Using comminution energy intensity curves to assess efficiency of gold processing circuits

G.R. Ballantyne, A. Mainza, and M.S. Powell
The University of Queensland, Australia

The mining industry has acknowledged the need for an effective method and platform to benchmark comminution energy intensity and motivate action to improve productivity and earnings. The familiar cost-curve format has been used to develop an energy curve report that compares the comminution energy intensity of a specific mine with that of other operations. The energy curve program allows operators to establish their current operating efficiency. It is designed to motivate the adoption of best practice by creating a competitive incentive to move 'down' the curve towards a more cost-efficient position by improving energy productivity. The energy curve is populated from a database covering a significant proportion of gold, copper, lead, zinc, and silver producers. CEEC International is supporting the industry's use of this program by making it available to the global industry; in line with their role as an industry-friendly organization.

This paper will focus on the use of the comminution energy intensity curves for the characterization of circuit efficiency and as a tool for increasing circuit energy productivity. Five interchangeable metrics have been used, including kWh/t, Bond work index, and size-specific energy. The generation of new -75 μm material is used to calculate the size-specific energy (SSE,) which has been previously been demonstrated to be a practical and fair measure of energy efficiency. The SSE is calculated across individual items of equipment, sections of a circuit, or the full circuit, enabling the benchmarking and comparison of comminution equipment. The SSE intensity energy curve is used to identify circuit inefficiencies at two mines; reinforced by more detailed circuit analysis. A methodology for assessing performance using energy curves and the calculation of SSE energy has been expanded in this paper. These methodologies clearly show the value that can be gained from improving energy productivity across the circuit.

Introduction

Comminution energy intensity is increasingly affecting the financial bottom line of many mines as energy costs increase, security of supply decreases, and environmental performance impacts the social license to operate. The Coalition for Eco-Efficient Comminution (CEEC) was founded to help the industry reduce energy usage and improve operations. During the CEEC's 2012 workshop, the lack of clear benchmarking and standard measurement techniques were identified as impediments to energy-efficient operation. As a response to this, Ballantyne and Powell (2014a) proposed an energy curve benchmarking strategy combined with a database of comminution performance data. At the 2014 workshop, this strategy was adopted by CEEC with the aim of increasing the number of mines captured in the database to cover at least half of global gold and copper production, as well as extending it to various other commodities.

Benchmarking of operations within the minerals industry has historically had limited success because of the large inherent variability in geology, differences in mining techniques, and processing circuit designs. Therefore, the tool being developed needed to be simple to understand, comprehensive in nature, and flexible in application. Allowing a number of measures for energy intensity to be included in the analysis (*e.g*. energy per unit rock milled or metal produced) provides a fairer comparison between sites. The easily recognizable financial cost curve format has been used to visualize the variability in energy intensity across the industry.

The energy curves have broad application. They can be used to map the position of the mine as production progresses with year-on-year analysis. Circuit design proposals can be compared to assess the position of the mine on the energy curve when operational. Operational efficiency improvements can be mapped on the curves to visually assess the magnitude of reductions in energy intensity achievable through various strategies. The efficiency with which various comminution devices reduce the size of the feed can be mapped down a circuit to identify opportunities for improvement and the magnitude of potential gains. This elegant technique allows the current position of the mine in the energy efficiency spectrum to be identified, motivating competitive behaviour aimed at moving down the curve.

Method

The energy curves have been developed as a visual benchmarking technique, and possibly more importantly, as an investigative tool to identify improvement opportunities. The cost curve graphical technique is used to quickly and easily identify underperforming equipment or circuits while ensuring that the other operations being compared are not identified. Each mine is presented as a separate bar in a bar chart, the width of which represents their annual production and the height representing various measures of comminution energy intensity. For more information, the CEEC website (www.ceecthefuture.org) has links to the energy curve portal.

A suite of four energy curves has been configured to rank the relative energy intensity of a mine of interest with respect to the effect of ore hardness, circuit efficiency, grind size, and feed grade. The first energy curve shows the impact of ore hardness as assessed using the Bond work index comparative methodology. Both the Bond work index (BWi) and the operating work index (OWi) are presented as separate overlayed curves (Figure 1). The BWi is an industry-standard laboratory measurement related to the specific energy requirement of an ore for a given P_{80} reduction. The OWi relates to how much energy is actually used on the plant to achieve the same P_{80} reduction. Presenting both these parameters together enables the mine to be benchmarked on both the laboratory competence measurement and the achieved energy consumption. Thus, if a mine was found to have an ore that is at the 70th percentile of BWi, but the 80% percentile of OWi (higher on the curve), this would indicate that this mine was underperforming in relation to ore hardness.

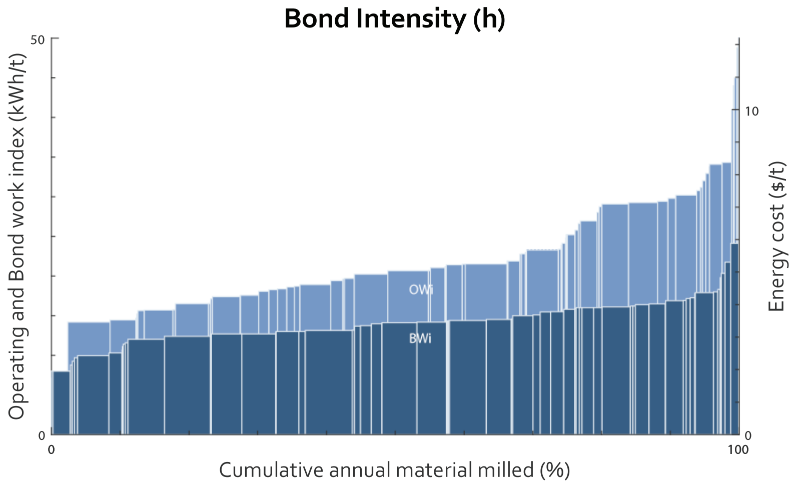


Figure 1 – Bond intensity energy curve

The size-specific energy (SSE) intensity is a measure of how much energy is used in generating new sub-75 µm material. The SSE method has been used as an alternative to P_{80} reduction because it more accurately reflects the fact that the majority of the energy is consumed in the generation of new surface area in the fines fraction (Ballantyne *et al.*, 2015). The use of 75 µm is acknowledged to have no particular value in itself; for coarser of finer circuit products, another marker size would be equally appropriate. Both ore hardness (*h*) and circuit efficiency (*c*) contribute to determine the position of an operation on the SSE intensity curve (Figure 2). Thus, if an operation appears in the bottom third of the Bond intensity curve, but near the top of the SSE intensity curve, it would indicate that at least one area of the circuit is underperforming.

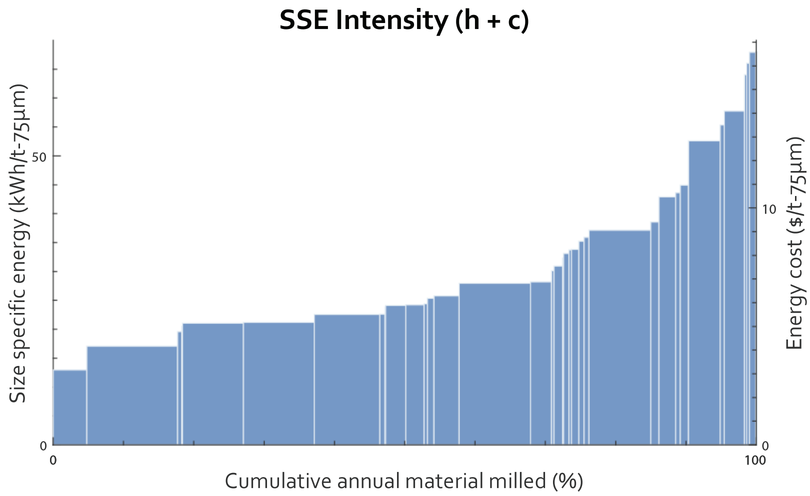


Figure 2– Size-specific energy (SSE) intensity curve

The data to derive the tonnage intensity curve is the most readily obtained and is most easily understood by non-technologist (Figure 3). The particle size of the circuit product (*s*) also affects the position of a mine on the tonnage intensity curve. Therefore, the mineralogy of the ore contributes to the tonnage intensity because it largely determines the required grind size. A fine-grained ore typically requires energy-intensive fine grinding, pushing it up the tonnage intensity curve.

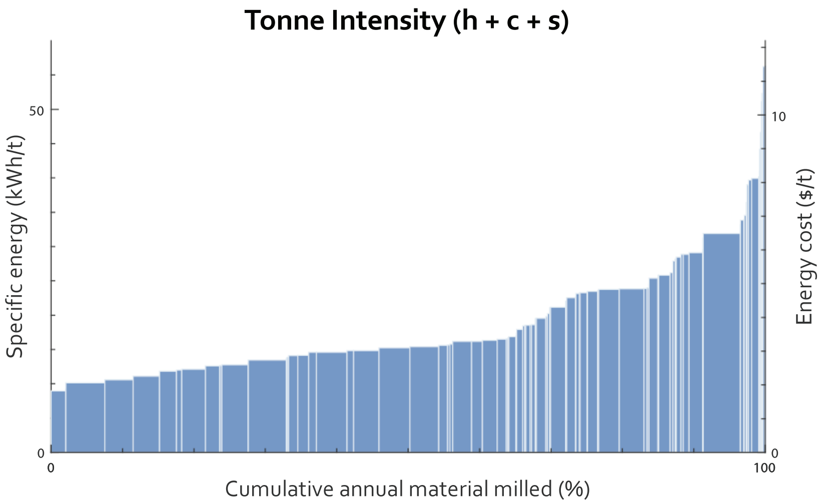
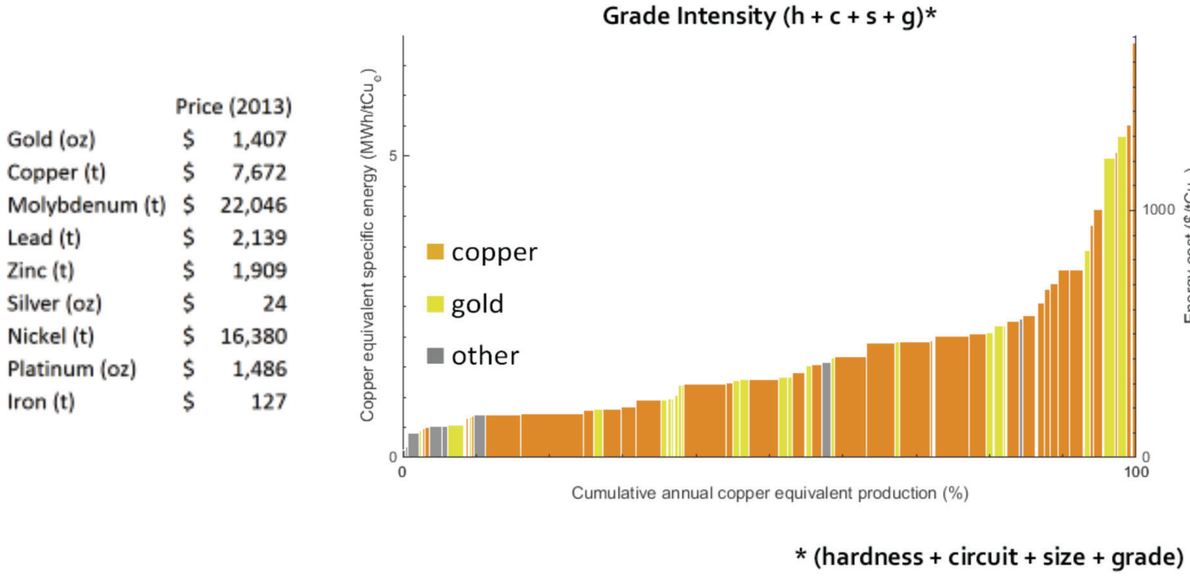


Figure 3 – Tonnage intensity energy curve

The primary output of a mine is the production of metal, which is captured by the grade intensity curve. The comminution energy required per unit of metal product is displayed in this curve. Poly-metallic ores are normalized by converting the respective metal values of other constituents to a copper-equivalent production. This is essentially the copper production that would be required to produce the same level of revenue as that from the other metals. The metal prices that were used in this analysis were obtained from annual reports in 2013 and represent the actual revenue realized by the mining companies. Figure 4 displays both the metal prices used and the grade intensity curve coloured by commodity. This shows that using copper equivalent production is useful in comparing gold and copper mines (there is an equal distribution along the curve), but has the potential to underestimate the contribution of comminution energy in other commodities (grouped at the bottom of the curve). The position of a mine on the grade intensity curve is largely determined by the metal grade of the mined material. Thus, a mine in the upper quartile of the grade intensity curve would likely benefit from investigating preconcentration strategies such as grade engineering.



	Price (2013)
Gold (oz)	$ 1,407
Copper (t)	$ 7,672
Molybdenum (t)	$ 22,046
Lead (t)	$ 2,139
Zinc (t)	$ 1,909
Silver (oz)	$ 24
Nickel (t)	$ 16,380
Platinum (oz)	$ 1,486
Iron (t)	$ 127

Figure 4 – Metal intensity energy curve

The database from which the energy curves are drawn contains detailed information on mines from around the world, covering nine commodities. The predominately gold-producing mines account for the largest number of mines in the database, but the copper production contained within the database is the largest proportion of global production across all commodities (see Figure 5). Increasing the gold production represented in the database is a tougher task than copper, since major mining companies account for 63% of global copper production, but only 36% of global gold production. This is due to the large quantity of informal gold production and the significant production levels in China and Russia, for which limited data is available (US Geological Survey, 2012). A significant proportion of global lead, zinc, molybdenum, and silver production are contained within the database, with a currently limited representation of platinum, nickel, and iron ore production.

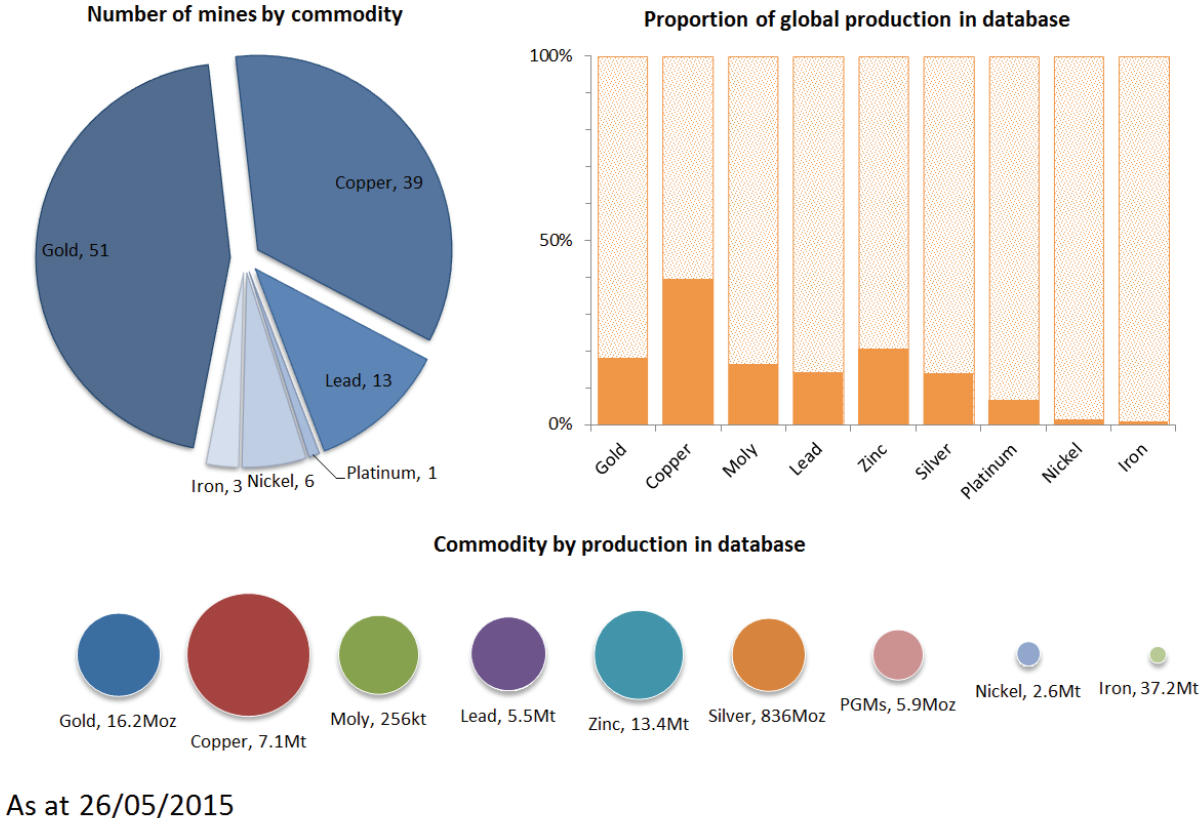


Figure 5 – Energy curve database by commodity

Results and discussion

This analysis focuses on two mines: Mine 1 produces both copper and gold, but its greatest revenue is from gold; Mine 2 is a large copper producer. The comminution circuit at Mine 1 consists of a partial pre-crushing circuit before an SABC circuit followed by three ball mills, whereas Mine 2 is a traditional SABC circuit consisting of a single SAG mill closed with a recycle crusher and followed by two ball mills. The energy curve methodology has been used to benchmark the mines and isolate the performance of each comminution device down the circuit to identify areas for productivity improvement.

The positions of Mine 1 and 2 on the suite of energy curves are presented in Figure 6. Mine 1 is consistently positioned higher on the energy curves than Mine 2. Although the ore from Mine 1 was significantly more competent (BWi), both mines were achieving a similar OWi and SSE. Mine 2 was close to the median on the tonnage intensity and grade intensity energy curves, whereas Mine 1 was at to the 70th and 90th percentile respectively on these two curves. This was due to the fine grinding requirement and low feed grade at Mine 1. Although the positions of these two mines are represented as a single point on these graphs, this is dependent on the ore type, equipment efficiency, and grind size at the time of assessment. For instance, the SSE can be calculated for a whole circuit, or across individual pieces of equipment, thus highlighting inefficiencies.

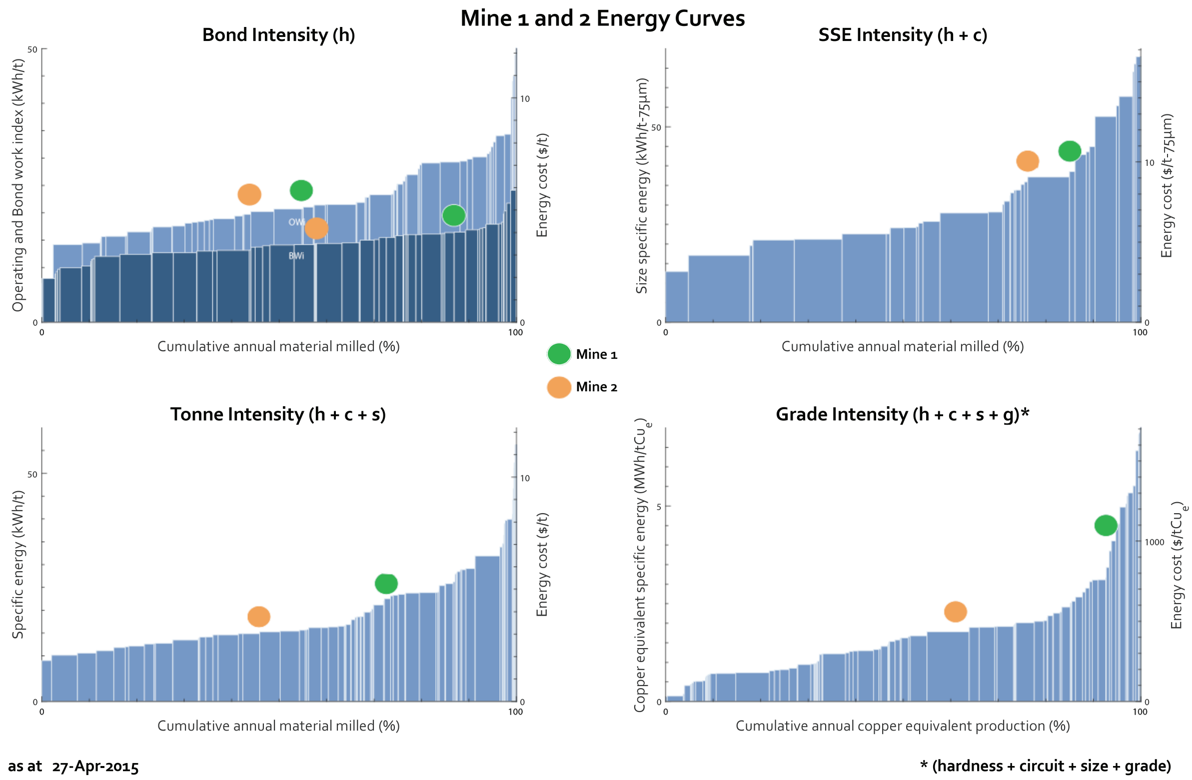


Figure 6 – Mine 1 (green) and Mine 2 (orange) positions on the full suite of energy curves

The size-specific energy (SSE) of each comminution device was calculated and benchmarked on the SSE energy curve. The SSE was calculated from the balanced size distributions and flow rates around the individual mills. To achieve this, the circuit boundaries must be drawn with inputs and outputs clearly identified. To avoid confusion, the SSE calculation for ball mill 1 at Mine 1 will be used as an example (see Figure 7). The total mass flow rate through this circuit was taken as the cyclone 1 overflow. Since the ball mill was the only comminution equipment within the circuit, the rate of new -75 μm material generated for the circuit was calculated by taking the difference in the flow rate of -75 μm in the mill feed and product. The specific energy was calculated by dividing the mill power by the circuit throughput. The generation of new -75 μm material was then calculated as a percentage of circuit throughput. Finally, the SSE was calculated by dividing the specific energy by the percentage generation of -75 μm material. The importance of standardizing these calculations becomes apparent when calculating the SSE of parallel mills, or non-standard circuit designs.

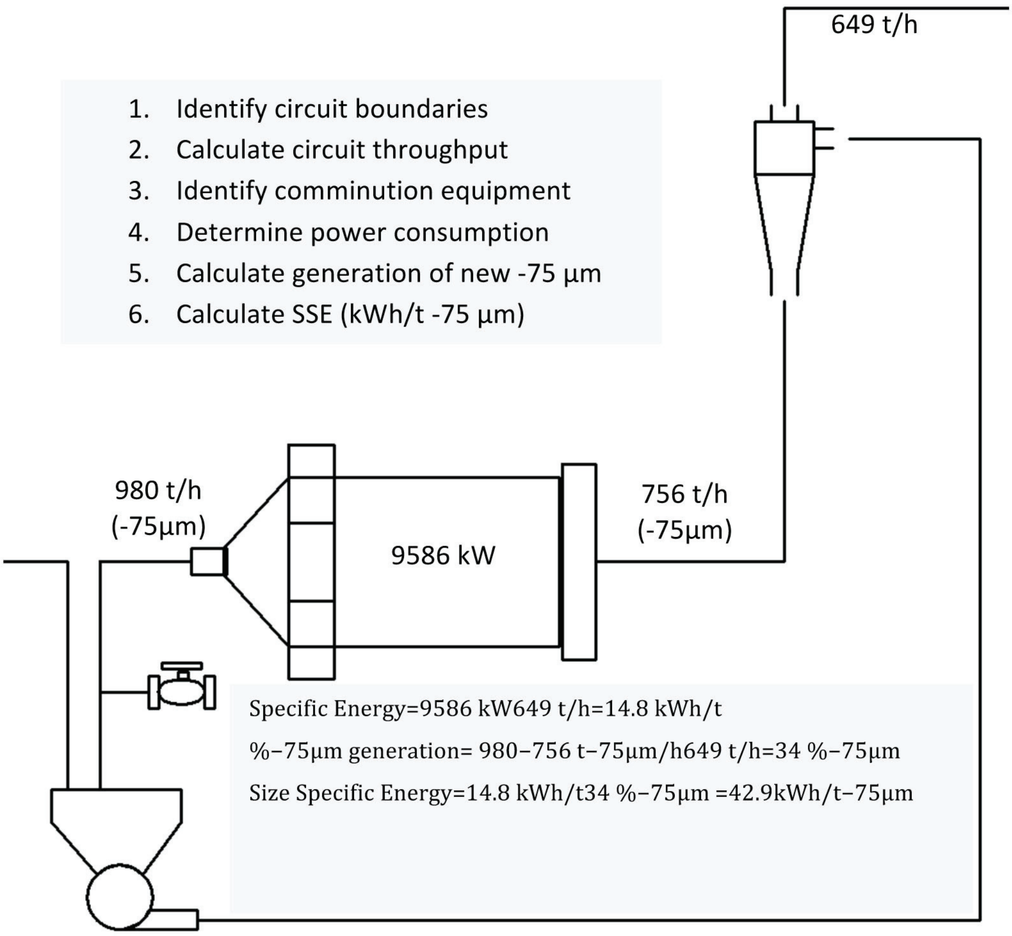


Figure 8 – Standard SSE calculation around ball mill circuit 1 at Mine 1

The cumulative specific energy required to generate new -75 μm material has been plotted down the circuit in Figure 8. The linearity between generation of new -75 μm material and specific energy consumption has been proposed to be similar to new surface area generation and thus correspond with Rittinger's law of comminution (Ballantyne *et al.*, 2015). Using it in this way enables an easy visual identification of underperforming equipment in the comminution circuit. Each comminution device is plotted as a data point and a line is drawn from the origin through the best performing piece of equipment. The inverse gradient of this line is the lowest SSE for the circuit, and any equipment not on this line should be investigated and its performance evaluated in greater detail. The advantage of this technique is that equipment performance is not related to a laboratory test or some theoretical minimum, but is compared to other equipment in the circuit that is actually achieving a better result. For Mine 1, the SAG mill and ball mill 1 were clearly underperforming, a result which was corroborated by more detailed assessment of the circuit. Because of the design of the partial pre-crush circuit, the SAG mill was not receiving coarse feed and thus was not able to maintain a sufficient load. The recirculating load around ball mill 1 was greater than 450%, resulting in reduced classification efficiency and thus increasing the SSE of the ball milling circuit. Because of the interplay between comminution equipment and classification (especially in ball milling), it is often the classification device that is the primary cause of inefficient operation. Jankovic and Valery (2012) summarized this interplay very effectively, including the impact of recirculating load.

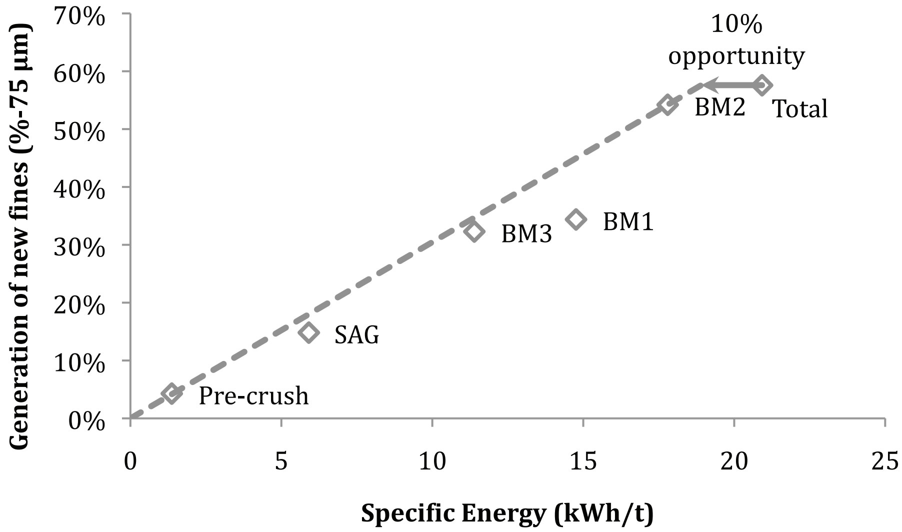


Figure 8 – Mine 1 SSE down the circuit

Figure 9 presents the SSE (kWh/t -75 μm) of the equipment on the SSE intensity energy curve. This clearly represents the different equipment efficiencies down the circuit and how this influences the resulting overall position of the mine. The SAG and ball mill 1 are both pulling the total circuit SSE up the curve, increasing the effective energy intensity. If the other equipment was operating at similar efficiencies, the total circuit would be closer to the 90th rather than the 80th percentile. Similarly, if all the equipment was performing as effectively as the pre-crushing and ball mill 2, the total circuit could achieve a 10% increase in throughput (at the same energy intensity and grind size) and move down to the 70th percentile on the SSE intensity curve.

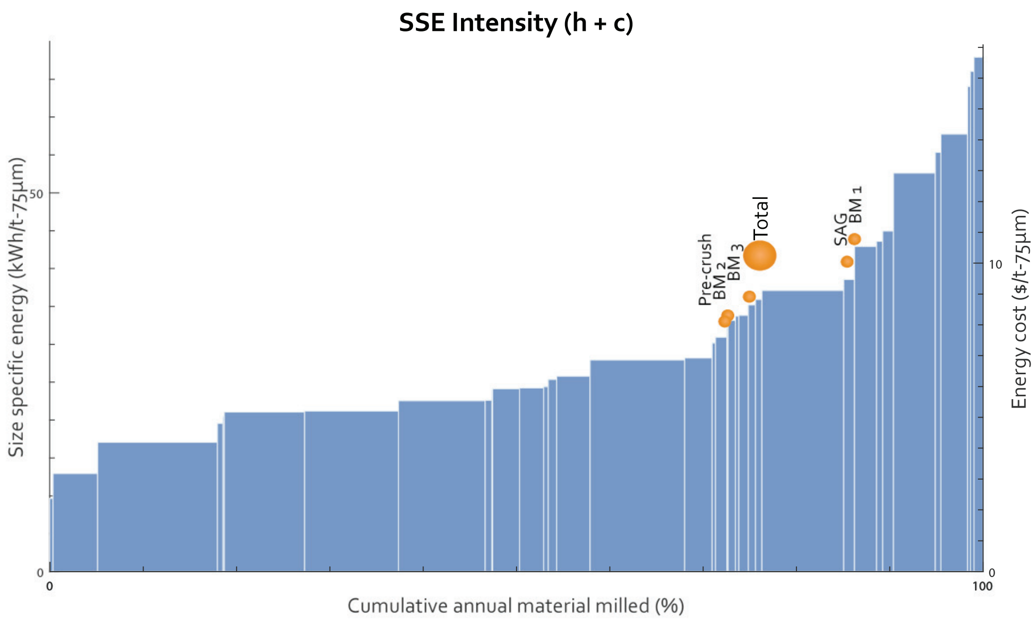


Figure 9 – Mine 1 SSE intensity energy curve benchmarking

For Mine 2, the SAG and ball mill 2 were identified as underperforming in relation to ball mill 1 (see Figure 10), a result that was also supported by detailed site analysis and observations. The throughput at the time of the survey was restrained by downstream circuit limitations, resulting in the underperformance of the SAG mill. The SAG speed was reduced in an attempt to constrain throughput while maintaining mill load. This result of this was a higher proportion of low-energy interactions within the mill, reducing the SAG mill performance. The high SSE of ball mill 2 was identified to be largely due to inefficient classification by the cyclones in closed circuit with the mill. Increasing the performance of both the SAG mill and ball mill 2 to the level achieved by ball mill 1 could result in a 10% increase in the generation of -75 μm material at the same energy and throughput. A finer product rather than increased throughput is favoured by the site because of the potential for increased liberation and thus improved flotation recovery. The SSE intensity energy curve (Figure 11) shows the potential benefit of this increased performance. The total operation could move from the 70th to the 50th percentile on this energy curve, reducing costs and increasing the mine's competitive advantage.

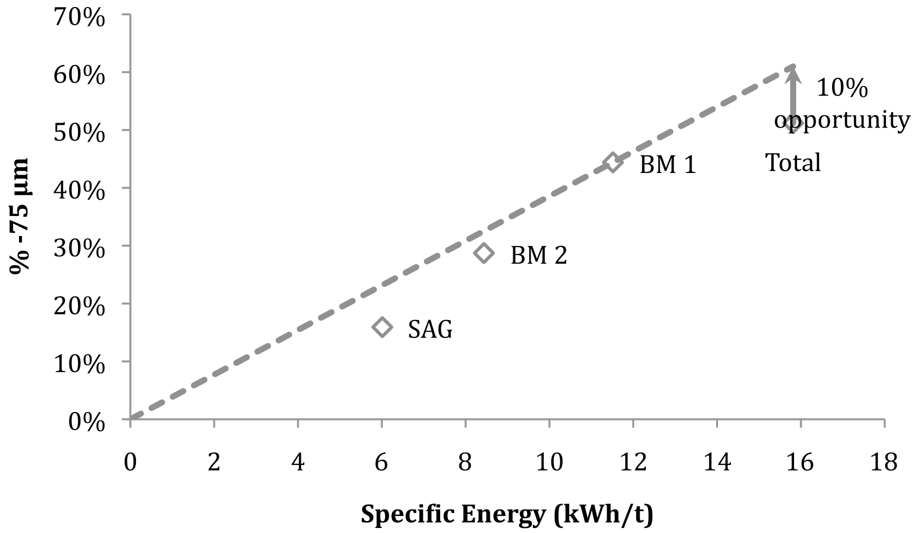


Figure 10 – Mine 2 SSE down the circuit

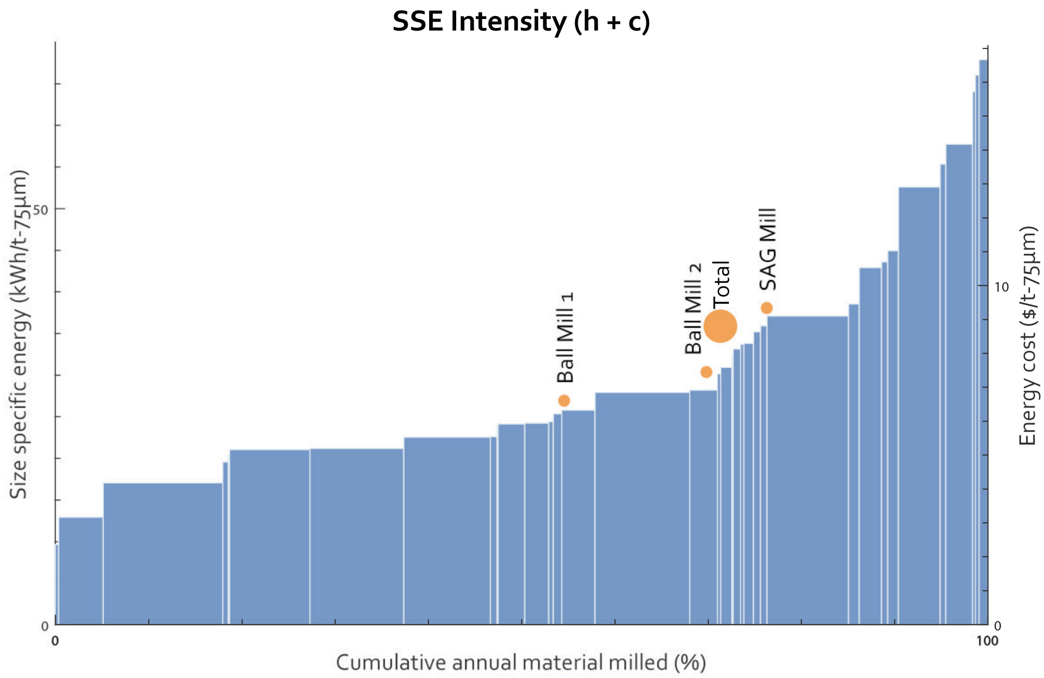


Figure 11 – Mine 2 SSE intensity energy curve benchmarking.

Conclusion

Energy curves have been shown to be useful in assessing the performance of comminution circuits at two mines. The concept of displaying four curves that illustrate the energy intensity in different ways has been utilized to enable comparison on the basis of grade, grind size, circuit efficiency, and ore competence. The database that the energy curves draw from has been increased by adding more gold- and copper-producing mines as well as commodities such as molybdenum, zinc, lead, silver, platinum, nickel, and iron ore. The total material milled by all the mines in the database is 150% greater than when last published by the authors (Ballantyne and Powell, 2014b).

The methodology for calculating size-specific energy from survey data has been expanded. The use of this to highlight equipment efficiency issues has been demonstrated for two mines. In both examples, the SAG mill and one of the ball mills were identified as performing poorly in comparison to the other equipment in the circuit. Both SAG mills were hindered from maintaining the mill load, one due to a fine feed, the other due to a reduced throughput. The underperformance of both ball mills was closely related to classification issues around the hydrocyclones.

The energy curve methodology will continue to gain acceptance in the industry over the coming years. There are many potential used for these curves, including:

- Identification of appropriate improvement opportunities for a mine
- Year-on-year analysis of changes in operation
- Assessment of the energy requirements of different ore types
- Evaluation of different design options in terms of energy intensity
- Down-the-circuit performance of comminution devices.

Acknowledgments

Our thanks to the Coalition for Eco-Efficient Comminution for funding these research activities, and to Sarah Boucaut, Joe Pease, and Tim Napier-Munn for promoting this research. Additionally, to Ben Bonfils, Mohsen Yahyaei, and Marko Hilden of the JKMRC for supporting this work with anecdotal summaries, providing information on the mines, and editing the manuscript.

References

Ballantyne, G.R., Peukert, W., and Powell, M.S. 2015. Size specific energy (SSE)—energy required to generate minus 75 micron material. *International Journal of Mineral Processing,* vol. 139. pp. 2-6.

Ballantyne, G.R. and Powell, M.S. 2014a. Benchmarking comminution energy consumption for the processing of copper and gold ores. *Minerals Engineering*, vol. 65. pp. 109-114.

Ballantyne, G.R. and Powell, M.S. 2014b. Benchmarking comminution energy consumption for improved efficiency. *12th AusIMM Mill Operators' Conference 2014*. Townsville, Queensland, Australia, 1-3 September 2014. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 95-100.

Jankovic, A. and Valery, W. 2012. The impact of classifi cation on the energy effi ciency of grinding circuits – the hidden opportunity. *11th AusIMM Mill Operators Conference*, Hobart, Australia, 29-31 October 2012. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 65-69.

US Geological Survey. 2012. Mineral Commodity Summaries. http://minerals.usgs.gov/minerals/pubs/commodity/index.html.

The Author