Industries consume the most energy in South Africa, with mining using 17.6% of the energy supplied by Eskom [2] [3]. As one of the most important industries for the growth and development of South Africa's economy, mining houses are under continuous pressure to increase production, while decreasing cost [2]. One way to achieve this is to use Eskom's DSM program. Various projects in mine pumping, compressed air, winding and refrigeration have been funded so far, but one aspect that has not been addressed is underground locomotive chargers.

Two types of chargers are available: older ferro-resonant chargers and new high frequency chargers. A number of South African mines are investigating the use of more efficient battery charger, but installation of the chargers is slow, being funded by the mines, and old chargers are replaced by high frequency chargers only when they deteriorate.

**Savings potential of new charger technology**

**Technology in use at a typical mine**

On a high production level underground, each locomotive usually has three battery sets. Each set is used for a different production shift, and charged during the following shifts. Constant current chargers are most commonly installed in battery bays on those levels where most of the development and mining activities take place. The charger's charging profile is given in Fig. 1, showing three charging rates. A more detailed discussion on the charger technology but may be found in the literature [5] [6] [7] [8].

After extensive discussions with mine personnel, combined with detailed measurements [9], it was established that the following assumptions can be used:

- Battery charging is started one-and-a-half hours after the start of a new shift.
- The charging cycle for the ferro-resonant charger is:
  - First stage: 38 A for 2 hours
  - Second stage: 20 A for 3 hours
  - Equalise: 5 A until the battery is needed, but a minimum of three hours
- The charging cycle for the high frequency charger is [10]:
  - First stage: 15 A for 1 hour
  - Second stage: 8 A for 2 hours
  - Equalise: 2 A until the battery is needed, but a minimum of two hours
- As the batteries are connected to the chargers until needed, the charger is always on the equalisation cycle after it has charged.

Before starting the investigation, a baseline representing the energy consumption of all the battery chargers on the mine over a typical 24 hour period was established, using one locomotive's batteries as a benchmark. This battery set consists of three batteries, one for each shift. This gave an accurate view of the potential total savings.

Charging times of the chargers are shown in Table 1.

<table>
<thead>
<tr>
<th>Shift</th>
<th>Morning</th>
<th>Afternoon</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>07h30</td>
<td>15h30</td>
<td>23h30</td>
</tr>
<tr>
<td>Stop</td>
<td>15h30</td>
<td>23h30</td>
<td>07h30</td>
</tr>
</tbody>
</table>

Table 1: Typical battery charging times in a mine.

The calculated power usage of each charger is shown in Table 2.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cycle Hour</th>
<th>Charger Voltage $V_	ext{c}$ [V]</th>
<th>Charger Current $I_	ext{c}$ [A]</th>
<th>Charger Power $P_	ext{c}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast rate</td>
<td>1</td>
<td>550</td>
<td>38</td>
<td>28 960</td>
</tr>
<tr>
<td>Fast rate</td>
<td>2</td>
<td>550</td>
<td>38</td>
<td>28 960</td>
</tr>
<tr>
<td>Second rate</td>
<td>3</td>
<td>550</td>
<td>20</td>
<td>15 242</td>
</tr>
<tr>
<td>Second rate</td>
<td>4</td>
<td>550</td>
<td>20</td>
<td>15 242</td>
</tr>
<tr>
<td>Second rate</td>
<td>5</td>
<td>550</td>
<td>20</td>
<td>15 242</td>
</tr>
<tr>
<td>Equalise</td>
<td>6</td>
<td>550</td>
<td>5</td>
<td>3 811</td>
</tr>
<tr>
<td>Equalise</td>
<td>7</td>
<td>550</td>
<td>5</td>
<td>3 811</td>
</tr>
<tr>
<td>Equalise</td>
<td>8</td>
<td>550</td>
<td>5</td>
<td>3 811</td>
</tr>
</tbody>
</table>

Table 2: Battery charger power.
The baseline for one battery set is thus shown in Fig. 2.

![Baseline for one battery set](image)

Fig. 2: Simulated baseline for one battery set.

Method A: Using the currently installed chargers

Energy cost savings can be realized (with a time-of-use tariff structure) by switching off the chargers installed during peak time(s), as the charger’s charge cycle lasts for eight hours and the typical shift in the mine is also eight hours long. Fig. 3 shows the charger profile if the charger is switched off during the evening peak.

![Charger profile by not charging in Eskom’s evening peak](image)

Fig. 3: Charger profile by not charging in Eskom’s evening peak.

As can be seen above, there is a 19 kW potential reduction per locomotive during the evening peak if three battery sets are used.

Methods B & C: Using high frequency battery chargers

The other two savings options involve use of high frequency battery chargers as replacement for the old chargers. A significant saving in electrical energy can be realised, as a typical high frequency converter’s efficiency is 80%, compared to 30% for a typical ferro-resonant charger [11].

This scenario is plotted against the baseline in Fig 4.

![Ferro-resonant vs. high frequency chargers](image)

Fig. 4: Ferro-resonant vs. high frequency chargers.

In Fig. 5, the same profile as in Fig. 4 is taken as the “new” baseline. Using this, load shift can be achieved, as shown with the solid line. Energy efficiency and load shift can therefore be combined into one DSM project.

Case study: Kopanang gold mine

Determining the baseline

Kopanang gold mine is part of the Vaal River section of AngloGold Ashanti’s South African operations. Measuring every single battery charger was neither feasible nor cost effective due to the large number of chargers installed on the mine. 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 uses constant current chargers, with a three-stage charging cycle. The approximate current that the chargers draw from the feeders is summarized in Table 3.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Duration[hr]</th>
<th>Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First stage</td>
<td>2</td>
<td>38</td>
</tr>
<tr>
<td>Second stage</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Third stage(equalize)</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3: Current drawn from the feeders by a charger.

The baseline was determined by combining the charging details with the following assumptions:

- 150 batteries are used.
- All the batteries that were used in the same shift start charging at the same time.
- All the batteries in the mine are fully discharged before being charged again.
- The mine does not employ load shift (manual or automatic) on the battery chargers.

The simulated baseline is given in Fig. 6.

The morning peak of just over 1 MW is in the middle of the morning peak demand, while the evening peak average load of approximately 950 kW just misses the peak time. The baseline was determined by measuring the battery bay on 62 level, with 25
batteries, for a period of four weeks and extrapolated to the total chargers. The weighted average of this gives the baseline as shown in Fig. 7.

There are three peaks visible on weekdays, confirming that Kopanang charges batteries three times per day Monday to Friday.

Simulation

Calibrating the simulated baseline to the measured baseline

From Fig. 8, it can be seen that the simulated baseline differs from the measured baseline, and it is first necessary to calibrate the simulated baseline to the measured baseline.

The confidence in the measured baseline is higher and the simulated baseline must be calibrated to the measured baseline. Comparing the two, it is obvious that some of the assumptions must be adjusted to arrive at a new simulated baseline.

The most obvious difference is the difference in scale, which may be due to the batteries not being fully discharged at the end of the shift. The second difference is that the simulated peak around 08:00 is about an hour earlier than that measured, which may be due to incorrect information. In the simulations the chargers should start charging an hour later than projected. Finally the baselines were 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 as:

\[
\text{factor} = \frac{\text{Energy}_{\text{measured}} - \text{Energy}_{\text{calculated}}}{24}
\]

After the baselines had been calibrated to be energy neutral, the new simulated baseline was drawn up. This is illustrated in Fig. 9.

Simulations using currently installed battery chargers

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. There are three possible ways to save energy cost using the existing chargers: by switching the chargers off in Eskom’s morning peak, evening peak, or both peaks. Fig. 10 shows the result of the simulation, switching the chargers off during the morning and evening peak times.

This results in 0.67 MW moved out of the morning peak and 0.65 MW out of the evening peak, resulting in an annual energy cost saving of R234 200. This optimized solution uses 14% less energy.

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 was assumed that these high frequency chargers use a third of the energy
than the previous installed chargers [9]. The simulation must make sure that a battery set is ready and fully charged for the next shift. The output of the simulation gives the energy cost savings, as well as any possible energy savings. Three different scenarios were investigated in the simulations: the use of the high frequency chargers against the currently installed chargers (realising energy efficiency), including load shift during the evening peak demand period, and well as both the morning and evening peak periods.]

Fig. 11 shows the results of replacing the currently installed chargers on the mine with high frequency chargers. This results in an annual electrical saving of 3 696 665 kWh, or 0.42 MW per day. The corresponding annual electricity cost savings is about R373 200.

Calculating 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. Taking this as the new baseline, the load shift will be 0.2 MW per day in the evening peak and 0.2 MW in the morning peak, and the energy efficiency value will become:

\[
\text{Energy Efficiency} = \frac{\text{Annual Electrical Savings}}{\text{Baseline Energy}} = \frac{3 696 665 \text{ kWh}}{3 696 665 \text{ kWh}} = 1
\]

The 200 kW is the 0.2 MW load shift per day (The only period that DSM considers for load shift). Approximately 17% less electricity is used when load shift is done in the morning and evening peaks, compared to using only the high frequency chargers. The annual electricity cost savings is estimated at R442 600.

Verification
Verifying the model used
The battery charge cycle at Kopanang lasts for eight hours. After this, the battery is trickle charged or equalized for another 8 hours, as another charged battery set is available. There is 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 R234 200, because of a 14% reduction in energy consumption.

Due to the relatively low annual savings of R 234 200, the mine was reluctant to verifying the proposed load shift schedules. Therefore, load shift with the currently installed locomotive battery chargers was not tested. The simulation model was verified against the measured data of the battery chargers, and it was found that some assumptions used for the simulation model were wrong. These were adjusted, resulting in a new simulation model and increasing confidence in the simulations.

Verification using currently installed chargers
Tests were done to determine the efficiency of the ferro-resonant chargers installed at Kopanang mine [13]. 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:

\[
\text{Power in} = \sqrt{3} \times V \times I \\
\text{Power out} = V \times I
\]
The measurements taken were 20 minutes apart with the same instruments. This was repeated, until the charger reached the equalize stage. The battery was fully discharged for this test. Table 4 shows the results from the tests, and Fig. 14 illustrates the efficiency of the ferro-resonant chargers. The average efficiency of the charger is 50%.

<table>
<thead>
<tr>
<th>Time</th>
<th>Input - AC</th>
<th>Output - DC</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volts</td>
<td>Amps</td>
<td>kW</td>
</tr>
<tr>
<td>(t_0)</td>
<td>545</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 20)</td>
<td>546</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 40)</td>
<td>546</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 60)</td>
<td>546</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 80)</td>
<td>546</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 100)</td>
<td>546</td>
<td>32,00</td>
<td>30,26</td>
</tr>
<tr>
<td>(t_0 + 120)</td>
<td>546</td>
<td>26,00</td>
<td>24,59</td>
</tr>
</tbody>
</table>

Table 4: Test results on ferro-resonant chargers.

Fig. 14: Efficiency of ferro-resonant charger.

The average efficiency of the chargers in the test is 50%, compared to the theoretical value of 30%. The difference of 20% may be due to a slightly different kind of ferro-resonant charger than mentioned before.

Verification using high frequency chargers

Tests were done to determine the efficiency of high frequency chargers used [13]. The voltage and current input to the charger was measured, as well as the voltage and current output of the charger. The following formulas were used:

\[
\text{Power}_{\text{in, AC}} = \sqrt{3} \times V \times I \\
\text{Power}_{\text{in, DC}} = V \times I \\
\eta = \frac{\text{Power}_{\text{out, DC}}}{\text{Power}_{\text{in, AC}}} 
\]

The average efficiency of the chargers in the test was 96%, compared to the theoretical value of 80%, which was obtained from literature study.

Economic feasibility

This section briefly deals with the economic feasibility of doing load shift and/or energy efficiency on locomotive battery chargers. There is low initial capital outset for implementing load shift only. A high frequency charger costs about R32,000. Replacing all 150 chargers at Kopanang would cost R 4,8-million. If the mine finances this project, the payback period on energy efficiency alone will be almost 13 years. If load shift is also implemented, the payback will be about 11 years. DSM funds 50% of the capital needed in an energy efficiency project.
With a total cost of R 4,8-million, the mine only needs to pay R 2,4-million with DSM funding, giving a payback period of six years.

DSM 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 the 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, meaning that energy efficiency contributes the other 50%. The load shift costs is 50% of the total (of which DSM funds 100%), while the energy efficiency cost is 50% of the total (of which DSM funds 50%). This is summarised in Table 6.

With this scenario, the client only pays R1,2-million, which gives a payback period of 2.7 years. This is summarised in Table 7.

Conclusion
An energy efficiency and load shift potential has been found using new technology, high frequency battery chargers. Load shift was found to be feasible with the older technology battery chargers, with electrical

 energy cost savings of up to R234 000 annually. By replacing the older technology with new technology, high frequency battery chargers, electrical energy cost savings of up to R442 600 can be achieved.

This electrical cost savings can be achieved by preventing the 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.

References
[4] Van der Linde, C: Electrical Foreman, GoldField’s Beatrix 3#, Personal communication, 057 733 9028

Contact M Kleingeld, HVAC International, Tel 012 991 3181

Table 6: Eskom’s contribution to a combined energy efficiency and load shift project.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Total cost</th>
<th>Eskom pays</th>
<th>Client pays</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS 0.2 MW</td>
<td>R2 400 000</td>
<td>R2 400 000</td>
<td>R0</td>
</tr>
<tr>
<td>LE 0.46 MW</td>
<td>R2 400 000</td>
<td>R2 400 000</td>
<td>R1 200 000</td>
</tr>
</tbody>
</table>

Table 7: Summary of payback periods.

<table>
<thead>
<tr>
<th>Without Eskom funding</th>
<th>With Eskom funding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evening load shift</strong></td>
<td>R 91 700 R 0 0 0 0</td>
</tr>
<tr>
<td><strong>Morning and evening load shift</strong></td>
<td>R 234 200 R 0 0 0 0</td>
</tr>
<tr>
<td><strong>Energy efficiency</strong></td>
<td>R 373 200 R 4 800 000 12.9 154</td>
</tr>
<tr>
<td><strong>Energy efficiency and evening load shift</strong></td>
<td>R 400 600 R 4 800 000 12.0 144</td>
</tr>
<tr>
<td><strong>Energy efficiency and load shift in the morning and evening</strong></td>
<td>R 442 600 R 4 800 000 10.8 130</td>
</tr>
</tbody>
</table>

Acknowledgements
This article was presented as a paper at the 2007 ICUE Conference in Cape Town and is reprinted with permission.