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Proportion of Energy Attributable to Comminution

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ABSTRACT

This paper reviews the proportion of energy attributable to comminution within the Australian gold and copper mining sector. The need for this is motivated by inconsistencies in the quoted energy usage data and the lack of a common basis for reporting the fraction of energy in mining that is attributable to comminution. This study should form a reliable basis from which to assess both demand and opportunities to reduce energy consumption.

The proportion of milling energy was calculated for the major producers in the Australian gold and copper sector. A sampling methodology created by Powell *et al* (2003 - 2010) was initially used to provide an accurate and meaningful measure of the energy used in the comminution process. However, no useful method for grouping similar mines was found. Fortunately, a surprisingly large amount of high quality data was found from a number of different sources, allowing the development of robust relationships to be used to estimate a high proportion of the unknown values. The fraction of energy attributable to comminution was found to be dependent on how the total energy consumption was defined. For instance, comminution accounted for 52 per cent of the electrical energy, but only 21 per cent of the total energy publicly reported by the mines because a substantial proportion of energy used on a mine is in the form of transportation fuel (mostly diesel). Critically, the measured electrical energy consumption does not account for transmission and generation losses, while diesel energy usage is typically quoted according to its calorific value. This review proposes that diesel should instead be converted via the mechanical efficiency factor for diesel engines. Using this conversion, comminution was found to account for 36 per cent of the available energy on average. This approach allows a useful basis of comparison for mines regardless of whether milling energy is obtained from electrical or diesel generation. A summary of the results are shown in Figure 7 with other values obtained from literature. The total comminution energy assessed in this study accounts for 1.3 per cent of Australia's electricity consumption, this figure will increase as the other mineral commodities are added to the study.

INTRODUCTION

Rock breakage, or comminution, is the most energy intensive process in almost all mines. Although a large number of studies have attempted to quantify how much energy is used in this process, the proportion of energy attributable to comminution is still debated or is reported as an unacceptably broad range (Daniel and Lewis-Gray, 2011; Tromans, 2008). Providing a more accurate figure will help provide incentive for the industry to improve the efficiency of comminution operations (DOE, 1981).

The proportion of energy attributable to comminution has been reported in a variety of ways in available studies. The US Department of Energy (DOE) has contributed a number of reports to this field going back to a comprehensive report published by the National Research Council for the DOE in 1981. The authors of this report revealed that US industries used approximately 29 TWh of electrical energy per annum for size reduction and an additional 3.7 TWh/a in grinding consumables such as mill liners and grinding media (DOE, 1981). This accounted for approximately two per cent of total US electricity consumption (Ibid). Interestingly, the specific energy requirements (kWh/t) for most commodities were obtained from a number of reports on energy use patterns in metallurgical and nonmetallic mineral processing produced by Battelle Columbus Laboratories in 1975. These reports contained comprehensive energy audits of a number of key commodities across the US. However, when the figures for comminution are scrutinised, anomalies can be identified. For instance, the comminution energy for copper appears to be calculated using an equation supplied by an unpublished source (Battelle Columbus Laboratories, 1975). A summary of the results from this study can be found in Figure 1. The specific comminution energy data was presented in relation to the production of the commodity. Gold was the most energy intensive commodity in terms of comminution because it is mined in such low grades. The specific energy required for iron ore and uranium stand out because they

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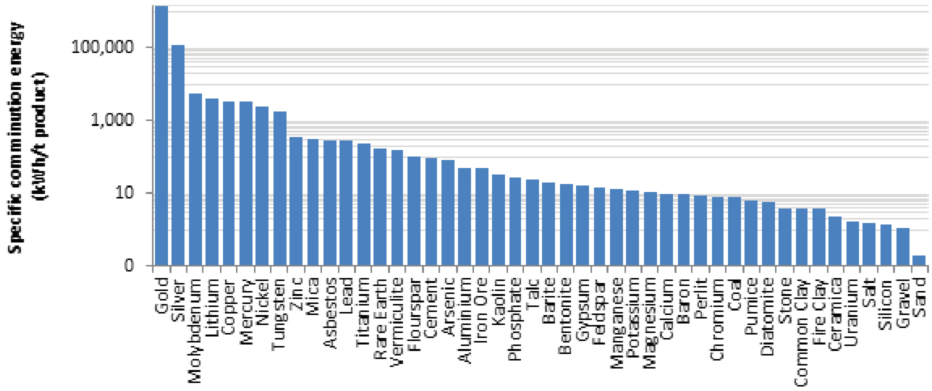

FIG 1 - Specific comminution energy for a number of different commodities (Battelle Columbus Laboratories, 1975).

are significantly different from what would be expected in a modern Australian study. It is also important to recognise that the equipment used in 1975 was significantly different to modern comminution equipment. This is most obvious in the move from rod mills to semi-autogenous (SAG) and autogenous (AG) mills.

The comminution energy intensity values quoted for the different commodities in the Battelle Columbus Laboratories study were applied to recent Australian production data to assess this methodology. The calculated results suggest that comminution would use the equivalent of 36 per cent of Australia's total energy consumption, a figure that is absurd since only five of the commodities had individual comminution fractions greater than 30 per cent (Battelle Columbus Laboratories, 1975). This result is biased by the large quantities of iron ore and coal mined in Australia that are not as energy intensive with respect to comminution as are US mines. Removing these two commodities resulted in a seemingly more realistic estimate of nine per cent for Australia's energy consumed by comminution.

Two other notable reports were produced by the US Department of Energy investigating the energy consumed by the mining industry. The energy and environmental profile of the US mining industry used a cost estimation model (SHERPA) and an estimators guide to mine and mill equipment costs to estimate the energy consumed by the different unit operations of the eight most significant commodities in the US (DOE, 2002). Using this method, beneficiation was found to consume 39 per cent of the energy in mining, with crushing and grinding activities accounting for 75 per cent of beneficiation energy (DOE, 2002). The mining industry energy bandwidth study also relied on the *SHERPA* modelling software to calculate the energy used by the different unit processes in coal, metal, and industrial mineral mining operations (US DOE, 2007). Using this methodology, grinding and crushing were found to account for 44 per cent of the total energy consumption across the mining industry (US DOE, 2007).

A number of full energy audits have been conducted on mines around Australia in recent times. These studies can be used to gain a better understanding of where the energy is being consumed in a particular mine and may be transferable to different sites in the industry. Figure 2 shows an example of an energy audit conducted on Kalgoorlie Consolidated Gold Mine (KCGM), with the results expressed in terms of CO_2 emissions. Automotive diesel and comminution are the two main contributors of CO_2 emissions on this site accounting for approximately 77 per cent of the emissions (Dorai, 2006).

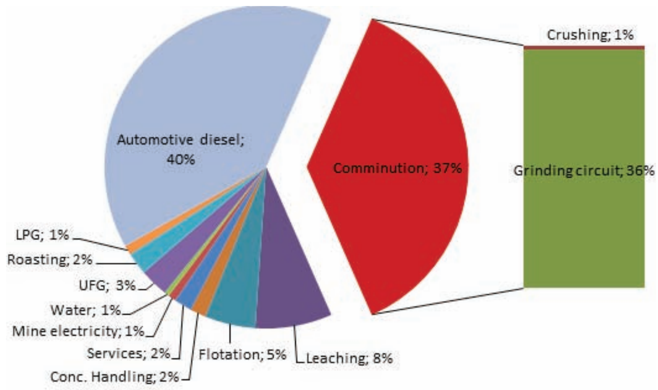

FIG 2 - An example of an energy audit, expressed in terms of CO_2 emissions, conducted on Kalgoorlie Consolidated Gold Mine in 2005 (Dorai, 2006).

Unfortunately the energy audits were not conducted on a consistent basis. For instance, the Northparkes audit was conducted on an energy (GJ) basis, whereas carbon dioxide emissions were the basis for the other audits. The fraction of energy attributable to comminution was also highly dependent on how the individual mine site has defined its total energy consumption. For instance, since milling uses electrical energy it can be quoted as a percentage of electrical energy. Or, the consumption of diesel could also be included in the calculation, thus introducing another complication. The authors found that the diesel energy consumption was generally calculated by multiplying the volumetric consumption by the calorific heating value of the fuel. This is at odds with the use of electricity consumption data because the calorific value of the energy used to generate the electricity is not considered in such a comparison, and neither are transmission and generation losses. This commonly used technique would result in the obvious anomaly of the fraction of energy attributable to comminution being larger for mine sites that employed electrical conveyor belts for transport as opposed to diesel trucks. Based on the study of Nam and Giannelli (2005) it is proposed that a standard mechanical efficiency value of 43 per cent is used to convert the calorific fuel value of diesel to the utilised engine power of the trucks.

The application of a consistent basis of comparison is particularly important when comparing mines employing on-site electricity generation and those that are connected to the national grid. In these cases, the efficiency of electrical generation also created a problem as these sites can publish their total energy use in terms of the total calorific heating value of all fuels entering the mine. The fraction of energy attributable to comminution can vary dramatically depending on the definition of total energy use that is utilised in the audit (see Figure 3).

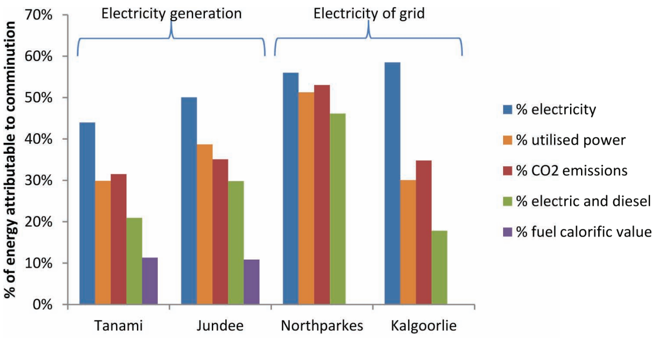

FIG 3 - Dependence of the fraction of energy attributable to comminution on the basis for the calculation.

METHODOLOGY

As discussed above, a consistent and reliable method for estimating the comminution energy requirements of the mining industry is required. It is proposed that a population census technique be used to group similar mines based on the commodity and a selection of operating parameters.

The size specific energy is proposed as an appropriate measure that can be used to group similar operations. The size specific energy is the energy required to generate new minus 75 µm material (Levin, 1992; Musa and Morrison, 2009). It is based on von Rittinger's hypothesis that energy required for size reduction is proportional to the new surface area generated (Hukki, 1962; von Rittinger, 1867). Musa and Morrison (2009) found that 70 - 80 per cent of the surface area of the product of AG/SAG/ball milling circuits is found in the -75 µm size fraction (Musa and Morrison, 2009). Therefore, the energy required to generate -75 µm material can be used to quantify ore competence and the comminution energy efficiency. If similar mine sites can be grouped according to a number of factors, then it may be possible to use the known size specific energy of a few mine sites to estimate the comminution energy required for the other mines in the group. This methodology was first developed by Powell *et al* (2003 - 2010).

The percentage of the total energy attributable to comminution was found by dividing the estimate of the comminution energy by the published total energy. It recently became mandatory to publish energy usage data in Australia through the *Energy Efficient Opportunities (EEO) Act 2006*. Public reports available through the EEO initiative were used in conjunction with sustainability and annual reports to analyse the total energy consumed and metal production of individual mines.

RESULTS AND DISCUSSION

Australian gold and copper mines were chosen as the basis of the initial evaluation study. Due to availability of data and ease of comparison, the study was further reduced to just contain AG/SAG, HPGR and ball milling energy. However, since milling generally accounts for the majority of the comminution energy (Figure 2), it can be used to give a reasonable estimate of the total comminution energy.

The total mine site energy consumption and metal production was found from a number of sources including energy efficient opportunities reports, sustainability reports and annual reports. Appendix A displays a list of the Australian copper and gold producing mines that were used as the scope of this study. Published data was able to cover approximately 96 per cent of the energy consumed by the Australian copper and gold mining industry.

Linear regression was used to calculate the energy usage for the remaining mines for which energy usage information was not available. The following equation was found to fit the data with a coefficient of determination (R^2) of 0.97. The relationship between the measured and predicted energy usage is shown in Figure 4.

$$\text{Energy usage (GJ)} = 1.059 \times 10^{-5}\ \text{Gold (oz)}^2 + 21.96\ \text{Copper (t)}$$

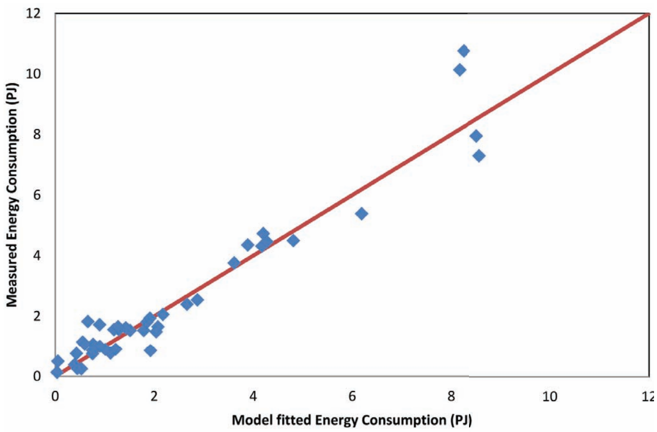

FIG 4 - Measured versus predicted energy consumption.

Interestingly, the total mine site energy usage was found to be proportional to gold production squared, while it was directly proportional to copper production. This may be due to some relationship between the rate of gold extraction and the gold grade. For instance, large gold mines might have relatively low gold grades and utilise bulk-mining methods, whereas smaller gold mines may have higher gold grades due to more selective mining techniques. It is also important to recognise that the regression of copper production may be skewed by results from Mt Isa and Olympic Dam mines where large amount of copper is produced in combination with a number of other co-products.

Historical comminution circuit survey (JKTech) reports between 1992 and 2012 were used to provide operating information on the milling circuits. These reports provided throughput, product size distributions, mill power measurements and hardness parameters. Installed power measurements for a number of sites have been published in a minerals processing survey in AMM magazine (Asphar Survey Group, 2011). An interesting result of comparing these two information sources was that the operating power of the mills measured during the surveys were on average within 96 per cent of the installed power. This may be a result of the perceived requirement to utilise the maximum power of the mill or it may be due to the mill control methodology used in the site surveys.

Using the milling power, throughput and the per cent passing 75 µm in the product, the size-specific energy could be determined for a number of Australian gold and copper producing mines (see Figure 5). The mine sites were treated individually, but because of the sensitive nature of the data, will be presented statistically. The solid lines in this plot represent possible groupings that could be used to classify mines based on their size specific energy. In order to see if the mines could be grouped according to ore competence, the size specific energy was graphed against two hardness parameters, Axb (JK drop-weight test result) and bond work index (BWi). No correlation was found for the Axb parameter, however, a weak correlation was observed with the bond

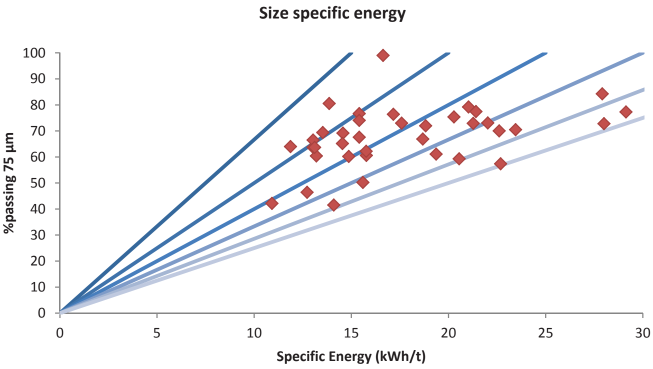

FIG 5 - Size-specific energy mapping for Australian gold and copper mines.

work index. This means that the bond work index may be able to be used to group similar mines for further analysis, however, the relationship is highly dependent on the two highest values, so is not utilised in this study.

The aim of this research was to measure the percentage of total energy use attributable to comminution. It was possible to calculate this directly from the available data for a number of mines. Because the mill power measurements used watts (W) as the unit of measurement and the total energy use of the mines used joules (J) per year, a standard estimated utilisation of 93 per cent was used to convert the units for comparison. The results were differentiated by whether a high or medium degree of confidence could be assigned to the data (see Figure 6). A high degree of confidence was assigned to results where both the comminution and total energy was sourced and did not require fitting. The uncertainty for the data that

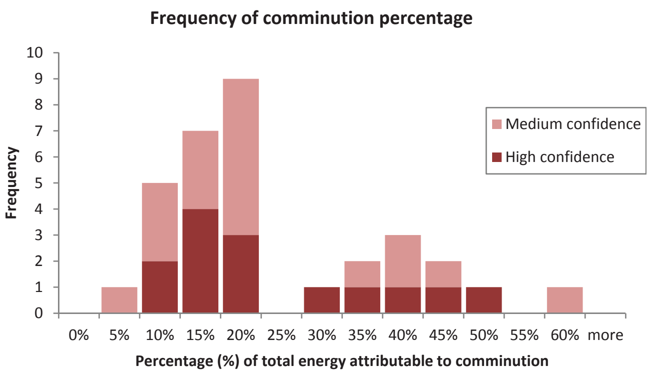

FIG 6 - Histogram of percentage of total energy attributable to milling in Australian copper and gold producing mines based on published total energy use data.

had to use calculations based on the fitted relationships, is estimated to lie within ±5 per cent. There may be a bi-modal distribution in the data, however, this cannot be accurately measured due to the large spread in results and the small number of data points. It was found that for the majority of mines less than 20 per cent of energy was attributable to comminution.

The problem with this method of analysis is that the total energy reportedly consumed by the mines is not generally itemised to include the proportion of electricity or diesel consumption. Also, there is no way of telling whether a particular mine is generating its own electricity, or receiving their supply from the national grid. As discussed earlier, because of the efficiency of converting fuel into power, the total energy consumption is highly dependent on the assumptions and scope of measurement.

In order to remove the variability due to the method of total energy reporting, the publically available documents were investigated further with the aim to obtain the electricity and diesel consumption independently. The largest energy consumers were initially targeted to obtain the largest sample size with the small amount of amount of data that was available. In total, the more detailed energy consumption data was only found for 20 per cent of the mines, but those mines accounted for 60 per cent of the total energy consumption (see Table 1). Using the itemised energy usage data, the fraction of energy attributable to comminution could be calculated in terms of electrical energy and utilised power. The utilised power was introduced as a concept earlier in the paper and refers to the total site energy usage when the diesel consumption is multiplied by the calorific value and the mechanical efficiency of a diesel engine (approximately 43 per cent).

The results for the different analysis techniques are provided in a summary form in Table 1. The fraction attributable to comminution was significantly larger when it was calculated on the basis of utilised power and electrical power than the total reported energy usage. However, the 95 per cent confidence interval was larger for the utilised power and electrical power samples because they were calculated on a smaller proportion of the overall sample. When the calculation was performed on the reported energy usage, a very high proportion (93 per cent) of the total energy usage of Australian gold and copper producing mines was incorporated in the sample. Therefore, if this sample size was to increase to 100 per cent, it is unlikely that the results would be dramatically different. However, for the other two basis, only 60 per cent of the total energy usage

TABLE 1

Percentage energy attributable to comminution calculated on three different basis.

	Percentage of total reported energy usage	Percentage of utilised power	Percentage of electrical energy consumption
Total energy (GJ)	58 769 528	25 516 268	17 492 756
Total energy (MW)	2004	870	596
Comminution power (GJ)	12 217 224	9 144 324	9 144 324
Comminution power (MW)	417	312	312
Fraction attributable to comminution	21%	36%	52%
95% confidence interval	5%	10%	10%
Fraction mines in sample	70%	20%	20%
Fraction of total energy in sample	93%	60%	60%
Fraction of total comminution power in sample	93%	69%	69%

of the industry and 69 per cent of the comminution power was accounted for. Therefore, to increase the confidence in these results, more information is required on the diesel and electricity consumption of the remaining mines.

CONCLUSIONS

This study has attempted to obtain a more accurate estimate for the percentage of total mine site energy attributable to comminution. Difficulties in comparing published data have been identified. In order to develop the methodology with a manageable data set for the initial study, the scope was confined to AG, SAG, HPGR and ball milling in Australian gold and copper producing mines.

The size specific energy was calculated for a number of mines. The aim was to group similar mines using a population census technique to attribute comminution energy values to mines where limited information was available. Unfortunately, for the current sample, a suitable grouping methodology was not found. The size specific energy was found to be weakly correlated to the bond work index, but this relationship was not robust enough to be used as a predictive model.

The percentage of total mine energy used for comminution was calculated for a number of mines without using the size specific energy grouping technique. It was found to be highly dependent on the basis used for the reporting of the mine's total energy consumption. The fraction of comminution energy was found using three different bases for total energy consumption: reported energy consumption, utilised power and supplied electrical energy. Depending on the basis that was used, comminution was found to either consume 21 per cent of the reported energy, 36 per cent of the utilised power or 52 per cent of the electrical energy of gold and copper producing mines in Australia. 93 per cent of the total industry energy use was included in the sample that was used to calculate the percentage of the reported energy, but only 60 per cent was able to be included for the other samples, therefore they have a larger confidence interval. However, the percentage of utilised power is considered to give the most representative comparison of energy usage because it takes into account both electrical and mechanical energy transfer efficiencies. This value compares well with the energy audits and other industry averages (see Figure 7). The total amount of comminution energy assessed in this study was 12.2 petajoules (see Table 1) which equates to 1.3 per cent of to Austalia's 2008/2009 electricity consumption (Department of Resources Energy and Tourism, 2011). Since this study was limited to AG, SAG, HPGR and ball milling in Australian gold and copper producing mines, this figure will increase as the other mineral commodities are added to the study.

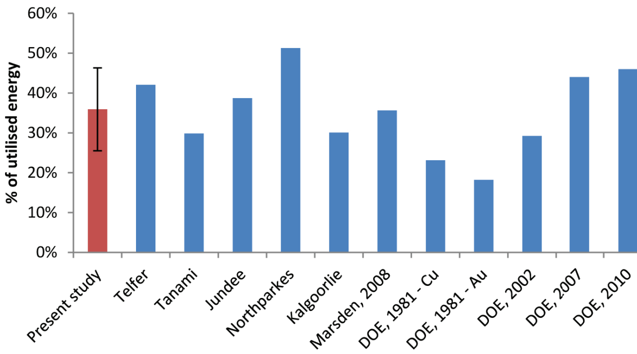

FIG 7 - Summary of reports calculating the percentage of mine energy attributable to comminution (DOE, 1981, 2002, 2007; Dorai, 2006; La Nauze and Temos, 2002; Marsden, 2008; Northparkes, 2006).

Future research will extend this methodology to more commodities, comminution equipment and include embedded energy of grinding media. Information from equipment suppliers will be collated to provide up to date installed mill power data including crushers and regrind mills. Also, a short, easy to answer questionnaire will be prepared in order to obtain the improved production information to move forward with this study. A substantial short fall in this methodology was that the embedded energy in the grinding media was omitted from the calculation. The embedded energy in grinding media is significant and can be between 30 per cent and 50 per cent of the direct energy used (Powell *et al*, 2003 - 2010).

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