# Characterising Energy Efficiency of Particle Sorting

**G. R. Ballantyne[1*], M. Hilden[1], K. Bartram[2] and V. Souto[2]**
[1] The University of Queensland, Sustainable Minerals Institute, Julius Kruttschnitt Mineral Research Centre
[2] STEINERT GmbH
*(*Corresponding author: g.ballantyne@uq.edu.au)*

Particle sorting allows partially liberated minerals to be separated prior to energy intensive fine grinding. Sensors select particles for separation and air, water or mechanical ejectors are used to physically deflect those selected. To achieve effective separation there has to be sufficient liberation, accurate detection and presentation of a separated monolayer of particles. These three physical constraints determine the particle size limits, the sorting technology utilised, the separation efficiency, and the throughput that can be achieved. The combination of all these factors controls the effective limits on the degree to which sorting can reduce the specific comminution requirements and increasing energy efficiency. This paper will explore two case studies: the application of sorting in base metal mining and precious metal mining.

## Introduction

Comminution is the most energy intensive process in the mining value chain, consuming on average 36% of onsite energy (Ballantyne et al., 2012a). The most effective way to save comminution energy is to avoid grinding low value material. Particle sorting is a separation technique used in the minerals industry to remove low grade particles prior to the energy intensive milling stages. Sorting devices utilise a range of different sensors to assess the composition of individual rocks and then eject those containing low value minerals using air, water or mechanical ejectors. This technique takes advantage of particle heterogeneity to avoid conducting energy intensive processing methods on material that would be more economically treated as either waste, deferred to later in the mine life or recovered using low intensity methods such as heap leaching.

One advantage of sorting is to reduce the comminution energy intensity, visually presenting this reduction will assist in increasing the confidence of industry to apply this new technology. A family of Comminution Energy Curves have been developed to present the benefits of techniques and technologies that help to reduce comminution energy efficiency (Ballantyne and Powell, 2014). One version of the curves, the grade intensity energy curve, can be used to show the benefit of pre-concentration strategies such as sorting (see Figure 1). The grade intensity energy curve plots the copper equivalent specific energy. The use of copper equivalent production reflects the wide range of commodities present in the energy curve database. Production of other minerals/metals are converted by calculating the equivalent copper production that would obtain the same revenue. Commodity prices in 2013 were used as they best follow current trends for the mix of commodities in the energy curve database.

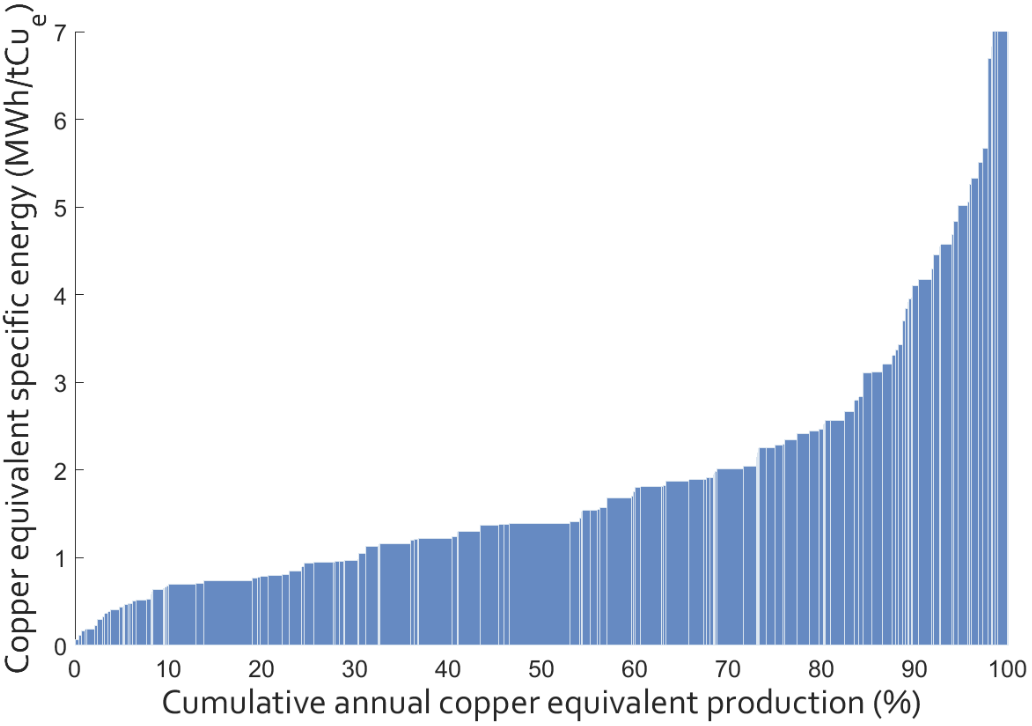

*Figure 1 - Grade intensity comminution energy curve. Each bar represents an individual mine, the height of which represents the metal specific energy, and the width represents the mine's annual metal production expressed as copper equivalent production.*

All sorting systems contain four main components (see Figure 2):

- feeding system
- sensors
- computer analyser
- ejector.

The feeding system arranges the particles in a monolayer with enough separation between particles to enable detection and ejection of individual particles. Many sensors are available for sorting and the choice depends on the mineral assemblages, particle size and required resolution. A computer algorithm decides which particles to eject depending on the detector measurement and selection criteria. The system can utilise air, water or mechanical ejectors to apply a separation force to the selected particles.

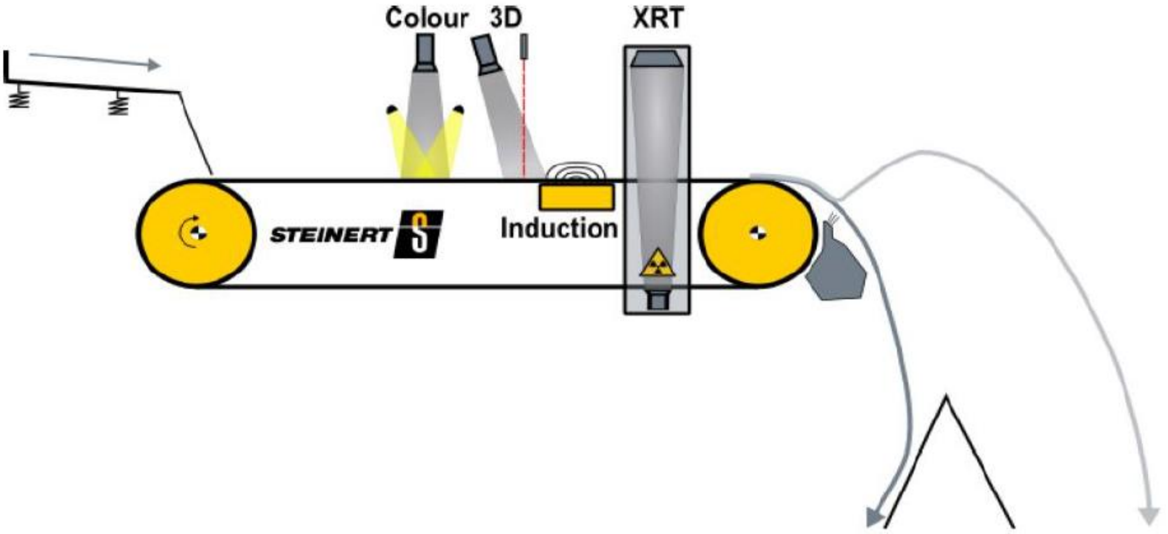

*Figure 2 - Schematic of a typical sorting unit (Australian Mining Monthly).*

Steinert produces sensor sorting systems that can incorporate a wide range of sensor types or combinations of those. This paper will concentrate on results of using a Dual Energy X-Ray Transmission system. The sensor measures the x-ray attenuation of individual particles, which is greater for particles containing minerals with higher atomic number, but also greater when the X-ray's travel the further through the particles. Although a narrow size distribution is still required, by using a dual energy X-ray detector system, the negative effect of variable particle thickness can be reduced. Figure 3 is a schematic describing the response of a sample to both low and high energy x-rays. The thickness of the sample will move the response up or down this response curve, but no matter what the thickness, particles with higher density particles will follow the top curve. However, a close feed size distribution is still required This process is not sensitive to surface conditions (e.g. presence of dust or water) and can therefore be utilised dry or wet and washing of material is mostly unnecessary. Relative atomic numbers form the basis of separation thus allowing this technology to be utilized in applications where other mineral processing techniques have been deemed infeasible.

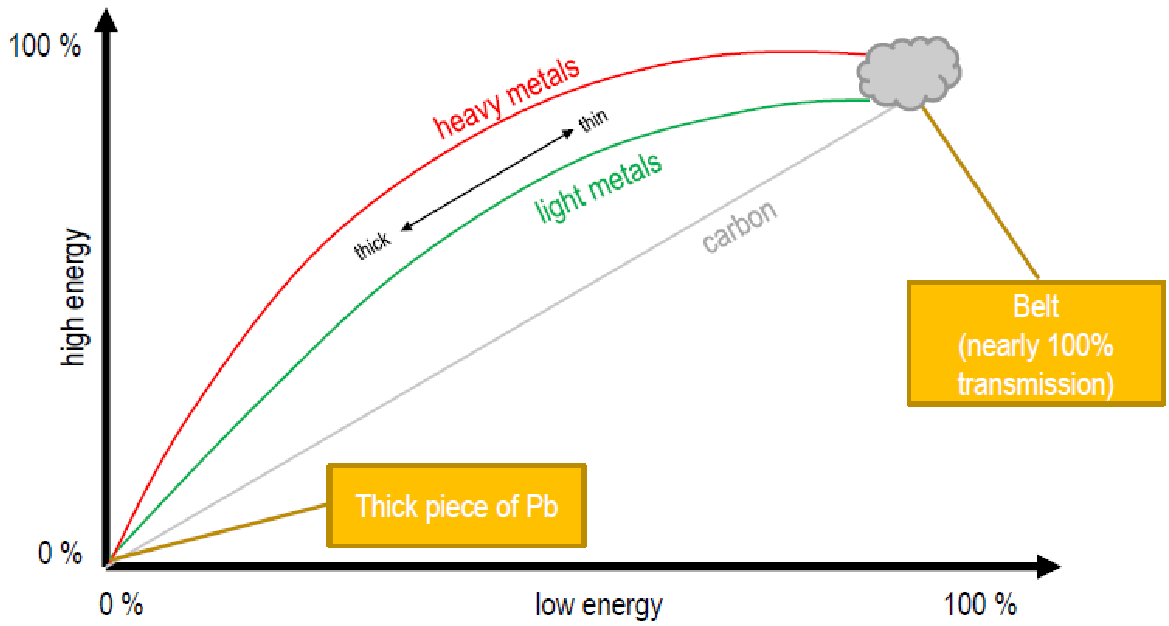

*Figure 3 - Dual energy x-ray transmission system schematic*

The mass throughput of a particle sorter is dependent on (Ballantyne et al., 2012b):

- belt coverage
- belt speed
- particle size
- particle density.

The belt coverage is constrained by the requirement that the particles are arranged in an isolated monolayer. The belt speed can be constrained by the particle size, the detection and the computing speed. However, data processing capabilities are sufficiently advanced that they do not restrict maximum capacity and can allow rates in excess of 2000 particles per second (de Jong and Harbeck, 2005). The average particle size has a large influence on the achievable material throughput. Throughput is directly proportional to the particle size, even with all particles touching, forming a geometric maximum monolayer (see Figure 4). This is due coarse particles having larger particle volume (or mass) in relation to their cross-sectional area. Figure 4 also shows the reduction in achievable throughput when realistic belt coverages of 10, 15 and 20% are chosen. In this example the percent occupancy is defined as the fraction of the belt area covered by rocks.

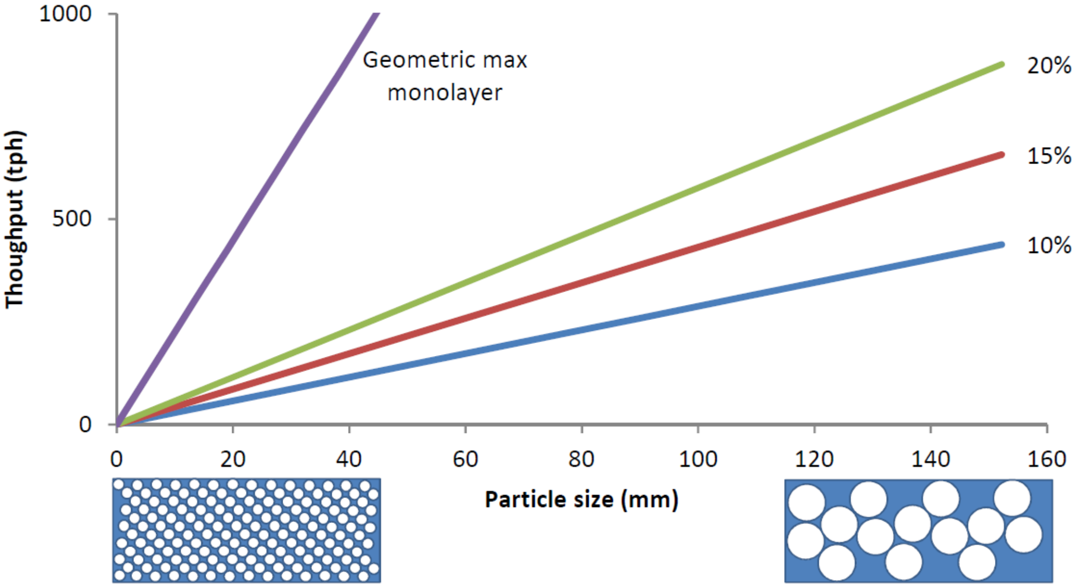

*Figure 4 - Maximum throughput calculated for spheres with a density of 3g/cm3 on a 1m wide conveyer (Ballantyne et al., 2012b).*

Another constraint for particle sorting is the energy consumed by the ejector system. Compressed air is most commonly used for particle ejection because of the high speed of the actuators and the minimal impact on surrounding particles. The energy required for compressed air systems is proportional to the required pressure and the air flowrate. The data available from one compressor equipment supplier (Sullair, 2012) showed the following relationship: $\text{Motor power (kW)} = \text{Air flowrate (L/s)} \times \left[0.0225 \times \text{Pressure (bar)} + 0.1768\right]$. The required air flowrate is a function of the size of the ejector nozzle, air pressure, and the required frequency and duration of ejection events. Although the size of the nozzle is fixed for a particular device, the duration of ejection events is dependent on the position, speed and size of the particle and the frequency is largely a factor of the number of particles that contain the mineral of interest. Although the air blast required for a small rock is less than that required for a large rock, the mass ejected per blast is much smaller. Therefore, the power required to eject a tonne of rock increases exponentially for smaller particle sizes (Ballantyne et al., 2012b).

Particle liberation can be used as a measurement of proportion of particles that contain minerals of interest. Because most mineral deposits have low concentrations of valuable minerals, the waste (or gangue) minerals begin to liberate at a much coarser size. Hilden and Powell (2017) model particle liberation using computer algorithms that apply random breakage to an assemblage of minerals. For example, ore can be modelled as a binary material containing grains of mineral A within a matrix of mineral B, or as clusters of high-grade rock surrounded by low-grade rock. The assemblage represents a mineral texture containing grains of different sizes, reflecting the properties of the ore; and the random breakage of which produces particles that when appropriately calibrated have a liberation distribution comparable to that of an ore sample. Using this method, the fraction of particles that contain only a small concentration of valuable minerals can be estimated (see Figure 5). This fraction constrains the maximum rejection rate that can be achieved without severely impacting recovery.

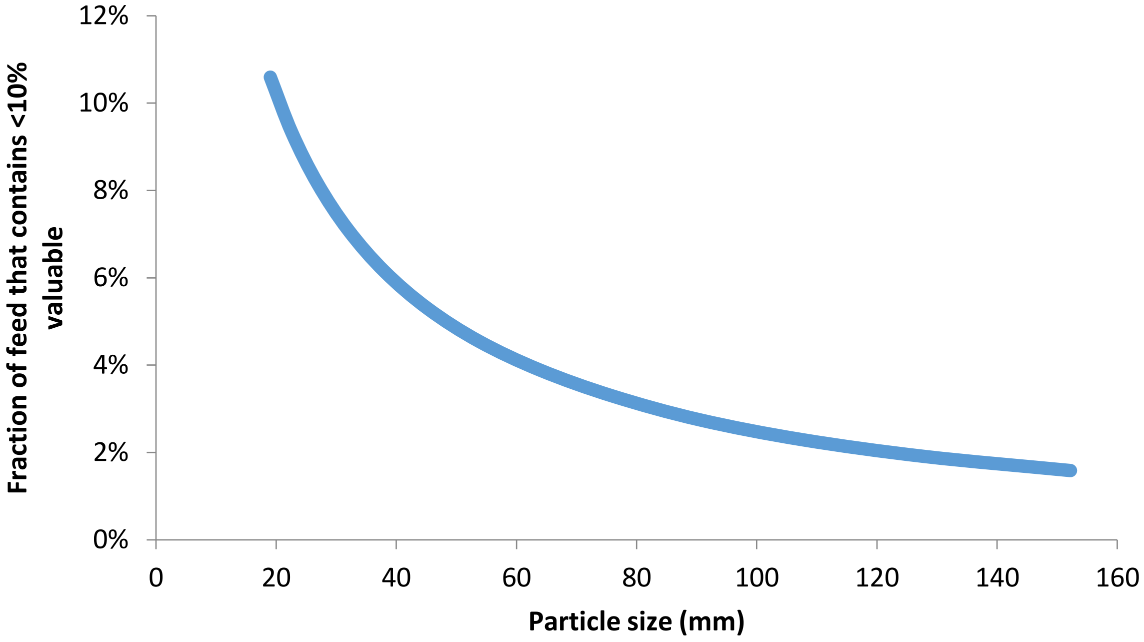

*Figure 5 - Maximum rejection rate based on liberation.*

The combination of throughput, air consumption and particle liberation constrains the operation of particle sorters. Although particle liberation increases for fine particles, the increased air consumption and reduced throughput lead to a disadvantageous operating regime. Therefore, coarser particle separation is preferred in most sorting applications.

### Mine 1 (gold) case study

Mine 1 is a gold mine producing 63 koz gold per annum (2013). The comminution circuit consists of a single-stage run of mine (ROM) ball mill grinding from a P80 of 141 mm to 84 μm at a throughput of 152 t/h. To investigate the suitability of the ore to dual x-ray sorting, a 500 kg sample was sent to Steinert to conduct a comprehensive sorting program. The ore contained two gold-bearing rock types; sulphides and quartzite (see Figure 6) and three typical waste rocks; marble, pegmatite and schist. The gold was fine-grained and predominately associated with pyrrhotite, and minor to trace amounts of pyrite, chalcopyrite, maldonite and bismuthinite.

*Figure 6 - Gold-bearing ore samples: Sulphides (left), Quartzite (right).*

Each rock-type was scanned using dual energy x-ray transmission to obtain the range of measurement from the detector. Each rock-type sample was scanned five times to obtain enough measured points to generate a reliable and representation scatter-plot for each rock-type. The low energy transmission was plotted on the x-axis and the high energy transmission on the y-axis as per Figure 3. The resulting scatter plots are presented as heat-maps in Figure 7. The location of the major waste rock-type (schist) was used as the basis for sorting and a white polygon was drawn around it. One of the other main waste rock types, marble was also found within the schist polygon, however, pegmatite lay outside the sorting regime which may add to dilution of the product grade. Most of the sulphide and quartzite particles fell outside of the demarcated schist polygon suggesting that a good separation may be possible.

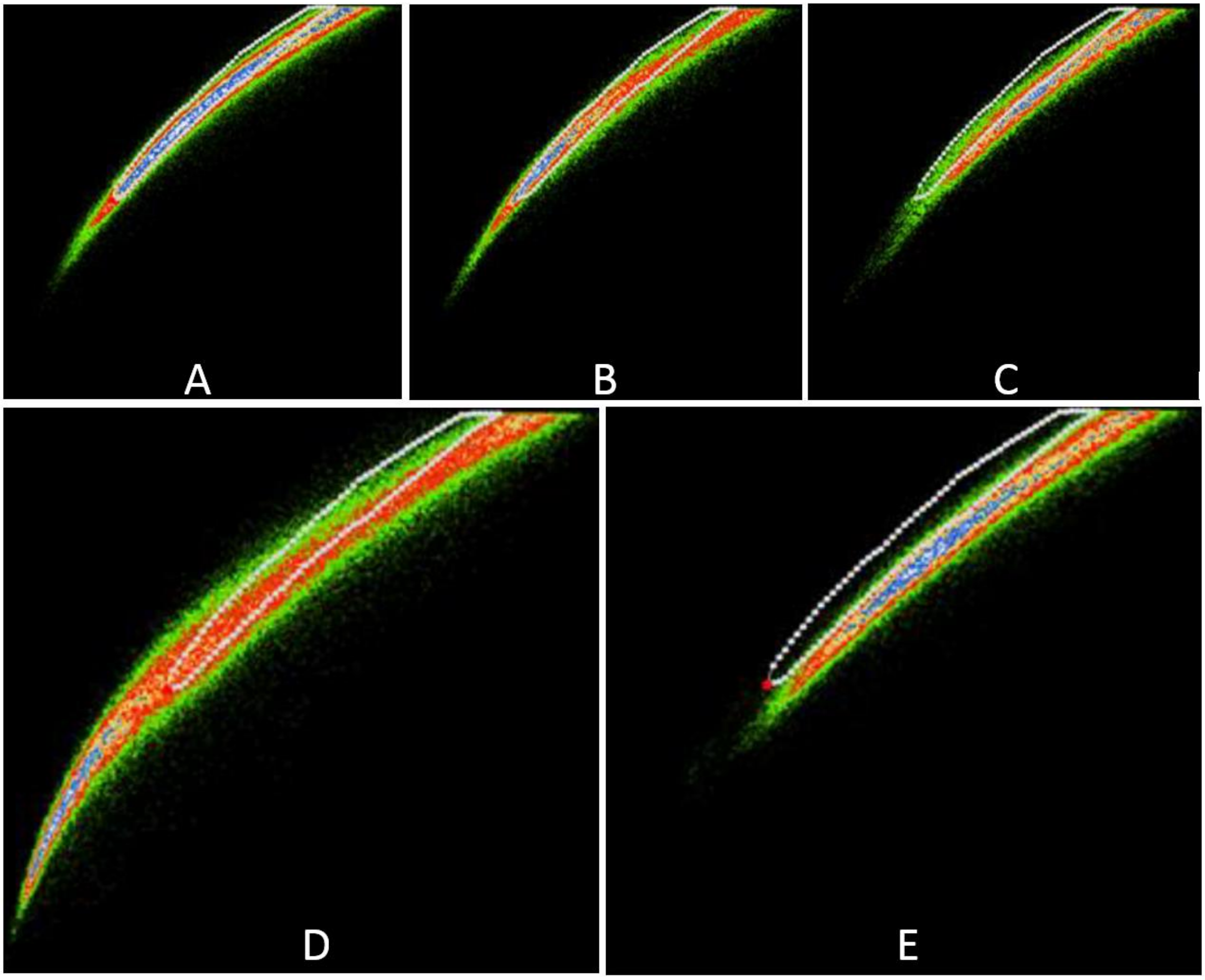

*Figure 7 - Dual energy X-ray transmission scatterplots for different rock types. A) Schist, B) Marble, C) Pegmatite, D) Sulphides, E) Quartzite. A white polygon has been drawn to demarcate the location of the majority of the Schist rock-type. As per Figure 3, the x-axis is the low energy and the y-axis is the high energy x-ray transmission readings. The colour scale represents a frequency plot of occurrence; blue/white represents high and green low frequency.*

Five pilot-scale (55-100 kg) sorting tests were conducted on two size fractions +9.5 -25 mm and +25 -50 mm. The mass yield to the concentrate was higher for the finer particles and so was the gold recovery (Figure 8). The improved recovery was related to the improved liberation that can be expected for the finer particle size distribution. The variability in recovery seen in the fine fractions is thought to be due to the gold nugget sampling effect. The coarse gangue rejection model developed by Carrasco et al. (2016) was used to give an indication of the expected overall trend.

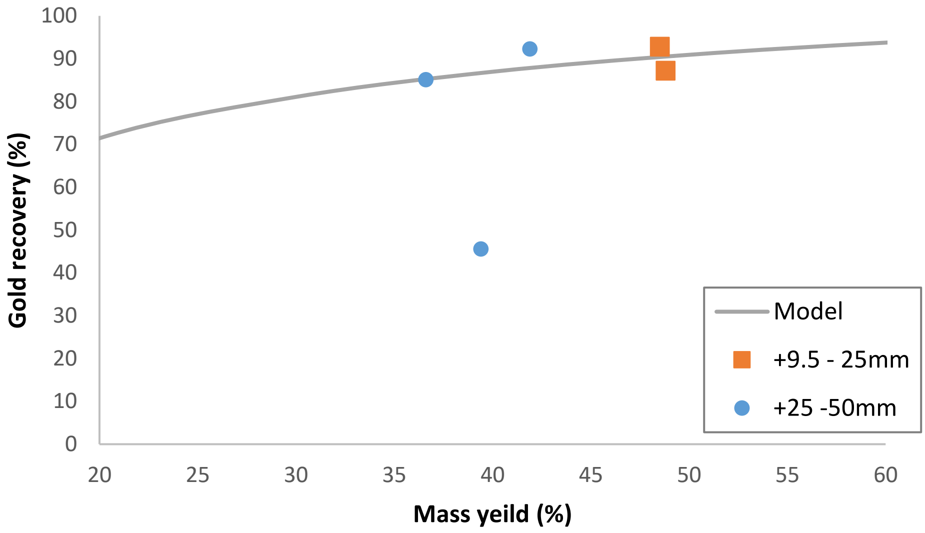

*Figure 8 - Yield-Recovery graphs for Mine 1.*

The results in Table 1 show the machine constraints that were applicable for sorting the fine and coarse samples. The achievable throughput was approximately four times larger for the coarse particles than the fine particles due to the monolayer constraints. The energy consumption of the fine particle sorter was also six times higher than the coarse particle sorter. This was predominately due to the larger particle ejection rate and thus increased air consumption that was required for the finer particles. The high energy consumption of the fine particle sorting actually led to an increase in the total specific energy requirements of the sorting, comminution system. Therefore, if the decision to install the sorter was based solely on energy reduction, the fine particles would not be sorted, or a lower reject rate would be targeted to reduce energy consumption and increase gold recovery.

*Table 1 - Throughput, air consumption, reject rate and energy savings achievable for the two samples tested.*

| | Fine | Coarse | Total |
|---|---|---|---|
| **Bottom size (mm)** | 9.5 | 25 | 9.5 |
| **Top size (mm)** | 25 | 60 | 60 |
| **Throughput (t/h)** | 22 | 81 | 103 |
| **Reject rate (t/h)** | 11 | 49 | 61 |
| **Mass yield to concentrate (%)** | 49% | 41% | 42% |
| **Gold recovery to concentrate (%)** | 89% | 73% | 76% |
| **Sorting specific energy (kWh/t)** | 12 | 2 | 4 |
| **Net mass specific energy reduction (kWh/t)** | -4 | 9 | 6 |
| **Net gold specific energy reduction (kWh/oz)** | -6 | 23 | 12 |

The reduction in copper equivalent specific energy due to the application of sorting for Mine 1 is presented in Figure 9. The reduction in overall recovery due to losses through sorting is not explicitly evaluated with the energy curves, the change in energy intensity is due to the interplay between mineral recovery and mass yield. The base case energy intensity assumed that the mill was fed directly with the average feed from the sorting tests. The 'gross sort total' scenario takes into account the reduced comminution energy intensity due to the upgraded sorted total (coarse plus fine) product being sent to the mill. The three 'net' scenarios include the specific energy consumed by air compression and electrical power used by the sorter in calculating the total energy consumption. For ore sorting, the energy consumption of screening, conveying, dust collection and additional materials handling of the bulk streams has not been included; for comminution the embedded energy in balls and pumping and tailings placement energy for the extra waste has not been included. What can be seen is that sorting the fines by themselves increased the copper equivalent specific energy, but since the sorting of the coarse particles was less energy intensive, the net energy reduction was 6-11%.

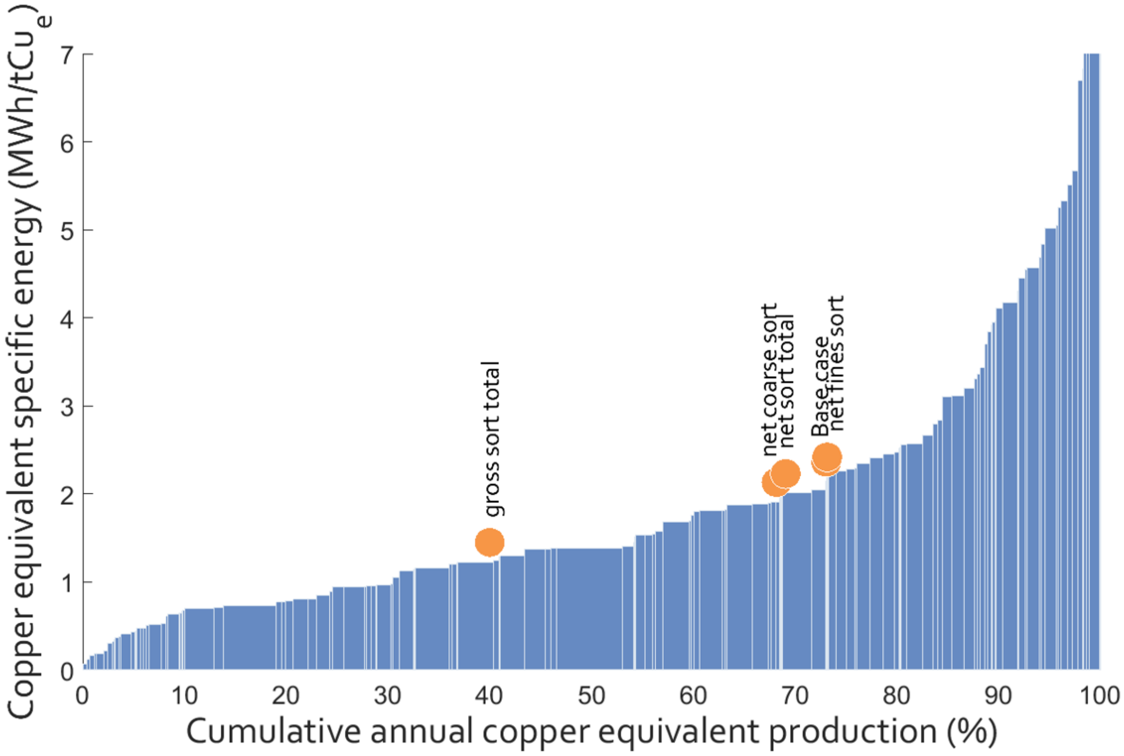

*Figure 9 - Reduction in grade intensity due to sorting for Mine 1, displayed using the comminution energy curve.*

**Mine 2 (Ferbasa) case study**

Chromite ore sorting test work was conducted by Steinert at Ferbasa's chromite mine at Cia de Ferro Ligas da Bahia Minera. The objective of the test work was to test the viability of sorting the fine fraction -32 +12mm to produce a high-grade lump ore for the export market and a lower grade disseminated ore for its own chrome smelters. Further test work on a coarse (-75 +25mm) low-grade waste material was also conducted. This case study shows the application of sorting to improve product quality, separate ore in high grade and mid-grade and reject waste material. One other major benefit of sorting in this case may be achieved through water savings by the future replacement of the jigging plant.

*The flowsheet in*

Figure 10 shows how two-stage sorting can be used to create a waste stream and two product streams. In this case the two product streams have different values and the testwork was aimed at maximising the recovery of chromite to the lump concentrate. The Chromite was easily identifiable in the dual energy x-ray system (Figure 11) and a successful separation was achieved. The waste material is stockpiled, the disseminated ore requires further concentration (including magnetic separation) before smelting, and the high value lump product is exported directly as final product.

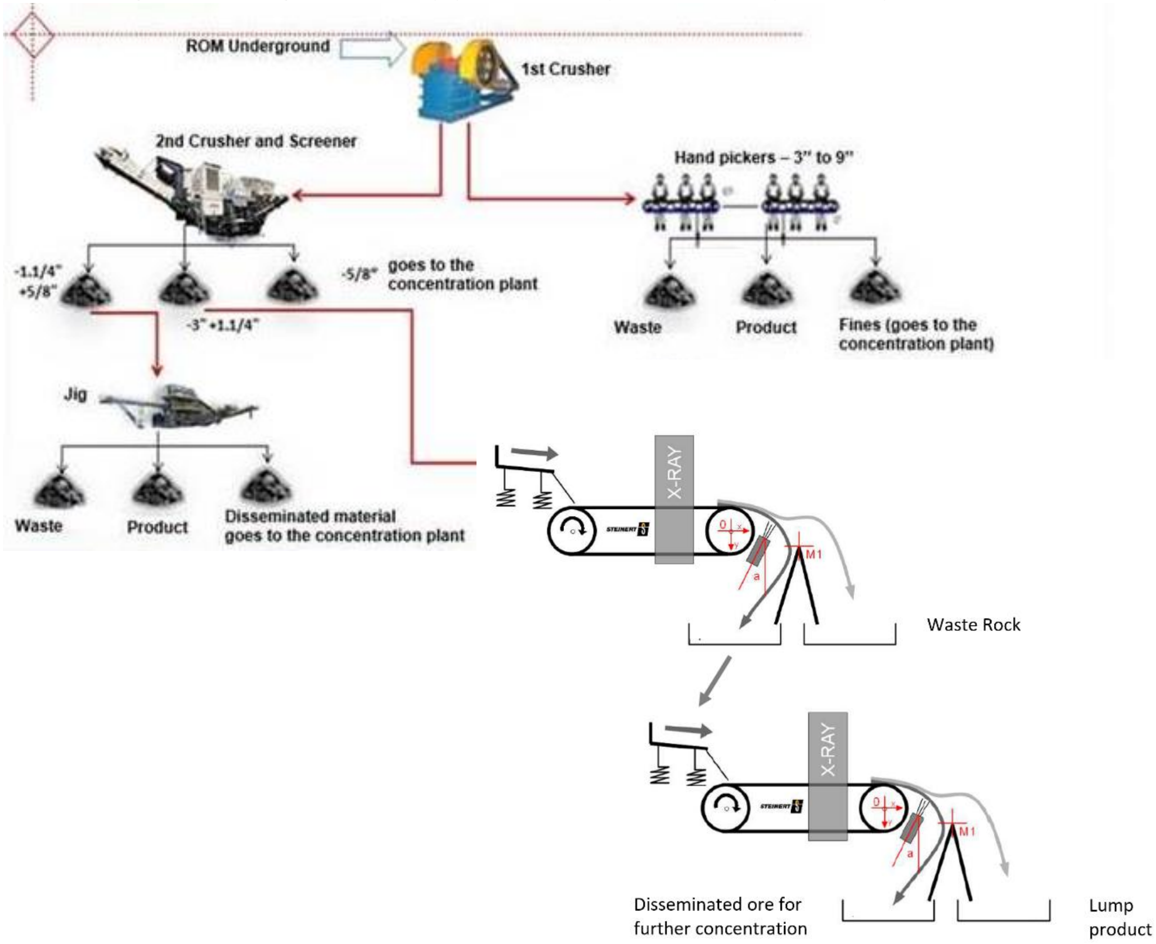

*Figure 10 - Ferbasa flowsheet.*

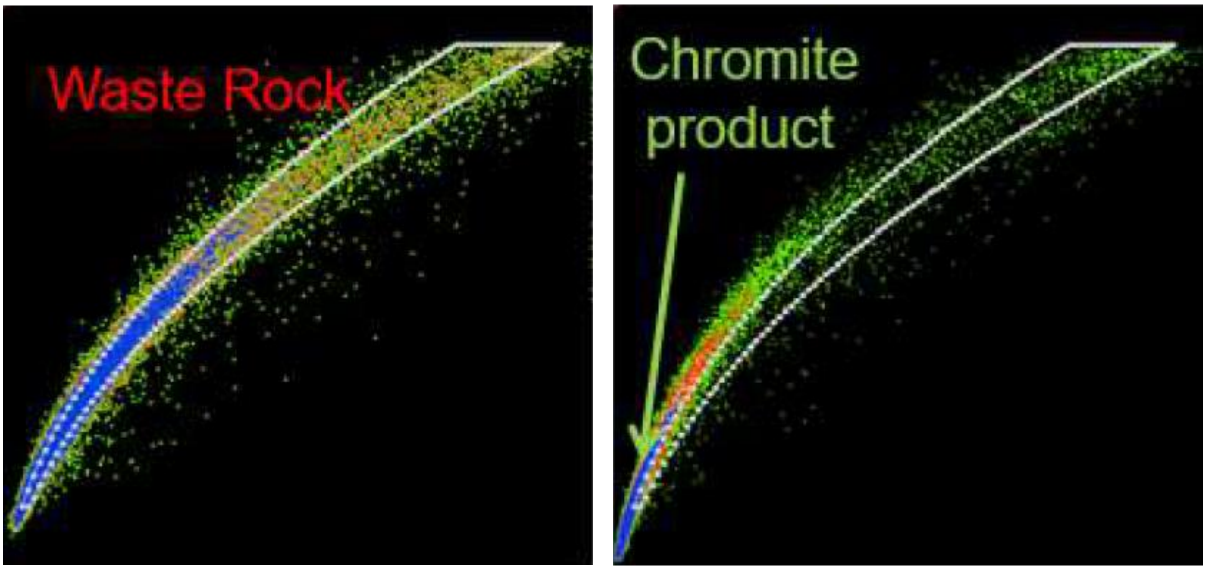

*Figure 11 - Dual energy x-ray results for Ferbasa showing the difference between the chromite product and the waste signatures. As per Figure 3, the x-axis is the low energy and the y-axis is the high energy x-ray transmission readings. The colour scale represents a frequency plot of occurrence; blue/white represents high and green low frequency.*

Large samples were tested in a pilot-scale sorter to obtain realistic estimates for ore recovery and chromite grade. Two samples were tested: the run of mine (ROM) fines and the low-grade dump material. The samples were tested at five and three different machine settings respectively, to determine the optimum operating point (see Figure 12). Sorting the ROM fines resulted in reasonable ore recoveries at product grades above the required target. Recently, experiments have been conducted on low-grade dump samples which produced better ore recoveries, but the product grade was below the required target. The energy consumed by the air compressor for the current -75 +20 mm material is 4.0 kWh per tonne rejected. Recently, adjustments were made to allow the sorter to operate on a coarser size fraction (-125 +75 mm) and the energy consumption per tonne rejected reduced to 1.2 kWh/$t_{rejected}$.

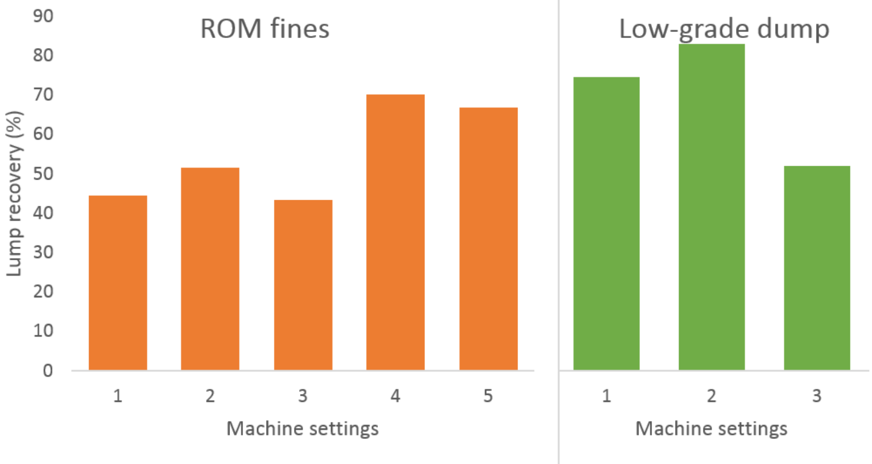

*Figure 12 - Recovery of lump from disseminated chromite for both samples: ROM fines and Low-grade dump.*

## Conclusions

Particle sorting can provide effective separation of liberated waste rocks from partially liberated ore at a coarse size. This technology can be effectively applied to various different commodities, this paper has reviewed the application to a gold and a chromite ore. The gold ore achieved recoveries of 73 to 89% of gold in less than half the mass. The net energy savings were in the order of 6-11%, moving the operation from the 73rd to the 70th percentile on the Grade Intensity Energy Curve. A significant reduction in comminution energy (as shown by the "gross" energy consumption) is offset by energy required for air ejection. An overall value of 6-11% is still an important reduction and has the potential to increase ore reserves and enable lower grade deposits. The energy saving has to justify capital expenditure, increase in the number of unit processes on site and some loss of metal recovery; but is accompanied by reduction in water usage and reduced fine tailings storage. The balance of these factors needs to be assessed for each potential application. The value of sorting is in both energy reduction and in increasing ore reserves by accessing lower grade deposits.

## References

Getting it sorted, Australian Mining Monthly - 18 September 2017.

Ballantyne, G., Powell, M., Tiang, M., 2012a. Proportion of energy attributable to comminution, 11th AusIMM Mill Operators' Conference 2012. AusIMM, Hobart, Tasmania.

Ballantyne, G.R., Hilden, M., Powell, M.S., 2012b. Early rejection of gangue – How much energy will it cost to save energy?, in: Wills, B. (Ed.), Comminution '12. Mineral Engineering, Capetown, South Africa.

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

Carrasco, C., Keeney, L., Walters, S.G., 2016. Development of a novel methodology to characterise preferential grade by size deportment and its operational significance. Minerals Engineering 91, 100-107.

de Jong, T., Harbeck, H., 2005. Automatic sorting of minerals: Current status and future outlook. Proceedings of the Canadian Mineral Processors, 629-648.

Hilden, M.M., Powell, M.S., 2017. A geometrical texture model for multi-mineral liberation prediction. Minerals Engineering 111, 25-35.

Sullair, 2012. Technical specifications of variable output compressors, www. sullair.com.au/brochures/voc-air-compressor-brochure.pdf.