Title: Benchmarking comminution energy consumption for the processing of copper and gold ores

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Published in: Minerals Engineering, 2014, Vol. 65,

Published version found online at: http://www.sciencedirect.com

DOI: 10.1016/j.mineng.2014.05.017

HIGHLIGHTS

1. On average, 36 per cent of the energy utilised by the mines was found to be consumed solely by comminution processes.

2. Comminution of gold and copper ores alone uses 0.2 per cent of global, and 1.3 per cent of Australia’s electricity consumption.

3. A cost curve-type graphical format is a good visual method for ranking comminution energy intensity at different mines across the industry.

4. The top third of consumers are responsible for 80% of the total consumption.

5. Variation in ore grade shows the largest contribution to the variability of specific energy which shows that the largest potential for energy reduction is through preconcentration strategies.
ABSTRACT

A survey of the comminution energy requirements of gold and copper producing mines has been conducted to provide reliable benchmarking data which can be used to compare comminution energy consumption across different mine sites. The total gold and copper production of the mines included in the study equated to 15 and 24 per cent respectively of global production and all of Australian production. The comminution energy per unit metal product has been presented in a graphical form similar to a cost curve. This simple technique allows individual mines to be ranked with respect to energy consumption and clearly displays the potential energy and cost benefits of moving down the graph into more efficient operating regimes. Assuming similar specific energy requirements for other sites, comminution of gold and copper ores can be expected to consume about 0.2% of global, and 1.3% of Australia’s electricity consumption. Efforts to reduce this figure should be aimed at the top third of consumers as they are responsible for 80% of the total consumption. Analysis of the contribution of circuit efficiency, ore competence, grind size and ore grade showed that ore grade was the greatest determinate of specific comminution energy. Therefore, concentrating the ore via gangue rejection or grade engineering prior to grinding is likely to achieve the largest positive effect on comminution energy efficiency.

INTRODUCTION

Comminution is the process by which rocks are reduced in size to liberate the valuable components for subsequent separation events. The process of rock breakage consumes a considerable quantity of energy and is a significant component of international electricity consumption. Curry et al. (2014) found that the mill (defined as crushing, grinding and separation) typically accounts for between 35

and 50 per cent of the total mine costs. The proportion of energy consumed by comminution has been calculated by a number of researchers in an attempt to create a context for research into energy reduction (Daniel and Lewis-Gray, 2011; Tromans, 2008). The US Department of Energy (DOE) has investigated this subject through a combination of industry surveys and computer modelling, and its seminal work in 1981 is widely referenced. The DOE (1981) found that comminution processes accounted for approximately two per cent of the total U.S. electricity consumption. The specific energy requirements (in kWh/t) were supplied by Battelle Columbus Laboratories (1976) through comprehensive energy audits of a number of key commodities across the U.S. Figure 1 shows the DOE results plus a number of other reviews. Four complete energy audits of Australian copper/gold mines are publicly available and provide a good picture of energy use at specific mines. Marsden (2008) used case studies of Chilean copper mines as the basis for an energy model incorporating grade and processing route, Figure 1 displays the result for an ore with a copper grade of 0.5 per cent and a flowsheet incorporating SAG and ball milling, flotation and smelting.

Ballantyne et al. (2012) completed an audit of the energy consumed by comminution in Australian copper and gold producing mines. On average, 36 per cent of the energy utilised by the mines was found to be consumed solely by comminution processes. Utilised energy was defined as the addition of electricity consumption and the mechanical energy utilised by diesel machinery. Forty six mines were analysed in this study and the 95% confidence in the average comminution proportion was +/-10 percentage points (not representing the error in measurement, but the variation between mines). On a national scale, the energy consumed in comminuting copper and gold ores corresponded to 1.3 per cent of Australia’s electricity consumption (Ballantyne et al., 2012; Cuevas-Cubria et al., 2011).

Figure 1 - Summary of calculated percentage of mine utilised energy attributable to comminution (Ballantyne et al., 2012; DOE, 1981, 2002, 2007; Dorai, 2006; Marsden, 2008; Northparkes, 2006).

The energy consumed through comminution is quantified using a number of different bases. It is most commonly reported as the specific energy per tonne of material processed (kWh/t). However it may be more useful to present the metal specific energy (MSE) in terms of final metal product as this incorporates the influence of grade. The competence of the ore and the energy can be assessed using the operating work index (Bond, 1952). Eq. 1 is the usual form of Bond’s theorem of comminution in which he assumes a linear relationship between energy and crack length. The size reduction and specific energy input (kWh/t) were used to calculate the work index (WI) which is a measure of rock hardness corresponding to the energy required to reduce one tonne of in-situ rock to a P80 of 100 microns.

\[ W = 10WI \left( \frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) \]  

Where P80 and F80 are the 80% passing size of the product and feed respectively (µm).

Levin (1992) proposed a new method for calculating the size specific energy (SSE) requirements of an ore based on the mass of fine material produced, usually defined by the proportion of material below 75 microns. The difference between the two indices is that the work index is based on P80 which is always fairly close to the size of the largest particle, whereas the percentage of minus 75 microns is a more variable quantity that may be close to, or far from the size of the largest particle (Levin, 1992). Bond’s theory also requires the feed and product cumulative size distributions to be parallel in log/log space. The size specific energy required to generate new minus 75 micron material is based on von Rittinger’s hypothesis that energy required for size reduction is proportional to the new surface area generated (Hukki, 1962; Rittinger, 1867). Musa and Morrison (2009) found that 70 to 80 per cent of the surface area of the product of AG/SAG/ball milling circuits exists in the minus 75 microns size fraction. Although not often credited, Hukki (1979) appears to be the earliest reference correlating the surface area with per cent minus 74 micron, in his seminal paper on closed circuit grinding.

The Coalition for Eco-Efficient Comminution (CEEC) roadmap proposed that clear benchmarks and standards are required to allow performance targets to be compared with industry standards (Napier-Munn et al., 2012). If a benchmark for current operations can be established, it may provide incentive for the industry to improve the efficiency of comminution processes (Napier-Munn et al., 2012). The present paper will attempt to provide a baseline for comminution energy in current gold and copper operations internationally.

**METHODOLOGY**

The focus of the current investigation was limited to gold and copper producing mines to assess the applicability of the analysis technique on commodities with the greatest availability of data. A database was constructed to calculate each mine’s comminution energy requirements individually before the results were combined, and anonymity was preserved. The comminution energy consumption for the processing of copper and gold ores. Minerals Engineering 65, 109-114.
requirements were obtained from JKTech surveys, published reports, energy audits and publications of installed equipment. Although a number of different sources have been used, consistency was maintained throughout the process. Historical comminution circuit survey (JKTech) reports between 1992 and 2012 were used to provide operating information on the milling circuits. These reports provided throughput, feed and product size distributions, mill power measurements and ore hardness parameters. Installed power requirements were obtained from a minerals processing survey published in AMM magazine (Asphar Survey Group, 2011). An interesting outcome of comparing these two information sources was that the mills were found to be consistently operating at an average utilisation of 96% in relation to the installed power (Ballantyne et al., 2012).

Complete power data was available for SAG and ball milling, but it was only partially available for fine grinding and crushing. The data is also heavily weighted towards Australian mines; international mines were sampled sparsely with a skew to larger mines. Comminution data was available for 68 mines, effectively accounting for all the copper and gold produced within Australia but only 24% of the copper and 15% of the gold produced internationally.

Copper and gold production data, as well as material milled, was obtained from publicly available annual reports. The most recent production data available for each mine was collected, but inconsistencies in reporting resulted in dates varying between 2007 and 2012 for different mines. The combination of this variance and the timing of the comminution circuit surveys may result in some inconsistencies in the results, but every attempt was made to minimise this effect. Total minesite energy consumption was also collected from compulsory reporting initiatives such as Australia’s Energy Efficient Opportunities Act (RET, 2006). Where possible this was also separated into electrical energy and diesel consumption for consistency.

RESULTS

The results have been presented in a graphical form similar to the cost curves that are generated by financial institutions. Each mine is presented as a separate bar in a bar chart, the width of which represents the annual production and the comminution energy intensity is the height (Figure 2). The mines are ranked in ascending order based on the specific energy, and the x-axis becomes the cumulative annual production. The average Australian residential electricity price in 2010/11 (22.4 c/kWh - AEMC, 2011) was used to calculate the energy cost which is displayed as a secondary y-axis. Using a fixed cost gives a consistent basis for comparison, but it should be noted that the actual costs vary considerably between (and within) countries and methods of energy generation.

The comminution energy intensity can be expressed in a number of different ways. The most powerful unit is energy per unit metal product as it is not only influenced by unit comminution efficiency but also upgrading strategies and recovery increases. Because copper and gold are associated geologically in orebodies, to compare like-with-like, mines were classified as either copper or gold producers depending on their major production. Grasberg was the only mine that was deemed to have equal production value of copper and gold.

The gold and copper comminution curves are displayed in Figure 3 and Figure 4 respectively. For gold producing mines the average energy was 353 kWh/oz and for copper it was 1,134 kWh/t. The Battelle Columbus Laboratories (1975) reported the comminution energy intensity of gold and copper to be 42.9 kWh/oz and 3,410 kWh/t respectively. It is interesting to see that the processing of gold was found to be significantly more energy intensive, in our work, but copper required less energy. The root causes for this discrepancy are unclear from the present data, but they are likely to be driven by marked differences in the dominant form of the orebodies in addition to differences in processing between 1975 and the present.
The concept of ‘copper equivalent gold production’ was used to present data from gold and copper mines on the same graph. Metal equivalent calculations are a common practice for polymetallic deposits and are especially popular in South America (Rendu, 2008). The copper equivalent production ($Cu_e$) is defined as the production of copper that would be required to obtain the same revenue assuming no gold production. For simplicity, complex factors relating to smelting, refining and recovery were removed. This reduced it to a simple relationship between copper and gold production and each commodity's price (see Equation 2). The formula for calculating the copper equivalent production is highly dependent on the price of the separate commodities. For this analysis the prices for copper and gold were assumed to be USD 7350/t and USD 1430/oz respectively—the spot prices on the 15 May 2013 for the London Metals Exchange and the London Bullion Market Association.

$$Cu_e\ production = (Au\ production \times Au\ price + Cu\ production \times Cu\ price)/Cu\ price \quad [2]$$

The results of this analysis are shown in Figure 5. This analysis facilitates the display of a master curve that is able to display the comminution energy intensity of the majority of the mines from this analysis. Using this analysis, individual mines can be benchmarked against their peers. Although the top three most energy intensive mines displayed here are predominately gold producers, there is no consistent trend between energy intensity and commodity. The average cost of the energy required for comminution was approximately $300/t Cu_e$ which accounts for 4% of the copper price.
The authors acknowledge that copper equivalent production relies heavily on the spot prices of the commodities at the day they were accessed but, it was deemed to be the most reasonable method available. To assess the validity of the calculation, the 2011 global production figures for gold and copper (United States Geological Survey, 2012) were used to calculate the copper equivalent production. From this analysis the contribution of each commodity were found to be equal with global copper production accounting for 49.6% of the total copper equivalent production. Therefore, if copper equivalent production was replaced by percentage of global production, it would result in no appreciable difference in the analysis.

The annual comminution energy consumption can also be effectively displayed using a Pareto chart (Figure 6). An ordered bar graph displays the individual annual comminution energy requirements of the minesites that were included in this study. The smooth line corresponds to the cumulative energy that results from the addition of each mine’s energy requirements to the last. From this graph it can be seen that a third of the minesites together consumed 80 per cent of the total comminution energy used by the industry.
Figure 6 - Pareto chart for comminution energy

The proportion of energy consumed by comminution is variable across the mines surveyed (Ballantyne et al., 2012), therefore it is appropriate to include the total mine site energy consumption figures in this analysis (Figure 7). Comminution specific energy is included in this graph to highlight the proportion of energy attributable to comminution. There is no relationship between comminution energy and total energy consumption in this graph. A mine’s total energy consumption is dependent on many factors including mining technique, electricity generation technique, and maybe most importantly, the ore:waste ratio. It should be noted that the total energy consumption figure reflects the reported energy consumption as opposed to the utilised energy figure that was defined earlier. This was due to the limited data available for the breakdown of energy between diesel and electricity. The weighted average total energy cost was $2,000/tCu which equates to 27 per cent of the price of copper. This high proportion is a result of the constant energy price employed in the analysis and is expected to over-estimate the real energy costs which are historically 12 to 15 per cent of the price of goods sold to gold mines (Brook Hunt, 2011).
DISCUSSION

The mines included in this study contribute 15 per cent of the global gold production and 24 per cent of the global copper production. 7.51 Terawatt hours of electrical energy was consumed by comminution at those mines annually. Three measurement bases were used to estimate the total world consumption for this survey. The average energy per tonne of ore, per ounce of gold, per tonne of copper, and per tonne of copper equivalent can all be used to calculate the remaining energy requirement. Using the average of all three methods, the annual comminution energy consumption for the mining of copper and gold is approximately 44 terawatt hours. This equates to approximately 0.2 per cent of the global electricity consumption (calculated as 22.12 petawatt hours by the CIA (2012)). To provide further perspective, it is approximately 16 times the electricity consumption of an average 2 million populace city (Brisbane) and 85 per cent that of a 4.5 million populace state (Queensland) (Energex). However, the national energy usage will be much higher for countries such as Australia which are large gold/copper producers where comminution of gold and copper ores accounts for 1.3 per cent of the national electricity consumption (Ballantyne et al., 2012).

The range of values for specific comminution energy across the surveyed mines is a marker of the variability that is inherent at different mineral processing plants. Metal specific energy (MSE) of final product is driven by ore competence, fineness of grind, comminution efficiency, the grade of the deposit and separation recovery. The Bond work index is a measure of competence and P80 can be used to benchmark the fineness of grind. Comminution circuit efficiency was defined as the ratio of operating work index and Bond work index. An estimate of the ore grade could be made by calculating the ratio of copper equivalent production and material throughput over a year. The influence of these factors was studied by calculating the expected change in MSE consumption if standard values were achievable. The standard values for the four factors are displayed in Table 1. Correcting the MSE to the standard values was simple for circuit efficiency and ore grade, but ore competence and grind size required the application of the Bond’s third theory (Eq. 1). An example of the percentage change in MSE when correcting the non-standard variables is included in Table 1, the cumulative result of this normalisation was a 59 per cent reduction. As each correction factor is introduced, the variance in copper equivalent MSE changes. Unfortunately, due to a dearth of data the ore-dependent relationship between recovery and grind size was not included in this analysis. This lack in the analysis results in a caveat for using this data, that a comparison of deposits with dramatically different mineralogy is difficult. For instance, due to its fine-grained nature, the McArthur River ore requires a substantially finer grind than Mt Isa to obtain a similar recovery level. In this case, the required comminution energy intensity is more dependent on the philosophical operating strategy of the mine or country (maximize resource recovery or production rate) than the energy efficiency of the process.

Table 1 - Standard values for variable factors including an example from one set of data.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Example values</th>
<th>Standard value</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit efficiency</td>
<td>72%</td>
<td>100% (Bond standard circuit)</td>
<td>-28%</td>
</tr>
<tr>
<td>Ore competence</td>
<td>16</td>
<td>BWi = 12 kWh/t</td>
<td>-25%</td>
</tr>
<tr>
<td>Grind size</td>
<td>170</td>
<td>P_{80} = 100 µm</td>
<td>+32%</td>
</tr>
<tr>
<td>Ore grade</td>
<td>0.57%</td>
<td>t_{Cu \text{ eq}}/t_{\text{material}} = 1.0 %</td>
<td>-43%</td>
</tr>
</tbody>
</table>

The objective of the analysis was to ascertain the additive contributions of each of the major factors to the total MSE. Due to the complex interplay of the parameters this is not a simple additive contribution, and despite extensive analysis of the data the authors have not been able to achieve this objective. However, a good semi-quantitative assessment is provided by the box and whisker plot presented in Figure 9. It is a standard graphical technique used to highlight the variation between populations. The box represents the interquartile range, the bar is the median, the whiskers extend to the maximum and minimum and the stand-alone stars are the outliers of the range. This graph shows that a correction for efficiency and competence effectively accounts for the outlier data shifting the maximum MSE from 3.1 to 1.7 MWh/tCue. However, normalising to a consistent grind size expands the MSE range. As the accurate measurement data is based on surveys conducted under steady operating conditions and at a point in time, it is likely that this increase in average energy range reflects a significant fluctuation in grind size over time at the mine sites.

Figure 9 - Analysis of variability of the copper equivalent specific energy using a box and whisker plot.

There is a significant reduction in the MSE range after converting to a standard grade. What is particularly noticeable is that it is the only factor which increases the lower end of the energy range from 0.2 to 0.5 MWh/tCue as well as reducing the inter-quartile range by 55 per cent. This shows that, not unexpectedly, only higher grade ore can drop a mine into the lower energy use category. If a low grade ore is mined the energy intensity per unit metal produced will be high—as shown by a reduction in the top end of the MSE range. The reduction of the upper limits of MSE after grade correction are small, a reflection of the majority of the ore bodies being massive low grade deposits. On the other hand, variation in ore grade shows the largest contribution to the variability of MSE.

The relationship between un-corrected specific energy and ore grade is shown in Figure 10. There is not a clear trend between grade and specific energy, but there appears to be a widening scatter for the lower grade deposits. The area of the circular data points is proportional to the throughput and this shows that the lower grade deposits tended to be higher throughput. This is an illustration of the economy of scale. Within the super-large, low grade mines, there appears to be a much clearer inverse trend between specific energy and grade. There is also a secondary trend visible that shows that within mines of similar grades, the specific energy requirements are lower for mines with much larger milling rates. Therefore, going super-large may not only improve capital efficiency (well-known trend) but also reduce operating costs.

**CONCLUSIONS**

The energy curves investigated in this paper are useful for mine sites to benchmark their operation in the context of the wider mining industry. Leveraging off the widely used cost curve and Pareto chart formats, the results are easily interpreted and adopted. By determining the relative efficiency rank of
a mine in this way also provides motivation for the mine to identify improvements that will help move down the curve, thus saving energy and also reducing the costs associated with energy. However, it must be kept in mind that the size specific energy is related to rock competence. Furthermore, the resulting energy reduction can be measured in relation to the energy consumption of the industry as a whole.

It is intended that this tool can be used by sites to identify opportunities to reduce energy and operating costs within the process, such as inefficient parts of the comminution circuit; changes to grind size (varying grind size to improve recovery); and the penalty of competent ore zones. Finally, addressing grade through ore upgrade strategies clearly provides a significant avenue to reduce comminution energy and processing costs (Powell and Bye, 2009).

Utilising a reliable measure of rock competence, such as energy required to generate new minus 75 micron material (SSE), can contribute to identifying opportunities to improve comminution efficiency across the processing chain. To this end, the authors are currently pursuing the evaluation of simple, reliable measures of size specific energy that will provide a robust basis to consistently assess comminution efficiency across each processing unit.

The authors have focused on comminution energy efficiency in this paper and acknowledge that overall profit must be optimised for individual cases according to the specific local drivers, with energy efficiency no doubt being a key driver in this assessment.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of CRC ORE, established and supported by the Australian Government’s Cooperative Research Centres Program and all their sponsors who provided financial assistance for this research. We thank JKTech management for their permission to access its database which was also integral to this study. We also thank Ming Tiang for his work in compiling the original data.

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