QUANTIFYING THE ADDITIONAL ENERGY CONSUMED BY ANCILLARY EQUIPMENT AND EMBODIED IN GRINDING MEDIA IN COMMINUTION CIRCUITS

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Abstract

Assessment of comminution energy intensity has traditionally been confined to the crusher and mill motor power consumption. However, a measure of ancillary equipment power and the embodied energy consumed through media wear is required to compare disparate equipment types and circuit configurations fairly, as they can contribute a significant (average 45% increase) proportion of energy to the comminution circuit. Conveyors and slurry pumps use electrical energy to move ore between comminution and classification equipment in mineral processing circuits. Steel balls and rods are regularly used as grinding media in tumbling mills to assist with ore breakage. The consumption of this media through wear processes can be viewed as a form of embodied energy consumption, as the mining, smelting, casting, and shipping of media consumes a substantial quantity of "embodied" energy.

The comminution energy curve database has been developed at the Julius Kruttschnitt Mineral Research Centre over recent years to capture comprehensive energy data for comminution circuits. The database also contains limited data for both ancillary equipment power and embodied energy of grinding media. However, as the database does not contain ancillary and embodied energy data for all the circuits, simplified models were required to populate circuits where these figures were not known. In the comminution circuits studied from the database, the average additional specific power attributable to pumps, conveyors, and media was 1.6, 0.6, and 3.4 kWh/t, respectively. These figures were highly dependent on the type of comminution circuit. New energy curves were generated that included the ancillary equipment power and embodied energy in the grinding media. The resulting energy curves allow mines to be benchmarked on specific comminution energy as well as media wear and ancillary equipment power draw.

In this paper, the authors will present two case studies that explore the effect of circuit type on electrical comminution energy as well as embodied and ancillary energy consumption. The first case study looks at the transition of a circuit from autogenous (AG) through semi-autogenous (SAG) and pre-crushed barely-autogenous (BAG) milling. Each circuit change achieved an increase in throughput, but the result of this decision also increased the specific comminution energy, the embodied energy, and the ancillary equipment power. The second case study explores the change in the trade-off between SAG and high pressure grinding rolls (HPGR) circuits when the increase in conveying requirement and change in media wear are considered when comparing comminution circuit options. These two case studies demonstrate the importance of including ancillary equipment power and the embodied energy of the grinding media wear in the assessment of comminution energy efficiency.

Keywords

Comminution energy, conveyors, pumps, media wear

Introduction

The comminution energy curves are a free resource that can be used to benchmark the energy intensity of comminution circuits. These types of benchmarks have traditionally only considered the crusher and mill motor power consumption. The power used to transport material between comminution equipment (ancillary power) and the energy required to manufacture the media that are consumed in the milling process (embodied energy) are not typically accounted. A measure of ancillary equipment power consumption and embodied energy are required to fairly compare disparate equipment types and circuit configurations.

Dry comminution circuits, such as those incorporating high pressure grinding rolls (HPGR), may have a power advantage in rock breakage but use more power in material transport as they typically require an extensive conveyor system. In comparison, wet milling circuits use less ancillary power as they usually require fewer conveyors. Both circuits require similar sized slurry pumps as this is more related to the required circulating load around the ball mill. Therefore, if the power consumption of the ancillary equipment such as conveyors is not considered, wet grinding circuits may be at a significant disadvantage in direct power consumption comparisons. The comminution energy curve database records the power consumption of ancillary equipment; however, this has not previously been included in the published curves. This deficiency is addressed below.

Steel balls and rods are frequently used in tumbling mills as grinding media to assist in ore breakage. Fresh balls are regularly fed into these mills to replace the media that are consumed though wear processes and to maintain a steady filling level. Replacement grinding media can cost as much as comminution power consumption (Daniel et al., 2010). Additionally, the mining, smelting, casting, and shipping of media consumes a substantial quantity of energy. Therefore, the embodied energy consumed through media wear is an important factor that is not regularly accounted for in the evaluation of comminution and tumbling mill energy efficiency.

Ancillary Equipment Power

The power consumption of conveyors are influenced by a number of factors including length, lift, capacity, velocity, belt width, belt type, weight of belt and rotating parts, frictional resistance of belts and pulleys, friction coefficient between the material and the skirtplates, and other factors. Equations are available (such as international standard: ISO5048) to size conveyor motors based on these parameters; however, for this exercise a simplified relationship was required. The aim was to create a model that could be used to apply an approximation of the conveyor power where data was not available. Satellite imaging of mine sites can be used to estimate the horizontal conveyor distance, and although vertical lift is a more accurate predictor of conveyor power, this could not be measured on as many mines. Additionally, Doll (2015) found that the proportion of conveying energy associated with lift at Boddington and Cerro Verde HPGR circuits was 55%, with the remainder consuming 45% of the power. This indicates that the ratio of vertical lift to horizontal transport (approximately 10% gradient) was consistent at these two sites at least and may have a wider application. In order to create a simplified model for conveyor power based on throughput and horizontal length, realistic values were chosen for all other factors. The result was a value for conveying power of the empty belt of 165 kW/km and the material of 0.35 kWh/t.km. Considering conveyors are typically sized on 1.25 times the belt capacity the figure increases to 0.44 kWh/t.km. This figure allowed realistic estimates to be made for conveying power where actual data was not available.

The majority of the comminution energy curve database is composed of SAG and ball mill circuits. In these circuits the conveying power is limited to the transport of material from the primary crusher to the SAG mill and pebble recycle stream. Based on experience and the energy curve database, a typical primary crusher and the SAG mill can be assumed 1,000 m apart, consuming about 0.44 kWh/t in conveying power. Another 250 m of conveying can be assumed to be required for the pebble recycle, but since the flowrate is only about 20% to 40% of the feed, the contribution of the pebble recycle may be as low as 0.02 kWh/t. The total conveying power for a SAG milling circuit would be close to 0.46 kWh/t which is similar to benchmarks available in the energy curve database. For HPGR and crusher-heavy circuits the conveyor distances can be assumed to be much greater, and are approximately between 5 km and 9 km. For instance, the HPGR circuit at Cerro Verde has 16 major conveyors with a combined length of 7.4 km and a total installed power of 31 MW (Table 1). Considering the instantaneous throughput of 10,000 t/h, this equates to 3.1 kWh/t, or 0.42 kWh/t.km, similar to the calculated figure presented in the previous paragraph. In comparison to other benchmarks available in the energy curve database, number and length of conveyors at Cerro Verde is large, but the kWh/t.km value is consistent.

Table 1 – Cerro Verde conveyor details (after Vanderbeek and Gunson, 2015)

	Coarse Ore	Coarse Ore Reclaim	Secondary Crusher Discharge	HPGR Discharge	HPGR Product	Tertiary Crusher Surge Bin Feed	Coarse Ore Screen Oversize	Ball Mill Screen Oversize	HPGR Feed	Ball Mill Screen Feed
Number of Conveyors	2	2	2	2	2	2	2	2	8	12
Wet Throughput (t/h)	8000	6800	11440	12950	12950	12950	5150	6190	3240	3640
Horizontal Distance	461	474	398	480	333	481	399	294	27	43
Vertical Distance	82.8	71.9	37.6	57	8.7	34.4	18.9	5.6	0	7.1
Drives (kW)	932	746	746	932	447	746	746	597	56	112
Number of Drives	3	3	3	3	2	3	1	1	1	1
Total power (kW)	5592	4476	4476	5592	1788	4476	1492	1194	448	1344
kWh/t	0.35	0.33	0.20	0.22	0.07	0.17	0.14	0.10	0.02	0.03
kWh/t.km	0.76	0.69	0.49	0.45	0.21	0.36	0.36	0.33	0.64	0.72

A similarly simple relationship was required to approximate the energy used in pumping slurries from the outlet of a SAG mill to an elevated cyclone nest. The required pump power needed to lift a slurry under a given set of conditions is a matter of relatively simple fluid mechanics, albeit one which must be approached with a constant awareness of the implications of pumping a slurry, as opposed to a single-phase Newtonian fluid. The major factors affecting pump power are the height of the cyclone nest above the pump, cyclone pressure, internal pipe diameter, pipe length, pipe roughness, slurry velocity, slurry density, slurry viscosity, and other factors. Average values for most of these factors are available, except the internal pipe diameter, which is expected to vary widely based on the throughput at a given plant. However, we can take advantage of the fact that the design velocity for a slurry pumping application is going to be constrained by the need to avoid both solids settlement and excessive pipe erosion—which respectively impose lower and upper limits on the allowable velocity. While there is no theoretical basis for estimating the appropriate velocity or the bounds of a suitable range of velocities, empirical relations do exist, such as Durand's relationship in the Weir slurry pumping manual. The average pumping power recorded in the energy curve database was 1.6 kWh/t, which agreed closely with these calculations.

The conveyor and pumping power were added to the specific comminution power to create a new tonne intensity energy curve that included the power intensity of these ancillary equipment. Figure 1 displays the standard comminution specific energy as a dark coloured energy curve in front of the tonne intensity curve including ancillary energy. The difference between the two curves is not large, but it is important to reflect on the increased ancillary power consumption of HPGR and crusher-heavy circuits.

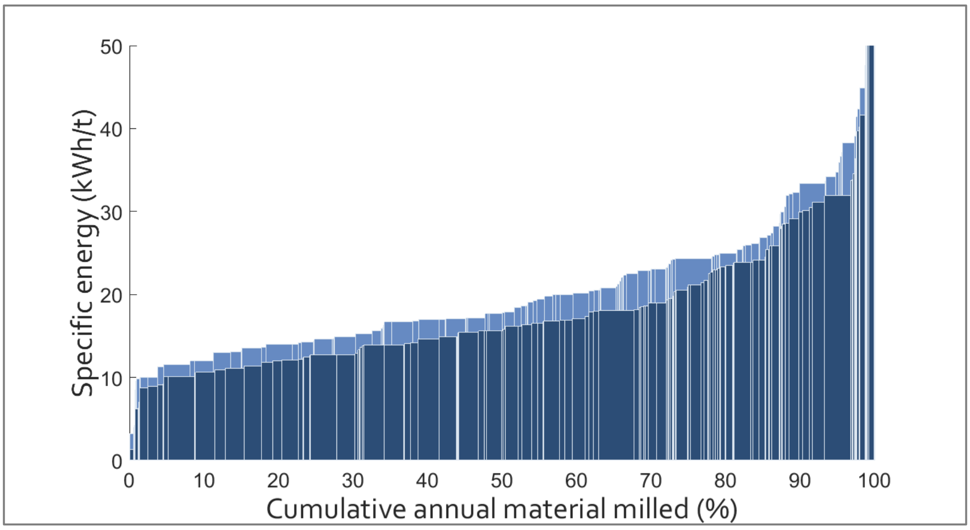

Figure 1 – Updated tonne intensity energy curve with ancillary equipment energy included. Darker coloured curve is the comminution energy only; the lighter curve includes ancillary equipment

Embodied Energy

Media consumption is typically reported as steel grams required per ore tonne treated. To convert this into the embodied energy consumption, a life cycle assessment (LCA) of the creation and transport of the media to sites is required. The world steel association provides an LCA for 1 kg of global steel hot-rolled coil, cradle to gate. Without including recycling, the creation of steel requires 6.011 kWh/kg and creates 2.01 tonne CO_2 equivalent emissions per tonne (Yang and Broadbent, 2017). Previous studies have used similar figures even though this excludes the energy in casting the grinding ball and transport to the site (Musa and Morrison, 2009). The energy consumed by diesel trucks can be between 0.15 and 0.25 kWh/kg.km (Nylund and Erkkilä, 2005). The proximity of the mine to a city with a population greater than 100,000 was used as the required trucking distance. The average distance recorded for the mines in the energy curve database was 300 km, therefore the average trucking energy for the return trip is approximately 120 kWh/kg. However, this figure varies significantly between different mines due to their remoteness and does not consider the potentially significant shipping energy required to get it to the closest population centre.

The ball metallurgy also plays a significant role in the embodied energy. For instance, forged balls and high chrome balls require completely different manufacturing processes and feed materials. The feedstock for forged balls is typically bar-stock from an iron and steel making plant. On the other hand, high chrome balls are cast and have a feedstock of 100% recycled scrap steel (including stainless steel and iron) and alloying materials such as graphite, ferrochrome, ferromanganese, and ferrosilicon. Although the manufacture of high chromium balls requires more energy than forging, the embodied energy in the steel feedstock reduces to 3.3 kWh/kg using steel with an end-of-life recycling rate of 85% (Yang and Broadbent, 2017). The energy required to manufacture both forged balls, as well as high and low chromium balls, is shown in Table 2. These calculations result in total embodied energy figures for steel grinding media ranging from 4.8 to 6.6 kWh/kg. This is dependent on ball metallurgy, ratio of recycled steel in the feedstock, and the trucking distance required to transport the media to site.

Table 2 - Embodied energy in the manufacture and transport of grinding media

	Process	Unit	High Cr Media	Low Cr Media	Forged Media
Steel energy cradle to gate		kWh/kg	3.30	3.30	6.01
Ball manufacture	Melting (induction furnace)	kWh/kg	0.59	-	0.38
	Melting (arc furnace)	kWh/kg	0.51	0.49	-
	HT. gas	kWh/kg	0.51	-	-
	HT. electricity	kWh/kg	0.39	0.31	-
	Others	kWh/kg	0.52	0.28	-
	Subtotal	kWh/kg	1.71	1.35	0.45
Average transport to site		kWh/kg	0.12	0.12	0.12
Total		**kWh/kg**	**5.62**	**4.76**	**6.58**

To calculate the embodied energy, media use data was obtained for 34 individual mills in addition to 27 comminution circuits. The total comminution energy for these mills was then calculated by combining the total electrical energy and the equivalent embodied energy (assuming forged balls) consumed through media wear (see Figure 2). In relation to the electrical energy consumption, SAG mills had the highest proportion embodied energy, followed by ball mills and stirred mills. The effect of circuit type on media consumption was also analysed; however, no clear difference in media wear for particular circuit types could be inferred from the current dataset (see Figure 3).

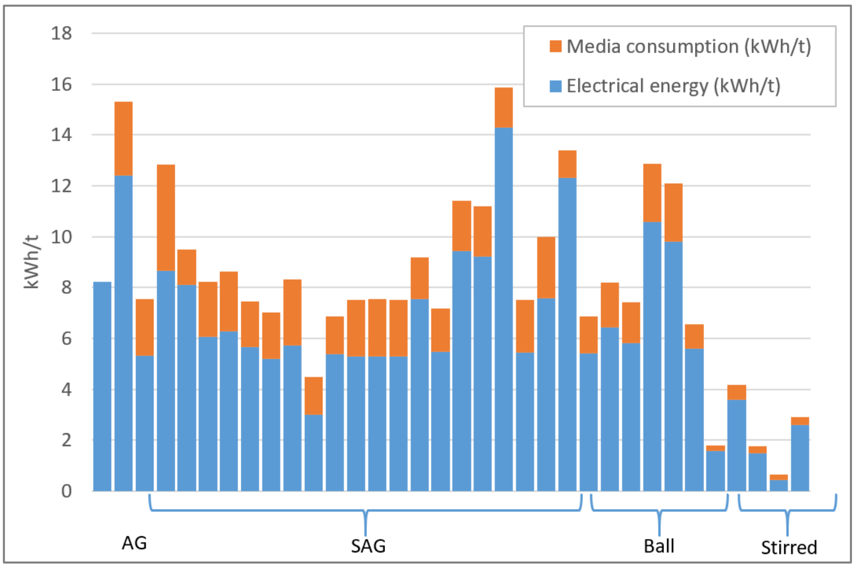

Figure 2 – Embodied energy combined with electrical comminution energy used for individual equipment types

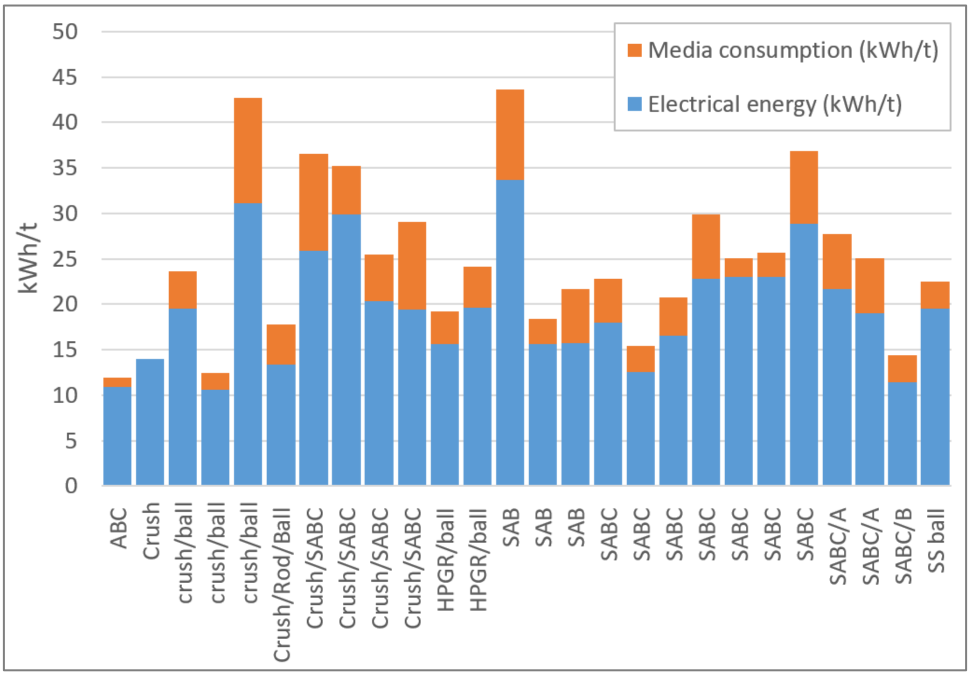

Figure 3 – Embodied energy combined with electrical comminution energy used for different circuit types

The media consumption rates were converted to the unit g/kWh$_{milling}$ as opposed to g/t to normalise for the effect of mill specific energy and allow the figures for individual mills to be combined with complete circuits. An additional historic dataset containing media and liner wear information for a large number of small mills was obtained from Powell (1988). Different types of mills were contained in this dataset including: run of mine ball mills, rod mills, pebble mills, composite (ball and pebble) mills, and ball mills. In Figure 4 the distribution of media consumption in the modern energy curve database is shown alongside the historical data from ball mills alone. The media consumption recorded by Powell (1988) was significantly higher than the modern mills contained in the energy curve database. Powell (personal communication) has suggested that this is likely due to poor quality of the semi-cast steel media that were prominent at that time. These media were manufactured using scrap steel poured into copper moulds, which were water-cooled for rapid solidification, resulting in uneven shrinkage and porosity. This porosity led to early failure of balls and high scatting rates (Powell and Smit, 2001). The bimodal distribution indicates that approximately 25% of mills may have had modern forged balls, whereas the rest contained inferior balls that wore on average 3.4 times faster. This dataset shows how important the steel metallurgy of the balls can be to the wear consumption rate. Powell (1988) also showed that the consumption of liners was on average 30 times less than the consumption of balls; therefore, it was not included in this study. Although liner design and ball compositions have changed dramatically since this time, the difference in wear rate (using g/kWh as the basis) is likely to be similar in modern mills. Liner design and wear rate is more critical to the mill availability than embodied energy.

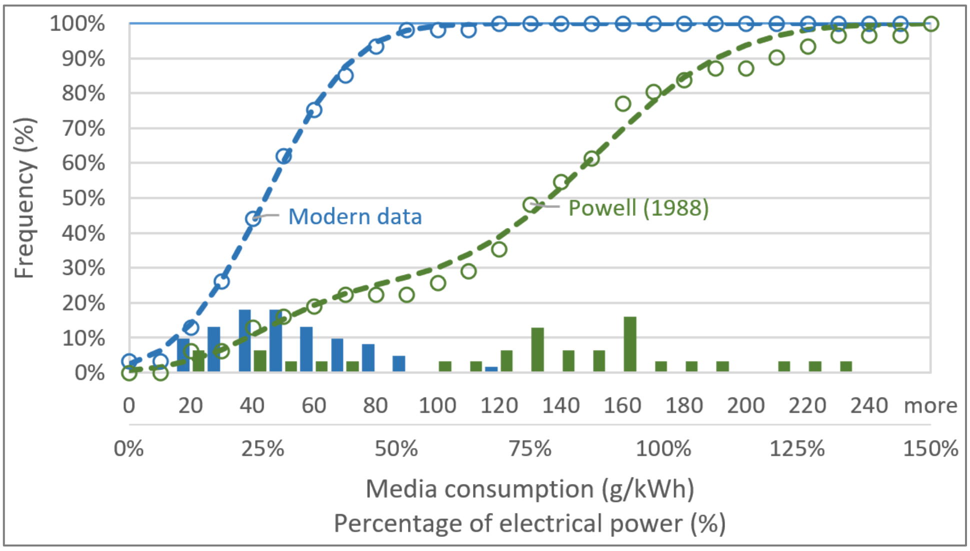

Figure 4 – Distribution of media consumption rates (g/kWh) and percentage of electrical power (%) for both the energy curve database and the ball mills in the Powell (1988) dataset. [Dotted lines represent fitted cumulative normal distribution functions]

Media consumption rates are only known for 18% of the energy curve database. Therefore, attempts were made to elucidate the drivers behind the degree of media wear so that realistic embodied energy figures could be attributed to the remainder of the database. Five key factors were explored:

1. Media metallurgy (composition and manufacture)
2. Ore abrasiveness (largely driven by silica mineralogy)
3. Mill type (SAG/rod/ball/stirred)
4. Mill size (diameter)
5. Operation of the mill (mill speed and filling)
6. Media size.

Unfortunately, the high degree of interrelation and the qualitative nature of these factors meant that no clear drivers for media wear could be determined. Regression analysis was attempted on a number of factors, but the results were highly scattered relationships with no identifiable prime drivers. Therefore, the only remaining options were to attribute a random statistical distribution or present a reduced energy curve with only the mines where the media consumption was known. Following the plotting of these options, the second option of the reduced energy curve was chosen as there were enough mines to retain anonymity and there was no extrapolation required. The tonne intensity comminution energy curve containing embodied energy resulting from this analysis is displayed in Figure 1.

The embodied energy in media wear was added to the specific comminution power to create a new tonne intensity energy curve. Figure 1 displays the standard comminution specific energy as a dark coloured energy curve in front of the light-coloured tonne intensity curve including embodied energy.

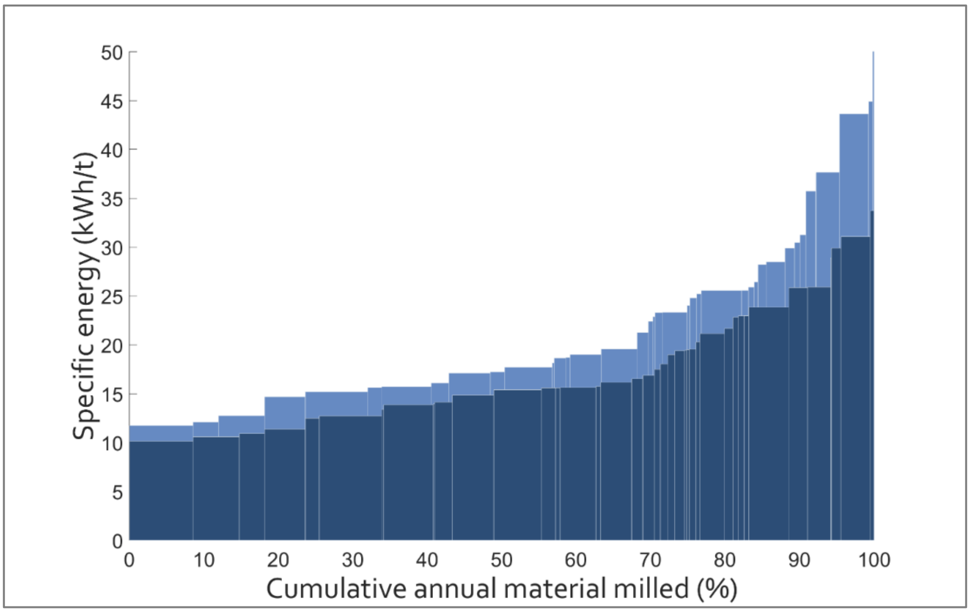

Figure 5 – Updated tonne intensity energy curve with embodied energy included. Darker coloured curve is the comminution energy only; the lighter curve includes ancillary equipment

Discussion

CASE STUDY 1: PROGRESSION FROM AG TO SAG TO BAG MILLING

As a response to the drive to increase throughput, sites with autogenous (AG) mills can add balls and convert their mills to semi-autogenous (SAG) mills. To increase throughput further, SAG mills can be converted to barely-autogenous (BAG) mills with the addition of pre-crushing and higher ball loads. The effect of these changes on direct electricity consumption is typically well understood, but the combined increase in embodied and ancillary energy is not typically highlighted. The increase in ball load for each change increases the ball wear rate and hence the embodied energy consumption. Additionally, the progression from SAG to BAG milling requires additional conveying power requirements that should be considered.

Typical figures from operations that have made these transformations were used to develop a case study. Figure 6 shows the change in direct, ancillary, and embodied energy in the case study. The throughput increase and P_{80} increase achieved with the progression through the different operations was similar to the increase in power draw of the mills. Therefore, the specific electrical energy consumption of the mills was similar for all the circuits. The ancillary energy did not change following the transition from AG to SAG; however, transitioning to BAG required an additional 2.4 kWh/t in conveying and pumping power. Finally, the embodied energy also increased by 1.4 kWh/t with the transition to SAG milling and a further 0.6 kWh/t with the addition of pre-crushing.

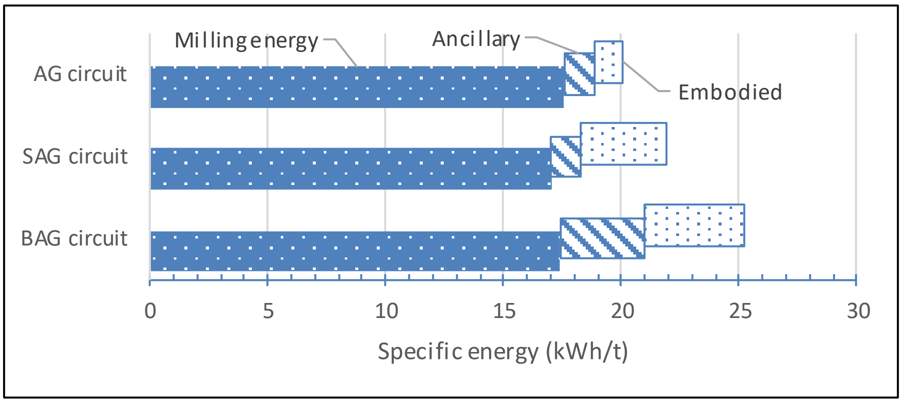

Figure 6 – Typical increases in direct, ancillary, and embodied energy seen with the transition from AG to SAG to BAG milling circuits

These results were shown in Figure 7 on the newly developed energy curve that contains both ancillary and embodied energy. Showing this data on the energy curves clearly shows the difference between looking at solely the comminution energy and adding in the ancillary and embodied energy. Transitioning from AG to BAG did not significantly alter the specific energy of the circuit when looking solely at the comminution equipment. However, the position of the AG circuit on the curve that includes ancillary and embodied energy was lower at the 43rd percentile, and the increase in position when it was converted to a BAG circuit was significantly larger, moving it to the 64th percentile.

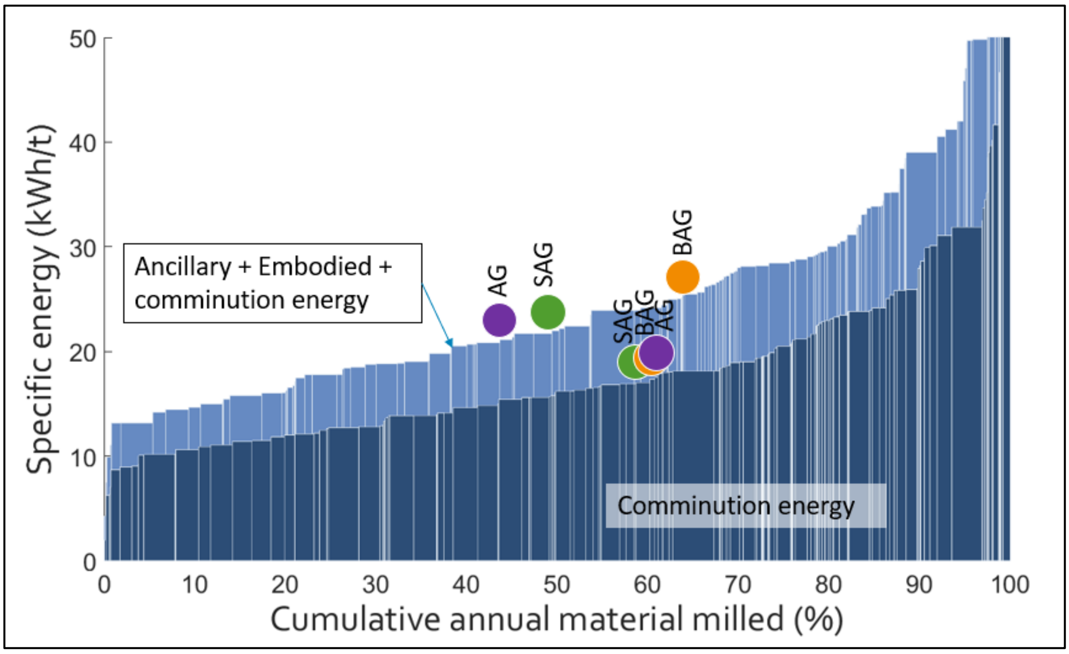

Figure 7 – Progression from AG to SAG to BAG milling on the comminution energy curves with ancillary and embodied energy included

CASE STUDY 2: TRADE-OFF BETWEEN HPGR AND SAG MILLS

This second case study looks at the difference between HPGR and SAG circuits when ancillary and embodied energy is considered. This case study is based off the trade-off conducted at Tropicana mine with some modifications (Ballantyne et al., 2017). HPGRs are operated dry and, therefore, the material is transported on conveyor belts, which can require additional power in comparison to SAG based circuits. Additionally, HPGR circuits still require similar sized pumps to feed the hydrocyclones in the wet ball milling circuit. This ancillary power is not always considered in trade-off studies and has the potential to erode some of the energy benefit of HPGRs. Figure 8 shows the potential impact of including ancillary equipment in the analysis; the difference between HPGR and SAG circuits when looking solely at comminution energy is much larger than when the ancillary energy is considered. The energy associated with conveying in this HPGR case is not actually taken from Tropicana, but from one of the early adopters of HPGRs. The conveying power at Tropicana was significantly lower because of the adoption of off-line emergency stockpiling and other updated circuit design. This shows that smart circuit design can allow the comminution energy efficiency benefits of HPGRs to be maintained even when ancillary energy is included.

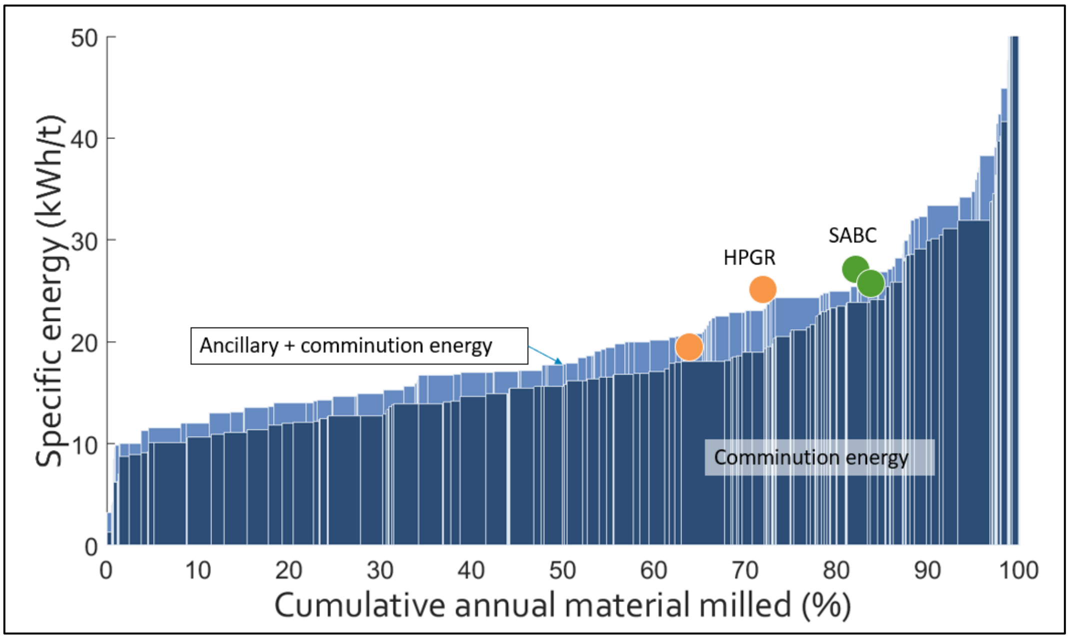

Figure 8 – Trade-off between SAG and HPGR base circuit when ancillary energy is considered

The trade-off between HPGR and SAG mills is also impacted by considering the embodied energy of the grinding media. Media consumption is typically proportional to the power draw of the tumbling mills. Since HPGR circuits are known to reduce the power of tumbling mills, the media consumption may be lower, although this is unproven. Figure 9 shows the energy curve benchmarking of the HPGR and SAG circuits when the embodied energy of the media is considered. The energy benefits of HPGRs increases marginally when embodied energy is included in the analysis. However, it should be noted that the energy embodied in the HPGR studs and roll were considered outside of the scope of this analysis.

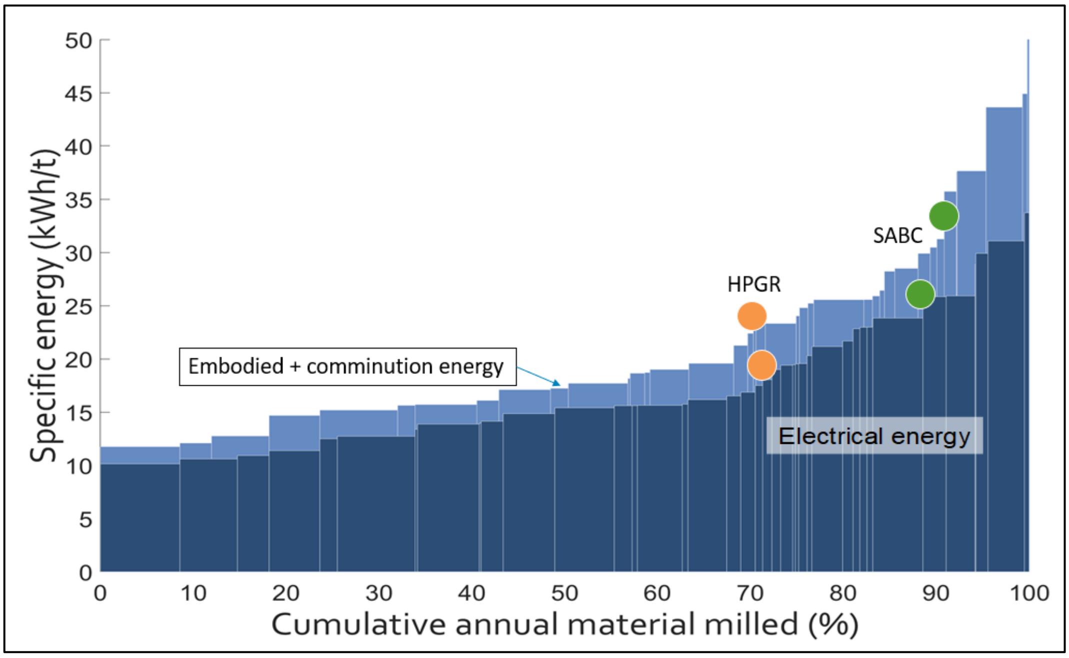

Figure 9 – Trade-off between SAG and HPGR base circuit when embodied energy is considered

Conclusions

The comminution energy curves have illustrated the benefit in benchmarking the energy intensity of comminution circuits. However, the energy consumed through ancillary equipment (conveyors and pumps) and embodied in the wear of grinding media was not previously included in the methodology. In this paper, the authors describe the calculation of ancillary and embodied energy and these factors have now been included in the advanced comminution energy curve methodology.

Two case studies have been presented to showcase these new capabilities and the benefits of considering the ancillary and embodied energy in the evaluation of energy intensity. The first showed that the transition from AG through SAG to BAG milling marginally increased the comminution energy intensity but had a much larger impact on the ancillary and embodied energy intensity. The second case study demonstrated that including conveyor power in HPGR/SAG trade-off studies is likely to erode some of the comminution energy efficiency gains. And this is only marginally reduced with the inclusion of embodied energy.

The authors highlight the danger of assessing comminution energy intensity with a narrow scope. The choice of equipment and circuit design has a larger impact than simply the power draw of the comminution equipment. The advanced comminution energy curves provide a framework for these wider scope assessments to be benchmarked accurately. This study may also assist engineers in targeting more energy efficiency solutions to materials transport.

This study used simplifying assumptions to estimate the conveying and pumping power requirements for a broad range of sites. These simplifications should not be used in the detailed design of mineral processing circuits.

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