A simple estimation method of materials handling specific energy consumption in HPGR circuits

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ABSTRACT

Multi-stage crushing plants, including high pressure grinding roll (HPGR) circuits, require more materials handling equipment than SAG and ball mill circuits. A temptation exists to neglect the energy consumption of materials handling when doing desktop comparisons of HPGR versus SAG milling circuits because estimation of materials handling power requirements can demand significant general arrangement drafting that is not available when performing preliminary scoping or "desktop" studies.

The largest component of materials handling power is consumed by conveyors when lifting material between stages of crushing, meaning that a simple potential energy model can be used to evaluate conveying specific power consumption. This potential energy consumption for conveying can then be factored to provide overall materials handling specific energy consumption suitable for desktop studies of HPGR and other multi-stage crushing circuits. The technique also permits different crushing circuit flowsheets to be evaluated, at a preliminary level, by simply counting the number of times a conveyor must "lift" ore from ground level up to a bin or other equipment mounted up high.

KEYWORDS

Studies, HPGR, conveying, materials handling

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INTRODUCTION

Trade-off studies of multi-stage crushing plants involving high pressure grinding rolls (HPGRs) versus semi-autogenous grinding (SAG) mill circuits typically focus on the operating cost savings of crushing plants versus the capital cost savings of SAG mill plants. Very high-level (or desktop) studies of this type do not include a great deal of engineering work, meaning that the details (and costs) of ancillary systems are often not captured when doing the comparisons. The more complicated nature of the multi-stage crushing plants means there are more ancillary systems than a SAG mill plant, risking a skewed analysis of the operating costs, benefiting the HPGR option.

One of the ancillary systems that may be overlooked is the more complicated conveying systems inherent in multi-stage crushing plants. Due to the mass of material being handled in large mining operations, these conveyors become a significant portion of the operating costs. A simple way to estimate the specific energy consumption of conveying systems without requiring engineering drawings and a site layout would allow high-level studies to capture this operating cost.

Conventional conveyor power draw calculations are complicated. Examples are the Conveyor Equipment Manufacturers Association method (CEMA, 2007) or the method in the SME Mineral Processing Handbook (Hays & Van Slyke, 1985). What is needed for high-level studies is a much simpler method that gives a "close enough" approximation of the conveyor system power demand.

METHODOLOGY

Existing Operations

Two existing operations are considered to be reasonable templates for most base metal HPGR plant designs: Cerro Verde in Peru ("CV" in Figure 1) and Boddington in Australia ("B" in Figure 2). The crushing circuit configuration at Boddington is suited to an ore with a small quantity of fines, meaning all the primary crushed ore is fed directly to the secondary crusher, the product of which is screened with oversize passing back to the secondary crusher. The ore at Cerro Verde contains more fines, and it is advantageous to perform whole-ore screening with only the oversize passing to the secondary crusher, the product of which is passed back to the screen.

The HPGR and fine ore unit operations of the Boddington and Cerro Verde circuits are the same for the purposes of a high-level study. The literature reports that the fine screen circulating load at Cerro Verde is 95%–110% (Koski et al, 2011) and the fine screen circulating load at Boddington is 80% (Hart et al, 2011). These are rounded off to 100% circulating load (meaning the HPGR feed rate is double the feed rate to the overall circuit). Both operations employ wet screening of fine ore, meaning that the fine screen oversize conveyors (CV-06 & B-06) are handling damp material. This conveyor would have to be enclosed and heated in cold conditions (which are not considered in this study).

Some additional assumptions can be introduced to simplify the mass balancing of these circuits. The secondary screen (with roughly 50 mm openings) will have a circulating load of 66% (meaning the oversize flow is 0.66 times the rate of fresh feed from the coarse ore stockpile) regardless of whether the secondary circuit is direct (Boddington) or reverse (Cerro Verde).

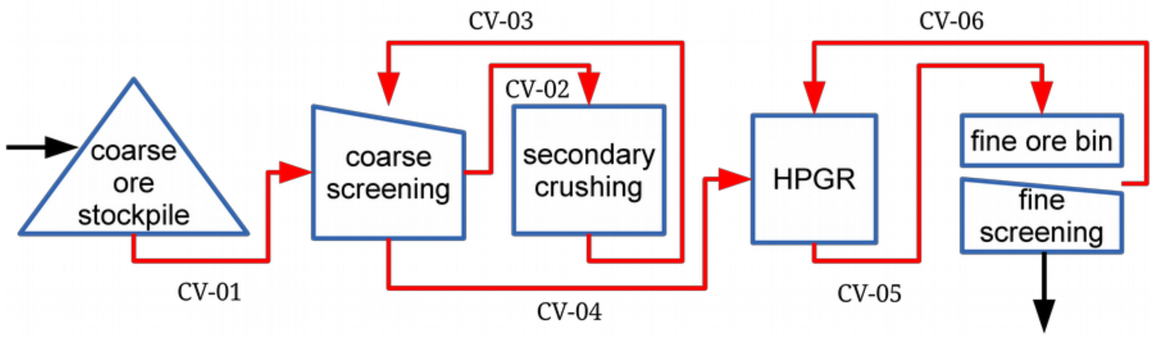

Figure 1– Block flow diagram of the Cerro Verde circuit, indicating major flows

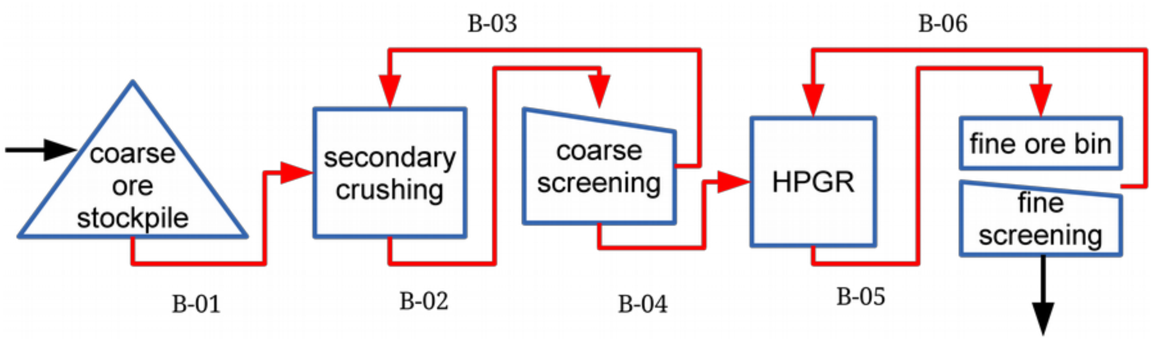

Figure 2– Block flow diagram of the Boddington circuit, indicating major flows

Simplifying Assumptions

- Only "large tonnage" plants are considered, such as copper porphyries (layouts of small plants, such as in the diamond industry, do not fit this assumption). The nominal throughput is assumed to be 4500 t/h, approximately 100 kt/d.

- Only two types of multi-stage crushing and HPGR plants will be considered, corresponding to Boddington (ore containing few fines) and Cerro Verde (ore containing significant fines).

- The primary crusher and coarse ore stockpile is neglected, as it is a common feature of HPGR and SAG mill based circuits.

- The site is flat, and all tops of the major structures (bins, stockpiles, crusher feed hoppers) are at the same elevation. The overall lift is assumed to be 30 m for all conveyors.

- The site layout is "compact" and the conveyors are not used to transport ore for significant lateral distances beyond what is necessary to lift the ore into the next unit operation. Conveyor 1 is assumed to be 350 m long, conveyors 2, 3 and 4 are assumed to be 200 m long, and conveyors 5 and 6 are assumed to be 400 m long.

- The circulating load of the coarse ore screen (closes the secondary crusher) is 66%.

- The circulating load of the fine ore screen (closes the HPGR) is 100%.

- All conveyor motors are fixed-speed motors with aggregate 90% motor and gearbox efficiency.

Conveyor Power Draw

Conveyor sizing calculations were run using a method similar to the SME Mineral Processing handbook (Hays & Van Slyke, 1985). This SME method is a bit old and the maximum belt size it is capable of using is sixty inches (1.5 m). Multiple belts are assumed to be used any time the capacity of a stream exceeds the capability of that maximum belt width. Because these results are converted into a factored specific energy consumption estimate, the factors do not change when multiple belts are used (there is no operating cost "economy of scale" benefit to using one belt versus two; any such benefits would apply to the capital cost). Conventional conveyor power draw can generally be divided into two categories:

- The power required to lift the conveyor load up to a specified height, and
- everything else.

The "everything else" category includes the rolling friction of the belt, both loaded and unloaded, the bending friction at the end and take-up pulleys, the friction associated with skirting and belt cleaning, and any other sources of power loss not related to the change in elevation of the conveyor load. By making some simplifying assumptions about the site layout, all these can be lumped into a factor applied to the power required to lift the conveyor load.

The energy required to lift the conveyor load of mass m to a specified height h is simply the potential energy of that mass at that height, given by

$$E = m \times h \times g \qquad (1)$$

where, E is the potential energy in Joules, m is the mass in kg, h is the height in m, and g is the gravitational constant, approximately 9.807 m/s^2. Metallurgists typically don't use energy in terms of Joules, preferring the form power × time: kilowatt·hours. Dividing E as Joules by 3.60 gives E as kW·h.

Inserting "unit values" of lifting one tonne by one metre into Equation 1 gives a unit energy of 2.724 $kW{\cdot}h{\cdot}t^{-1}{\cdot}m^{-1}$. Specific energy consumption (SEC), as kWh/t, is obtained simply by multiplying by the height that a conveyor lifts, the value h.

The results of the detailed conveyor sizing calculations compared to the specific energy consumption due to lifting material are presented in Table 1. All conveyor motors were sized using the SME method with an extra 25% allowance for ancillary power draw, such as unaccounted trippers and conveyors in transfer points. The layout of conveyor 4 is very different in the two existing plants: Boddington has a single conveyor directly connecting the coarse screening area to the HPGR bins, whereas Cerro Verde has the coarse screen oversize conveyed up and through two 90° transfers, then up again to discharge into the HPGR feed bins (effectively, double the distance and height of the equivalent stream at Boddington). The key output of Table 1 is the determination of what proportion of a conveyor's power is not related to the change in elevation of the load. The aggregate total suggests that the total conveyor power, as measured at the motor input, is 1.85 times the power required to lift the conveyor load (alternatively, "lifting" is 55% of the conveyor power draw, "everything else" is 45%).

Table 1 – Conveyor power draw, SEC versus SEC to lift conveyor load

Conveyor N°	Lift, m	Motor Power, input kW†		Throughput, t/h		SEC of conveying, kWh/t††		SEC of lifting, kWh/t†		Factor, total SEC:lift SEC	
		B	**CV**	**B**	**CV**	**B**	**CV**	**B**	**CV**	**B**	**CV**
1	30	701	701	4500	4500	0.16	0.16	0.08	0.08	1.91	1.91
2	30	1069	427	7470	2970	0.14	0.14	0.08	0.08	1.75	1.76
3	30	426	426	2970	2970	0.14	0.14	0.08	0.08	1.75	1.75
4	30/60	636	1271	4500	4500	0.14	0.28	0.08	0.16	1.73	1.73
5	30	1480	1480	9000	9000	0.16	0.16	0.08	0.08	2.01	2.01
6	30	724	724	4500	4500	0.16	0.16	0.08	0.08	1.97	1.97
overall								**0.49**	**0.57**	**1.85**	**1.85**

† based on 0.90 conversion motor input:output †† based on as-conveyed tonnes.

Composite Circulating Load

The degree of recirculation within the crushing circuit will affect the power requirement. A simple measure of "how much" material the conveyor is transporting is needed to account for the energy consumed when recirculating material within the circuit.

Table 2 – Conveyor feed rates as proportion of circuit fresh feed

Conveyor N°	Throughput, t/h		Proportion of fresh feed	
	B	**CV**	**B**	**CV**
1	4500	4500	100%	100%
2	7470	2970	166%	66%
3	2970	2970	66%	66%
4	4500	4500	100%	100%
5	9000	9000	200%	200%
6	4500	4500	100%	100%
overall			**122%**	**105%**

Table 2 demonstrates a throughput-independent "proportion of feed rate", effectively, the circulating load + 100% for each conveyor. Numerically, this is the throughput of a conveyor divided by the circuit fresh feed rate. Averaging the proportion value of all the conveyors within the circuit yields a composite proportion that can apply to a whole circuit (this can be thought of as the typical conveyor in the plant sees this composite throughput). It turns out that this value is a property of the circuit flowsheet: a circuit similar to Boddington will have a typical conveyor carrying a factor of 122% times the circuit feed rate, and the equivalent value for Cerro Verde is 105%.

Conveyor Specific Energy Consumption by a Simplified Factoring Method

The pieces of a simplified factoring method for crushing plant conveyor specific energy consumption are now all in place. "How high" the conveyors must lift their load, the specific energy consumption of this change in potential energy for the load, and the overall conveyor power factor versus potential energy of lifting is given in Table 1. "How much" material is conveyed is measured using the proportion of feed is given in Table 2. Combining these elements in Table 3 gives the estimated specific energy consumption of individual conveyors and for an entire circuit.

Table 3 – Conveyor SEC estimated by simplified factoring method

Conveyor N°	Lift, m		SEC of lifting		Proportion of fresh feed		Conveyor total power factor		SEC of conveying, fresh feed basis	
	B	**CV**	**B**	**CV**	**B**	**CV**	**B**	**CV**	**B**	**CV**
1	30	30	0.08	0.08	100%	100%	1.85	1.85	0.15	0.15
2	30	30	0.08	0.08	166%	66%	1.85	1.85	0.25	0.10
3	30	30	0.08	0.08	66%	66%	1.85	1.85	0.10	0.10
4	30	60	0.08	0.16	100%	100%	1.85	1.85	0.15	0.30
5	30	30	0.08	0.08	200%	200%	1.85	1.85	0.30	0.30
6	30	30	0.08	0.08	100%	100%	1.85	1.85	0.15	0.15
overall	**180**	**210**	**0.49**	**0.57**	**122%**	**105%**	**1.85**	**1.85**	**1.11**	**1.11**

The SEC of conveying, kWh/t on a fresh feed basis, is calculated using Equation 2:

$$E = h \times 2.724 \times (\textit{Proportion of fresh feed} \,/\, 100) \times 1.85 \qquad (2)$$

A significant observation is that Equation 2 works for individual conveyors, and also for the overall plant if the cumulative lift of all conveyor stages is used. This simplifies desktop studies as it is not necessary to account for every conveyor, only the sum of the lifting done by all conveyors.

Another interesting observation is that the overall conveying specific energy consumption won't change whether a Boddington or Cerro Verde style circuit is chosen (both are 1.11 kWh/t). Boddington has less lifting of ore than Cerro Verde (fewer transfer points), but a Boddington conveyor typically a greater load that completely cancels out the difference in elevation change of ore.

RESULTS AND DISCUSSION

The specific energy consumption of conveying a fines-poor ore, such as Boddington, can be estimated by Equation 3, and the specific energy consumption of a fines-rich ore, such as Cerro Verde, can be estimated by Equation 4:

$$E = h \times 1.85 \times (122\% / 100) \times 2.724 \qquad (3)$$

$$E = h \times 1.85 \times (105\% / 100) \times 2.724 \qquad (4)$$

where, h is the sum of the elevation change of all conveyors downstream of the coarse ore stockpile (the vertically lift of the ore). The constants are: a conveyor power draw allowance 1.85 accounting for non-elevation power draw, a circulating load term of 122% or 105% to represent the average proportion of fresh ore feed rate that is lifted by a typical conveyor, and a potential energy term of 2.724 kW·h to lift a tonne of ore by a height of 1 m.

The h term is the sum of the elevation change (vertical lift). Boddington has roughly six conveyor "stages" with a lift of 30 m in each stage, for a total h of 180 m. Cerro Verde has roughly seven conveyor "stages" with a lift of 30 m in each stage, for a total h of 210 m. It is suggested that the stage height of 30 m is the reasonable maximum that should be considered for a desktop study, and additional process trains of 30 m high process blocks should be considered rather than going higher in situations where more throughput is desired.

Plants at least half the size of Boddington and Cerro Verde can use the same size of crushing machines (reducing the quantity of large crushers in each stage rather than installing the same quantity of smaller crushers), which will require the same 30 m height. Cerro Verde has four large secondary crushers (MP1000) and four large HPGR units (POLYCOM 24/17) to treat 5000 t/h, so the 30 m height can be used for feed rates down to 2500 t/h before smaller equipment are required for plant availability reasons. The factors in this method will still work for smaller crushing plants that use module heights less than 30 m as long as the actual height is accumulated and entered into the appropriate equations.

Discussion, Comparison to Published Data

Published conveyor specific energy consumption values are 1.30 kWh/t for Boddington (Parker et al., 2001) and between 1.27 kWh/t (Vanderbeek et al., 2006) and 1.29 kWh/t (Koski et al, 2011) for Cerro Verde.

The simplified method (Equations 3 and 4) is compared to the published specific energy consumption values in Table 4. Both the operating plants make a significant deviation from the list of assumptions used to develop the simplified method, so an adjustment is required. The fine ore bin feed conveyor, number 5, lifts significantly higher than the assumed 30 m, actually being about 35 m at both Boddington and Cerro Verde. The reasons why this was done is believed to be site-specific and is not necessarily required if one assumes a flat location.

After deducting the extra conveyor lift at the operating plants, the simplified method predictions are within 12% of the published values.

Table 4 – Simplified method compared to published plant data

	Boddington	Cerro Verde
Published conveyor SEC, kWh/t	1.30	1.28
Deduct extra height conveyor 5, kWh/t	(-0.04)	(-0.04)
Published SEC for comparison, kWh/t	**1.26**	**1.24**
SEC by simplified method, kWh/t	**1.11**	**1.11**
difference	0.15	0.13
	12%	10%

Discussion, Comparisons to SAG Mill Circuits

The introduction to this paper states that the reason for performing this sort of calculation is to better represent the total energy used in a multi-stage crushing and HPGR plant for the purpose of comparing to a SAG mill circuit. A number of topics beyond the scope of this paper are needed to complete such a comparison:

- Dust collection is needed in screening plants and conveyor transfer points. Both Boddington (Parker et al., 2001) and Cerro Verde (Koski et al, 2011) claim a 0.5 kWh/t specific energy consumption for dust collection.

- Fine ore bins will need freeze protection and belts conveying damp crushed ore require enclosure and heating in very cold climates (MacLellan, 1972). Many places in Canada do not enjoy Ottawa's mild mid-winter climate; such locations require additional capital and operating costs to prevent very cold weather from interfering with materials handling.

- Ball mills for multi-stage crushing and HPGR circuits will be bigger than ball mills for closed-circuit SAG mill circuits (Burchardt & Ojeda, 2010). There are two reasons for this: first is that the product size out of an HPGR circuit (3 mm to 6 mm according to Burchardt et al., 2011) is coarser than the typical product size of a SAG mill circuit (½ mm to 3 mm according to Morrell, 2011); and second is that the SAG mills make more fines than HPGR circuits (Amelunxen, 2013), even after accounting for "microcracking" (Doll et al., 2010). A typical copper porphyry treated by HPGR will see a 0% to 10% reduction in ball mill operating work index versus the Bond ball mill work index test; a typical copper porphyry treated by a SAG mill will see a "phantom cyclone effect" that reduces the operating work index 5% to 15% versus the laboratory (Amelunxen, 2013).

- The specific energy consumption of the ball mill circuit ancillary systems, most notably the cyclone feed pump, are probably very similar whether the feed is derived from a SAG mill or an HPGR. These can be neglected for the purposes of HPGR:SAG comparison studies.

- Most circuit comparisons ignore the SAG mill pebble crushing conveyor specific energy consumption. The method presented in this paper is not suitable for estimating such a value because the conveyors in a pebble crushing circuit may not include a significant degree of lifting. The SAG feed and pebble crushing conveyor power is generally small, near 0.1 kWh/t for a simple recirculating belt system without a pebble crusher, or 0.15 kWh/t with a pebble crusher. The SAG mill feed belt will consume less than 0.06 kWh/t, depending on the belt length and the height ore is elevated to.

CONCLUSIONS

Specific energy consumption of conveyors in multi-stage crushing plants, E as kWh/t, can be approximated using a simple potential energy model where one only considers "how much" material is to be lifted "how high." Multiplying the conveyor specific energy consumption associated with lifting the charge by a factor of 1.85 provides a prediction of the conveyor specific energy consumption consumed by all processes, including the elevation change.

Different circuit configurations can be approximated as two values so that the specific energy consumption is independent of the actual feed rate:

- "Proportion of fresh feed": The effective overall circulating load of a fines-rich ore, such as Cerro Verde, is 105%; whereas, the overall circulating load of a fines-poor ore, such as Boddington, is 122%.

- h – "Cumulative conveyor lift": The cumulative elevation change of all the conveyors in the process; 180 m for a site layout similar to Boddington or 210 m for a site layout similar to Cerro Verde.

$$E = h \times 1.85 \times (\textit{Proportion of fresh feed} / 100) \times 2.724$$

Using these input values, the method predicts a conveyor specific energy within 12% of published data for two operating HPGR circuits, Boddington and Cerro Verde. The method is suitable for performing a desktop-level scoping study where the detailed layouts and conveyor sizing calculations of a feasibility study are not available, but a reasonable assumption of the "bin height" can be made.

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