pumping system

What makes Elandsrand Mine's system so unique is the fact that it consists of two fridge plants. One fridge plant is situated on surface and the other one is underground on 71 level.

A problem area that was identified from the simulation was that 52 level pump station is forming a bottleneck in the pumping system. The reason for this is that the pump capabilities on 52 level are not as good as those of the other pumping stations.

Figure 18 shows the water pumping system on Elandsrand. The diagram shows that there are five controllers present. Each of these controllers controls a specific pump station according to certain constraints as mentioned in paragraph 6.3.

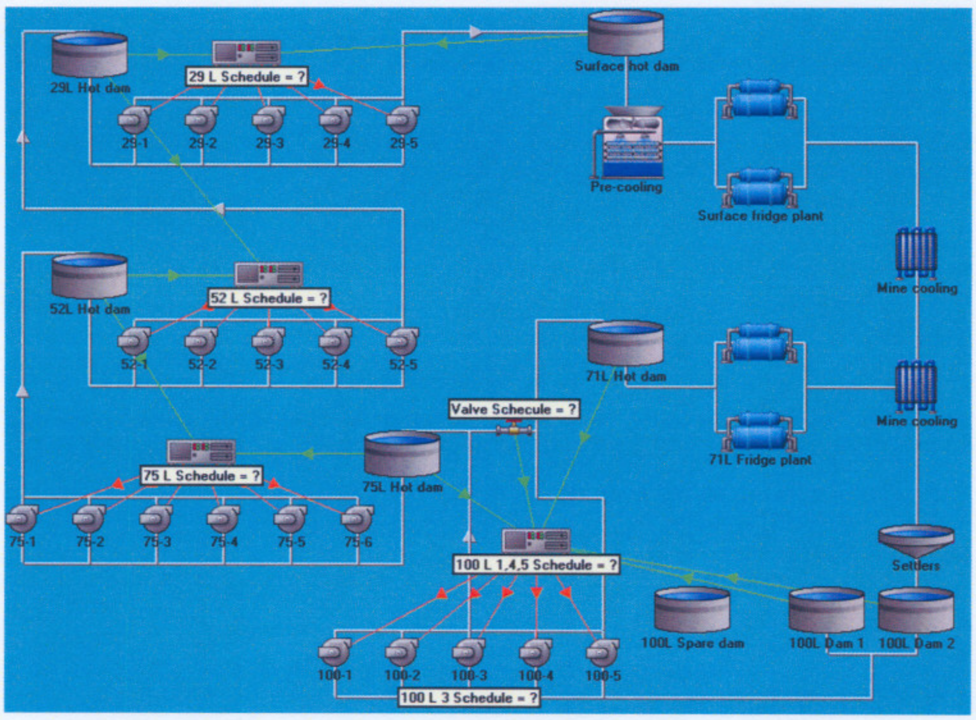

Figure 18: Simulation model of the pumping processes at Elandsrand.

The water cycle starts when the water exits the surface hot dam. This water then enters the pre-cooling were the cooling process starts. From here it travels to the surface fridge plant to be cooled. This water is cooled down to about 5°C from where it goes down the mineshaft to cool down the mine.

After the water has been used for cooling or for the different mining operations, it is re-collected into settlers from where it is pumped through different stages back to the surface dam for re-cooling.

Elandsrand make use of four pump stations to pump this water to the surface dams. After the water has been re-collected in the settlers and the mud has been separated from it by means of the process described in Chapter 3, the water ends up in the 100 level dams, and from here the hot water pumping cycle to the surface starts.

There are two dams on 100 level each with a volume of 4,000 litres. An additional spare dam, with a volume of 4,000 litres, is available if something should happen and extra storage capacity is needed [35] . The spare dam should always be as empty as possible to ensure that the emergency storage is at its maximum. The spare dam was not included in the simulation because it is only a pre-cautionary measure in the event of something happening and storage capacity being needed.

On 100 level there are 5 pumps installed. Pump 100-2 is out of order and could not be included in the simulation. 100 level has been split up into two controllers, viz. 100-1,4,5 controller and 100-3 controller.

First look at the 100-1,4,5 controller. The pumps controlled by this controller are 100-1, 100-4 and 100-5. All three of these are 1600 kW pumps and pump water from 100 level to a bypass valve on 73 level. The bypass valve connects the 75 level and 71 level water columns. This bypass valve is also controlled by REMS and can therefore control the water going to 75 level and 71 level by monitoring their dam levels.

Almost 40% of the total daily water that is pumped from 100 level goes to the 71 level dam that supplies the underground fridge plant with water.

Looking at 100-3 controller, this controller controls only one 1600kW pump and that is pump 100-3. Unlike pumps 100-1,4,5 that are linked with the 73 bypass valve, and from there distribute water to either 71 or 75 level, this pump is directly connected to 75 level.

75 Controller controls the five pumps present on 75 level. This controller looks at 52 level dam as a downstream dam and 75 level dam as an upstream dam.

52 Controller controls the five pumps present on 52 level. This looks at 29 level as a downstream dam and 52 as a upstream dam. It was determined from the simulation model that the 52 level pump station forms a bottleneck in the hot water pumping system. To keep the water cycle in balance, there should always be one more pump running on this level than is the case on the other levels.

6.3 System constraints and parameters

In this paragraph the detailed system constraints according to which the clear water pumping system needs to be controlled is discussed. These constraints are the same criteria according to which the control operators controlled the pumps previously before an automatic control system was installed.

The tables below specify the maximum number of pumps allowed to run simultaneously, for each level. This is done for safety and maintenance purposes, as requested by the mine. If more pumps are running than a specific column can handle, the risk of column bursts increases and REMS will therefore not start more pumps than specified.

The maximum and minimum dam levels for the upstream and downstream dam are specified. All the necessary safety and precautionary measures have already been incorporated into the specified values.

First of all we look at the constraints on 100 level controller 1,4,5

100 Level Controller 1,4,5 Constraints	
Maximum number of pumps	2
UPSTREAM	
Maximum damlevel	75%
Minimum damlevel	35%
DOWNSTREAM	
Maximum damlevel	110%
Minimum damlevel	96%

The constraints on 100 level Controller 3.

100 Level Controller 3 Constraints	
Maximum number of pumps	1
UPSTREAM	
Maximum damlevel	79%
Minimum damlevel	36%
DOWNSTREAM	
Maximum damlevel	110%
Minimum damlevel	96%

The constraints on 75 level Controller.

75 Level Controller Constraints	
Maximum number of pumps	5
UPSTREAM	
Maximum damlevel	99%
Minimum damlevel	92%
DOWNSTREAM	
Maximum damlevel	95%
Minimum damlevel	87%

The constraints on 52 level Controller.

52 Level Controller Constraints	
Maximum number of pumps	5
UPSTREAM	
Maximum damlevel	93%
Minimum damlevel	90%
DOWNSTREAM	
Maximum damlevel	94%
Minimum damlevel	87%

The constraints on 29 level Controller.

29 Level Controller Constraints	
Maximum number of pumps	5
UPSTREAM	
Maximum damlevel	93%
Minimum damlevel	89%
DOWNSTREAM	
Maximum damlevel	100%
Minimum damlevel	60%

The constraints for the 73 bypass valve are as follows:

73 Level Valve Controller	
OPEN DAM	
Maximum damlevel	100%
Minimum damlevel	90%
CLOSED DAM	
Maximum damlevel	98%
Minimum damlevel	72%
Control Range	22%

The valve controller looks at the dam where the water flows to as the open dam, and the dam that does not get any water as the closed dam. The control range has been inserted into the controller to keep the valve from opening and closing within minutes. After the valve has switched over, therefore, the dam level of the closed dam must drop by 22% before the valve will be able to switch over again.

6.4 Calculating the expected results

There are always practical and theoretical calculations in any study. During the simulation a number of pumps were running. This number can actually be calculated by looking at some basic calculations to determine whether the simulation results are within limits.

A: Calculations considering the volume of water that is pumped out of the mine on a daily basis.

Water that should be pumped out daily:	=	22 ML
Thus water that should be pumped hourly	=	22/24
	=	0.9166 ML/hr*(1×10^6ℓ/3600sec)
	=	254,63 l/s
Pump capacity on 100 level	=	110 l/s pump per day

Thus number of pumps	=	254.63/110
	=	2,3 pumps

Thus an average of 2.3 pumps on 100 Level must run to pump the 22 ML water from the mine.

Number of daily pump hours	=	2.3 x 24
	=	55.2 pump hrs / day
	=	1656 pump hrs/month of 30 days

Because the pump energy used is	=	2000 kW per pump
the monthly energy usage is	=	2000 x 1656
	=	**3 312 000 kWh per month**

This figure is only for 100 level pumping station

For the other pumping stations a similar calculation can be done. The only difference is that only 60% of the total amount of water that is pumped from 100 level is pumped to the surface via 75, 52 and 29 levels. The other 40% of the water ends up in the 73 level dam that supplies the underground fridge plant. Therefore only 13.2 ML of water is pumped to the surface.

Water that should be pumped out daily:	=	13.2 ML
Thus water that should be pumped hourly	=	13.2/24
	=	0.55 ML/hr*($1x10^6$ℓ/3600sec)
	=	152,77 l/s
Pump capacity on 100 level	=	110 l/s pump per day
Thus number of pumps	=	152.77/110
	=	1,38 pumps

Thus an average of 1.38 pumps on 75 level must run to pump the 13.2 ML water from the mine.

Number of daily pump hours	=	1.38 x 24
	=	33.12 pump hrs / day
	=	993.6 pump hrs/month of 30 days

Because the pump energy used is = 2000 kW per pump

the monthly energy usage is = 2000 x 1656

= **1 987 200 kWh per month per pumping station**

This value is the same for 75 level, 52 level, and 29 level. The total theoretical value for energy used in this mine's pumping system is

[redacted]	[redacted]
100 Level	3,312,000
75 Level	1,987,200
52 Level	1,987,200
29 Level	1,987,200
[redacted]	**9,273,600**
[redacted]	**309,120**

B: Calculating the financial benefits that the mine can expect

Daily load shift

The pump statuses of each pump that is automatically controlled are logged every 2 minutes. These statuses are then processed into a usable format to determine for what fraction of the hour the pump was running and the kW that the pump used for that specific hour. This usable format for a actual day looks as follows:

[redacted]	[redacted]
1	13403
2	13290
3	12690
4	10877
5	14117
6	12883
7	11703
8	10863
9	12430
10	13050
11	13417
12	11237
13	12397
14	5610
15	12597
16	14103
17	10397
18	12870
19	3277
20	6755
21	11752
22	14403
23	11063
24	13490

Table 4: Hourly energy usage

Use the tariff structure applicable for that day. Use either the Weekday, Saturday or Sunday profile, for either a Winter or a Summer day. The table below shows an example of a typical Winter weekday profile.

1	9.84
2	9.84
3	9.84
4	9.84
5	9.84
6	9.84
7	16.59
8	57.50
9	57.50
10	57.50
11	16.59
12	16.59
13	16.59
14	16.59
15	16.59
16	16.59
17	16.59
18	16.59
19	57.50
20	57.50
21	16.59
22	16.59
23	9.84
24	9.84

Table 5: MegaFlex price tariff

Calculating the electricity cost for a specific hour is done as follows:
For hour 19 the energy used was 3277 kW. The hourly tariff for hour 19 was 57.5c/kWh.

Therefore = 3277 * 57.5
= R1 884.27

Thus the energy cost for hour 19 was R1 884.27. To determine the daily energy cost this process is repeated hourly and all these values are added.

Cost saving calculation

To calculate the electricity cost saving for a day, a base load is needed with which to compare the daily energy that is used. See Figure 5 on p.7 to better understand the following explanation. Electricity cost savings is only generated if the energy usage for a specific hour is below the base load. If the energy usage profile is above the base load profile a loss in savings is generated.

If we use Table 4 and Table 5 as examples to determine the electricity cost savings generated for that specific day, the result looks as follows:

[illegible]	[illegible]
1	-14,298.23
2	-7,457.30
3	-437.78
4	14,015.77
5	-15,936.50
6	-2,808.45
7	-5,767.15
8	-5,886.59
9	-114,793.93
10	-152,748.71
11	-36,739.28
12	8,152.59
13	-428.27
14	115,810.27
15	-642.53
16	-29,545.05
17	29,184.59
18	-28,203.85
19	289,303.76
20	140,853.86
21	-5,178.19
22	-44,757.34
23	11,592.31
24	-12,609.34
[illegible]	[illegible]

Table 6: Hourly saving generated

This saving can be increased by using even less energy during the high cost hours.

6.5 Building and optimising the Elandsrand simulation

As mentioned earlier in the thesis, an extensively verified simulation procedure was used to find the optimised equipment control for maximum load shift. Let us discuss the procedure in more detail.

To shift load, the operation schedule on a mine has to be changed from its current one. However, mines will only change their operations if there is a very high level of confidence that these changes will not in any way affect the safety and production of the mine. In order to gain the confidence of the mine, we first have to prove beyond any doubt that there will be no negative effects as a result of any load shift suggestions by the REMS system.

This can only be achieved if the fully integrated operation of the mine can be simulated in exact detail and extensively verified through previous years' detailed operational data. Except for TEMMI's system, such a detailed integrated, dynamic, control simulation procedure for the full mine operation could not be found in South Africa or internationally.

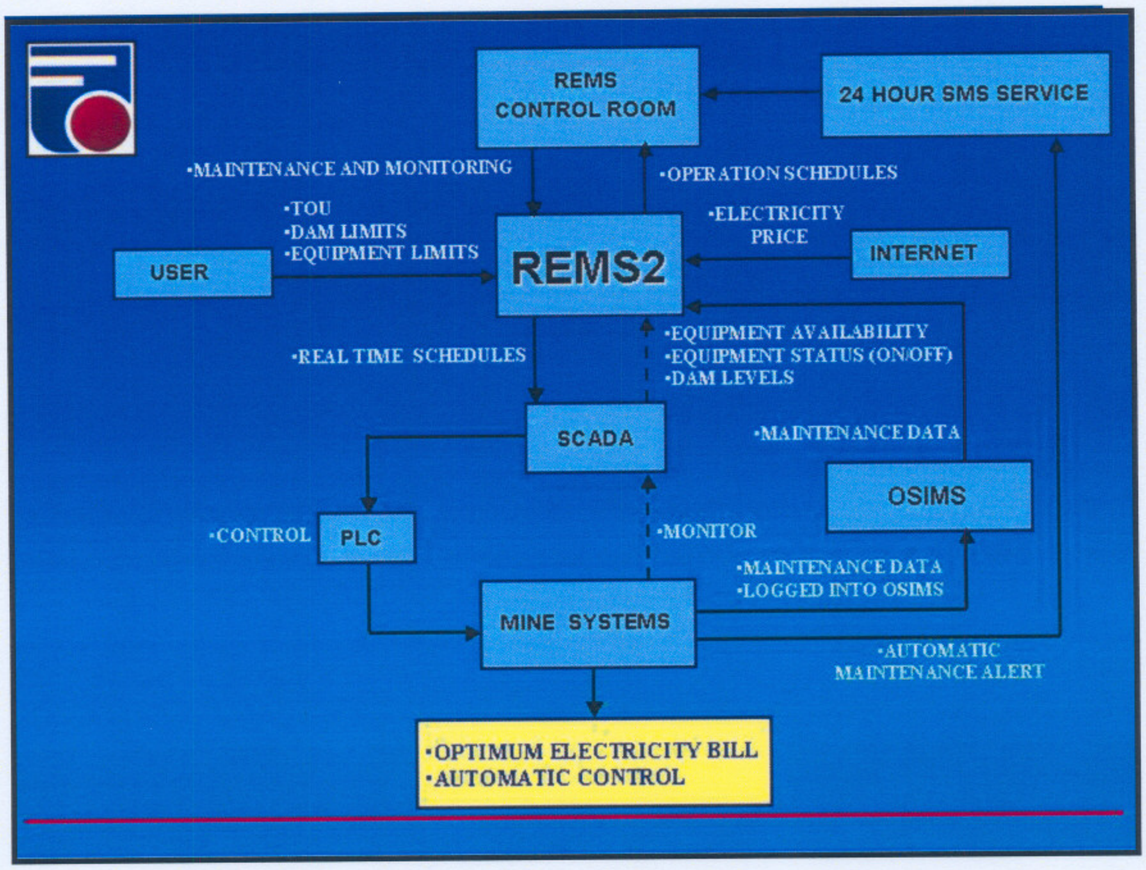

Figure 19: Patented integrated REMS technology.

The average daily pump load profile, before the REMS intervention, and our recommended optimised profile, are shown in Figure 19. Note that it was previously only possible for this very energy-conscious mine to react partly on the second high price signal.

It is very difficult, if not impossible, to stay within constraints, e.g. dam levels, amount of pumps available, etc. if a full optimisation of the complete system is not done as we suggested with REMS. The result is a missed load shift opportunity during the evening peak.

The full potential of the on-site REMS technology can be realised when the current profile is compared to the recommended optimised profile. By comparing the current load profile with our recommended optimised profile it can be seen that more than a 3 MW load shift potential exists between 18:00 and 20:00.

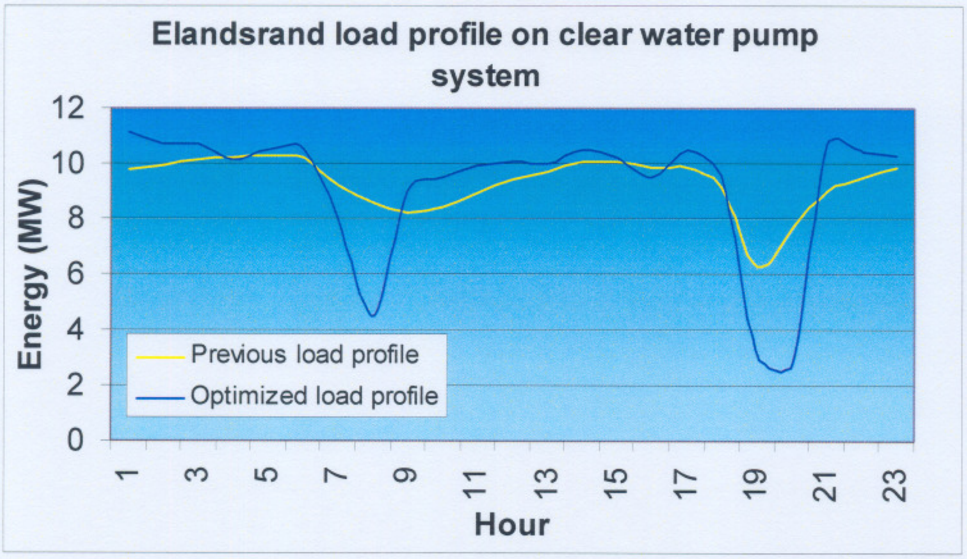

Figure 20: Load profile for the pumps for Elandsrand.

The area under each load profile represents the average daily energy use on the pumps. The amount of energy used for each profile is the same. As the peak time energy is more expensive, a load shift results in an energy cost saving.

A ballpark figure for the extra energy savings, based on our experience up to now and the best calculations we can do, is R100 000/MW/year. This means that REMS will lead to an extra saving of ± R300 000.

Production and operating constraints that were taken into account are the following:

1. Maximum number of pumps active daily
2. Minimum and maximum dam levels and dam capacities
3. Underground water usage
4. Safety constraints
5. Maintenance constraints
6. Allowable on/off switch periods for all elements

The following additional work was carried out at the request of Elandsrand mining personnel to ensure better control:

1) There was a problem in making the tags available through the ADROIT SCADA system. To solve this problem, OPC software was obtained from ADROIT.
2) There was some difficulty in reading and manipulating the necessary ADROIT tags. Rebuilding some of the tag groups of the mine solved this problem.
3) Because of the new use of OPC the mine ran out of scan points. ADROIT kindly gave the mine 2500 scan points free of charge.
4) There was some interference between the ADROIT and REMS control. ADROIT would switch pumps off and REMS would immediately switch them on again. This problem was rectified by developing a new control function for REMS.
5) During the time that REMS was in control of the pumping system, the mine personnel were concerned that the opening and closing of the level 73 bypass valve occurred too frequently. New and modified functions were developed for REMS to address this situation.
6) Mine officials were concerned that some of the pumps were stopping and starting too frequently. New functions were built into REMS to prevent this from happening.
7) Initially it was difficult to maintain the correct water balance in the mine. A new water control paradigm was developed to carry out hourly water control optimisations.
8) A new alarm system was developed and included in the REMS package. This system will alert the control operator when any of the dam levels are either too low or too high.

7. RESULTS AND DISCUSSIONS

The results which were obtained from the simulation model had first to be verified. The verification process was done by comparing the dam levels in the simulation model with the actual dam levels. A very small deviation was observed and therefore the simulation data was used to do the necessary calculations.

7.1 Verification method

The complete Elandsrand pumping system was built up in the simulation platform. The system was exactly duplicated where mathematical pump models were used to represent real pumps and so on. This complete simulation will from here on called the Elandsrand simulation. Figure 21 shows a simplified schematic representation of the Elandsrand water pumping system that was simulated.

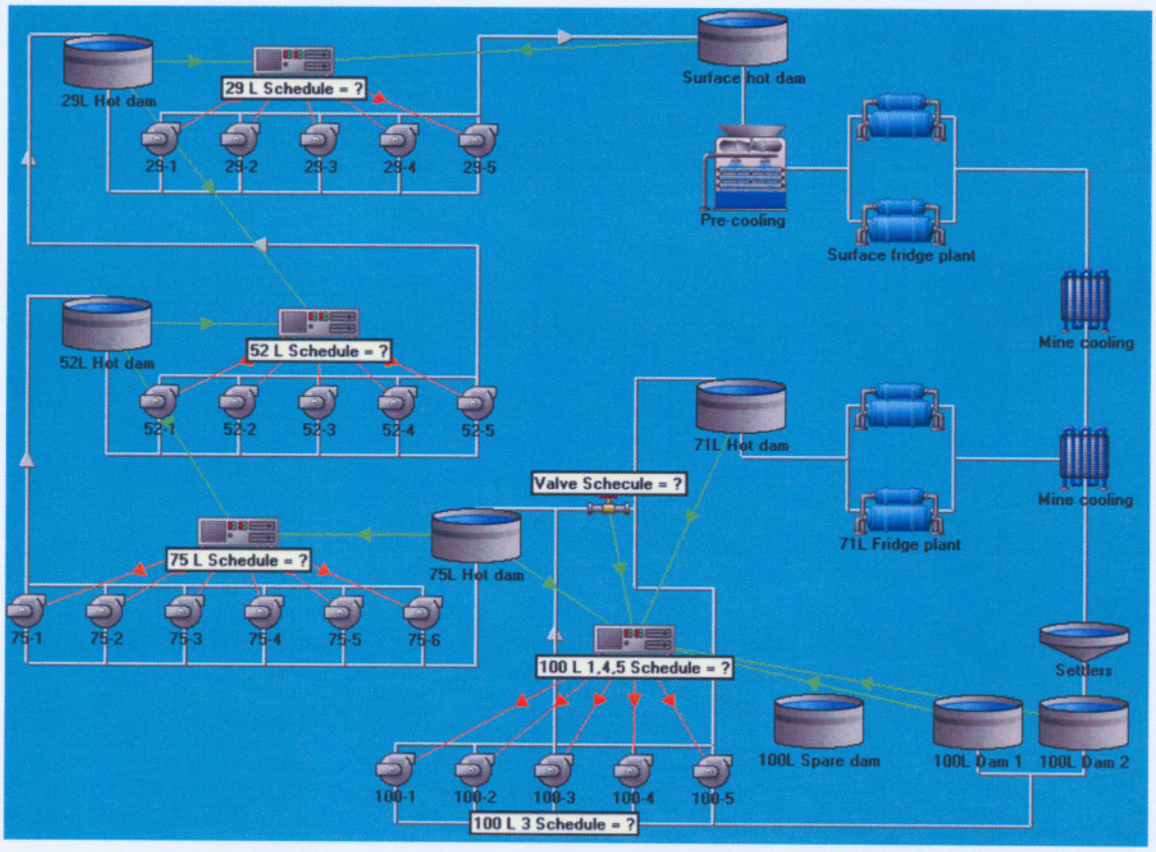

Figure 21: Simplified representation of the Elandsrand Water Pumping System

The Elandsrand simulation was verified by running it in conjunction with the real-world hot water pumping system. To do the verification the simulation was started with the real-world systems status as start values. This includes dam water levels and pump statuses. The outcome of the simulation is then compared to the conditions in the real-world system.

The controllable components of the system are the pumps. Because of this the pumps in the simulation were controlled in the same way as the pumps in the real world system. In other words, every time a pump was started in the real-word system, the representative pump in the simulation was started and the other way around.

The accuracy of simulation was then measured by comparing the real-world dam levels with the simulated dam levels. The simulation was run for a couple of days where the simulation status was synchronised with the real-word status at the beginning of each day.

The figures below show the real world and simulated dam levels of different dams in the same simulation. All these figures report results for a 24-hour period. The simulation status was synchronised with the real-world status at the start of each day.

Looking at Figures 22, 23, 24, 25 one will see the dam levels that were registered during the simulation period for each of the dams.

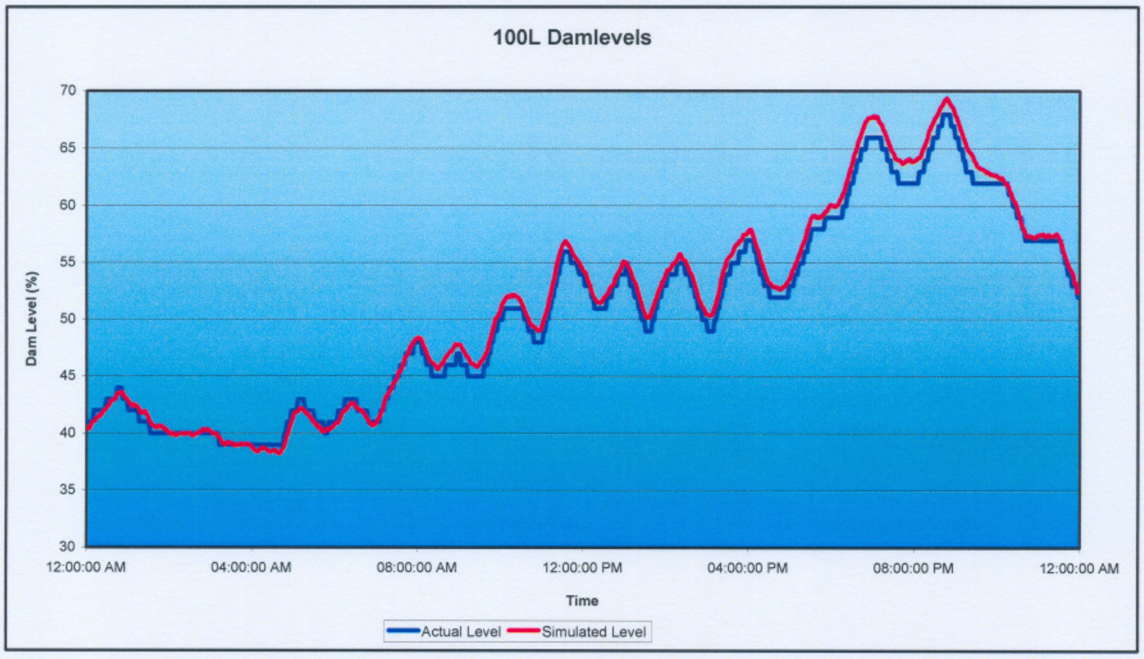

Figure 22: Measured and simulated dam levels – 100 Level

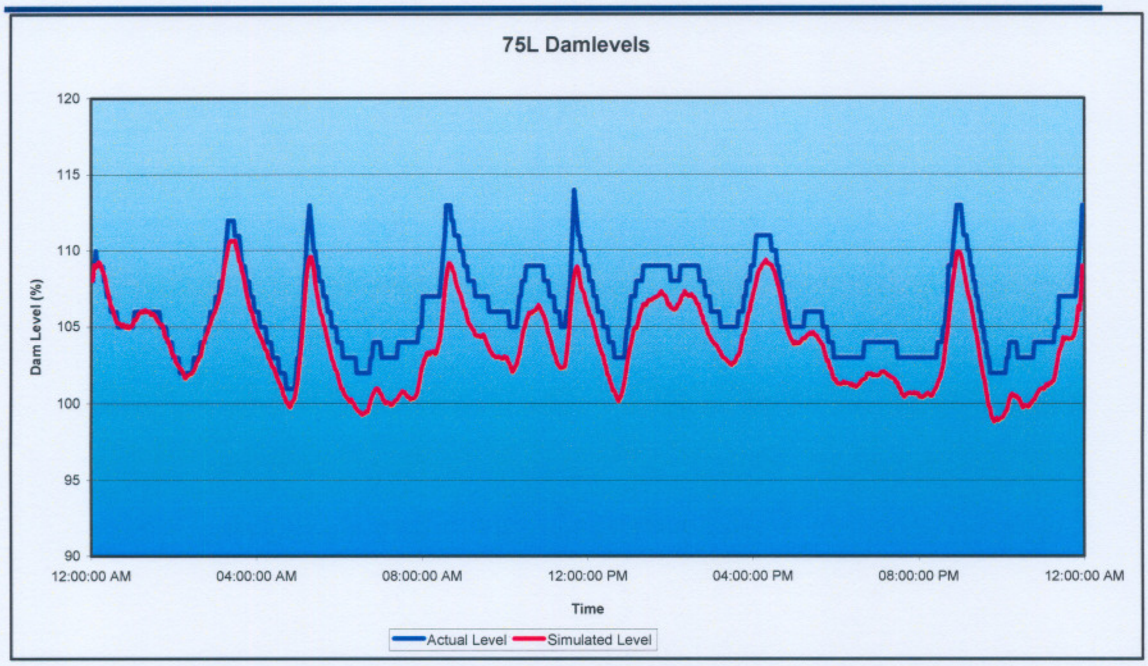

Figure 23: Measured and simulated dam levels - 75 Level

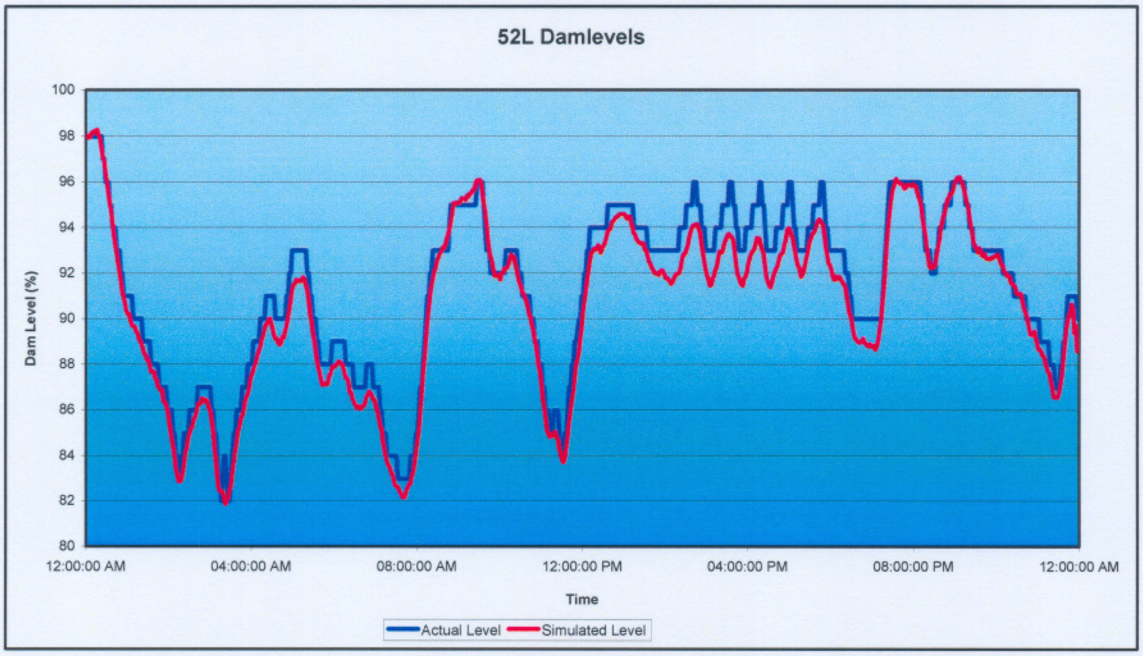

Figure 24: Measured and simulated dam levels - 52 Level

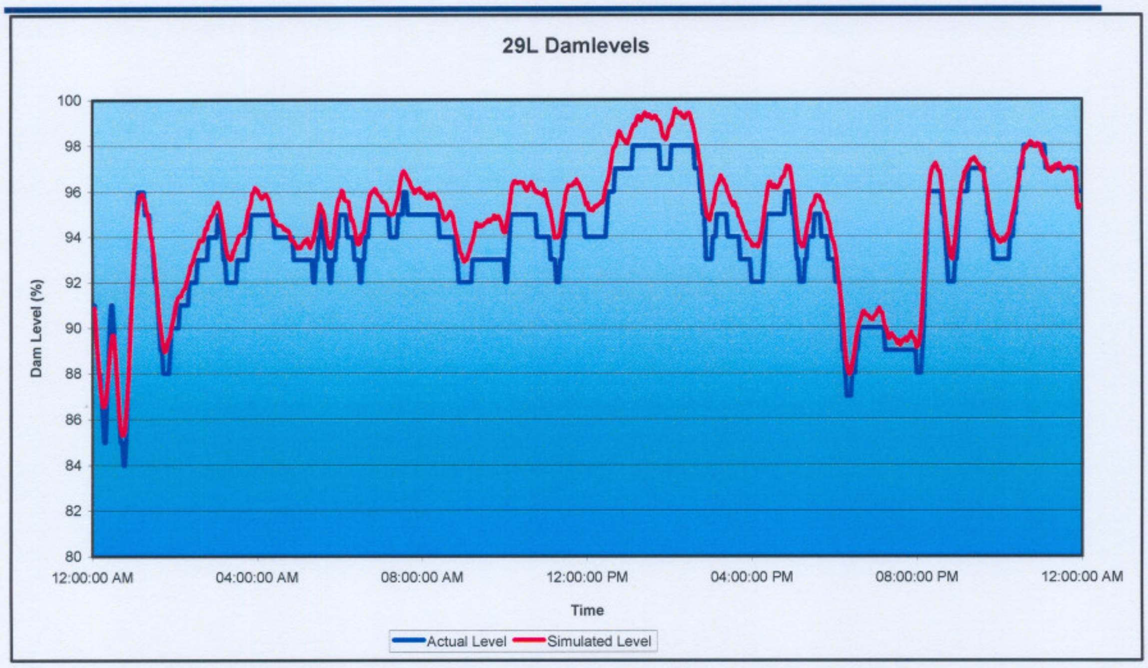

Figure 25: Measured and simulated dam levels - 29 Level

On average, less than 3,5% deviation accumulated in a 24-hour time period. This gives an indication of the accuracy of the Elandsrand simulation. This also indicates that the simulation will be adequate to give a 24-hour ahead of time prediction of the Elandsrand hot water pumping system.

After this verification process it can be said with certainty that the simulation model correctly represents the integrated operation on the mine.

7.2 Results

The objective of this study was to implement a cost effective energy control system on a complex mine pumping system. To achieve this goal, there were objectives that needed to be adhered to. These objectives were discussed in paragraph 5.2. The most important objective is surely the load shift that should be achieved, because if these criteria are met, the cost savings will automatically result. In this paragraph the results obtained from the study are shown.

The project was commissioned in June 2004. Since then the pumping system reacted well to the price tariff structure and very good load shift results were obtained. In the table below one can see the results obtained since the day of commissioning.

The possible load shift that was calculated from the simulation program was 3 MW. This value was promised to Eskom and from this value the mine could save R600 000 for the year. One can see from the table that over this period an average load shift of 3.66 MW was achieved. The load shift over this 5-month period has saved the mine R357 039.

Load shifted:

June	4.96 MW
July	3.09 MW
August	4.15 MW
September	3.12 MW
October	3.49 MW
November	3.15 MW
Average	**3.66 MW**

Financial benefits:

June	R 91 652
July	R 73 897
August	R 136 358
September	R 18 697
October	R 21 954
November	R 15 501
Average	**R 59 986.50**

7.3 Discussion of results

The purpose of this project was to do an energy cost optimisation on a specific complex mine pumping system by means of load shift. A Real-Time Energy Management System (REMS) was installed on the mine and the pumps were controlled according to certain constraints.

A load shift factor of 3 MW was obtained from the simulation and this value was promised to Eskom. This load shift value would have resulted annually in a R600 000 saving for the mine.

The results that were obtained were very satisfactory as can be seen from the tables above. An average load shift of 3.66 MW was sustained over the 5-month period. This load shift resulted in a cost saving of R357 039.

During the implementation phase, while the real-time simulation has run on the mine, some other factors that influence the load shift were identified and an even further optimisation has been done. This further optimisation has resulted in a better load shift realisation.

8. CONCLUSIONS AND RECOMMENDATIONS

The results that were obtained in Chapter 7 are summarised and discussed in this chapter. Recommendations are made to optimise the energy cost and ensure that even better automatic control is achieved on the mine.

8.1 Introduction

After Elandsrand mine was identified as a possible candidate for a DSM project in June 2003, a detailed survey of the mine was executed. From this survey it was clear that a load shift of 3 MW peak load can sustainably be shifted to another time during the day.

After the simulation model of the mine had been run, some results were obtained. As shown in paragraph 7.1 the simulation values of the dam levels correlated very well with the real life values.

8.2 Promised load shift

The promised load shift on Elandrand Mine was 3 MW. After REMS was implemented on the mine pumping system, the results were very satisfying. The load shift results were above the expected values as can be seen in the table below.

[illegible]	[illegible]
June	4.96 MW
July	3.09 MW
August	4.15 MW
September	3.12 MW
October	3.49 MW
November	3.15 MW
Average	**3.66 MW**

The reason for this was that the control strategy was optimised even further after implementation. Due to the fact that the simulation model was run on faster-than-normal time, all the problem areas could not immediately have been identified. But during the implementation when the control strategy was monitored, the fine-tuning was done which resulted in even better load shift possibilities.

8.3 Financial benefits

The financial benefits have also increased because of the better load shift. Therefore where the mine could only have gained R300 000 per year from this project, the possibility now exists of saving R360 000 a year. A summary of the monthly savings is shown below.

June	R 91 652
July	R 73 897
August	R 136 358
September	R 18 697
October	R 21 954
November	R 15 501
Average	**R 59 986.50**

8.4 Recommendations for further work

Some important recommendations have resulted from this study which could make this energy cost optimisation on the mine an even bigger success.

Firstly, the same study that was conducted on the mine pumping system should be done on other big electricity-using components such as the fridge plants, compressors, winders and mills. Controlling all of these components as a network of electricity-using components will ensure an even bigger load shift from the peak periods and directly generate bigger savings on the monthly electricity bill.

Another big advantage of controlling all the electrical components as an integrated network, is the maximum demand (MD) control. The MD is part of the electricity calculation formula. The maximum value that is reached, and maintained for 30 minutes, during a month, determines the MD factor. The electricity usage is multiplied by this MD factor to calculate the electricity usage. If the MD is exceeded the monthly electricity bill is affected.

Therefore if the MD can be controlled by the switching of some electrical components whenever the MD is near its critical point, the MD will not exceed the maximum value and money will be saved.

REFERENCES

[1] Goldberg, I., South Africa's Mineral Industry, 1992, pp. 1-12

[2] Preliminary energy outlook for South Africa, Energy Research Institute, Dept of Mechanical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, October 2001.

[3] Mining: production and sales, Statistical release P2041, Statistics South Africa, http://www.statssa.gov.za/Statistical release/ Contact numbers +27 12 310 8095 / 8390 / 8351, Postal address: Private Bag X44, Pretoria, 0001.

[4] Lane I.E., Report for Department of Mineral & Energy Affairs, Load Audits and Simulations to Develop DSM Potential in the Mining Sector, Chief Directorate Energy, Department of Minerals & Energy Affairs, Private Bag X59, Pretoria, 0001, 1996.

[5] DME, Energy balances, http://www.dme.gov.za/energy/ Energy balance for 1997. Contact details: Tel: +27 12 317 9000, Private Bag X59, Pretoria, 0001.

[6] Eskom (DSM), Electricity Supply Statistics for South Africa, Electricity Demand Department, P O Box 1091, Johannesburg, 2000, South Africa. www.Eskom.co.za/tariffs/tariffs/megaflex.htm

[7] Eskom Tariffs, 2002/2003.

[8] Kern C.F., Real-Time Pricing Directive, Key Customer Marketing, Eskom, May 1998.

[9] Eskom / Urban Tariffs / Real-Time Pricing.

[10] McDonald, J.R., Whiting P.A., Lo K.L., Optimised reaction of large electrical consumers in response to spot-price tariffs, Electrical Power and Energy Systems, Vol. 16, No. 1, pp 35-48, 1994

[11] Eskom / Urban Tariffs / Megaflex.

[12] What is an ESCO, www.naesco.org, 1615 M Street, NW, Suite 800, Washington DC, 20036, USA, June 2000.

[13] Delport G.J., Lane I.E., Electricity cost management in mining, Power Engineering Journal, Vol. 10, No. 4, pp 169-175, 1996.

[14] NAESCO Press Release: New Report Documents $2 Billion Annual Investment in Energy Efficiency by ESCOs, www.naesco.org, 1615 M Street, NW, Suite 800, Washington DC, 20036, USA, 30 May, 2002.

[15] Rousseau P.G., Mathews E.H., Needs and trends in integrated building and HVAC thermal design tools. Building and Environment 1993; 28 (4): 439-52.

[16] Hirsch J.J., Winkelmann F.C., Buhl W.F., Ellington K.L., Powerdoe, A windows-based visually oriented analysis tool. In: Mitchell J.W., Beckman W.A., editors. Building simulation 1995 Fourth International Conference Proceedings, Madison, W.I., USA, August 1995, IBPSA.

[17] Leburn, Simulation of HVAC systems, Renewable Energy 1994, 5 (5) pp.1151-1158.

[18] Zaloom, U.S. Pat. No. 6366889, www.uspto.gov, U.S. Patent and Trademark Office, Crystal Plaza 3, Room 2C02, Washington, DC, 20231, 2002.

[19] Woolard et al, U.S. Pat. No. 6178362, www.uspto.gov, U.S. Patent and Trademark Office, Crystal Plaza 3, Room 2C02, Washington, DC, 20231, 2001.

[20] Cascia et al, U.S. Pat. No. 5963458, www.uspto.gov, U.S. Patent and Trademark Office, Crystal Plaza 3, Room 2C02, Washington, DC, 20231, 1999.

[21] Irvin et al, U.S. Pat. No. 6178393, www.uspto.gov, U.S. Patent and Trademark Office, Crystal Plaza 3, Room 2C02, Washington, DC, 20231, 2001.

[22] IST Otokon Pty (Ltd), P O Box 6358, Baillie Park, 2526, South Africa, www.ist.co.za, 2002.

[23] H20NET Scheduler, MWH Soft Inc., 370 Interlocken Boulevard, Suite 300, Broomfield, CO 80021 USA, www.mwhsoft.com, 2002.

[24] MISER Pump scheduling, Tynemarch Systems Engineering Ltd, Crossways House, 54-60 South Street, Dorking, Surrey, RH4 2HQ, United Kingdom, www.tynemarch.co.uk, 2002.

[25] The DERCETOE, Beca Applied Technologies Ltd, PO Box 6345 Auckland, New Zealand, www.derceto.com, 2002.

[26] Rousseau P.G., Integrated building and HVAC Thermal Simulation. PhD thesis, Mechanical Engineering, University of Pretoria 1994.

[27] Van Heerden E., Integrated simulation of building thermal performance, HVAC systems and control. PhD thesis, Mechanical Engineering, University of Pretoria 1997.

[28] Doebelin E.O., System modelling and response. John Wiley & Sons, Culinary Centre, 225 Crummer Lane, Reno, Nevada, 1980.

[29] Dr Ruiter H., Energy savings in mining, Mining Magazine, Vol. 167, No 4, October 1992.

[30] Vold P., O'Neill P.J., Carmichael L., Control systems for use with real-time pricing tariffs, Proceedings of the American Power Conference, Volume 59, No. 2, pp 1052-2057, 1997.

[31] Daryanian B., Northford L.K., Tabors R.D., RTP-based energy management system: monitoring, communication and control requirements for buildings under real-time pricing.

[32] Baker-Duly H.C., Ramsden R., Mackay J.G., Water system management and the implication of energy use and cost, The South African Mechanical Engineer, Vol. 43, February 1993.

[33] De Ruiter H., Lauzon D., The design and installation of a mine monitoring and control system, CIM Bulletin, Canadian Institute of Mining Metallurgy and Petroleum, Suite 1210, 3400 de Maisonneuve Blvd. W. Montreal, QC H3Z 3B8, October 1991.

[34] Harmony gold, website, www.harmony.co.za/operations_elandsrand.cfm

[35] Janse van Vuuren, S.P., A thermal storage system for surface fridge plants, journal of the Mine Ventilation Society, (May 1983), 36, 45-52.

[36] Els R, Potential for load shifting in Ventilation and Cooling Systems 2000, pp. 56 –57.