Investigating Load Shift and Energy Efficiency of New Technology Loco Battery Chargers

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ABSTRACT

Title	:	Investigating Load Shift and Energy Efficiency of New Technology Loco Battery Chargers
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An investigation was conducted into the potential to do demand side management on the locomotive battery chargers on South African mines. The potential to do load shift and energy efficiency on new technology battery chargers was examined.

A simulation model was drawn up to simulate the potential to do load shift on the currently installed battery chargers. This model was further extended to include the high frequency battery chargers, to enable the simulation of load shift and energy efficiency of these chargers.

Electricity utilisation on the locomotive battery chargers on a mine can be increased from about 50% to 96% by replacing the currently installed ferro resonant chargers with new technology, high frequency battery chargers. This results in an energy efficient implementation.

It is also possible to realise load shift on these high frequency battery chargers to realise more electricity cost savings, as well as to reduce the electrical load in Eskom's peak time(s). Electrical energy cost savings of up to R 442 600 is possible by replacing all the chargers with high frequency chargers and doing load shift in Eskom's peak times. The payback can be as short as 2.7 years.

It is also possible to realise load shift on the currently installed ferro resonant battery chargers on a mine. Annual electrical energy cost savings of up to R 234 200 is possible by implementing load shift in Eskom's morning and evening peak periods.

A case study was done at Kopanang gold mine to test the simulation model, as well as the feasibility of these new technology chargers for energy efficiency and load shift. There exist potential to do energy efficiency and load shift on these chargers, and it was proven possible.

OPSOMMING

Titel : Lasskuif- en doeltreffende energieverbruik ondersoeke rakende nuwe tegnologie lokomotief batterylaaiers
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Soekterme : lokomotief batterylaaiers, aanvraagskant bestuur, DSM, lasskuif, energie doeltreffendheid, elektriese energie koste besparings, energiekoste besparings

‘n Ondersoek is geloods om die potensiaal van aanvraagskant bestuur op die lokomotief batterylaaiers in Suid Afrikaanse myne te bepaal. Die potensiaal om lasskuif en energie doeltreffendheid op nuwe tegnologie batterylaaiers te doen is getoets.

‘n Simulasiemodel is opgestel om die lasskuifpotensiaal op die huidige ferro resonante batterylaaiers te toets. Hierdie model is verder uitgebrei om die hoë-frekwensie batterylaaiers ook te simuleer. Die lasskuif- en energie effektiwiteitspotensiaal van die hoë-frekwensie batterylaaiers is daarna gesimuleer.

Die effektiwiteit van kragverbruik op die batterylaaiers van lokomotiewe in myne kan vanaf omtrent 50% na 96% verbeter word, deur die huidige ferro resonante batterylaaiers te vervang met nuwer tegnologie, hoë-frekwensie batterylaaiers. Dit het ‘n energie effektiewe toepassing tot gevolg.

Dit is moontlik om lasskuif op hierdie hoë-frekwensie batterylaaiers toe te pas, wat ‘n besparing op die energiekostes het, sowel as om las uit Eskom se piektyd te verwyder. Jaarlikse besparing van tot R 442 600 op die energiekostes is moontlik. Die terugebtaal periode kan so kort soos 2.7 jaar wees.

Dit is ook moontlik om die huidige ferro resonante batterylaaiers te gebruik en slegs lasskuif op hulle toe te pas. Die gevolg hiervan is minder las wat in Eskom se piektye sal wees, asook besparings op die energiekostes van tot R 234 200.

'n Studie wat die simulasie model, sowel as die toepassing van die nuwe tegnologie laaiers bevestig, is by Kopanang goudmyn geloods.

LIST OF ABBREVIATIONS

DSM	:	demand side management
EE	:	energy efficiency
kW	:	kilowatt
kWh	:	kilowatt-hour
LM	:	load management
LR	:	load reduction
LS	:	load shift
MW	:	Megawatt
MWh	:	Megawatt-hour

LIST OF DEFINITIONS

Demand side management : the process whereby an electricity supplier influences the way electricity is used by customers.

Energy efficiency : changing the operation of electrical equipment to use less energy than before

Load shift : taking load out of Eskom's evening peak time between 18:00 and 20:00 to other times of the day, while still being energy neutral (using the same amount of energy as was previously used)

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

South Africa has growing energy needs. Figure 1 below illustrates the growth in energy production, and hence energy demand, in the country. There has been a 1.5% increase in electricity production in the period between August to October 2004 and November 2004 to January 2005 [1].

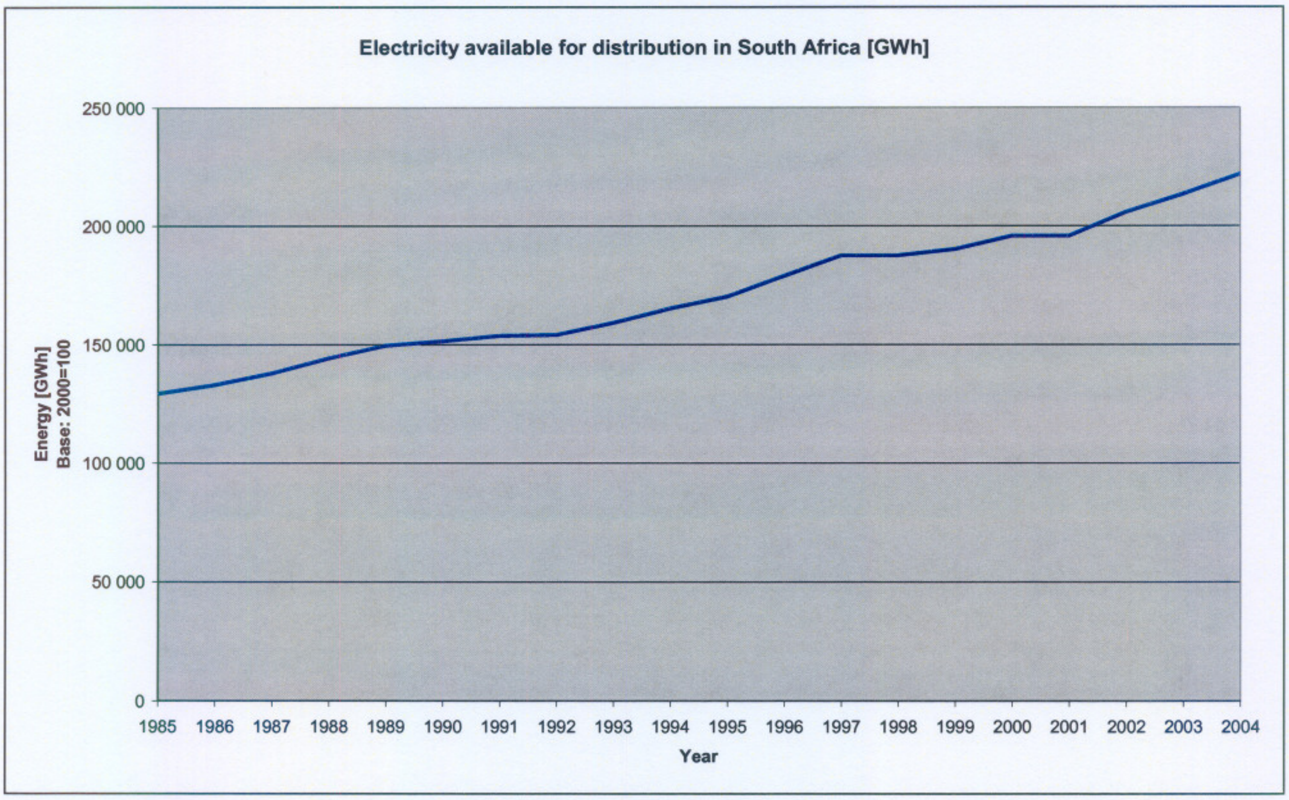

Figure 1: Energy growth in South Africa

This rise in electricity usage is mainly attributable to the electrification of more households in South Africa. The biggest contributor was the electrification of households in the rural areas, where the number of households with electricity was 21% in 1995, growing to 54% in 2003. 76% of households in urban areas had electricity in 1995, increasing to 79% in 2003 [2].

The generating capacity of Eskom is given in Figure 2 including a 15% reserve margin. It also shows the forecasted maximum demand of the country [3].

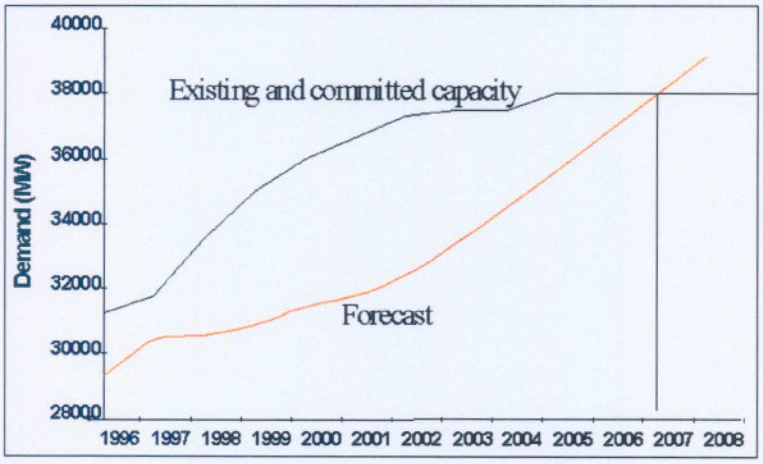

Figure 2: Generating capacity of Eskom and forecast of Maximum Demand

This shows that Eskom will run out of generating capacity early in 2007.

The yearly peak demand profile for 2003 is given in Figure 3 [4]. This shows that the energy usage in the winter is higher than that in the summer. In the summer there is a bigger reserve margin than in the winter.

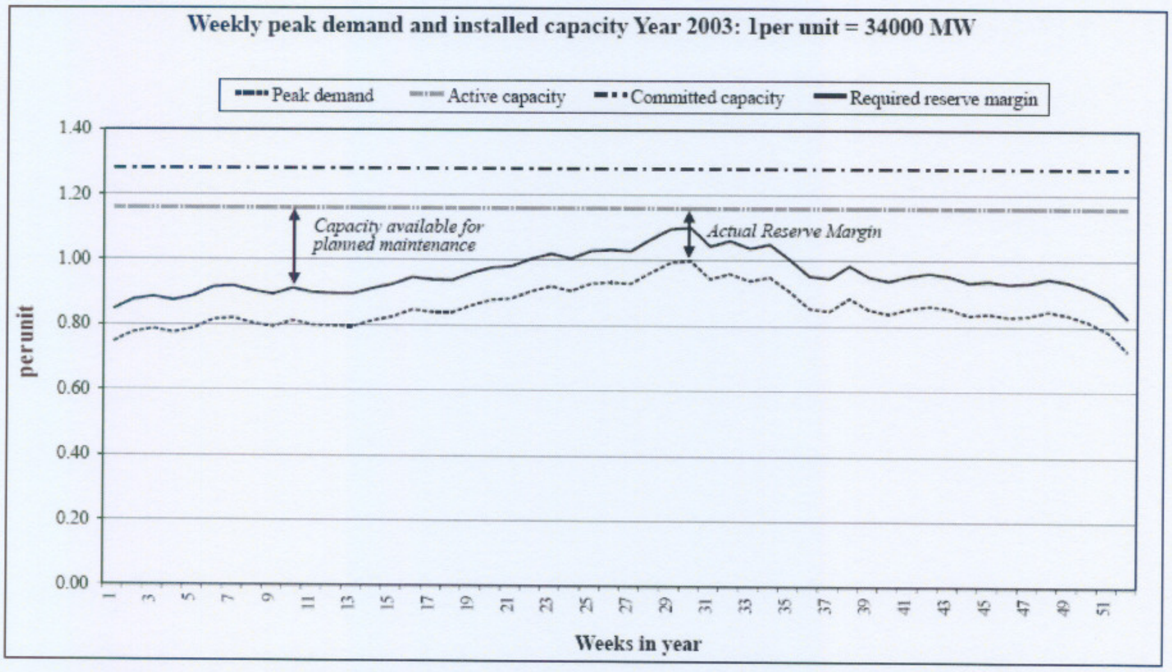

Figure 3: Electricity generation reserve margin for 2003

Mining is a significant user of the electrical energy supplied by Eskom. It accounted for a considerable amount of the supply and demand for energy [5] [6]. Mining consumed 32 620 848 MWh, 17.6% of the total electricity consumption of 2003. (Figure 4)

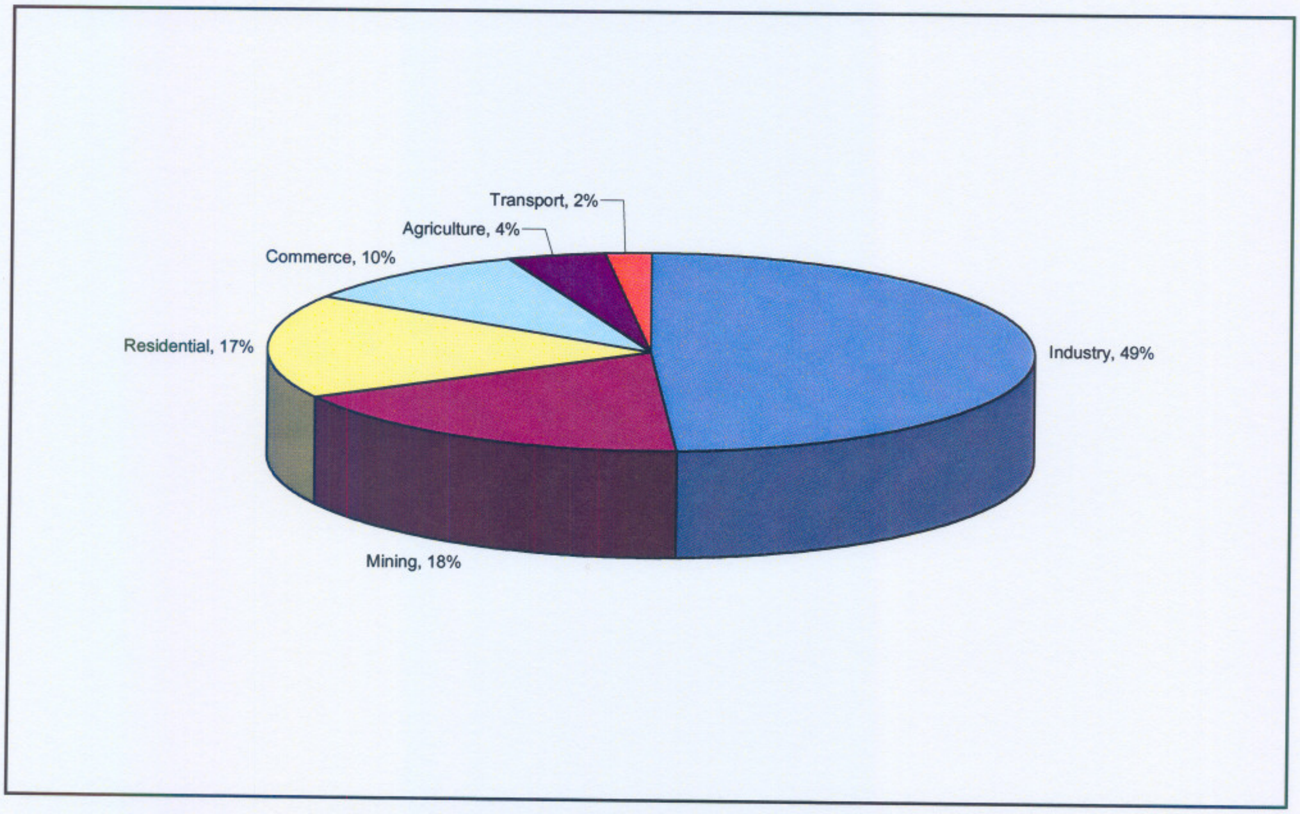

Figure 4: Energy consumption per sector in 2003

Mining (along with manufacturing, trade and industry) is one of South Africa's biggest industries [7]. It continues to be one of the most important industries for the growth and development of South Africa's economy [5]. It accounted for 7.1% of the gross domestic product (GDP) of South Africa in 2003, accounting for 11.9% of the total fixed investment in the economy. Mining dominated the Johannesburg Securities Exchange (JSE), accounting for 39% of the R 1.4 trillion market capitalisation of the JSE by the end of 2003.

Of this, gold sales accounted for 28.1%, or R 33.1 billion, of all mineral sales in 2003. The platinum group metals (PGM's), contributed 24.5%, or R 28.8 billion. Unfortunately, these sales are market-driven and the selling price varies with time, influencing the profit margin of mines [5].

The mining industry is directly responsible for vast infrastructure development in the country. 3 000 km of railway lines is attributable to the mining industry, together with 3 ports and much of the bulk handling infrastructure of other ports. It is also the dominant user of the country's railways and ports. With its 98.9 million tons of bulk commodity ores export, it represented 53% of Transnet's volume in 2003 [5].

Mines employed an average of approximately 451 600 workers during the first six months of 2004. There are a further 146 000 workers employed in associated industries. An estimated 5.8 million people are directly dependant on the mining industry for survival [5]. Mines are also the exclusive provider of social infrastructure to many communities, including clinics, schools and social facilities.

Recently, the gold mines were in a crisis and some were threatening to close down. ERPM did close down in 1999. If mines close down, this would spell disaster for South Africa. As was seen in the discussion, mines play a major role in South Africa's economy. They also have an immense social responsibility to many communities, and millions of people depend on the mines for work. Eskom will also lose one of its biggest customer bases.

There is continuous pressure to increase production, while decreasing cost. This can be seen by the large number of companies in the industrial sector that joined the voluntary Energy Efficiency Accord in 2005 [8].

It is therefore beneficial to the country, Eskom and the mines if the mines can reduce their energy usage and thus operating costs. One of the ways they can achieve this is to be more energy conscious. Fortunately, Eskom has a program called Demand Side Management (DSM), which can be used to achieve this through energy efficiency and load management (previously known as load shift).

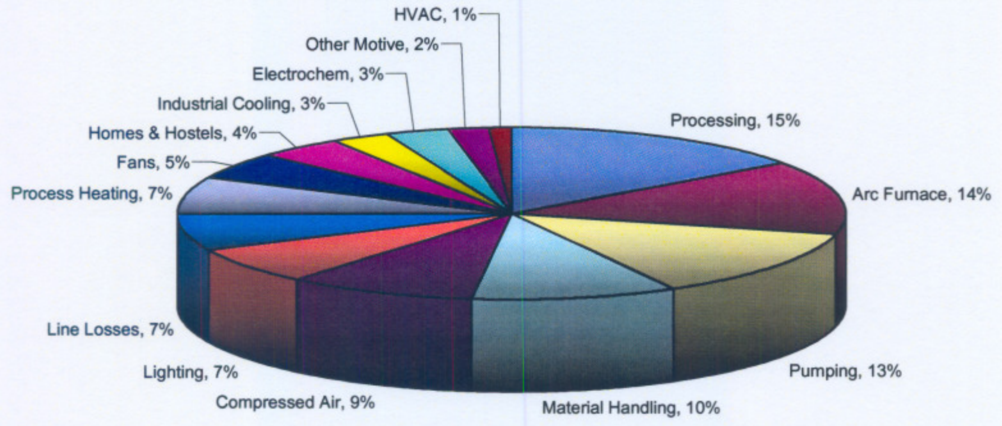

Figure 5: Contribution to the individual Maximum Demand and other areas representing savings potential in industry, mining and agriculture

When looking for savings potential in the industrial sector (as well as is the case in the residential and commercial sectors), the best place to look for is those that contribute significantly to the maximum demand [6]. Looking at *Figure 5*, illustrating the contribution to the maximum demand in the industrial sector, it can be seen that processing, arc furnaces, pumping and material handling are major contributors to the maximum demand, and hence gives great savings potential.

The industrial sector, including mining and agriculture, consumes about 71% of the annual electricity consumption, while contributing 52% to the maximum demand of the country.

There has been a lot of research into the possible energy savings in the areas of processing, arc furnaces, lighting, pumping and fridge plants [9] [10] [11] [12]. There have also been investigations into savings in the material handling sector [13].

This study will look at possible energy savings in the material handling sector which contributes 10% of the MD. Specifically, the investigation will focus on the locomotive battery chargers installed at most of the mines in South Africa.

Locomotives are used underground for the same reason as their counterparts on surface, for pulling a train. These trains are mainly used for the transportation of material. Unlike their surface counterparts, underground locomotives don't use coal as an energy source. This is because of the danger of explosions underground, as well as the possible build up of dangerous gasses. The only alternative is to use electricity as the power source. Due to the ever changing environment and new developments, it is uneconomical and not practical to use the same infrastructure (overhead electrical lines for the distribution of electricity) as electrical trains on the surface. Instead, mines rely on batteries to supply the electrical energy necessary to power the locomotive.

These batteries need to be recharged, and this is where it may be possible for electricity, and hence monetary, savings.

Each locomotive has two or three battery sets, depending on the production levels on the underground level where the locomotive are stationed. There are also different size batteries (and hence chargers) for the different locomotive sizes. Turffontein, for example, has 10 ton battery locomotives and 5 ton battery locomotives. They use 850 Ah and 600 Ah battery chargers respectively. Turffontein is one of the shafts at Anglo Platinum's Rustenburg Platinum Mines, Rustenburg section.

Lead acid batteries are used in mines. This is one of the oldest battery technologies, but still widely used as traction batteries. A traction battery is used in electrical industrial or road vehicles. The main benefit of this type of battery is high specific energy per volume and good deep discharge properties.

There are two types of chargers for charging batteries. These are the ferro resonant charger and high frequency chargers. The ferro resonant charger is the older technology and comes in basically three types. These are the taper charger, the constant current charger and the modified constant current/taper charger [14] [15].

The main benefit of the high frequency charger is that it is about 96% efficient, compared to a ferro resonant charger's efficiency of about 50%. It will be discussed in greater detail later in this document.

A typical mine has more than 60 locomotives, around 180 batteries and more than 60 battery chargers. There are thus potential savings opportunities on the locomotive battery chargers on a mine.

No references could be found in the literature where battery chargers have been adapted or replaced on a large scale as part of a demand side management initiative, including energy efficiency and load shift.

There are South African mines that are investigating the use of more efficient high frequency battery chargers. These include Kopanang Gold mine, Beatrix 3# and Tau Lekoa [16]. AngloGold and Anglo Platinum have expressed interest but only if it can be funded through the Eskom-DSM programme. As a result, the installation of the chargers are slow as they are funded through the mine's own capital. As the old chargers deteriorate they are replaced by high frequency chargers. There are some high frequency locomotive battery chargers installed at Beatrix 3#.

1.2 PROBLEM STATEMENT

1. To investigate the consumption, pattern and cost of electrical energy by the underground locomotive system at South African gold mines
2. To research and investigate possible changes in equipment and/or procedures that could affect savings in electricity costs and consumption
3. To determine the economic viability of such changes

1.3 METHODOLOGY

1. Do a background investigation into the need for DSM in South Africa
2. Identify the potential of locomotive battery chargers as a suitable field for the investigation
3. Carry out a literature study on the different charger technologies
4. Identify different ways to do load shift and energy efficiency on new technology battery chargers
5. Evaluate alternatives to using new technology battery chargers
6. Compile a baseline from measured data of a mine's locomotive battery chargers
7. Simulate different scenarios for load shift and energy efficiency
8. Verify the obtained results from the measured baseline
9. Interpret and evaluate the results obtained

1.4 CONTRIBUTIONS OF THIS STUDY

The following contributions have been made with this study:

- The potential of energy efficiency and load shift on locomotive battery chargers has been investigated and proven possible
- There are possible electrical savings, and hence monetary savings, with using new technology battery chargers, and it has been found that there is some potential for an Eskom DSM project

1.5 OUTLINE OF THIS STUDY

Eskom's Demand Side Management (DSM) program is discussed in Chapter 2. It will discuss the need for DSM from Eskom's as well as the country's perspective. DSM will be explained further in this chapter, as well as how Eskom is trying to promote the implementation of DSM programs through specific price profiles.

In Chapter 3 old and new battery charging technologies will be investigated, as well as the DSM and associated savings potential of new battery charging technologies. This discussion will be restricted to the locomotive battery chargers.

A case study done on the potential savings of new charger technology at Anglo Gold Ashanti's Kopanang mine will be discussed in Chapter 4.

CHAPTER 2: THE ESKOM DEMAND SIDE MANAGEMENT PROGRAM

2.1 INTRODUCTION

Demand Side Management (DSM) is defined by Eskom as *"the process whereby an electricity supplier influences the way electricity is used by customers"* [17].

Other definitions include: *"Energy demand management is often referred to also as demand side management (DSM). Energy demand management usually implies actions that influence the quantity of energy consumed by users. It can also include actions targeting reduction of peak demand during periods when energy supply systems are constrained. Peak demand management does not necessarily decrease total energy consumption but could be expected to reduce the need for investments in networks and/or power plants"* [18] and *"the planning, implementation and monitoring of utility activities designed to influence customer use of electricity in ways that will produce desired changes in a utility's load shape (i.e., changes in the time pattern and magnitude of a utility's load). Utility programs falling under the umbrella of DSM include: load management, energy efficiency, energy conservation, and innovative rates"* [19].

In short, DSM is a way to reduce energy usage, as well as to alter the time of use of electricity. Benefits of this include energy cost savings and reduced energy usage, thus being more energy efficient.

2.1.1 Demand Side Management in the world

DSM started in the 1970's, the same time that the term was first used [18], during the energy crisis in the United States of America. This was in 1973 and 1979, when it was made clear that the convenient fossil fuel energy reserves (like coal and crude oil) might become exhausted in the near future [20].

This DSM concept, as an alternative to building more power stations, was later adopted in the United Kingdom, Europe and Australia. Many countries all over the world started to introduce demand management programs after this, but not necessarily referring to it as DSM programs.

2.1.2 Demand Side Management in South Africa

DSM is still a relatively new concept in South Africa. Eskom formally recognised it in 1992 when integrated electricity planning (IEP) was first introduced [21]. There was a wide range of possible DSM opportunities and alternatives identified for Eskom. These options and opportunities were solutions for various growth scenarios that were investigated, meeting an acceptable quality of supply. Least cost principles were applied, from both the customer's and Eskom's perspective.

The then Minister of Mineral and Energy Affairs (DME), Dr. P.N. Maduna, set forth a new vision for energy in his budget speech on 21st May 1997. In it, he identified the opportunity to restructure and consolidate the State's assets in the industry, while at the same time achieving maximum value from them [22]. This led to the development of the White Paper on Energy Policy.

In 1998, the White Paper on Energy Policy was published. The white paper had mainly 5 objectives [23]. These are:

1. Increasing access to affordable energy services
2. Improving energy governance
3. Stimulating economic development
4. Managing energy-related environmental impacts
5. Securing supply through diversity

Integrated energy planning (IEP) is also discussed. It has a couple of technical functions, but the one relating to DSM states: *"analyzing the potential of energy supply systems and demand side management to meet current and potential future energy needs. This would include analyses of individual supply sub-sectors and the linkages between sub-sectors".*

The DME in effect passed a mandate to the National Energy Regulator (NER) to facilitate the DSM-program. The NER published a regulatory policy on the energy efficiency (EE) and DSM for the South African electricity industry. In it they have put a regulatory framework where EE and DSM were to be implemented, while also supporting government objectives on energy efficiency [24].

In this regulatory policy, Eskom are obliged to meet certain targets. These are:

- 152 MW annual reduction in peak demand
- 292 GWh annual energy displaced

There are different program categories identified for EE and DSM, with its associated annual targets [25]. The following table summarizes this.

Table 1: Categories for energy efficiency and demand side management

Programme Category	Annual MW displacement	Annual Energy Displaced [GWh]
Residential Energy Efficiency	32	115
Commercial Energy Efficiency	14	68
Industrial and Mining Efficiency	16	109
Residential Load Management	49	-
Industrial and Mining Load Management	41	-
TOTAL	**152**	**292**

Now Eskom has to implement DSM strategies to meet these targets. Eskom has a specific department dealing with EE and DSM, namely Eskom-DSM.

2.1.3 Eskom facts

- Eskom is rated as the 11th largest power company in the world rated by generated capacity [26]
- Eskom is rated as the 7th largest power company in the world rated by generating sales [27] (206 TWh)
- Eskom is the lowest-priced industrial electricity supplier in the world [28]

2.1.4 Chapter overview

This chapter will take a closer look into the Eskom DSM program. Firstly, it will look into the need for DSM. Why is it necessary? What are the benefits of DSM?

Next, the components of the Eskom-DSM program are discussed. These are EE and load shift (LS), also known as load management (LM). It will give examples of how EE and LM can be implemented.

After this, the pricing profiles of Eskom will be introduced. In this section, the price profiles that promote DSM will be discussed in more detail. It will concentrate on Mega Flex, the profile that is more commonly in use in industry. It will also include the effect of maximum demand.

2.2 THE NEED FOR DSM

The electricity usage in the country is growing. In Figure 6 it can be seen that South Africa will run out of generating capacity in early 2007 [3].

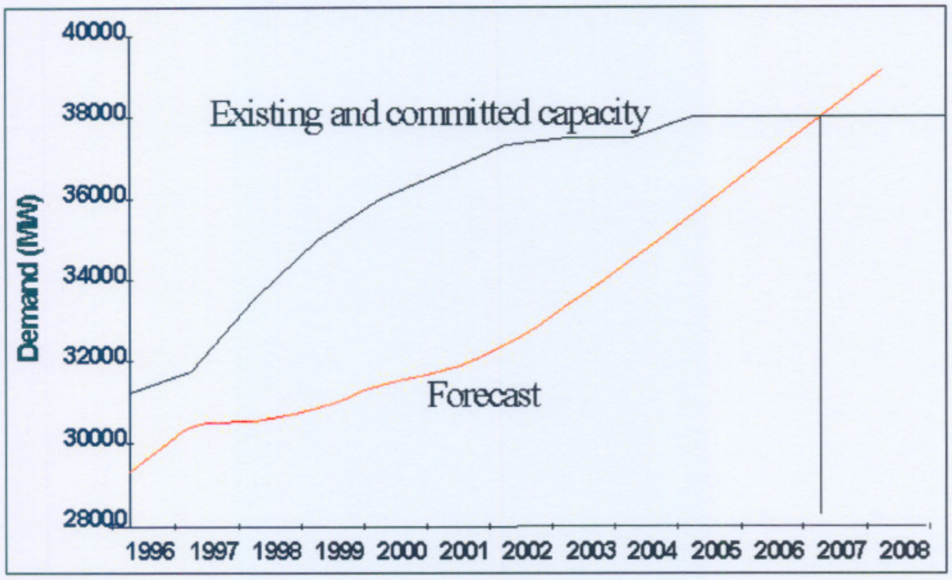

Figure 6: Generating capacity of Eskom and forecast of Maximum Demand

There have been a lot of different forecasts into the electricity usage of the country. One of them, done by Eskom, is given in Figure 7.

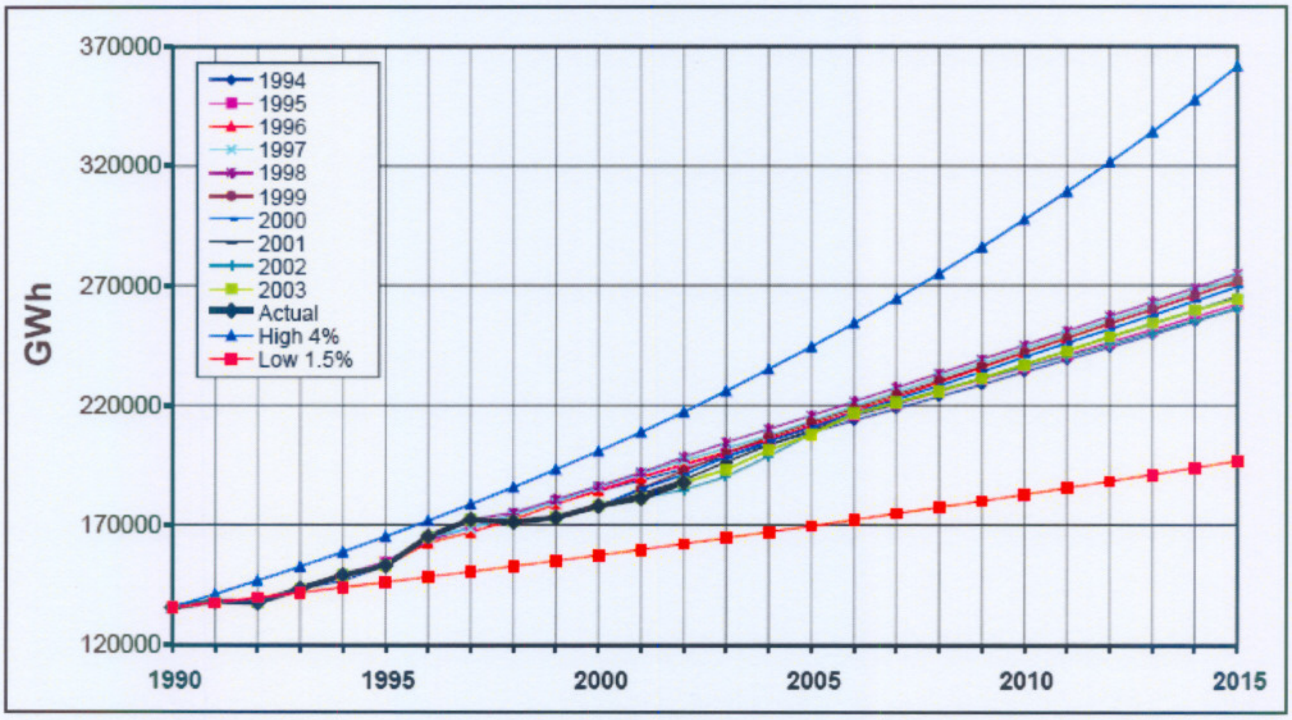

Figure 7: Electricity forecast and actual usage

This figure shows that Eskom's forecasts into electricity usage are quite accurate. The electricity demand in the country is currently estimated to be growing at 1 000 MW per annum [6], whereas the targets for EE and DSM are about 150 MW per annum [25]. This results a net demand growth of approximately 850 MW annually.

South Africa's current generation capacity is 37 056 MW [6], meeting the forecasted peak demand of the country until early 2007 [3] [6]. Something must be done to ensure that there is adequate supply of power for the country's demand.

The capacity outlook for South Africa's energy is given in Figure 8.

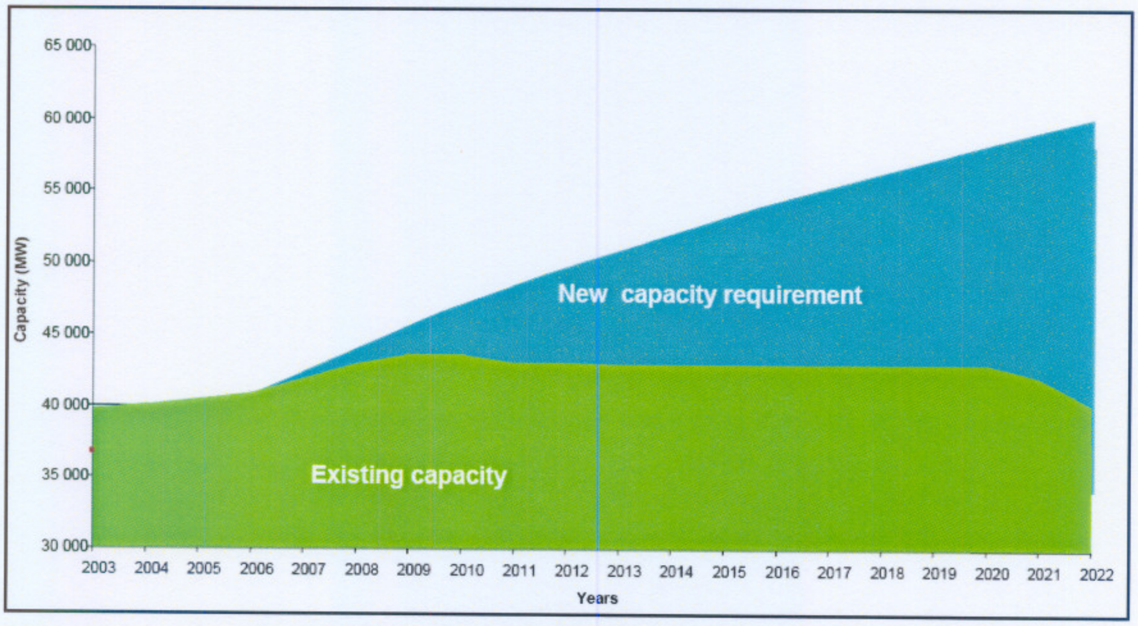

Figure 8: South Africa's capacity outlook without DSM

It is obvious to see that Eskom will run out of generating capacity very quickly. Without any other means to meet the country's growing demand for energy, new power stations must have been built a while back. With the DSM-initiative, the building of new power stations can be postponed for a while. Figure 9 shows the capacity outlook for the country's demand with DSM.

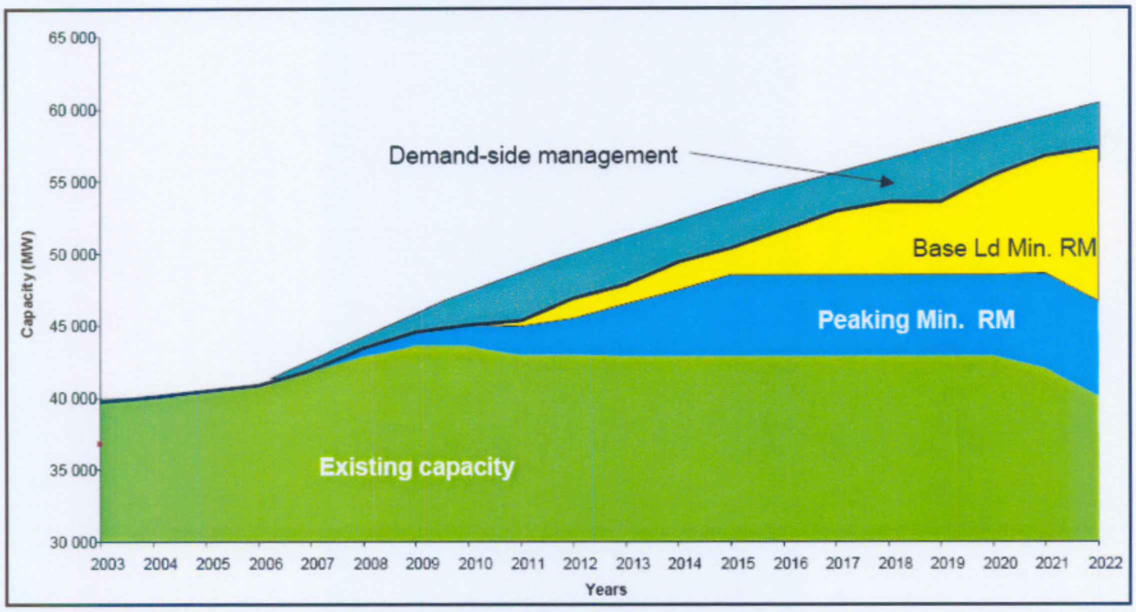

Figure 9: South Africa's capacity outlook with DSM

With the building of new power stations and peaking stations postponed, DSM fills the gap for our immediate and future energy requirements.

When looking for savings opportunities for DSM, the best place to look for them is in those areas that contribute to maximum demand [6]. But why look into those areas that contribute to the maximum demand? One way to look at it is to view the weekly or daily electricity usage profile. The summer and winter profiles for the country are given in Figure 10 and Figure 11.

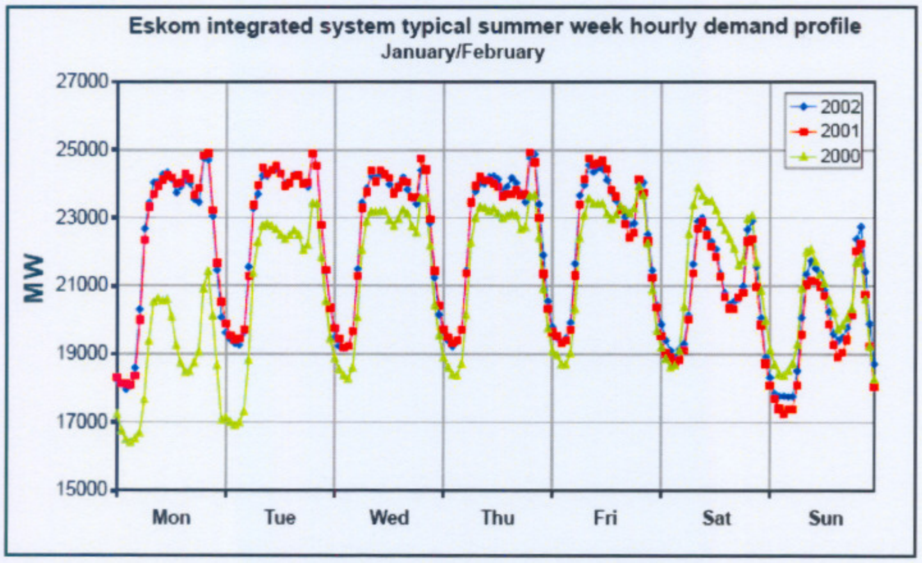

Figure 10: Weekly demand profile for the summer

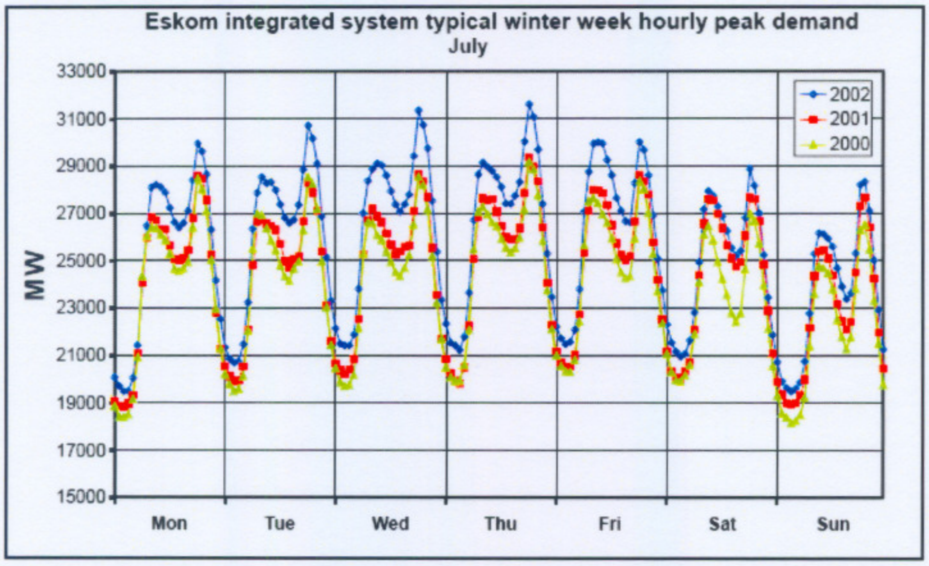

Figure 11: Weekly demand profile for the winter

It can be seen that the winter demand is much higher than the summer's. Weekdays' demand are also significantly higher than the demand over weekends, with Sundays' demand being the lowest of all. There are also two peaks in demand clearly visible for each day, more or less at the same time. To see when these peaks are, an average daily load profile is needed. This is given in Figure 12.

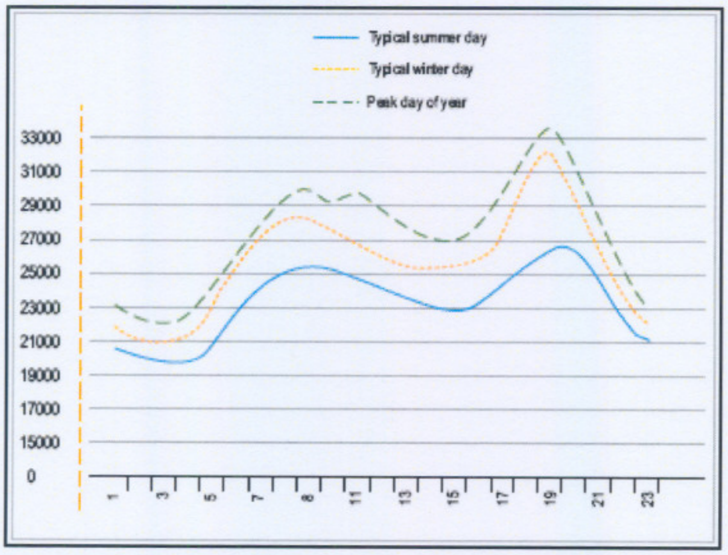

Figure 12: Daily demand profile

Figure 12 shows the average daily demand for the summer and winter. It also shows the peak day of the year. It can be seen that these peaks are between 07:00 and 10:00 in the mornings and between 18:00 and 20:00 in the evenings.

Now that it has been established that there are certain times in the day that there are more demand for electricity, it can be investigated how EE and DSM influence these profiles.

2.3 COMPONENTS OF DSM

One of the main problems the energy efficiency and demand side management (EEDSM) policy framework of the NER identified was the problems of peak generation capacity and the inefficient end-use of electricity. There are two ways to look at these problems, namely EE and DSM.

Although EE falls under DSM, it also has many other societal and environmental impacts. The government also puts additional emphasis on EE. Therefore in the EEDSM policy, EE has been looked at as a measure alongside DSM.

There are a lot of different ways in which EE and DSM activities can be implemented. Figure 13 shows a typical load profile, as well as ways to implement EE and DSM through different activities.

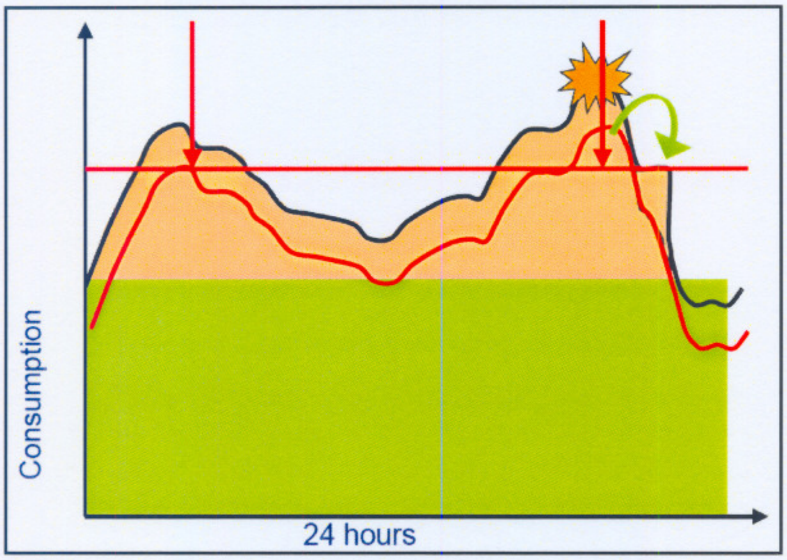

Figure 13: Typical 24 hour load profile with demand side options

The red line graphically demonstrates energy efficiency, where energy usage is consistently lower than previously. This can be done for example by the use of more energy efficient technologies. DSM through load management is done by removal of demand during peak times into non-peak times, shown by the green arrow. This is typically done through better control and scheduling of electrical machines and appliances.

EE and DSM will be further explained in this section, as well as the different ways in which it can be implemented.

2.3.1 Energy efficiency

EE refers to the overall reduction in energy use by the customer. This can be through the use of energy efficient technologies or through the retrofit of current technology. It also refers to the adoption of more efficient behavioural practices [29]. In Figure 14 this is shown graphically.

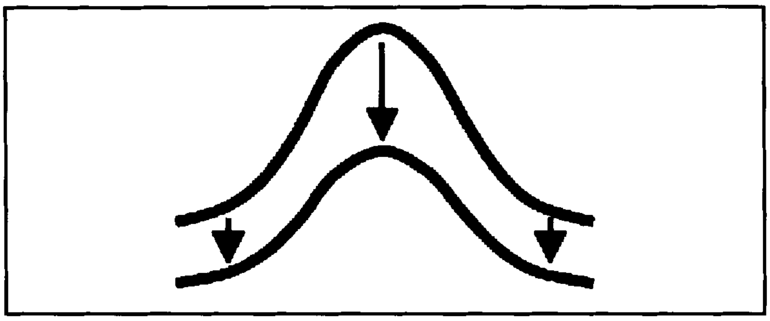

Figure 14: Energy Efficiency

Benefits of energy efficiency include [30] [31]:

- By using less electricity, energy cost savings is realized
- Non-renewable resources, like coal, is preserved
- Environmental conservation, by reducing emissions and water consumption at power stations
- EE is a key resource for sustainable development on a local, national and global basis

2.3.2 Demand Side Management

DSM activities involve a wide range of load management activities to reduce the electricity use during peak times. Although EE also falls under DSM, it has been discussed in the previous section.

There are mainly two categories of load management (LM). These are load shift (LS) and load reduction (LR). LS is energy neutral, meaning that the energy taken out of peak times must be used somewhere else. This can be done trough valley filling and strategic load growth in other time frames.

LS is graphically demonstrated in Figure 15. To keep the energy use before and after the load management activity the same, i.e. energy neutral, more energy must be used in other times. This is done trough valley filling, shown in Figure 16 and strategic load growth, shown in Figure 17.

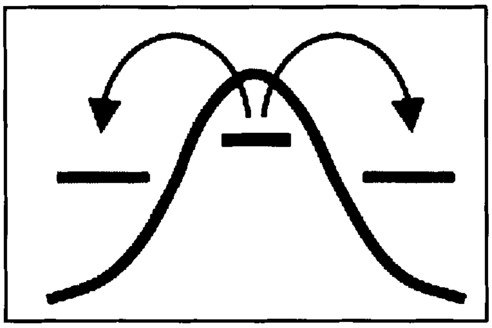

Figure 15: Load shift

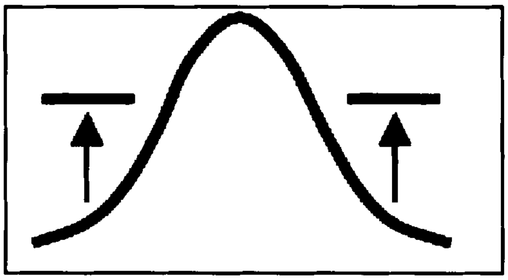

Figure 16: Valley filling

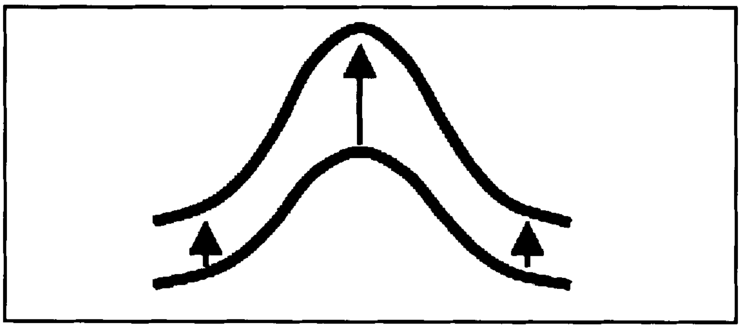

Figure 17: Strategic load growth

LS involves the modification of the time of use of electricity. This is achieved through incentives such as time-of-use (TOU) tariffs and real-time-pricing (RTP). Through these incentives, it is possible to realize considerable electricity cost savings, although the overall energy use has remained the same.

LR is the process where energy is taken out of peak times, but not shifted to other times. It is thus not energy neutral. In Figure 18 this is shown graphically. LR is also known as peak clipping.

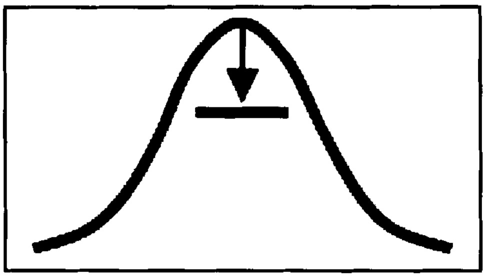

Figure 18: Load reduction

Benefits of DSM and LM include **Error! Reference source not found.**:

- Reducing demand during peak times
- Delaying capital investment for infrastructure
- Keep electricity costs down
- Supporting the macro-economic development of the economy through improved productivity

2.4 PRICE PROFILES

The NER is not only concerned about the level of the electricity price, but also by the structure of available tariffs. It is the pricing policy that determines the degree of cost-reflectivity in recovering the income in the different user groups. This includes the different times of day, as well as different seasons **Error! Reference source not found.**.

There are mainly four purposes for tariffs. These are:

1. Recovering of supplier costs
2. It must be fair and equitable
3. Tariffs should be logical and simple
4. It should promote efficiency

The tariff itself is made up of the tariff structure, as well as the tariff rate. There are different tariff structures available. These are: flat rate, single energy rate, inclining block rate, declining block rate and demand tariff, consisting of TOU and RTP.

With the flat rate tariff, a flat rate is charged for the energy regardless of the amount of energy used. It is graphically demonstrated in Figure 19.

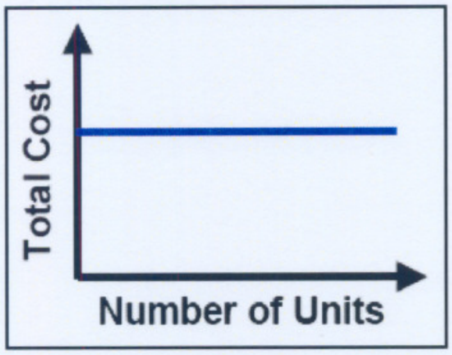

Figure 19: Flat rate tariff structure

With the single energy rate, a constant rate is charged per energy unit (kWh). The more energy used, the more the associated energy cost. Thus the total cost is proportional to the number of energy used. This is demonstrated in Figure 20.

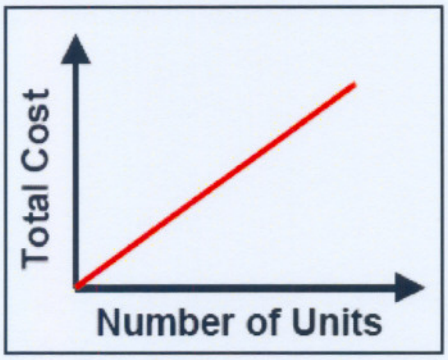

Figure 20: Single energy rate tariff structure

Inclining block rate is the same as the single energy rate, but it differs in that after a certain amount of energy used, the rate is increased. Declining block rate is the opposite of inclining block rate. The more energy used, the cheaper the rate. Inclining block rate is illustrated in Figure 21.

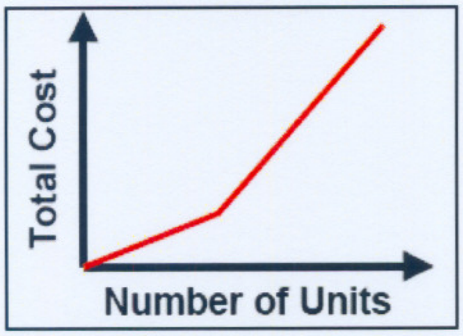

Figure 21: Inclining block rate energy tariff structure

The last tariff structure type is the demand tariff. With this type of tariff, the energy cost differs in the time of day it is used, as well as the total energy demand. This is illustrated in Figure 22.

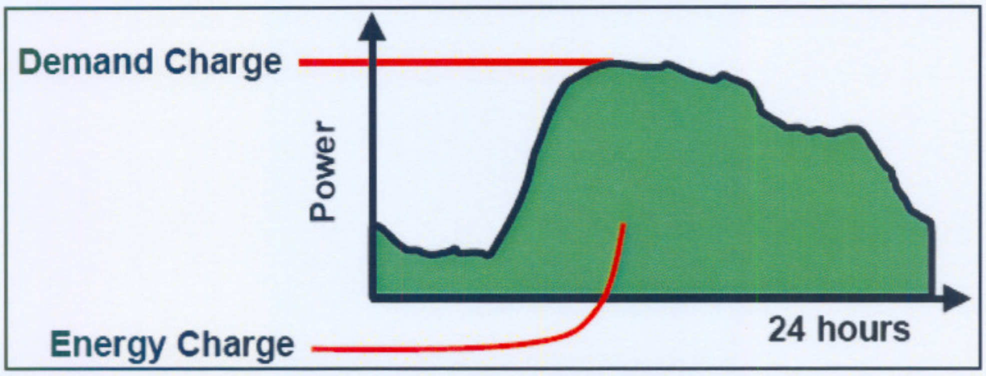

Figure 22: Demand tariff structure

As already mentioned, there are two types of demand charge. The first one is TOU-tariffs. There are fixed energy charges for certain times of the day. This is demonstrated in Figure 23.

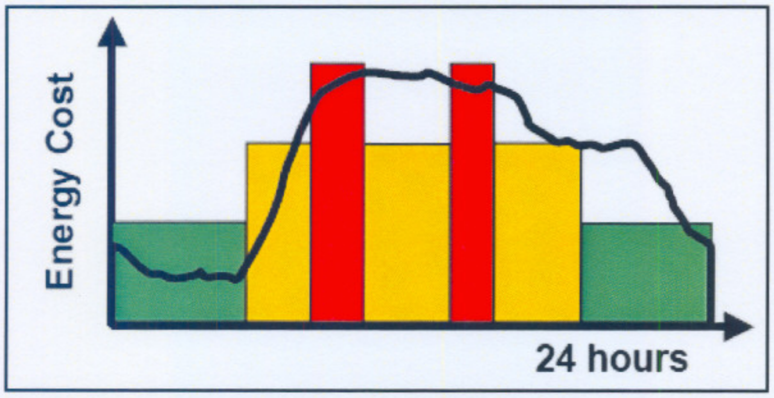

Figure 23: Time of Use tariff structure

The other demand charge is RTP. With RTP, the price differs every hour, every day of the year. The cost of generation differs each day, and RTP tries to recover these costs more realistically.

The other part making up the tariff structure is the tariff rate. This is the actual per unit amount payable for the tariff charges. It consists of a basic charge, the energy charge and the demand charge. For example, an energy rate of 13.56 c/kWh. This energy rate is usually revised annually.

2.4.1 Different pricing structures

Eskom has a couple of urban tariffs which facilitates DSM. These are Nightsave, Megaflex and Miniflex.

Nightsave are intended for customers with a notified maximum demand (NMD) of 25 kVA or more [36]. It is also beneficial if the customer can move all or most of its electricity demand to Eskom's off-peak times between 22:00 and 06:00 on weekdays and the entire Saturday, Sunday and public holidays.

Megaflex is intended for customers with a NMD of more than 1 MVA and who can shift their load to certain time periods. Miniflex is intended for customers with a NMD of between 25 kVA and 5 MVA and who can shift their load to certain time periods.

For the purpose of this study only Megaflex will be considered, as this is the tariff structure most mines use.

2.4.2 Megaflex

Megaflex is a TOU profile. As already stated, Megaflex is intended for customers with a supply of at least 1 MVA. The customer must also be able to shift most of their load to certain times of the day. Earlier in this chapter it was seen that the country has two peak demands for electricity.

Eskom calculated these times to be between 07:00 and 10:00 in the mornings and between 18:00 and 20:00 in the evenings on weekdays. The Megaflex pricing structure is modeled on this demand for energy. The time periods for Megaflex are given in Figure 24 below.

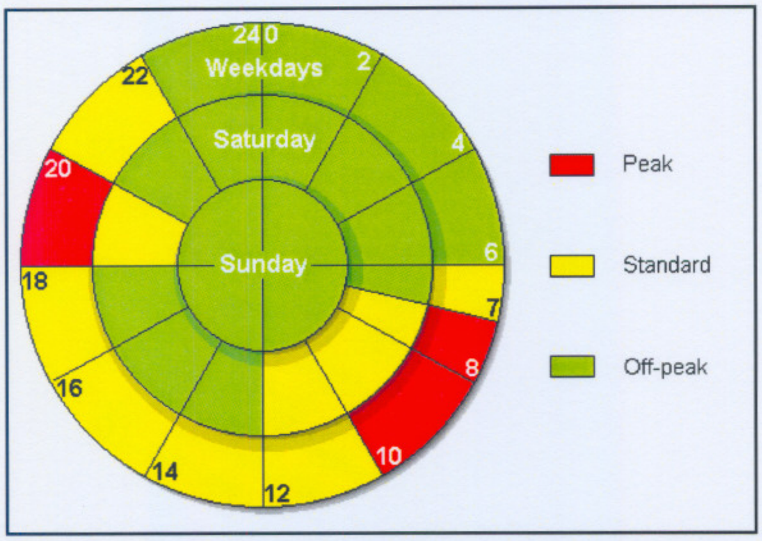

Figure 24: Megaflex time periods

Table 2: Megaflex energy charge

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**

Figure 25 shows the energy charge and time periods more graphically.

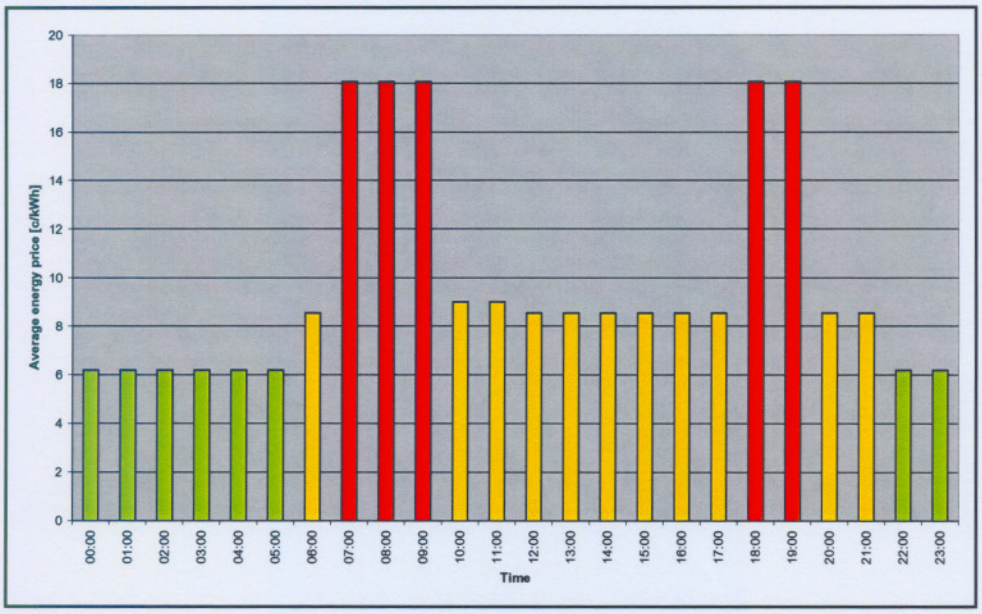

Figure 25: Megaflex time of use and average weekly energy cost

Note the similarities between Figure 25 and Figure 12 where the daily demand profile for the country is given.

2.5 CONCLUSION

South Africa recently started its demand side management project. The Department of Minerals and Energy passed a mandate to the National Energy Regulator, who forced Eskom to implement its DSM program. In it, they put targets forth that Eskom must meet each year.

This will result in a virtual power station to be built, delaying the building of a new coal fired power station by a couple of years. This has many social and environmental advantages, which include:

- job creation
- less CO_2 emissions by coal fired power station
- less water usage by power stations

If the DSM initiative wasn't passed from the DME to the NER to Eskom, South Africa would in most likelihood not have had a DSM program yet. This is because Eskom actually loses money, because the goal of the EEDSM program is to be more energy conscious, resulting in less energy to be used. The Megaflex price profile was put forth to facilitate the DSM program.

The industrial electricity price in South Africa is one of the lowest in the world. This is not necessarily good for the implementation of DSM. The person in charge in industry is the production manager. Production is more important in industry than energy consciousness. The electricity price is very low compared to the revenue coming from production. If the electricity price is higher, it would result in lower profit margins, making the production manager more energy conscious.

CHAPTER 3: SAVINGS POTENTIAL OF NEW CHARGER TECHNOLOGY

3.1 INTRODUCTION

To understand how battery chargers work, a basic understanding of the lead-acid battery is needed. The lead-acid battery was invented in 1860 [38] and has been used as the power source for electric vehicles for more than 100 years.

A lead-acid battery is a secondary battery [39]. The difference between a primary and a secondary battery is that a primary battery is intended to be used only once, while a secondary battery is rechargeable [40].

A battery consists of two or more cells, connected in series or in parallel or in a combination of both. A cell is the actual electrochemical element that generates a nominal voltage of 2V between its two electrodes [40] [41].

The physical surface area of the electrodes determine the size of the cell, and hence the capacity of the battery. This capacity is measured in Ampere-hours (Ah). 1 Ah is the ability of the cell to deliver 1 A for 1 hour. Traction cells would typically have capacities of between 350 and 900 Ah.

In a fully charged lead-acid battery the negative electrode (anode) is made up of sponge lead (Pb), while the positive electrode (cathode) is composed of lead-dioxide (PbO_2). The anode supplies electrons to the external load. To complete the circuit, an electrode is needed in the battery to supply ions to the cathode and anode. Dilute sulphuric acid (H_2SO_4) is used as the electrolyte. If the battery is fully-charged, the electrolyte consists of 25% H_2SO_4 and 75% water (H_2O).

The chemical reactions that govern this reaction is (charged to discharge) [41]:

Anode (oxidation):

$$Pb(s) + SO_4^{2-}(aq) \leftrightarrow PbSO_4(s) + 2e^- \quad \varepsilon^0 = 0.356V$$

Cathode (reduction):

$$PbO_2(s) + SO_4^{2-}(aq) + 4H^+ + 2e^- \leftrightarrow PbSO_4(s) + 2H_2O(l) \quad \varepsilon^0 = 1.685V$$

From the reaction on the anode with the spongy lead electrons are released. From the reaction on the cathode with the lead dioxide, electrons are absorbed. These two reactions result in an electrical current to flow between the two plates.

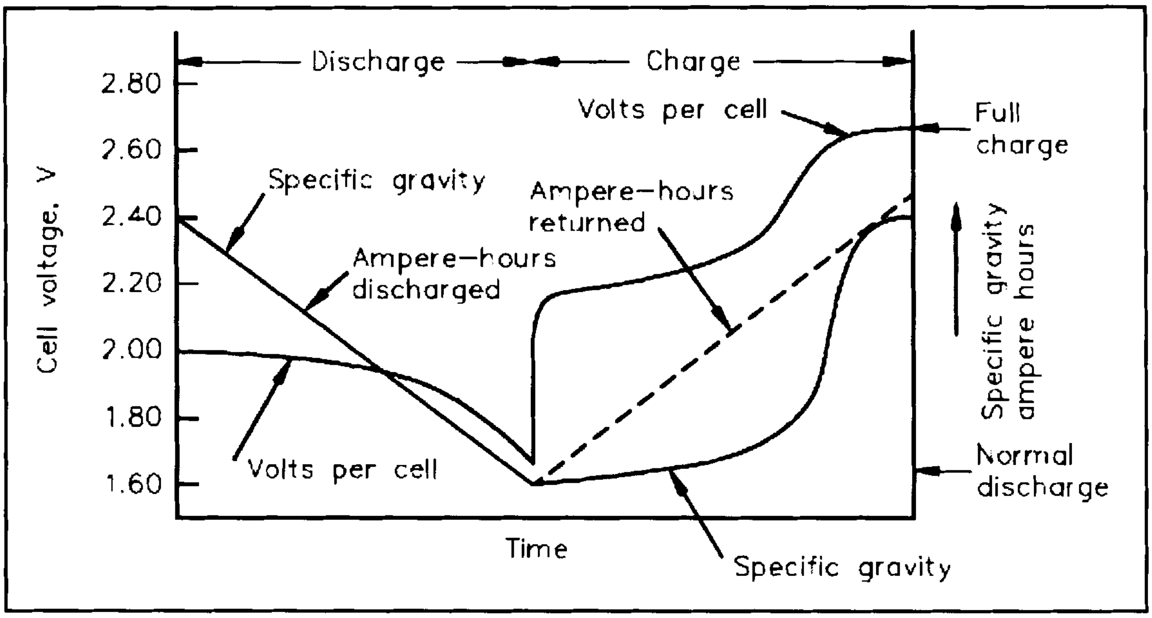

Figure 26: Changes in the voltage and specific gravity of a battery or cell

The reactive materials are converted, in both reactions, to lead sulphate while the sulphuric acid is converted to water. Sulphuric acid is heavier than water, resulting in a drop of the specific gravity (SG) of the electrolyte as the battery is discharging. As this is happening, the volume of the electrolyte decreases, with a drop in the level of the electrolyte. The changes in the voltage and SG of a battery are illustrated in Figure 26.

To recharge the battery, the chemical reaction must be reversed. This involves connecting the battery to an external power source (the charger), causing current to flow into the battery.

When recharged, the sulphate ions recombine with the excess water in the electrolyte to convert back to the sulphuric acid. This results in the SG to increase back to the previous (fully charged) level. The lead sulphate converts back to lead dioxide and spongy lead on the cathode and anode respectively. The volume of the electrolyte increases and the level of the electrolyte rise to the previous (charged) level.

As the cell reaches its fully charged state, the chemical conversion can no longer absorb all of the charging current. The surplus current causes hydrogen to be released from the anode and oxygen from the cathode. This is commonly known as gassing and is the primary reason why normal lead-acid batteries need topping up with water. Gassing usually starts at 2.35V.

Gassing produces bubbles that rise from the electrolyte and escape from the cell. This bubbles help to agitate the heavy sulphuric acid, preventing it from forming layers on the bottom of the cell. If excessive gasses are produced, it can damage the electrodes. The hydrogen-oxygen mixture is also highly explosive and must be limited for safety reasons.

It is therefore necessary to have good control on the charger to reduce the charging current in the cells when the voltage reaches 1.35V per cell. There are basically two types of chargers available for lead-acid batteries. These are the ferro resonant chargers and high-frequency chargers.

3.2 CHARGER TECHNOLOGIES

3.2.1 Ferro resonant chargers

From the discussion on the battery, it can be seen that the ideal battery charger would be a device that consists of a variable voltage DC power source with a current limiting device. The basic charger consists of a transformer, rectifier and a means to control and limit the current. Such a system is shown in Figure 27.

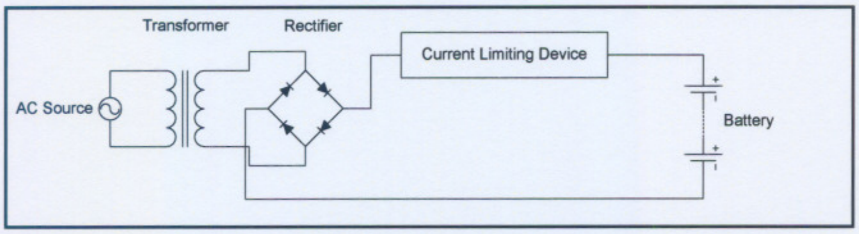

Figure 27: Basic charger system

The transformer is used to reduce the voltage from the mains to just above the battery's fully charged voltage, while the rectifier rectifies the mains voltage. The current must be regulated to ensure that the battery is not over charged.

Current always flows from a higher to a lower voltage. This means that current can only flow when the voltage from the charger is higher than that of the battery. This can be seen in Figure 28 and Figure 29.

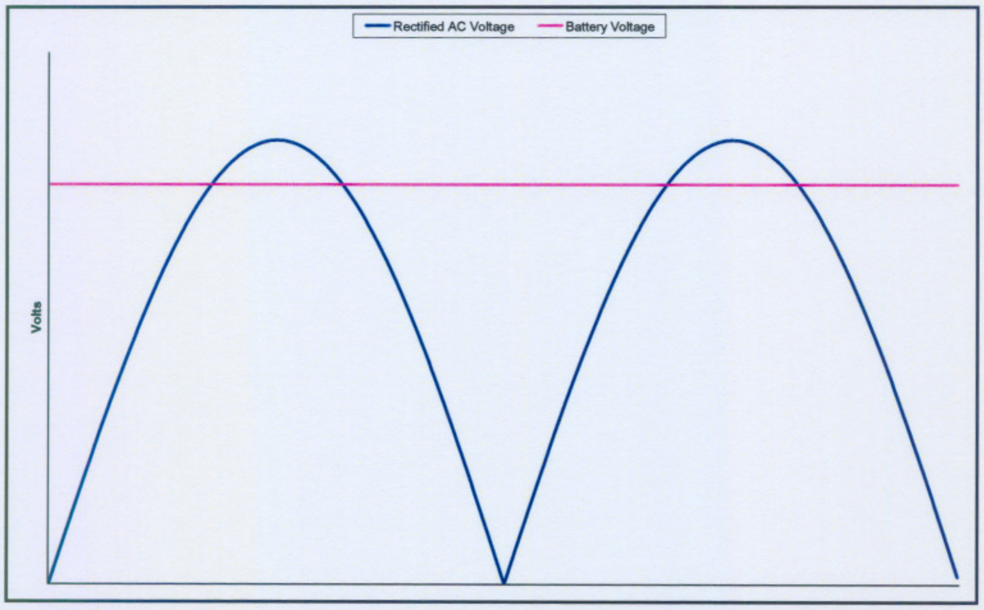

Figure 28: Rectified AC voltage and battery voltage

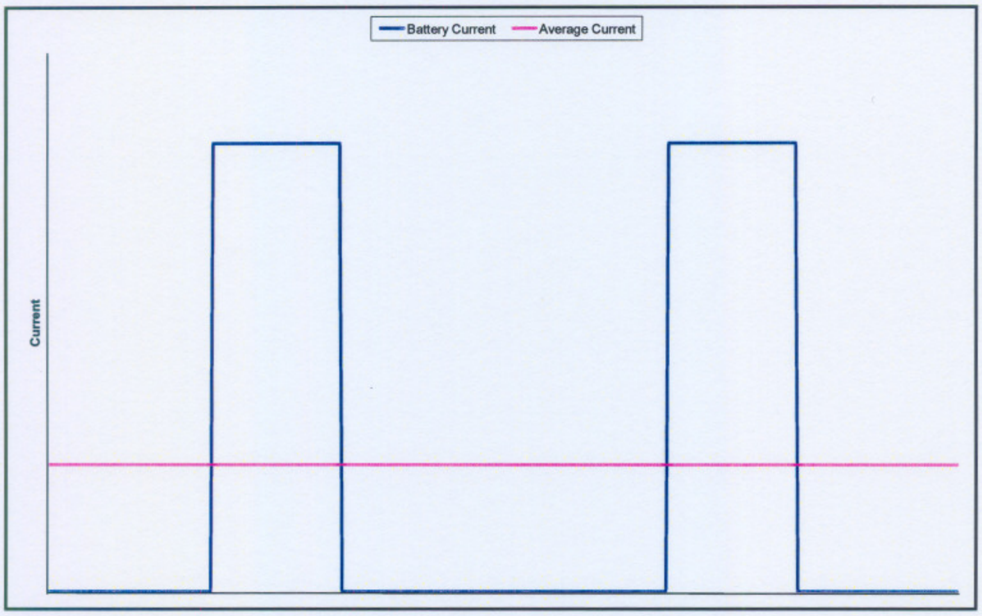

Figure 29: Resulting current through battery

This means that to get an average current of about 100A through the battery, it would have to consist of a series of pulses of about 300 to 400A. This leads to current being drawn from the AC power source being a series of narrow pulses.

This has some drawbacks. One of them is that the AC power source must be rated to supply these high peak currents. The mains supply can also be severely distorted due to drawing a series of high current pulses from the source. It is possible to make the voltage after the transformer higher to avoid these problems.

The ferro resonant charger is the older technology compared to high frequency chargers and comes in basically three types. These are the taper charger, the constant current charger and the modified constant current/taper charger [14] [15].

Taper charger

The taper charger supplies a current to the battery that falls as the voltage over the battery rises. This is illustrated in Figure 30.

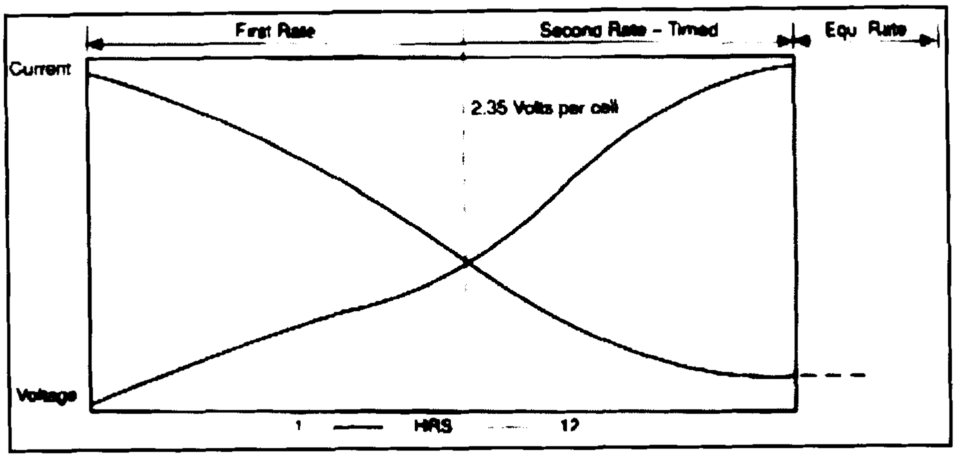

Figure 30: Typical recharge characteristics of a 12-hour taper charger

The first rate charge is for an undefined period, until the voltage over the battery reaches 2.35V. The starting current for this period should be:

$$Current_{FirstRate} = \frac{Ah_{Battery}}{7.2}$$

Second rate charging is activated when the charger control senses that the battery's voltage is 2.35V. This period lasts for 3-4 hours. The maximum current at 2.5V per cell is specified by the battery's manufacturer and is usually:

$$Current_{SecondRate} = \frac{Ah_{Battery}}{12}$$

After the second rate charging period is finished, the unit can either enter equalization stage, or it can switch of with a manual switch to enter the equalization stage. This current should be:

$$Current_{Equalization} = \frac{Ah_{Battery}}{30}$$

The taper charger usually takes about 12 hours to fully charge a battery.

Constant current charger

The constant current charger supplies constant current to the battery over three stages. This is illustrated in Figure 31.

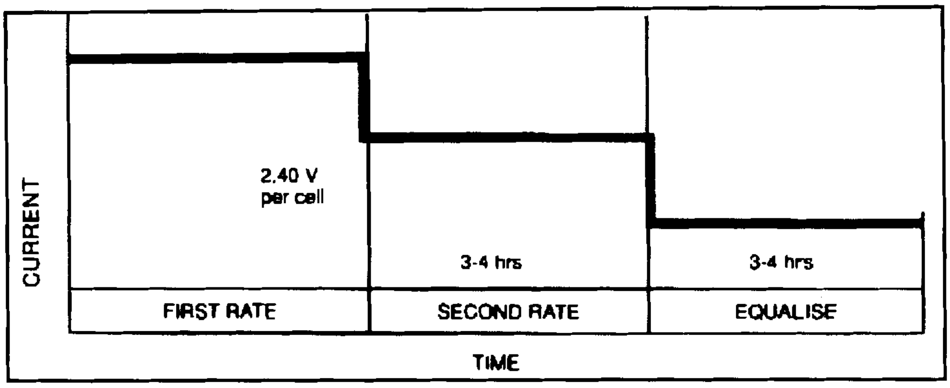

Figure 31: Typical recharge characteristics of a constant current charger

First rate charging is continued for an undefined period, until each cell in the battery reaches 2.4V. The current for this stage is:

$$Current_{FirstRate} = \frac{Ah_{Battery}}{5}$$

The charger control senses when 2.4V per cell is reached, and switches to second rate charging. This lasts for 3-4 hours and the current is given by:

$$Current_{SecondRate} = \frac{Ah_{Battery}}{15}$$

After second rate charging is finished, the charger switches to an equalization charge. This stage lasts for 3-4 hours after which the charger is switched off. The current in this stage is given by:

$$Current_{Equalization} = \frac{Ah}{30}$$

The constant current charger takes about 8 hours to fully charge a battery.

Modified constant current/taper charger

The modified constant current/taper charger supplies current to the battery over three stages. This is illustrated in Figure 32.

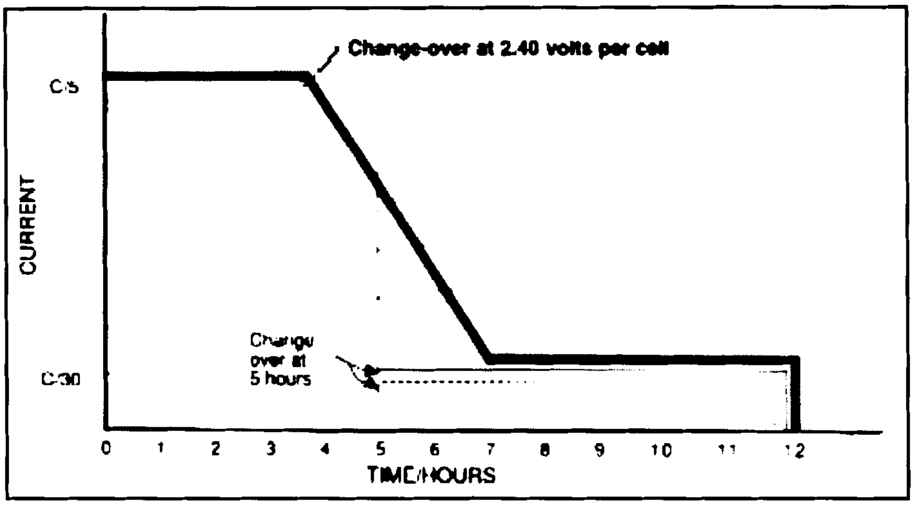

Figure 32: Typical recharge characteristics of a modified constant current or taper charger

First rate charging is continued for an undefined period, until each cell in the battery reaches 2.4V. The current for this stage is:

$$Current_{FirstRate} = \frac{Ah_{Battery}}{5}$$

The charger control senses when 2.4V per cell is reached, and switches to second rate charging. This lasts for 5 hours where the battery's cell voltage rises to 2.44V and the current is allowed to taper down.

After second rate charging, the charger switches to equalization mode. The current is given by:

$$Current_{Equalization} = \frac{Ah}{30}$$

The modified constant current/taper charger takes about 12 hours to fully charge a battery.

3.2.2 High frequency chargers

In power electronics, high frequency chargers fall under the category of power converters. High frequency chargers are also known as switch-mode power supplies. Power converters are normally classified as [42]:

- AC-DC converter (or phase-controlled converters)
- direct AC-AC converters (or cycloconverters)
- DC-AC converters (or inverters)
- DC-DC converters (or choppers, buck- or boost converters)

In designing a transformer, the operating frequency of the transformer must be taken into account. One of the characteristics in designing the transformer's core is that the cross-sectional area of the core is inversely proportional to the operating frequency. Therefore, by increasing the operational frequency from 50 Hz (the normal AC power's frequency from Eskom) to 50 kHz the cross-sectional area of the transformer's core would be 1 000 times reduced [43].

The basic operation of a high-frequency charger is as follows. The mains supply is rectified and smoothed to provide a DC supply. This DC voltage is switched at a high frequency into the primary of a transformer. This transformer output is rectified and used to charge the battery. By controlling the conduction of the switching devices, the charging current is adjusted.

The AC power source, transformer and rectifier in Figure 27 can be seen as a DC source, if a smoothing capacitor is also placed in parallel. This is shown in Figure 33.

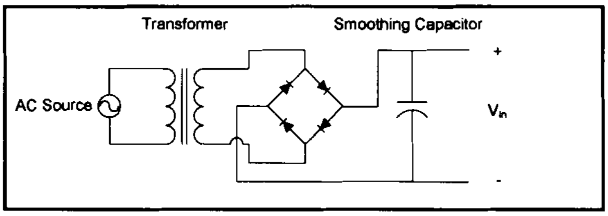

Figure 33: Circuit diagram of a basic DC source

Because a battery is also a DC source, a DC-DC converter can be used to charge batteries. A DC-DC converter converts unregulated DC power into regulated DC power or variable DC power as output. The most common DC-DC converter topologies are:

- Buck converter (also known as a step-down converter)
- Boost converter (also known as a step-up converter)
- Buck-boost converter

High frequency power supplies come in pulse width-modulation (PWM) converters and resonant converters. For the purpose of this study only the PWM converters will be investigated, as this is the technology in use for this investigation.

PWM converters use square wave pulse width modulation to achieve voltage regulation. Benefits of PWM converters include that they are easy to control; they are well understood; and have a wide control range. On the other hand, the switching losses increase as the switching frequency is increased; and the stress on the switches are higher due to the generation of high electromagnetic interference (EMI).

PWM converters can be further classified as non-isolated single-ended, isolated single-ended and double-ended PWM converters. Double-ended PWM converters are used where the output power requirement are 300 W or more. For this reason, one of the double-ended PWM converters will be discussed in further detail below.

There are three basic different types of double-ended PWM converter. These are the push-pull converter, half-bridge converter and the full bridge converter. The push-pull converter's operation will be discussed.

In Figure 34 a typical schematic diagram of a push-pull converter is shown.

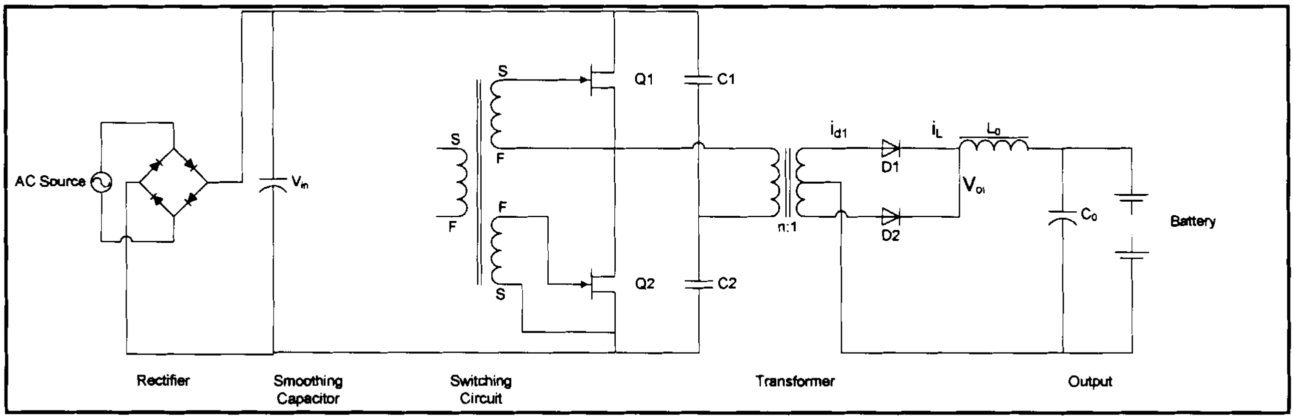

Figure 34: Simplified schematic of a push-pull converter

The duty ratio of transistors Q1 and Q2 are less that 0.5. Advantages of this configuration include that the transformer flux swings fully, resulting in a smaller transformer (typically half the size) than single-ended converters, and the output ripple is double the switching frequency, resulting in a smaller filter that is needed.

Disadvantages of the push-pull converter include that the transistors must block twice the input voltage, and the use of a center-tap transformer increase the number of copper windings needed, resulting in a higher VA-rating.

The operation of the push-pull converter, shown in Figure 34, will be discussed further. In Figure 35 below, the operating waveforms for the push-pull converter is given.

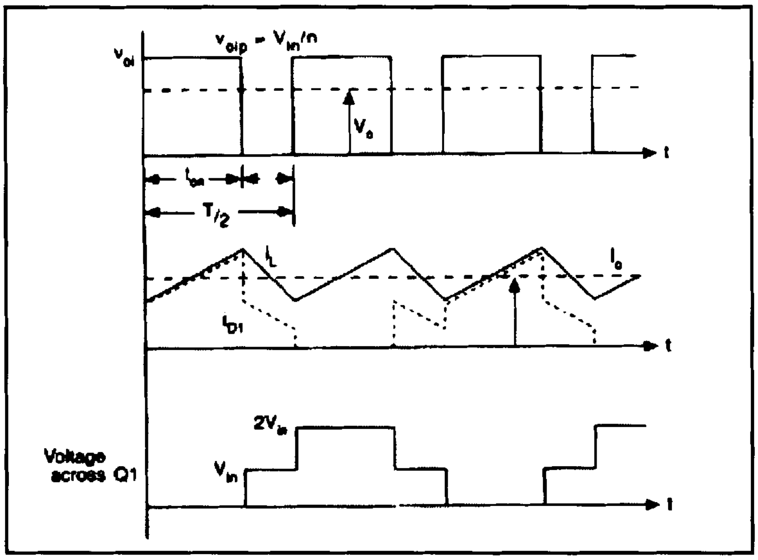

Figure 35: Operating waveform for the push-pull converter

When Q1 is turned on, current flows from the positive terminal through Q1, through the transformer's primary windings, through C2, and finally, to the negative terminal. Secondary current flows through D1 to the battery. When Q2 is turned on, current flows from positive through C2, through the transformer's primary winding (in the opposite direction) and then through Q2 to the negative terminal. Secondary current flows through D2 to the battery.

A driving transformer is used in the switching circuit to switch Q1 and Q2 on and off. Due to the operation of the transformer, it is ensured that only one transistor is switched on at any one time.

Unfortunately, current is still only being drawn from the mains near the peak of the AC waveform, resulting in inefficient use of the power. A power factor correction circuit, as shown in Figure 36, can be used to overcome this problem.

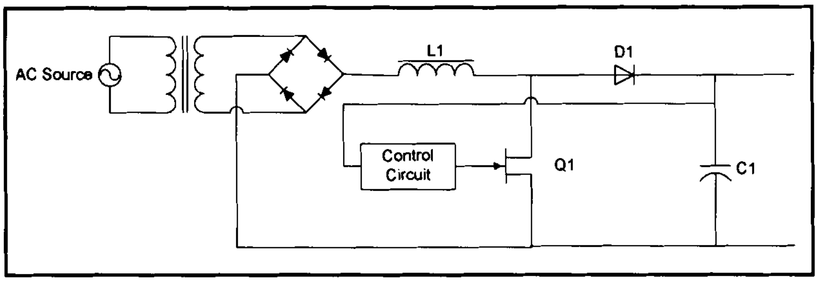

Figure 36: Typical power factor correction circuit

The purpose of the circuit shown in Figure 36 is to cause the current drawn from the mains to be drawn over the complete voltage cycle. Rectified mains voltage is fed through inductor L1. When Q1 is turned on, current flows through L1 to diode D1, charging the reservoir capacitor C1. When Q1 is switched off, current in L1 continues to flow through D1 to charge C1. C1 is charged to a point above that of the mains voltage and can be controlled by varying the conductance of Q1.

By choosing the switching frequency of Q1 to be much higher than that of the mains, it is possible to build up enough current through L1 to maintain the voltage on C1, even if the supply voltage is zero. This means that current is drawn from the mains over the complete cycle, eliminating waveform distortion associated with ferro-resonant chargers.

3.3 TECHNOLOGY IN USE AT A TYPICAL MINE

On a busy level where there is a high level of production, each locomotive commonly has three battery sets. Each locomotive has one battery that is used in the morning shift, one battery for the afternoon shift and one battery for the evening shift. These batteries are charged during the following shift.

Constant current chargers are most commonly installed at a mine. Mines are relatively old, and the newer high frequency chargers weren't available at the time.

Chargers are installed where most of the development and mining activities are taking place. These are scattered over multiple levels, and it occurs frequently that there are more than one battery bay on a level. The battery charger bays on a level can also be in completely different sections.

Figure 37 shows a picture of a typical battery bay. Note the crane needed for the lifting of the batteries.

Figure 37: Photo of a typical battery bay

What usually happens is the locomotive (shown in Figure 38) comes into the battery bay on the tracks, where the battery (shown in Figure 39) is lifted off the locomotive and replaced with a fully charged battery.

Figure 38: Typical mining locomotive

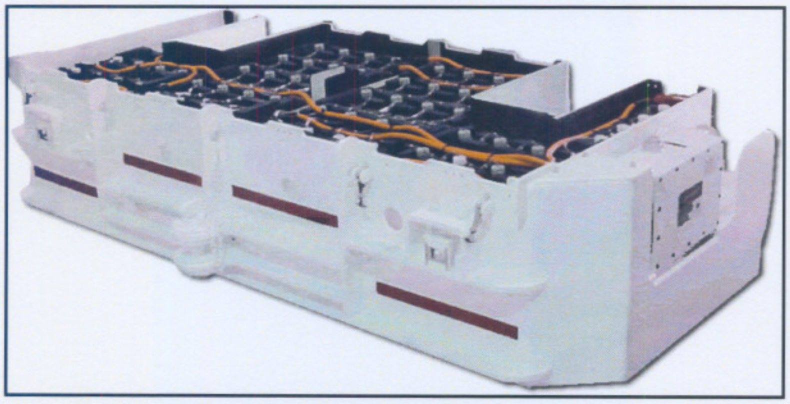

Figure 39: Typical locomotive traction battery

At Turffontein shaft, one of Rustenburg Platinum Mines Rustenburg Section's shafts, there are for example 10 ton battery locomotives and 5 ton battery locomotives. They require 850 Ah and 600 Ah battery chargers respectively. Kopanang mine on the Vaal River ring has 800 Ah and 600 Ah chargers installed [35].

3.4 SOLUTION TO THE PROBLEM: DETERMINING THE SAVINGS POTENTIAL

3.4.1 The simulation model

There are a couple of possible combinations when investigating savings potential on battery chargers. These involve load shift on ferro resonant chargers and installing high frequency chargers for energy efficiency with/without load shift. The following combinations will be investigated:

- Doing load shift on the ferro resonant chargers in the evening peak demand period.
- Replacing the ferro resonant chargers with high frequency chargers, realising energy efficiency.
- Replacing the ferro resonant chargers with high frequency chargers (realising energy efficiency), and then doing load shift on the high frequency chargers in the evening peak demand period.

The following assumptions will be made:

1. A baseline will be set up using three battery sets – for the morning, afternoon and night shifts.
2. The usual shift times found on a mine will be used
3. The battery chargers are charged, starting an hour and a half after the start of a new shift
4. The current that the ferro resonant charger draws are:
    a. First rate: 38A
    b. Second rate: 20A
    c. Equalise: 5A
5. The charging times for the different charge cycles of the ferro resonant charger is as follows:
    a. First rate: 2 hours
    b. Second rate: 3 hours
    c. Equalise: until the battery is needed, but a minimum of three hours
6. The current that the high frequency charger draws are a third that of the ferro resonant charger [35]:
    a. First rate: 15A

   b. Second rate: 8A
   c. Equalise: 2A
7. The total charging time for the high frequency charger has been taken as five hours. The high frequency charger's charge time is between four and five hours as was discussed previously. Taking it as five hours will give a worst case scenario.
8. The charging times for the different charge cycles of the high frequency charger is as follows:
   a. First rate: 1 hour
   b. Second rate: 2 hours
   c. Equalise: until the battery is needed, but a minimum of 2 hours
9. The batteries are kept on the charger, until it is needed during the shift. This has the effect that the charger is always on the equalisation cycle.

These assumptions where confirmed by mine personnel [35] and the simulations where based on these assumptions.

The usual shift times in a mine is summarised in Table 3 below.

Table 3: Typical shift times in a mine

	Morning	Afternoon	Night
Start	06:00	14:00	22:00
Stop	14:00	22:00	06:00

Firstly, some kind of baseline needs to be drawn up. It was decided to use one locomotive's batteries as a benchmark. This battery set consists of three batteries, one for the morning shift, one for the afternoon shift and one for the evening shift. This will give an accurate view of the savings that may be realised, if the total number of locomotives is known.

By keeping the shift times in Table 3 in mind, as well as the fact that the batteries will be charged starting an hour and a half after the start of each shift, charging times of the chargers are determined and shown in Table 4.

Table 4: Typical battery charging times in a mine

	Morning	Afternoon	Night
Start	07:30	15:30	23:30
Stop	15:30	23:30	07:30

By using the charging times and the current drawn by the ferro resonant charger during certain cycle periods, the power usage of each charger can be determined as shown in Table 5 and Table 6 can be drawn up. A power factor of 0.8 was used as this was the value typically measured.

Table 5: Battery charger power

Charging Algorithm				
Cycle	**Cycle Hour**	**Charger Voltage V_{line} [V]**	**Charger Current I_{line} [A]**	**Charger Power - 3ø [W]**
First rate	1	550	38	28 960
First rate	2	550	38	28 960
Second rate	3	550	20	15 242
Second rate	4	550	20	15 242
Second rate	5	550	20	15 242
Equalise	6	550	5	3 811
Equalise	7	550	5	3 811
Equalise	8	550	5	3 811

Table 6: Charging power for three battery sets

Time	Battery Charger Power Used [W]		
	Morning Shift's Batteries	Afternoon Shift's Batteries	Night Shift's Batteries
00:00	3 811	28 960	0
00:30	3 811	28 960	0
01:00	3 811	28 960	0
01:30	3 811	15 242	0
02:00	3 811	15 242	0
02:30	3 811	15 242	0
03:00	3 811	15 242	0
03:30	3 811	15 242	0
04:00	3 811	15 242	0
04:30	3 811	3 811	0
05:00	3 811	3 811	0
05:30	3 811	3 811	0
06:00	0	3 811	3 811
06:30	0	3 811	3 811
07:00	0	3 811	3 811
07:30	0	3 811	28 960
08:00	0	3 811	28 960
08:30	0	3 811	28 960
09:00	0	3 811	28 960
09:30	0	3 811	15 242
10:00	0	3 811	15 242
10:30	0	3 811	15 242
11:00	0	3 811	15 242
11:30	0	3 811	15 242
12:00	0	3 811	15 242
12:30	0	3 811	3 811
13:00	0	3 811	3 811
13:30	0	3 811	3 811
14:00	3 811	0	3 811
14:30	3 811	0	3 811
15:00	3 811	0	3 811
15:30	28 960	0	3 811
16:00	28 960	0	3 811
16:30	28 960	0	3 811
17:00	28 960	0	3 811
17:30	15 242	0	3 811
18:00	15 242	0	3 811
18:30	15 242	0	3 811
19:00	15 242	0	3 811
19:30	15 242	0	3 811
20:00	15 242	0	3 811
20:30	3 811	0	3 811
21:00	3 811	0	3 811
21:30	3 811	0	3 811
22:00	3 811	3 811	0
22:30	3 811	3 811	0
23:00	3 811	3 811	0
23:30	3 811	28 960	0

By taking the total power and averaging it over an hour, the baseline shown in Figure 40 can be determined.

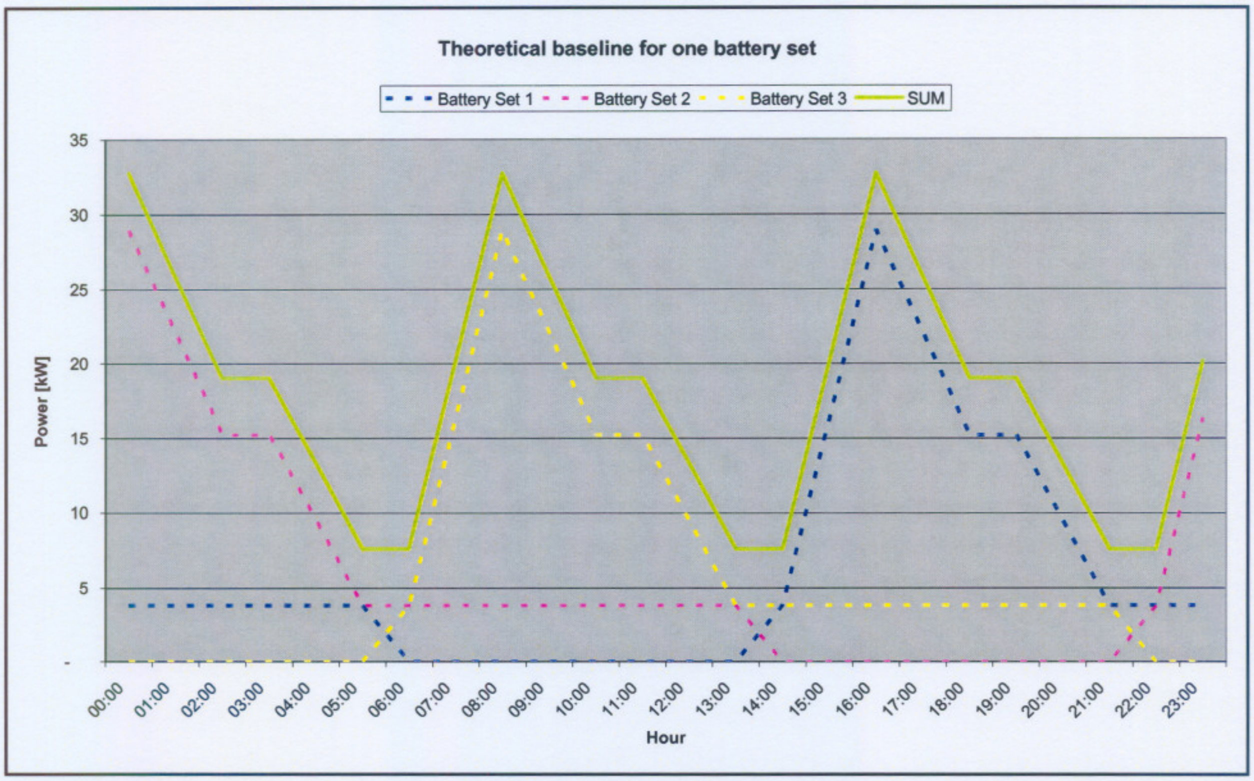

Figure 40: Baseline for one battery set

By taking battery set one as an example: It can be seen that the battery charger's charging current is 0A between 06:00 and 13:00. This means that it is used during this period (in the morning shift). After this it starts charging on the first rate charging cycle, switching over to second rate charging and then equalising.

The sum of all three battery sets gives the theoretical baseline for one locomotive's battery charger. As can be seen, there exists a 19kW potential for load shift out of the evening peak demand period.

The method that will be used throughout this study is to simply install a switch on the chargers. During Eskom's evening peak time, the charger will be switched off enabling energy cost savings. After Eskom's evening peak, the charger will start charging the battery again, starting from where it left of before the peak.

3.4.2 Using the currently installed chargers

It is possible to realise energy cost savings by using the ferro resonant battery chargers that are currently installed at a typical mine, simply by switching them off during Eskom's peak time(s). It has to be kept in mind that the ferro resonant charger's charge cycle lasts for 8 hours and the typical shift in the mine is also 8 hours long.

Table 7 and Figure 41 show the charger profile if the charger is switched off during Eskom's evening peak.

Table 7: Charger profile by not charging in Eskom's evening peak

Time	Work Shift	SIMULATION - EVENING PEAK [W]			
		Morning Shift	Afternoon Shift	Night Shift	SUM
00:00	Night	3 811	28 960	-	32 770
01:00	Night	3 811	22 101	-	25 911
02:00	Night	3 811	15 242	-	19 053
03:00	Night	3 811	15 242	-	19 053
04:00	Night	3 811	9 526	-	13 337
05:00	Night	3 811	3 811	-	7 621
06:00	Morning	-	3 811	3 811	7 621
07:00	Morning	-	3 811	16 385	20 196
08:00	Morning	-	3 811	28 960	32 770
09:00	Morning	-	3 811	22 101	25 911
10:00	Morning	-	3 811	15 242	19 053
11:00	Morning	-	3 811	15 242	19 053
12:00	Morning	-	3 811	9 526	13 337
13:00	Morning	-	3 811	3 811	7 621
14:00	Afternoon	3 811	-	3 811	7 621
15:00	Afternoon	16 385	-	3 811	20 196
16:00	Afternoon	28 960	-	3 811	32 770
17:00	Afternoon	22 101	-	3 811	25 911
18:00	Afternoon	-	-	-	-
19:00	Afternoon	-	-	-	-
20:00	Afternoon	15 242	-	3 811	19 053
21:00	Afternoon	15 242	-	3 811	19 053
22:00	Night	9 526	3 811	-	13 337
23:00	Night	3 811	16 385	-	20 196

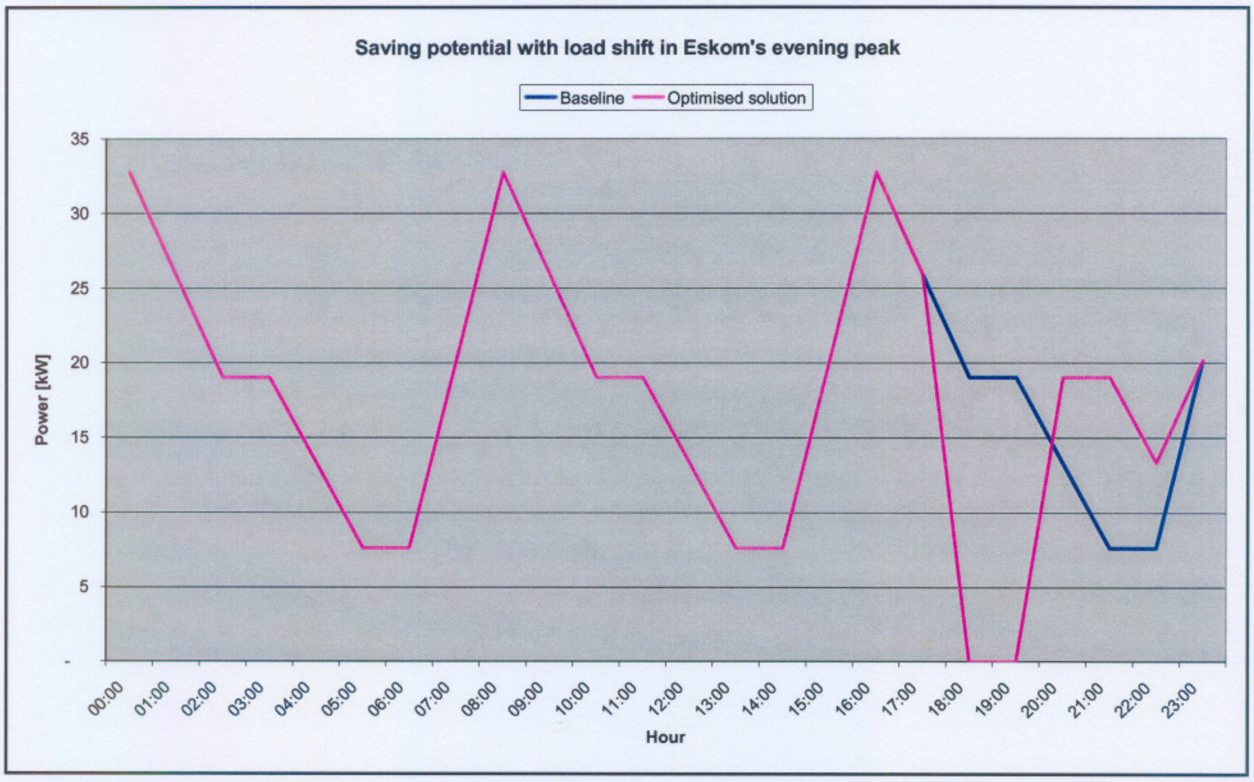

Figure 41: Charger profile by not charging in Eskom's evening peak

As can be seen above, there exist a 19kW potential out of Eskom's evening peak if three battery sets are used. To give an approximate saving for the whole mine, this potential saving can be multiplied by the number of locomotives in the mine.

3.4.3 Using high frequency battery chargers

The other two ways involves installing high frequency battery chargers. By just using the high frequency battery charger a huge saving in electrical energy is realised. A typical push-pull converter's efficiency is 80%, compared to a typical linear charger's efficiency of only 30% [44].

In the following table (Table 8) the electrical usage of the high frequency charger is given. This is plotted against the baseline in Figure 42.

Table 8: Power usage profile of high frequency chargers

Time	Work Shift	BASELINE [W]			
		Battery Set 1	Battery Set 2	Battery Set 3	SUM
00:00	Night	1 477	8 564	-	10 041
01:00	Night	1 477	5 906	-	7 383
02:00	Night	1 477	3 691	-	5 168
03:00	Night	1 477	1 477	-	2 953
04:00	Night	1 477	1 477	-	2 953
05:00	Night	1 477	1 477	-	2 953
06:00	Morning	-	1 477	1 477	2 953
07:00	Morning	-	1 477	6 349	7 826
08:00	Morning	-	1 477	8 564	10 041
09:00	Morning	-	1 477	5 906	7 383
10:00	Morning	-	1 477	3 691	5 168
11:00	Morning	-	1 477	1 477	2 953
12:00	Morning	-	1 477	1 477	2 953
13:00	Morning	-	1 477	1 477	2 953
14:00	Afternoon	1 477	-	1 477	2 953
15:00	Afternoon	6 349	-	1 477	7 826
16:00	Afternoon	8 564	-	1 477	10 041
17:00	Afternoon	5 906	-	1 477	7 383
18:00	Afternoon	3 691	-	1 477	5 168
19:00	Afternoon	1 477	-	1 477	2 953
20:00	Afternoon	1 477	-	1 477	2 953
21:00	Afternoon	1 477	-	1 477	2 953
22:00	Night	1 477	1 477	-	2 953
23:00	Night	1 477	6 349	-	7 826

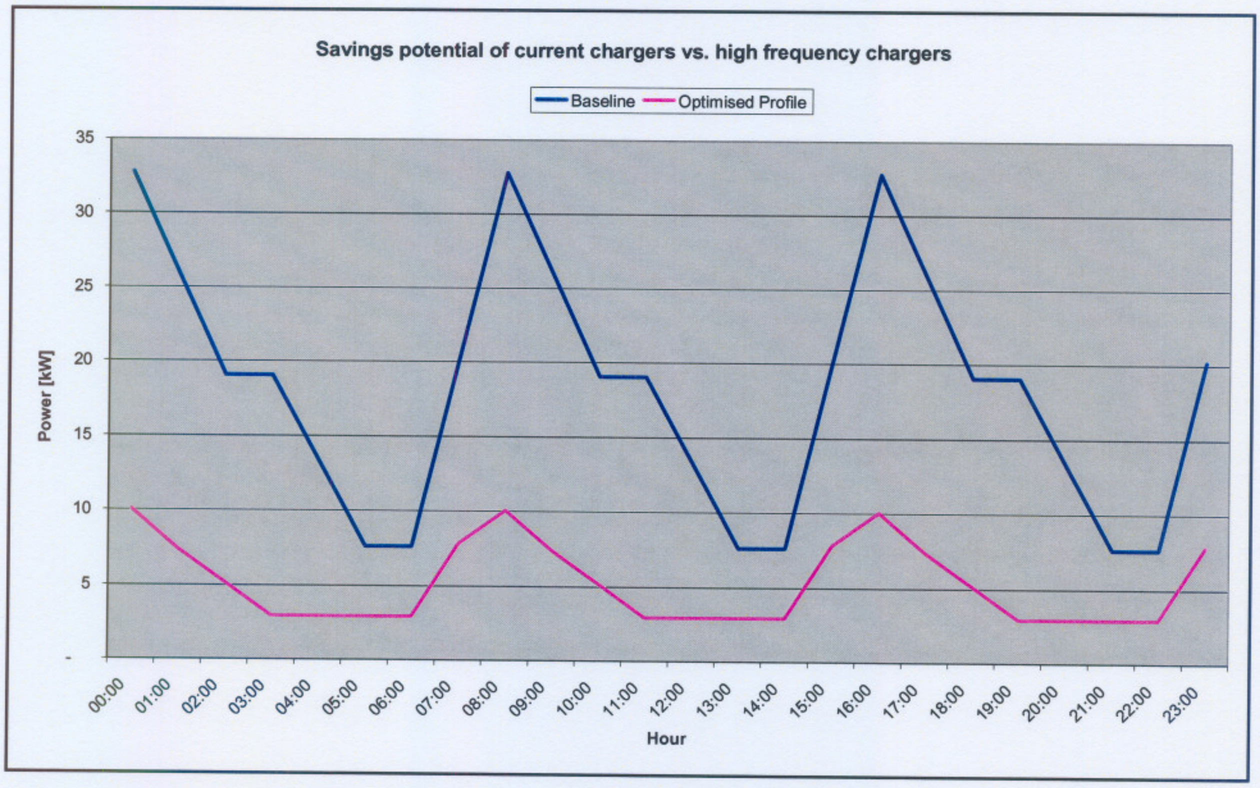

Figure 42: Constant current vs high frequency chargers

This equates to an annual electrical energy saving of 113 148 kWh, or an average of 12.92 kW per day.

The other way is to make sure that the high frequency battery chargers don't run in Eskom's peak time(s). This will result in energy savings, as well as the associated energy cost savings, if the mine is on Megaflex or another similar price profile. It will also result in a smaller amount of load shift than with the first scenario, thereby combining load shift and energy efficiency.

In Table 9 the average hourly energy usage is given where load shift and energy efficiency is combined. This is graphically illustrated in Figure 43.

Table 9: Power usage profile of high frequency chargers with load shifting in Eskom's evening peak

Time	Work Shift	SIMULATION - EVENING PEAK [W]			
		Morning Shift	Afternoon Shift	Night Shift	SUM
00:00	Night	1 477	8 564	-	10 041
01:00	Night	1 477	5 906	-	7 383
02:00	Night	1 477	3 691	-	5 168
03:00	Night	1 477	1 477	-	2 953
04:00	Night	1 477	1 477	-	2 953
05:00	Night	1 477	1 477	-	2 953
06:00	Morning	-	1 477	1 477	2 953
07:00	Morning	-	1 477	6 349	7 826
08:00	Morning	-	1 477	8 564	10 041
09:00	Morning	-	1 477	5 906	7 383
10:00	Morning	-	1 477	3 691	5 168
11:00	Morning	-	1 477	1 477	2 953
12:00	Morning	-	1 477	1 477	2 953
13:00	Morning	-	1 477	1 477	2 953
14:00	Afternoon	1 477	-	1 477	2 953
15:00	Afternoon	6 349	-	1 477	7 826
16:00	Afternoon	8 564	-	1 477	10 041
17:00	Afternoon	5 906	-	1 477	7 383
18:00	Afternoon	-	-	-	-
19:00	Afternoon	-	-	-	-
20:00	Afternoon	3 691	-	1 477	5 168
21:00	Afternoon	1 477	-	1 477	2 953
22:00	Night	1 477	1 477	-	2 953
23:00	Night	1 477	6 349	-	7 826

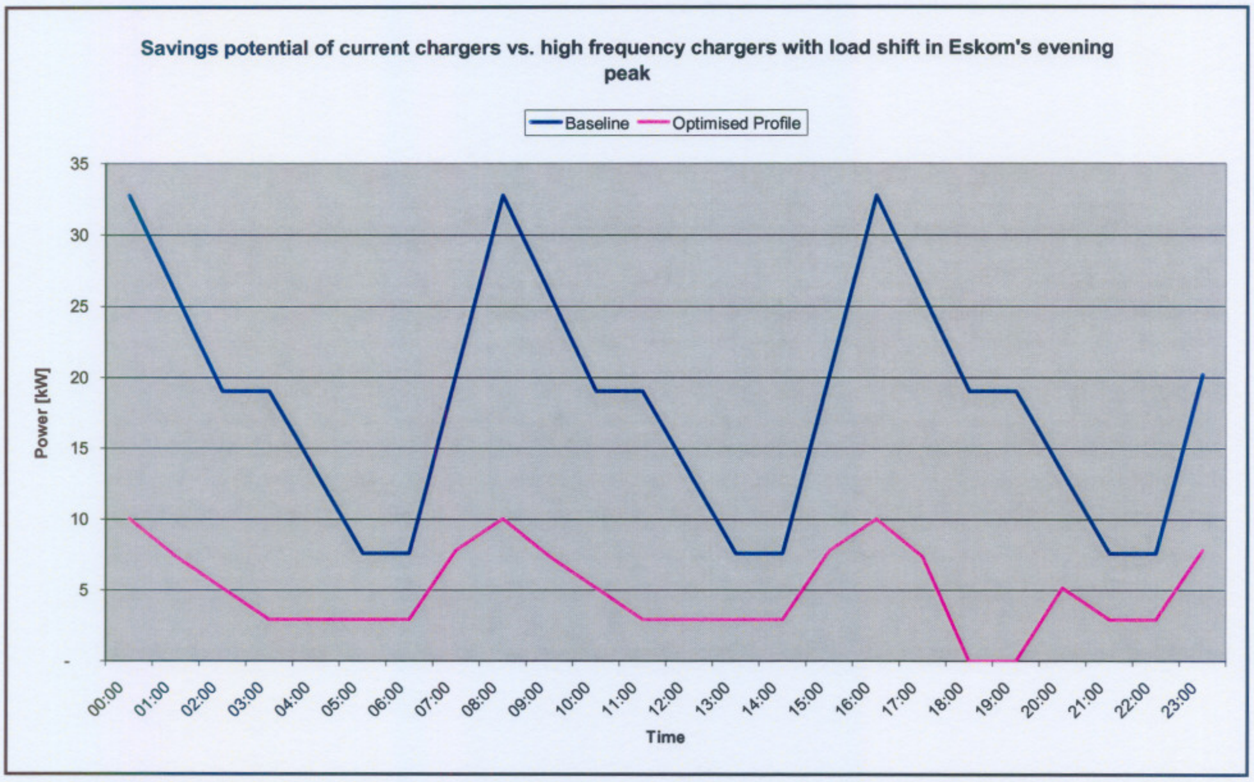

Figure 43: Constant current chargers vs high frequency chargers with load shift

The combination of load shift and energy efficiency can be better understood if the energy efficiency and load shift components are compared graphically. This is done in Figure 44.

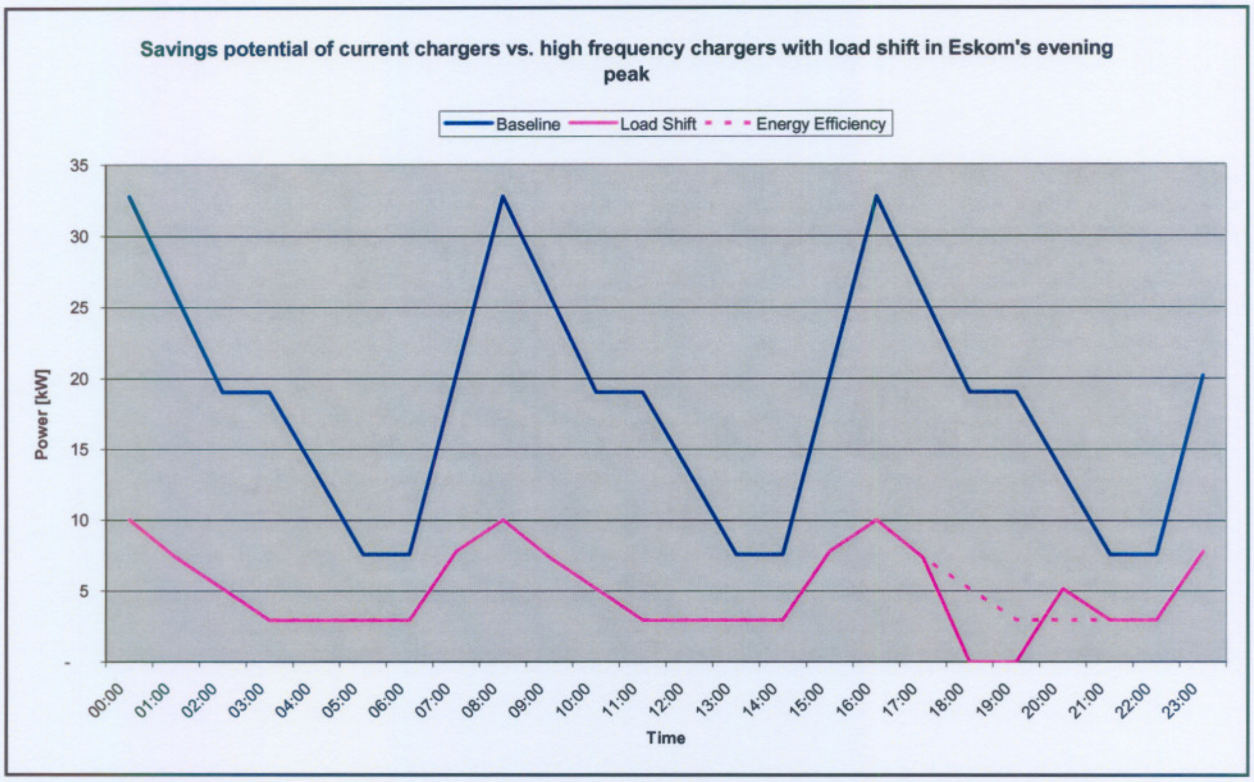

Figure 44: Energy efficiency and load shift combined

In Figure 44, the energy efficiency is done first, giving the dotted magenta-colour line. This is exactly the same profile as given in Figure 42. If this is taken as the "new" baseline, load shift can be done on this. This is shown with the solid magenta line. Therefore, energy efficiency and load shift is combined into one DSM project.

3.5 CONCLUSION

The lead acid battery is one of the oldest battery technologies available, making it one of the best understood batteries. There are two basic types of chargers available for the battery, namely the ferro resonant charger and the high frequency charger. The high frequency charger is the newer technology, making use of newer semiconductor material.

Benefits of using high frequency chargers include:

- smaller size as the transformer's size is very small
- transformer's small size does not necessitate it to be oil cooled – resulting in
  - fewer oil leakages
  - smaller risk of fires because of lack of transformer oil

- the charger is lighter than ferro resonant chargers
- average efficiency of 80%, compared to efficiencies of 30% of ferro resonant chargers
- smaller breakers and thinner cables would have to be used due to lower electrical energy use
- charge time is less – typically 4-5 hours

There is potential energy savings, as well as energy cost savings, with the use of both types of charger. By simply not charging batteries in Eskom's peak time, it is possible to realise energy cost savings with the ferro resonant chargers.

The high frequency chargers use less electricity, resulting in energy savings, as well as energy cost savings. The charging time is also less – typically 4-5 hours, compared to 8 hours with the ferro resonant charger. This would make it easier to not charge the batteries in Eskom's peak time, as there is less chance that the batteries would not be completely charged for the next shift.

CHAPTER 4: CASE STUDY: KOPANANG GOLD MINE

4.1 DETERMINING THE BASELINE

The cross-sectional view of a typical mine is given in Figure 45.

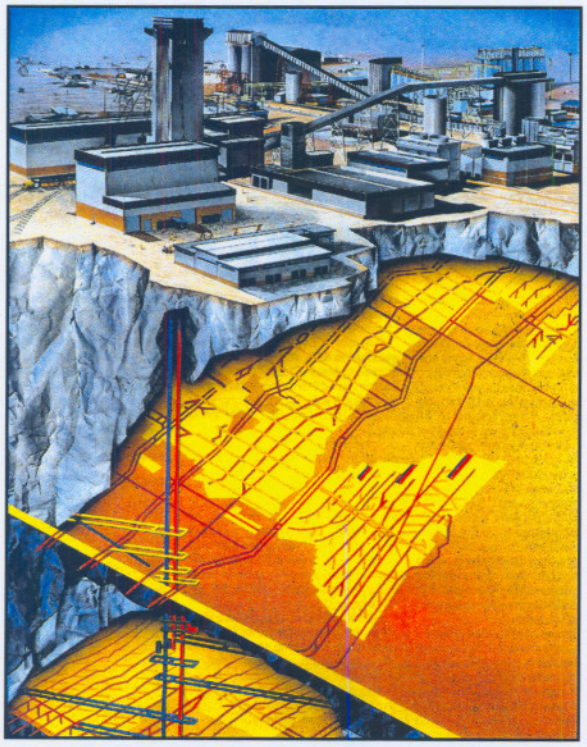

Figure 45: Cross section of a typical mine

As can be seen, a typical mine has many levels. Kopanang has 10 levels where battery bays are located. There are 15 battery bays on these levels, with approximately 10 chargers per bay. This means that Kopanang has approximately 150 locomotive battery chargers installed on the mine.

To measure every single battery charger would not be feasible due to the huge amount of chargers installed on the mine. Measuring every battery bay would also not be feasible, because they are scattered over 10 levels.

Therefore one battery bay was measured and this was extrapolated to the rest of the battery bays, and hence to all the locomotive battery chargers on the mine.

Kopanang goldmine's shift times is shown in Table 10. It can be seen that these times are that of a typical mine.

Table 10: Shift times at Kopanang

Morning shift	Afternoon shift	Night shift
06:00 – 14:00	14:00 – 22:00	22:00 – 06:00

On average, the charging of the batteries are started an hour and a half before the start of the new shift. These times are summarized in Table 11. The charge cycle for the batteries is 8 hours.

Table 11: Battery charge times at Kopanang

Morning	Afternoon	Night
04:30 – 12:30	12:30 – 20:30	20:30 – 04:30

Kopanang uses constant current chargers, with a three-stage charging cycle. The approximate current that the chargers draw from the feeders is summarized in Table 12.

Table 12: Current drawn from the feeders by a charger

Cycle	Current [A]
First rate	38
Second rate	20
Third rate (equalize)	5

4.2 THE BASELINE

By using the detail given in Section 4.1, it can be determined what the baseline could look like. The following assumptions are made:

Table 13: Data for simulated charger baseline for Kopanang

Hour	Power [kW]
1	1 639
2	1 296
3	953
4	953
5	667
6	381
7	381
8	1 010
9	1 639
10	1 296
11	953
12	953
13	667
14	381
15	381
16	1 010
17	1 639
18	1 296
19	953
20	953
21	667
22	381
23	381
24	1 010
	21 834

The total energy used per day is 21 834 kWh, with an average load of 910 kW.

The morning peak of just over 1 MW is in the middle of the morning peak demand time, while the evening peak just misses Eskom's peak time. In the evening peak demand period, the average load is about 950 kW.

The baseline for all the chargers was determined by measuring one battery bay for a period of four weeks. The battery bay on 62 level, with 25 batteries, was measured. The baseline for this battery bay is given in Figure 47, with the corresponding values tabulated in Table 14. In this figure, it can be seen that the mine does not employ load shift (either manual or automatic) on the battery chargers.

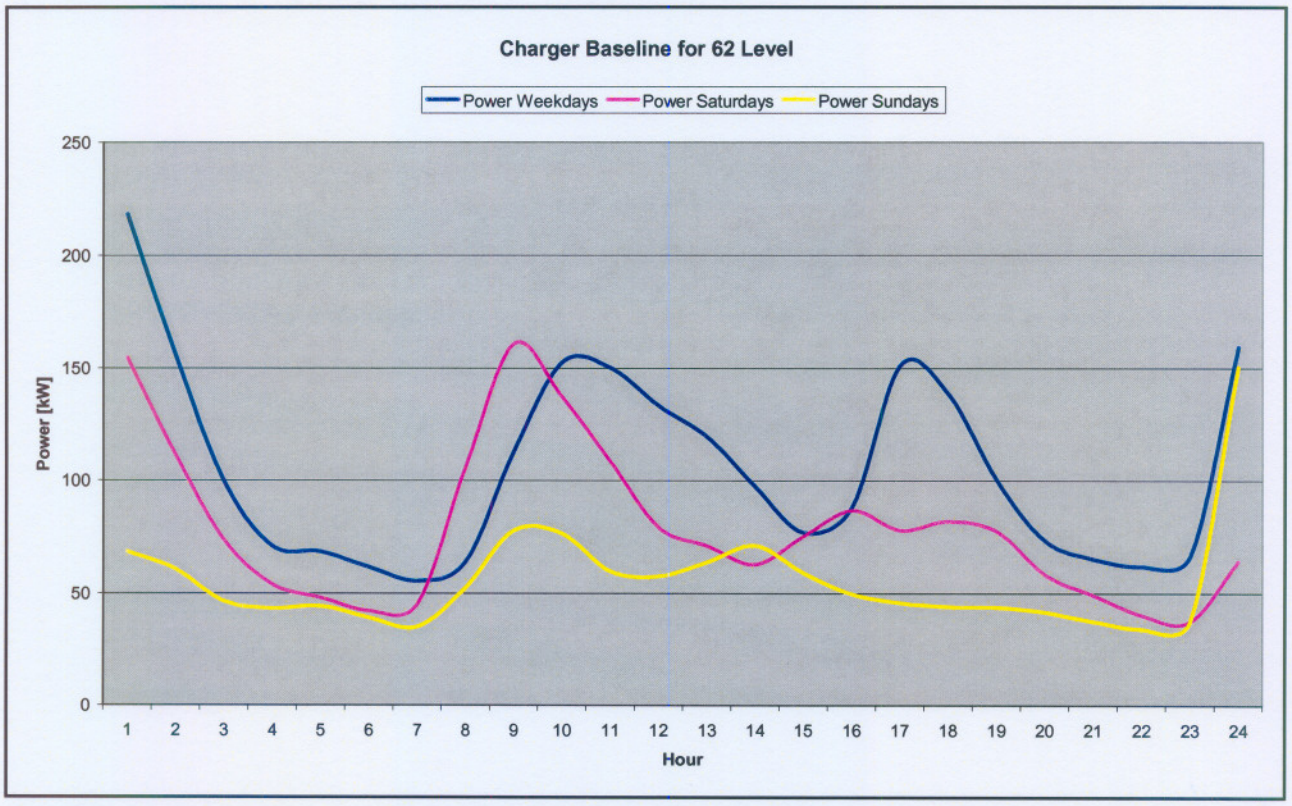

Figure 47: Charger baseline for 62 Level

Table 14: Baseline data for 62 Level

Hour	Power			
	Weekdays	Saturdays	Sundays	Average
1	218	155	69	188
2	156	111	61	136
3	100	74	47	88
4	71	54	43	65
5	69	48	44	62
6	62	42	39	56
7	56	45	35	51
8	64	106	53	68
9	113	161	78	115
10	153	137	77	140
11	150	108	60	131
12	133	79	58	115
13	119	71	64	105
14	97	63	71	89
15	77	75	59	74
16	88	87	50	83
17	151	78	46	126
18	138	82	44	117
19	100	78	44	89
20	73	58	42	67
21	65	49	37	59
22	62	40	34	55
23	67	37	37	58
24	159	64	150	145
TOTAL	2 542	1 905	1 341	2 279

This data is extrapolated to 150, the total chargers on the mine. This is given in Figure 48 and Table 15.

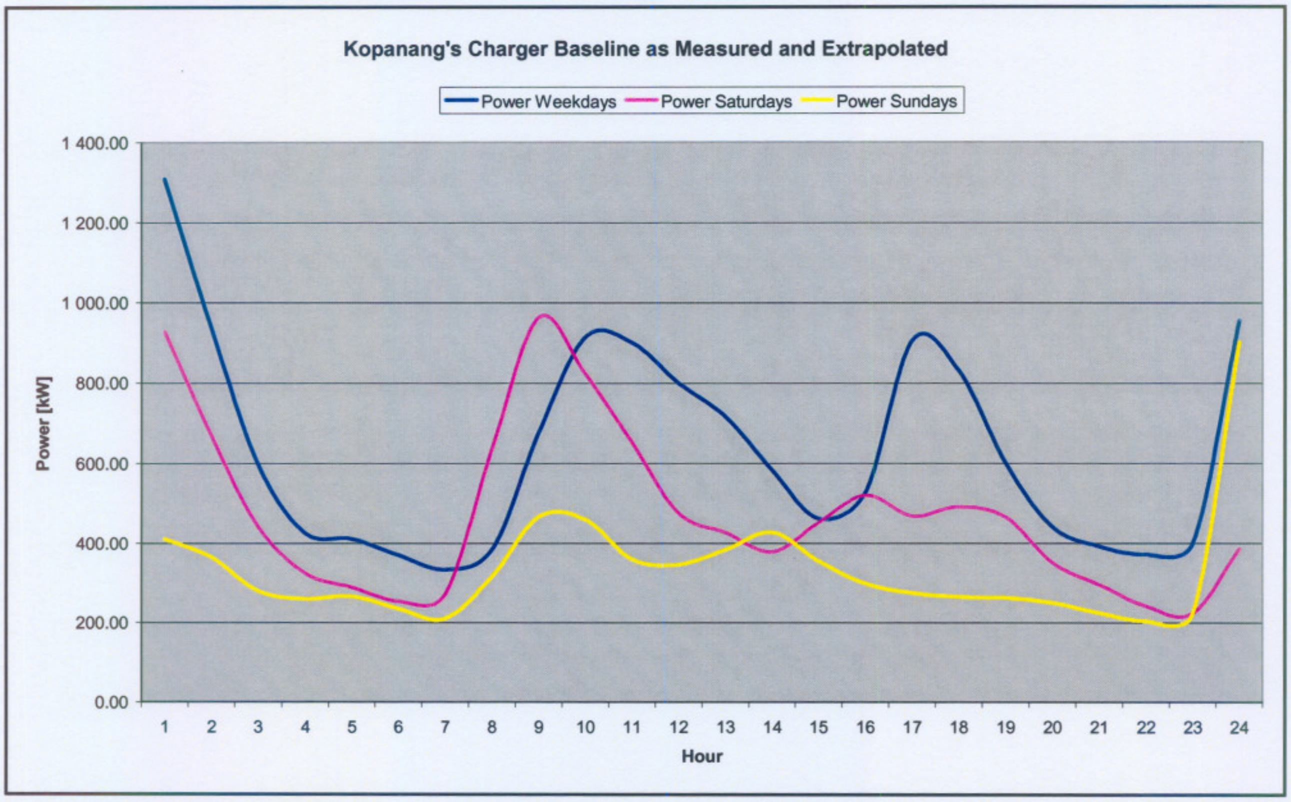

Figure 48: Kopanang's charger baseline

Table 15: Baseline data for Kopanang

Hour	Power			
	Weekdays	Saturdays	Sundays	Average
1	1 310	928	411	1 127
2	934	668	364	815
3	598	442	279	530
4	426	324	260	388
5	411	289	266	373
6	370	254	235	334
7	333	271	211	307
8	384	637	315	410
9	676	964	467	688
10	916	823	459	837
11	901	651	359	788
12	800	476	346	689
13	717	427	383	628
14	583	378	428	532
15	462	453	354	446
16	529	521	298	495
17	908	469	275	755
18	830	492	265	701
19	600	465	263	533
20	441	350	250	401
21	392	295	225	354
22	372	242	204	329
23	400	224	223	349
24	956	386	903	867
TOTAL	**15 251**	**11 429**	**8 045**	**13 675**

There are three peaks visible on weekdays, confirming that Kopanang charges batteries three times per day Monday to Friday. Saturdays show two peaks, one in the early morning and the other roundabout 08:00. This shows that the previous day's batteries are charged, and one set for Saturdays. On Sundays, the batteries are kept on trickle charge for the whole day as no work is done.

The weighted average of the baseline shown in Figure 48, gives the baseline as shown in Figure 49.

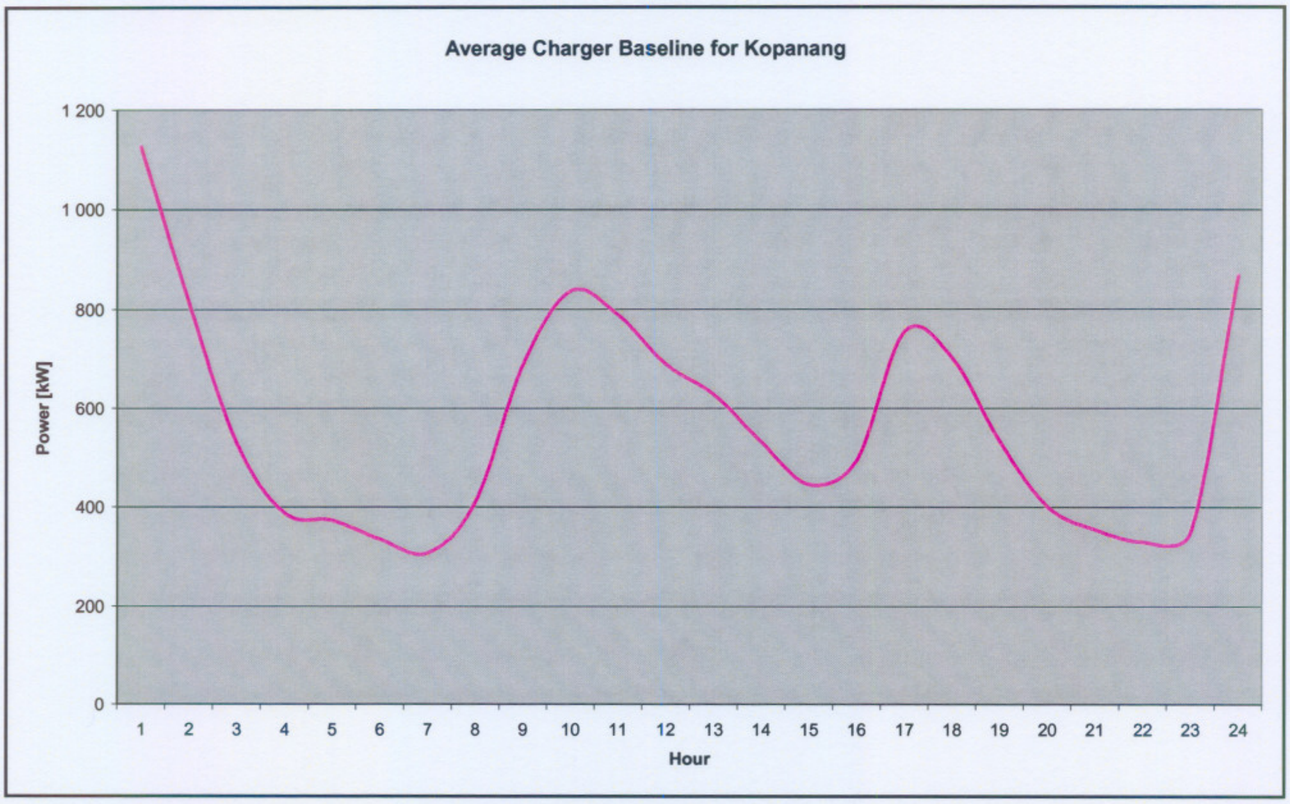

Figure 49: Kopanang's weekly average baseline

The total energy used per day is 13 675 kWh, with an average load of 570 kW.

4.3 SIMULATION

4.3.1 Using the currently installed chargers

This section deals with simulations done on putting a simple switch on the chargers, as discussed in section 3.4. However, by looking at Figure 50, it can be seen that the simulated baseline and the measured baseline differs. It is first necessary to calibrate the simulated baseline to the measured baseline.

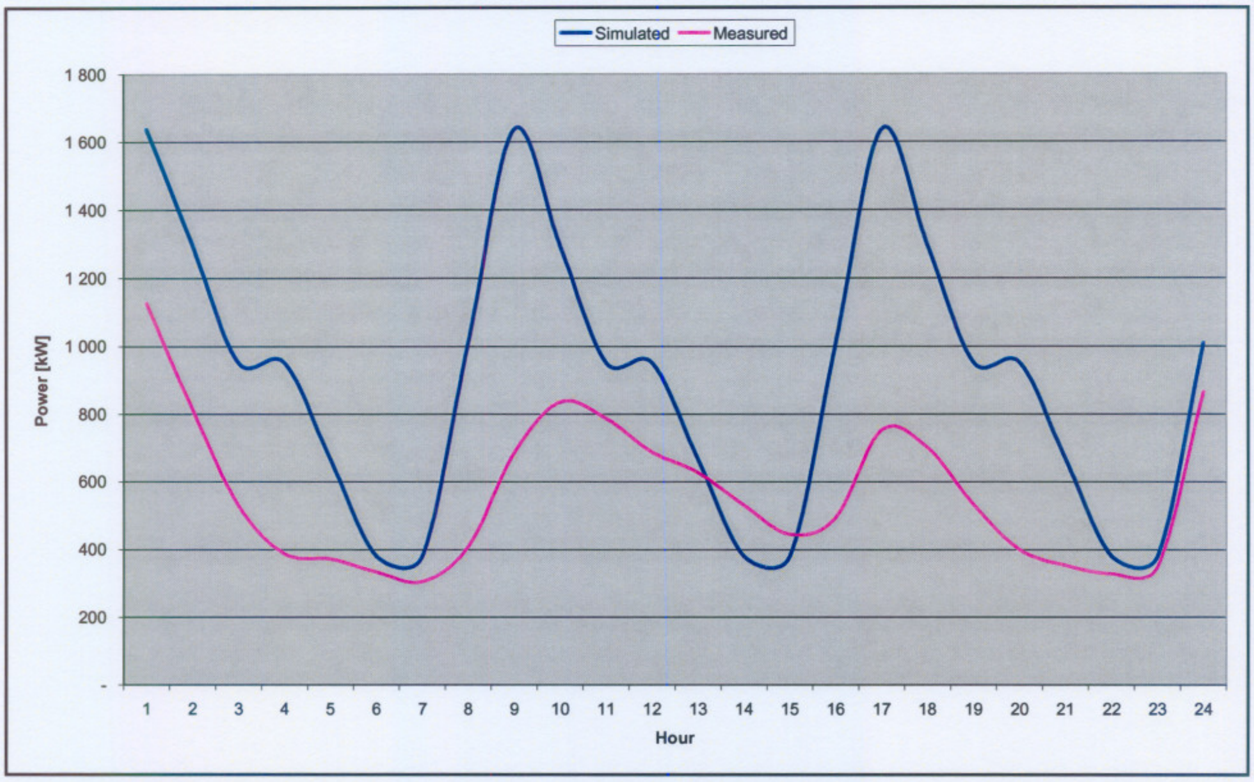

Figure 50: Simulated vs. measured baseline

The confidence in the measured baseline is higher because it is based on what is actually happening at the mine. Therefore the simulated baseline will be calibrated to the measured baseline.

It is obvious that some of the assumptions that have been made were wrong. These assumptions must be adjusted to arrive at a new simulated baseline, before the simulations can be done.

The most obvious difference between the two baselines is the difference in scale. This may be due to the fact that the batteries are not fully discharged at the end of the shift. Therefore the time spent on the first stage charging is less, resulting in lower peaks in the baseline.

The second difference between the two baselines is that the simulated peak around 08:00 is about an hour earlier than the measured baseline. This may be that the information from the mine wasn't correct for this time of the day, but rather an average starting time to charge the batteries. In the simulations the chargers must start charging an hour later in this peak.

Finally the baselines are calibrated to have the same total energy values for the day. This is done by adding a factor to each of the hourly power values to the simulated baseline. This factor is determined by subtracting the total energy usage for the simulated baseline from the total energy usage for the measured baseline, and dividing the result by 24 (the total hours in the day). It is given by the following formula.

$$factor = \frac{Energy_{measured} - Energy_{simulated}}{24}$$

Table 16 compares the hourly power readings for the simulated and measured baseline.

Table 16: Simulated vs. measured baseline

Time	Simulated Baseline [kW]	Measured Baseline [kW]
00:00	1 639	1 310
01:00	1 296	934
02:00	953	598
03:00	953	426
04:00	667	411
05:00	381	370
06:00	381	333
07:00	1 010	384
08:00	1 639	676
09:00	1 296	916
10:00	953	901
11:00	953	800
12:00	667	717
13:00	381	583
14:00	381	462
15:00	1 010	529
16:00	1 639	908
17:00	1 296	830
18:00	953	600
19:00	953	441
20:00	667	392
21:00	381	372
22:00	381	400
23:00	1 010	956
TOTAL	**21 834**	**15 251**

After the assumptions that have been made for the simulation has been adjusted, and the baselines have been calibrated to be energy neutral, the new simulated baseline can be drawn up. This is shown in Table 17.

Table 17: Calibrated simulated baseline showing the measured and uncalibrated baselines

Time	Simulated Baseline [kW]	Measured Baeline [kW]	Simulated Baseline (Calibrated) [kW]
00:00	1 639	1 310	905
01:00	1 296	934	778
02:00	953	598	651
03:00	953	426	651
04:00	667	411	546
05:00	381	370	440
06:00	381	333	440
07:00	1 010	384	440
08:00	1 639	676	672
09:00	1 296	916	905
10:00	953	901	778
11:00	953	800	651
12:00	667	717	651
13:00	381	583	546
14:00	381	462	440
15:00	1 010	529	672
16:00	1 639	908	905
17:00	1 296	830	778
18:00	953	600	651
19:00	953	441	651
20:00	667	392	546
21:00	381	372	440
22:00	381	400	440
23:00	1 010	956	672
TOTAL	**21 834**	**15 251**	**15 251**

As can be seen, the simulated baseline is calibrated to the measure baseline, having the same total amount of energy used during a day. This is illustrated in Figure 51.

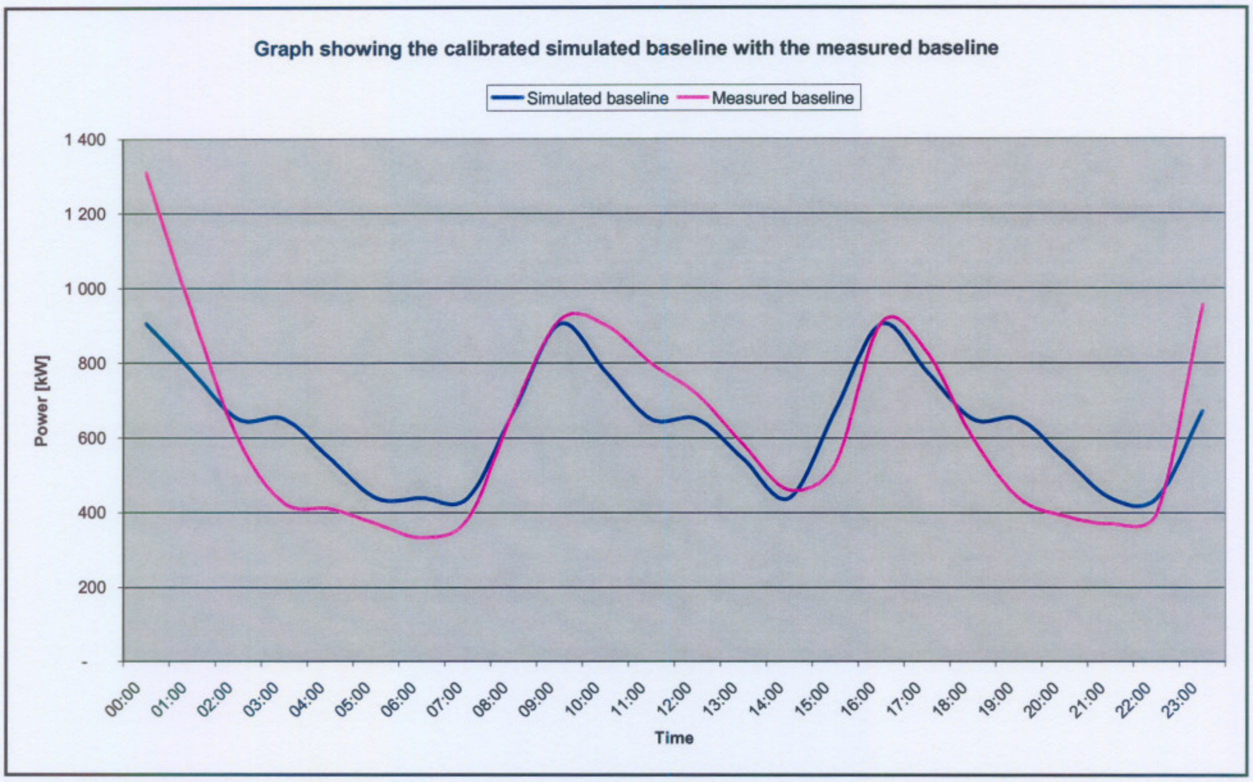

Figure 51: Measured baseline with the calibrated simulated baseline

The simulated baseline that has been calibrated will be used in the simulations.

The simulations will be done as described in section 3.4.

The following are inputs to the simulation:

- Kopanang's shift times
- charge times for the chargers at Kopanang
- the charging algorithm
- number of locomotives
- number of batteries
- number of battery chargers
- Eskom's Megaflex profile

The simulation must make sure that a battery set is ready, fully charged, for the next shift's work to be done. The output of the simulation gives the energy cost savings, as well as any possible energy savings.

Figure 52 shows the conceptual working for three battery sets at Kopanang.

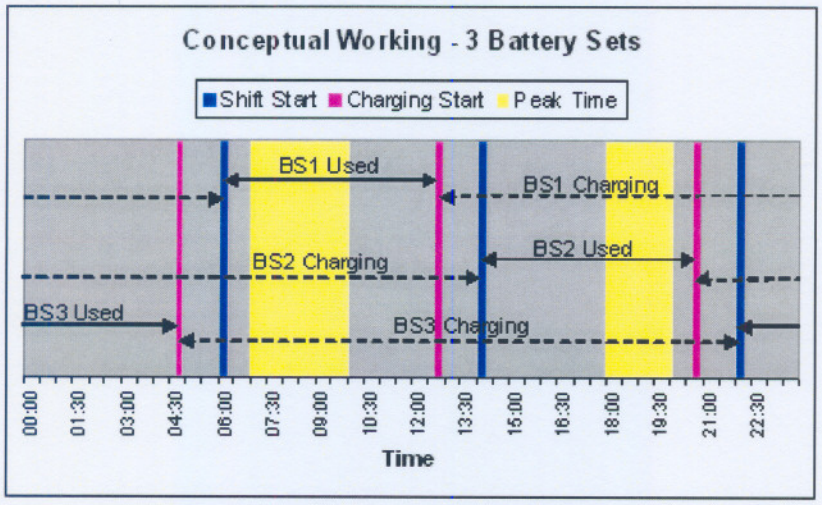

Figure 52: Conceptual working of the chargers at Kopanang

There are three possible ways to save energy cost with using the current chargers. These are by switching the chargers off in Eskom's morning peak, evening peak, or both peaks.

Eskom's MegaFlex tariff profile is given again in Table 18 for quick reference. The approximate annual savings is determined by calculating the hourly electricity cost for the baseline and the optimized profile (using the average price), totaling both costs for the day and taking the difference between the two costs. By multiplying this with the total number of days in the year, the approximate annual savings is determined.

Table 18: 2005 MegaFlex tariff structure

Hour	Unit Price - Winter [c/kWh]				Unit Price - Summer [c/kWh]			
	Weeksday	Saterday	Sunday	Avg Price	Weeksday	Saterday	Sunday	Avg Price
1	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
2	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
3	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
4	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
5	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
6	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
7	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
8	57.50	16.59	9.84	44.85	17.61	17.61	8.80	16.35
9	57.50	16.59	9.84	44.85	17.61	17.61	8.80	16.35
10	57.50	16.59	9.84	44.85	17.61	17.61	8.80	16.35
11	16.59	16.59	9.84	15.63	11.66	11.66	8.80	11.25
12	16.59	16.59	9.84	15.63	11.66	11.66	8.80	11.25
13	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
14	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
15	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
16	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
17	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
18	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
19	57.50	16.59	9.84	44.85	17.61	11.66	8.80	15.50
20	57.50	16.59	9.84	44.85	17.61	11.66	8.80	15.50
21	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
22	16.59	9.84	9.84	14.66	11.66	8.80	8.80	10.84
23	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80
24	9.84	9.84	9.84	9.84	8.80	8.80	8.80	8.80

Figure 53 shows the result from the simulation done by switching the chargers off in Eskom's morning peak.

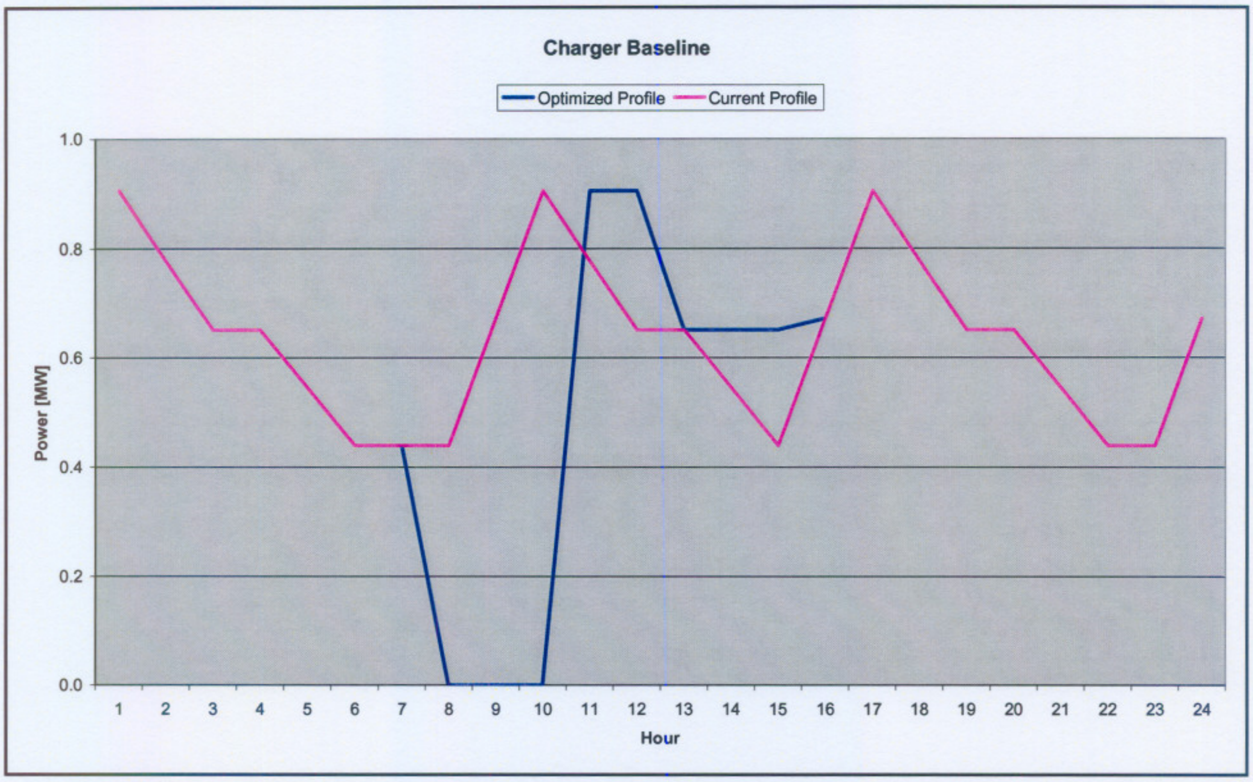

Figure 53: Not charging during Eskom's morning peak

This results in 0.67 MW moved out of Eskom's morning peak, resulting in an annual energy cost saving of R 142 500. This optimized solution uses 9% less energy than the previous one. It is important to note that this is not a viable project to finance through Eskom-DSM, as Eskom is only interested in the evening peak between 18:00 and 20:00. This results only in energy cost savings for the client.

Figure 54 shows the result of the simulation done by switching the chargers off during Eskom's evening peak.

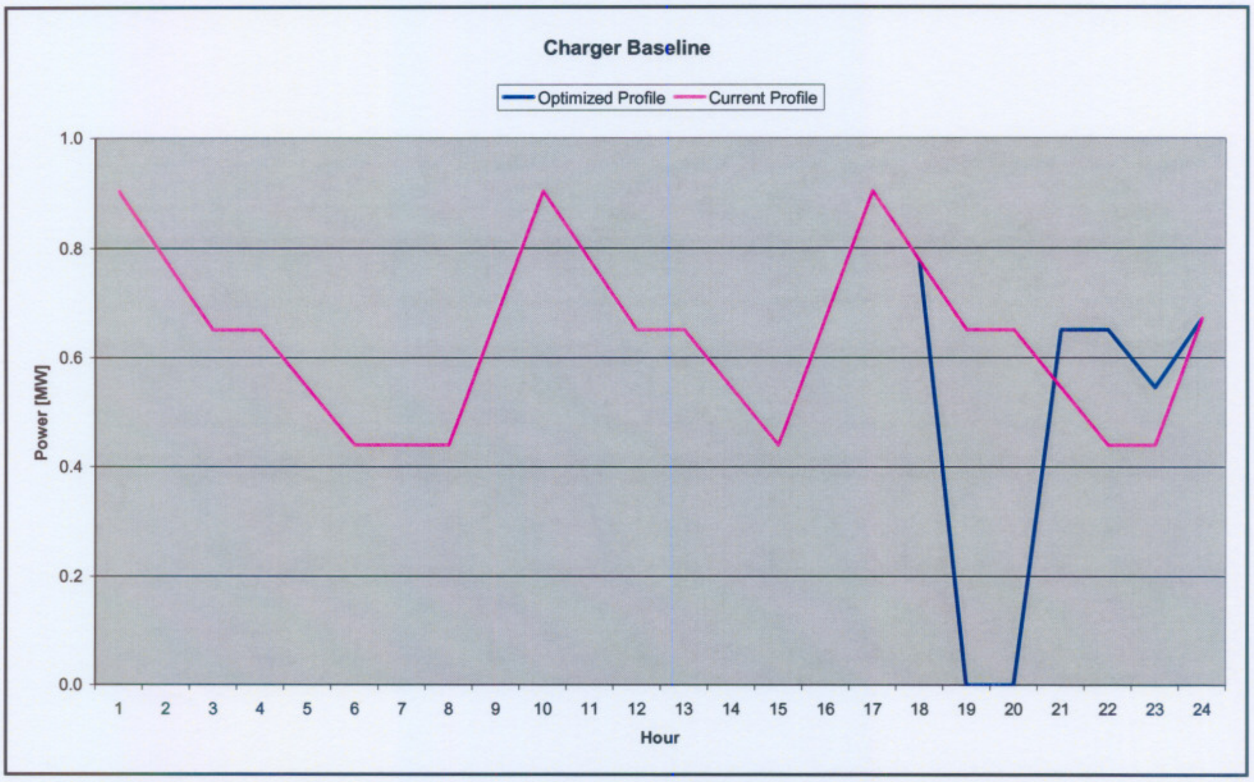

Figure 54: Not charging during Eskom's evening peak

This results in 0.65 MW moved out of Eskom's evening peak, resulting in an annual energy cost saving of R 91 700. This optimized solution uses 6% less energy than the previous one.

Figure 55 shows the result of the simulation by switching the chargers off during Eskom's morning and evening peak times.

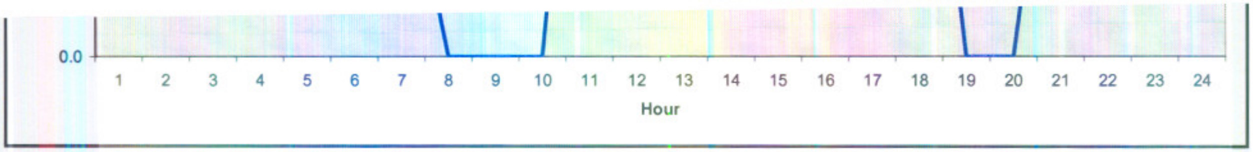

Figure 55: Not charging during Eskom's morning and evening peak times

This results in 0.67 MW moved out of Eskom's morning peak and 0.65 MW out of Eskom's evening peak, resulting in an annual energy cost saving of R 234 200. This optimized solution uses 14% less energy than the previous one.

4.3.2 Using high frequency chargers

This section deals with the simulation of the high frequency chargers to realise energy efficiency and load shift on the locomotive battery chargers. It will be assumed that these high frequency chargers use a third less energy than the previous installed chargers when doing the simulations.

The inputs to the simulation are the same as was the case using the currently installed chargers on the mine. They are given again below:

- Kopanang's shift times
- charge times for the chargers at Kopanang
- the charging algorithm
- number of locomotives
- number of batteries

- number of battery chargers
- Eskom's Megaflex profile

The simulation must make sure that a battery set is ready, fully charged, for the next shift's work to be done. The output of the simulation gives the energy cost savings, as well as any possible energy savings.

Three different scenarios to realise load shift and energy efficiency will be investigated in the simulations. These are comparing the use of the high frequency chargers against the currently installed chargers on the mine (realising energy efficiency), and doing load shift with the high frequency chargers (realising both energy efficiency and load shift) during the evening peak demand period, as well as both the morning and evening peak demand periods.

Figure 56 shows the results of replacing the currently installed chargers on the mine with high frequency chargers.

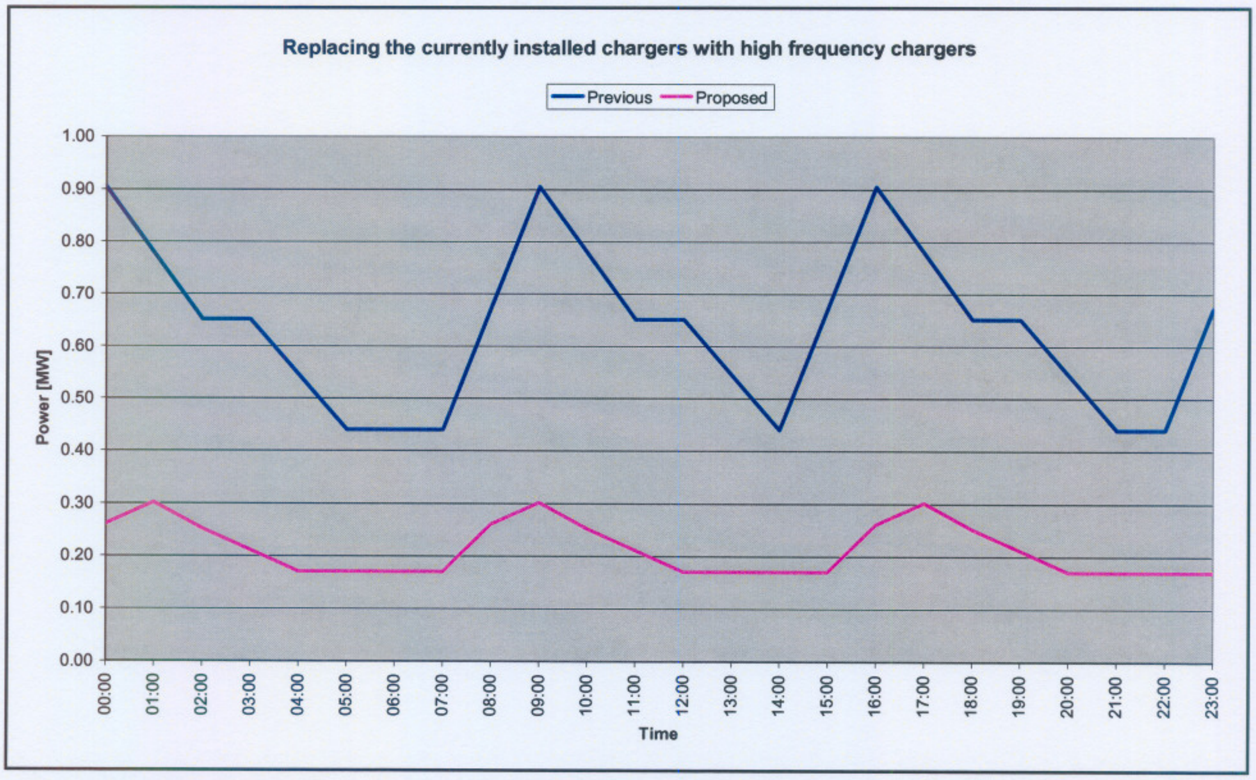

Figure 56: Realising energy efficiency by replacing the currently installed chargers with high frequency chargers

This results in an annual electrical energy savings of 3 696 665 kWh, or 0.42 MW per day. The corresponding annual electricity cost savings is about R 373 200.

It is also possible to realise both energy efficiency and load shift as discussed in section 3.4. Figure 57 shows the results of the simulation if the currently installed chargers are replaced by high frequency chargers and load shift is done in Eskom's evening peak.

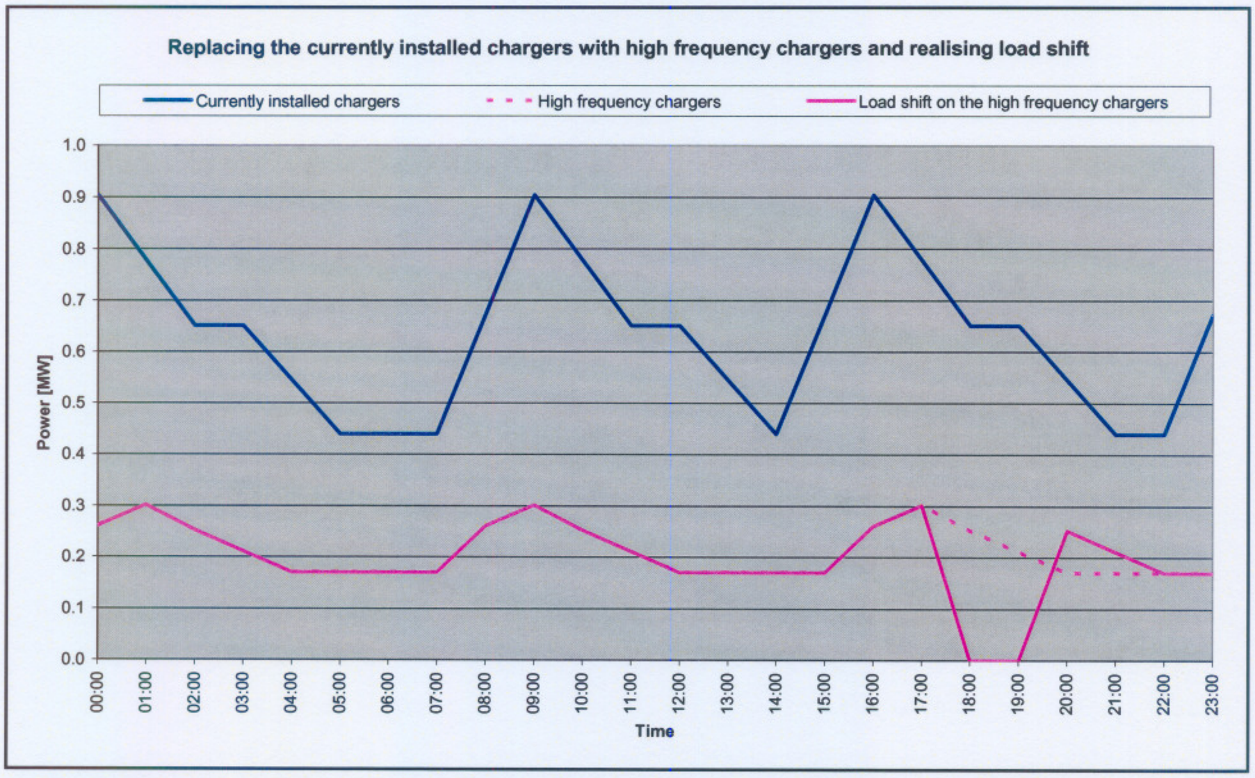

Figure 57: Realising energy efficiency by replacing the currently installed chargers with high frequency chargers, and doing load shift on the high frequency chargers

Table 19: Energy efficiency and load shift by using high frequency chargers

Time	Currently installed chargers	High frequency chargers	Load shift on high frequency chargers
00:00	905	261	261
01:00	778	302	302
02:00	651	252	252
03:00	651	211	211
04:00	546	170	170
05:00	440	170	170
06:00	440	170	170
07:00	440	170	170
08:00	672	261	261
09:00	905	302	302
10:00	778	252	252
11:00	651	211	211
12:00	651	170	170
13:00	546	170	170
14:00	440	170	170
15:00	672	170	170
16:00	905	261	261
17:00	778	302	302
18:00	651	252	0
19:00	651	211	0
20:00	546	170	252
21:00	440	170	211
22:00	440	170	170
23:00	672	170	170
TOTAL	**15 251**	**5 123**	**4 782**

By doing the energy efficiency first on this simulation, it is seen that the annual electrical savings is the same as in the previous simulation, i.e. 3 696 665 kWh, or 0.42 MW per day. If this is then taken as the new baseline, the load shift will be 0.2 MW per day, and the energy efficiency value will become $\frac{15{,}251kWh-4{,}782kWh}{24h}-200kW=0.2MW$. The 200 kW is the 0.2 MW load shift per day. Approximately 7% less electricity is used when load shift is done on the high frequency chargers, compared to using only the high frequency chargers.

The combination of energy efficiency and load shift results in an annual electricity cost saving of about R 400 600. It is R 27 400 more than implementing just energy efficiency on the chargers.

To increase the electricity cost savings for the mine, load can be shifted out of Eskom's morning peak as well. The results from these simulations are shown in Figure 58 and Table 20.

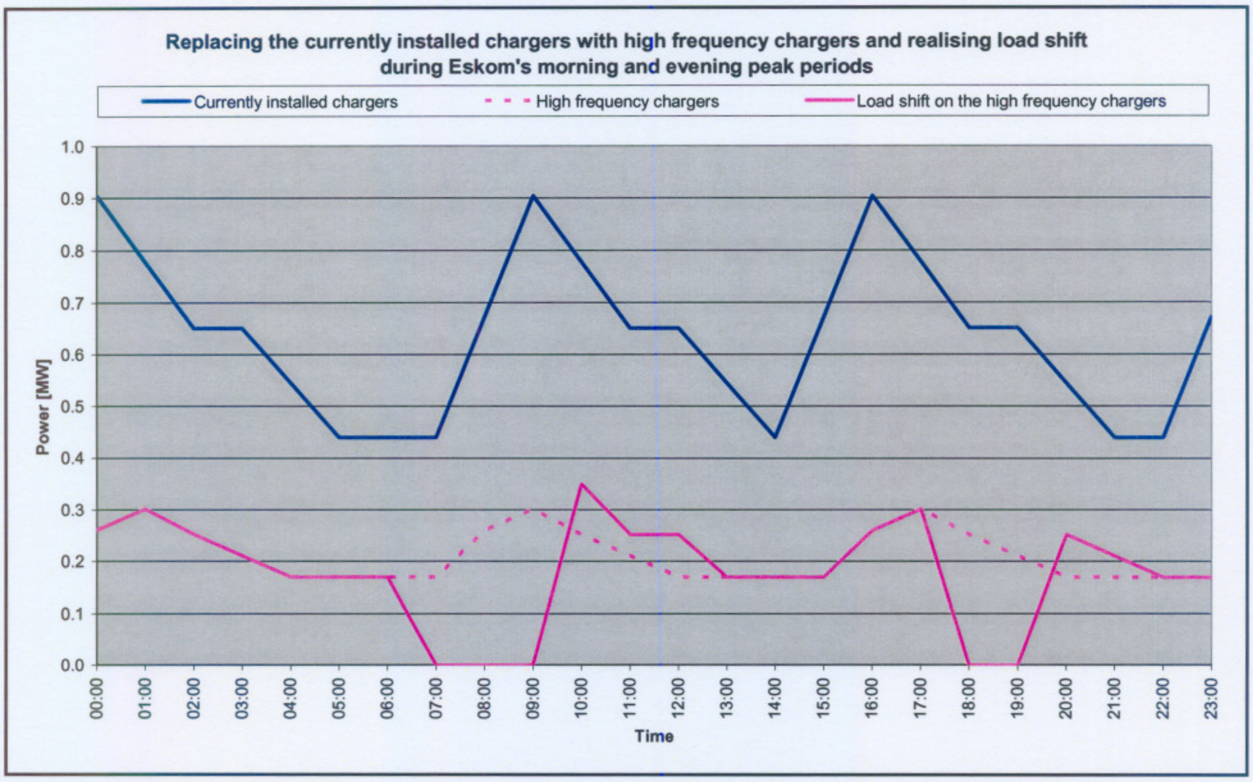

Figure 58: Energy efficiency and load shift in both of Eskom's peaks using high frequency chargers

Table 20: Energy efficiency and load shift during both of Eskom's peaks using high frequency chargers

Time	Currently installed chargers	High frequency chargers	Load shift on high frequency chargers
00:00	905	261	261
01:00	778	302	302
02:00	651	252	252
03:00	651	211	211
04:00	546	170	170
05:00	440	170	170
06:00	440	170	170
07:00	440	170	0
08:00	672	261	0
09:00	905	302	0
10:00	778	252	351
11:00	651	211	252
12:00	651	170	252
13:00	546	170	170
14:00	440	170	170
15:00	672	170	170
16:00	905	261	261
17:00	778	302	302
18:00	651	252	0
19:00	651	211	0
20:00	546	170	252
21:00	440	170	211
22:00	440	170	170
23:00	672	170	170
TOTAL	**15 251**	**5 123**	**4 271**

By doing the energy efficiency first on this simulation, it is seen that the annual electrical savings is the same as in the previous simulation, i.e. 3 696 665 kWh, or 0.42 MW per day. If this is then taken as the new baseline, the load shift will be 0.2 MW per day in Eskom's evening peak and 0.2 MW in Eskom's morning peak, and the energy efficiency value will become $\frac{15{,}251kWh-4{,}782kWh}{24h}-200kW=0.2MW$. The 200 kW is the 0.2 MW load shift in the evening peak per day (this is the only period that Eskom is interested in for load shift). Approximately 17% less electricity is used when load shift is done on the high frequency chargers in Eskom's morning and evening peaks, compared to using only the high frequency chargers.

The annual electricity cost savings is estimated at R 442 600.

4.4 VERIFICATION

4.4.1 Using installed chargers on the mine

The battery charge cycle at Kopanang lasts for 8 hours. After this, the battery is still not used, as another battery set is already charged and it is used instead. These batteries are therefore trickle charged or equalized for another 8 hours.

There are ample room for the batteries to be switched off during the morning and evening peak demand times, resulting in an annual energy cost saving of R 234 200. 14% less energy will also be used.

Due to the relatively low annual savings of R 234 200, the mine was not keen in verifying the proposed load shift schedules on the battery chargers. Therefore, load shift with the currently installed locomotive battery chargers was not tested on Kopanang mine.

The simulation model was verified against the measured data of the battery chargers. It was found that some of the assumptions that have been used for the simulation model were wrong. These assumptions were adjusted accordingly, resulting in a new simulation model and increasing the confidence in the simulations.

Tests were done to determine the efficiency of the ferro resonant chargers installed at Kopanang mine [45]. The voltage and current input to the charger was measured, as well as the voltage and current output of the charger. The following formulas are used:

$$Power_{AC\_input} = \sqrt{3} \times V \times I$$

$$Power_{DC\_output} = V \times I$$

$$\eta = \frac{Power_{DC\_output}}{Power_{AC\_input}}$$

The measurements taken were 20 minutes apart and measured with the same instruments. This was repeated, until the charger reached the equalize stage. The battery was fully discharged for this test.

Table 21 shows the results from the tests, and Figure 59 illustrates the efficiency of the ferro-resonant chargers. The average efficiency of the charger is 50%.

Table 21: Test results on ferro-resonant chargers

Time	Input - AC			Output - DC			Efficiency
	Volts	Amps	kW	Volts	Amps	kW	
t_0	546	32.00	30.26	128.00	108.00	13.82	46%
t_0 + 20	546	32.00	30.26	133.00	102.00	13.57	45%
t_0 + 40	546	32.00	30.26	135.00	105.00	14.18	47%
t_0 + 60	546	32.00	30.26	136.60	105.00	14.34	47%
t_0 + 80	546	32.00	30.26	139.90	107.00	14.97	49%
t_0 + 100	546	32.00	30.26	141.00	106.00	14.95	49%
t_0 + 120	546	26.00	24.59	141.90	86.00	12.20	50%
t_0 + 140	546	24.80	23.45	144.40	82.00	11.84	50%
t_0 + 160	546	19.60	18.54	145.00	64.40	9.34	50%
t_0 + 180	546	14.80	14.00	145.50	49.80	7.25	52%
t_0 + 200	546	13.40	12.67	145.60	49.20	7.16	57%
t_0 + 220	544	13.00	12.25	145.60	42.30	6.16	50%
t_0 + 240	546	11.80	11.16	145.80	39.60	5.77	52%
t_0 + 260	544	12.00	11.31	145.80	40.00	5.83	52%
t_0 + 280	546	10.80	10.21	145.80	36.00	5.25	51%

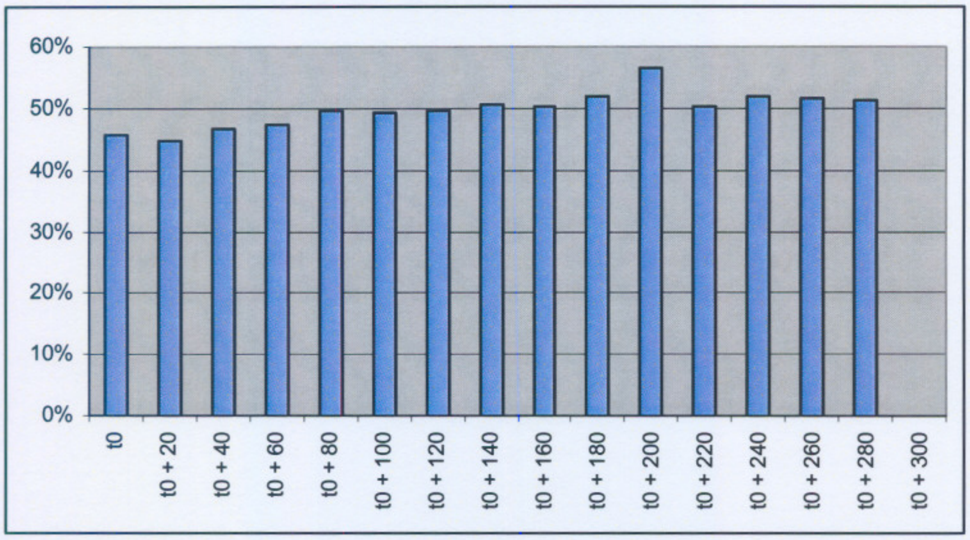

Figure 59: Efficiency of ferro-resonant charger

The average efficiency of the chargers in the test is 50%, compared to the theoretical value of 30%. This is a difference of 20% between the theoretical and measured efficiencies of the chargers. This may be due to a slightly different layout and operation than the one discussed in section 3.2.1.

4.4.2 Using high-frequency chargers

Tests were done to determine the efficiency of high frequency chargers at Kopanang mine [45]. The voltage and current input to the charger was measured, as well as the voltage and current output of the charger. The following formulas are used:

$$Power_{AC\_input} = \sqrt{3} \times V \times I$$

$$Power_{DC\_output} = V \times I$$

$$\eta = \frac{Power_{DC\_output}}{Power_{AC\_input}}$$

The measurements taken were 20 minutes apart and measured with the same instruments. This was repeated, until the charger reached the equalize stage. The battery was fully discharged for this test.

Table 1 shows the results from the tests, and Figure 60 illustrates the efficiency of the ferro-resonant chargers. The average efficiency of the charger is 96%.

Table 22: Test results on high frequency chargers

Time	Input - AC			Output - DC			Efficiency
	Volts	Amps	kW	Volts	Amps	kW	
t_0	545	12.40	11.71	129.00	82.00	10.58	90%
t_0 + 20	553	11.00	10.54	130.00	80.00	10.40	99%
t_0 + 40	553	10.80	10.34	130.60	78.00	10.19	98%
t_0 + 60	552	11.50	11.00	131.30	81.00	10.64	97%
t_0 + 80	548	11.50	10.92	132.60	78.00	10.34	95%
t_0 + 100	547	11.50	10.90	133.50	78.00	10.41	96%
t_0 + 120	550	11.50	10.96	134.50	78.00	10.49	96%
t_0 + 140	551	11.50	10.98	134.20	78.00	10.47	95%
t_0 + 160	547	11.10	10.52	136.50	75.00	10.24	97%
t_0 + 180	551	11.60	11.07	137.40	78.00	10.72	97%
t_0 + 200	551	11.30	10.78	139.50	76.00	10.60	98%
t_0 + 220	550	12.30	11.72	140.50	81.00	11.38	97%
t_0 + 240	551	10.80	10.31	142.10	69.00	9.80	95%
t_0 + 260	552	9.20	8.80	144.40	60.00	8.66	98%
t_0 + 280	554	8.50	8.16	145.40	54.00	7.85	96%
t_0 + 300	554	7.40	7.10	145.70	42.00	6.12	86%

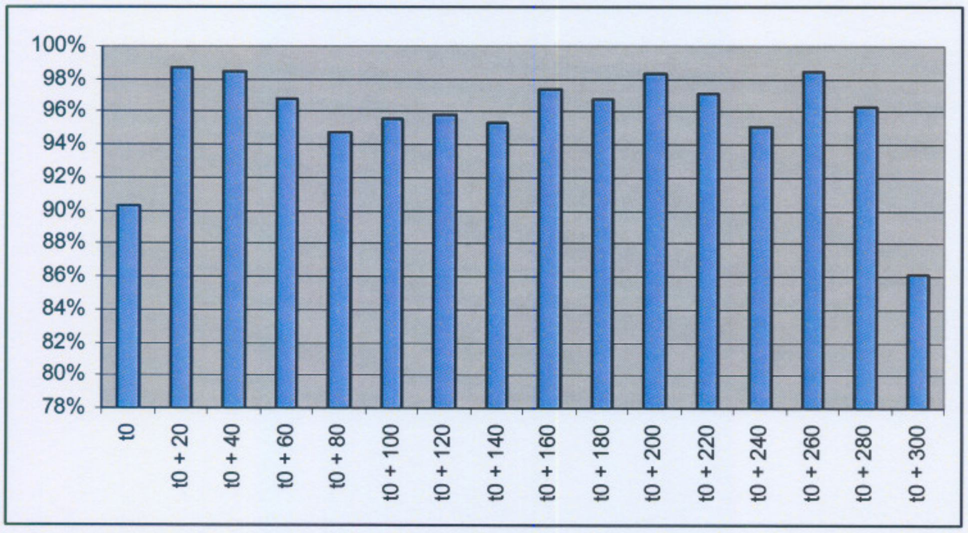

Figure 60: Efficiency of high frequency charger

The average efficiency of the chargers in the test is 96%, compared to the theoretical value of 80%. This is a difference of 16% between the theoretical and measured efficiencies of the chargers. This may be due to a slightly different layout and operation than the one discussed in section 3.2.2.

4.5 ECONOMIC FEASIBILITY

This section briefly deals with the economic feasibility of doing load shift and/or energy efficiency on locomotive battery chargers.

There is no or very low initial capital outset for implementing load shift only. This is because only a simple switch is needed to automatically switch the chargers off during the peak demand time(s). It can also be done manually.

A single high frequency charger costs about R 32 000. To replace all 150 chargers at Kopanang will cost R 4.8 million. If the mine decides to finance this project on its own, the payback period on the energy efficiency alone will be almost 13 years (with an annual saving of R 373 200). If load shift is also implemented, the payback will be about 11 years (with an annual saving of R 442 600). This is summarised in Table 24.

Eskom funds 50% of the capital needed in an energy efficiency project. This means that with a total cost of R 4.8 million, the mine only needs to pay R 2.4 million if they decide to get funding from Eskom-DSM. The payback period for this is six years, compared to almost 13 years without Eskom-DSM funding.

Eskom funds 100% of the capital needed for a load shift project. By combining an energy efficiency and load shift project, the financing becomes a bit more complicated. It is easiest to look at the contribution to the total effect of the load shift in Eskom's evening peak and energy efficiency in these projects.

In the simulations, the load shift was 0.2 MW, while the energy efficiency was 0.2 MW. The load shift's contribution is $\frac{0.2}{0.2+0.2} = 50\%$ to the total DSM value. This means that the energy efficiency contributes the other 50%. The load shift part costs thus 50% of the total costs (for which Eskom funds 100%), while the energy efficiency costs 50% of the total costs (for which Eskom funds 50%). This is summarised in Table 23.

Table 23: Eskom's contribution to a combined energy efficiency and load shift project

		% Contribution	Total Cost	Eskom pays	Client pays
LS	0.2 MW	50%	R 2 400 000	R 2 400 000	R 0
EE	0.46 MW	50%	R 2 400 000	R 2 400 000	R 1 200 000

With this scenario, the client only pays R 1.2 million, which gives a payback period of 2.7 years. This is summarised in Table 24.

Table 24: Summary of payback periods

		Without Eskom funding			With Eskom funding			
	Annual Savings	Initial costs	Payback period (years)	Payback period (months)	Funding from Eskom	New costs	Payback period (years)	Payback period (months)
Evening load shift	R 91 700	R 0	0.0	0	R 0	R 0	0.0	0
Morning and evening load shift	R 234 200	R 0	0.0	0	R 0	R 0	0.0	0
Energy efficiency	R 373 200	R 4 800 000	12.9	154	R 2 400 000	R 2 400 000	6.4	77
Energy efficiency and evening load shift	R 400 600	R 4 800 000	12.0	144	R 3 600 000	R 1 200 000	3.0	36
Energy efficiency and load shift in the morning and evening	R 442 600	R 4 800 000	10.8	130	R 3 600 000	R 1 200 000	2.7	33

4.6 CONCLUSION

The baseline as measured for the locomotive battery chargers at Kopanang differs from the expected one. The shape is more or less the same, with three peaks during the day. This confirms the fact that Kopanang uses mostly three battery sets, with high current being drawn in the first phase, and less current during the following phases.

The peaks of the expected baseline are twice as high as the peaks from the measured one. Reasons for this include:

- the batteries are not fully discharged, and the first phase charging duration is considerably less than anticipated
- the charge on different batteries differ
- charging on all the batteries does not start at the same time

As the batteries spend most of their time on the equalization charge, it is possible to switch these chargers off for two or three hours per day. This will not influence the production of the mine, as there are other batteries ready and fully charged for the next shift.

The average efficiency of the ferro resonant chargers is 50% as measured. This compares poorly to the 96% efficiency of the high frequency chargers. This translates to an improvement in efficiency of 92%.

If Kopanang replace their current ferro resonant chargers with high frequency ones, they will roughly half their energy usage on the locomotive battery chargers. Another advantage of using the high-frequency charger is that the charge time of 8 hours will be reduced to 4-5 hours with the high frequency chargers.

The payback period for replacing all the locomotive battery chargers on the mine is almost 13 years. As most mines will implement a project with a payback period of 2-3 years, this may not be a feasible project for Kopanang.

If Eskom-DSM funds 50% of this project, the payback period will halve, becoming about six and a half years. However, due to the increase in electricity cost savings if load shift out of Eskom's peak times is realised together with the energy efficiency, the payback period will become 2.7 years. Suddenly, this becomes a viable project for Kopanang.

CHAPTER 5: CONCLUSION

5.1 CONCLUSION

An energy efficiency and load shift potential has been found using new technology, high frequency battery chargers. Some of the conclusions that can be made regarding the load shift using the older technology battery chargers, and the energy efficiency and load shift of the high frequency battery chargers is summarised below.

- Load shift was found to be feasible with the older technology battery chargers.
- Electrical energy cost savings of up to R 234 200 was realised by implementing load shift out of Eskom's morning and evening peak periods.
- Energy efficiency and load shift was found to be feasible, by replacing the older technology battery chargers with new technology, high frequency battery chargers.
- Electrical energy cost savings of up to R 442 600 was realised by replacing all the older technology battery chargers with new technology, high frequency battery chargers and by realising load shift out of the daily peak demand periods.
- High frequency chargers have an efficiency of 96%, compared to an efficiency of 50% of the older technology.
- Electricity cost savings is realised by preventing the locomotive battery chargers from charging during Eskom's peak periods.
- Through funding from Eskom-DSM, it is economically feasible for most mines to replace all their current locomotive battery chargers with new technology, high frequency battery chargers.

5.2 RECOMMENDATION FOR FURTHER WORK

Based on the results of this thesis, the following recommendations for future work are made:

- The difference between the theoretical and the measured baselines on the locomotive battery chargers are big. It is necessary to get a more accurate measured baseline, by measuring all the locomotive battery chargers on the mine.
- An accurately measured baseline was determined for one locomotive battery bay on Kopanang. The following experiments are recommended on this battery bay to verify the simulated results:
    - Realise load shift out of Eskom's evening peak using the methods described.
    - Realise load shift out of Eskom's morning and evening peak periods using the methods described.
    - Replace all of these battery chargers with high frequency chargers to realise energy efficiency.
    - Do load shift out of Eskom's evening peak period on the high frequency battery chargers.
- If these results were positive, implement one or more of the methods described on all the locomotive battery chargers on the mine.
- Roll these methods out to more mines.

CHAPTER 6: REFERENCES

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