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The Impact of Media Embodied Carbon Emissions on Regrind Technology Selection

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ABSTRACT

Environmental, Social, and Governance (ESG) considerations are playing a more significant role in the mining industry, and ESG factors are becoming increasingly important. Ballantyne et al. (2023) proposed a method that integrates greenhouse gases (GHG) emissions into economic evaluations of comminution flowsheets. This paper applies the methodology to estimate the carbon dioxide (CO_2) emissions inventory of regrind circuits.

Stirred milling technologies are used extensively in regrinding duties (mainly to regrind concentrates) due to its ability to deliver improved energy efficiency. The traditional approach for regrind technology selection is energy efficiency. However, aspects such as the embodied emissions of steel or ceramic grinding media need to be considered in the context of sustainable mining. The production of media requires mining, grinding, smelting and forging (for steel media), pelletizing and sintering (for ceramic media), and transport to site—with each stage contributing to GHG emissions.

This paper presents an assessment of three regrind technologies: ball mills, slow-speed vertical stirred mills and high-speed vertical stirred mills, for the expansion of an existing regrind circuit treating a rougher flotation concentrate. The Scopes 2 and 3 emissions associated with the operation of the regrind circuits were estimated to provide a robust CO_2 emission inventory comparison that can be integrated into the economic evaluations of various regrind technologies.

INTRODUCTION

Daniel, Lane and McLean (2010) indicated in their publication that sustainable mining development of the future would shift from the traditional approach, predominantly associated with achieving reductions in energy consumption and best economic outcome, to include environmental metrics into the analysis. They anticipated that direct and indirect energy savings and the impact on environment would be assessed in conjunction with economic evaluations and presented a holistic approach to understand the concept of reduced carbon and energy footprints of comminution circuits. The authors demonstrated that the major contributor to indirect energy cost savings was the consumption of grinding media.

More recently, Environmental, Social, and Governance (ESG) considerations are playing a more significant role in the mining industry. This is leading to growing awareness of sustainability issues and the need to ensure responsible practices throughout minerals processing. The selection and operation mineral processing circuits can determine a large part of the environmental impact. These circuits are responsible for a large portion of the energy consumption, water usage, and emissions of greenhouse gases (GHG). Sustainable minerals processing aims to develop and adopt cleaner technologies and innovative processes that minimize the carbon footprint and conserve resources.

Ballantyne et al. (2023) suggested that to minimize the GHG emissions associated with the extraction of minerals, emissions need to be accounted for and presented clearly to inform decision-makers. The authors proposed a method for integrating GHG emissions into economic evaluations, which considered separate evaluations for the construction and operational phases of alternative comminution circuit configurations. The study concluded that indirect emissions associated with operating comminution circuits are an order of magnitude larger than the emissions associated with steel and concrete used in construction. Lane et al. (2023) validated this conclusion in their analysis of carbon dioxide (CO_2) emissions of a 4 Mt/y operating plant, in which the total CO_2 emissions related with plant construction were equivalent to 7 to 10 weeks steel media consumption.

Similar to comminution circuits, the main driver for regrind technology selection is energy efficiency and traditional economic assessments. However, aspects such as the embodied emissions of steel or ceramic grinding media need to be considered in the context of sustainable mining. The production of media requires mining, grinding, smelting and forging (for steel media), pelletizing and sintering (for ceramic media), and transport to site—with each stage contributing to GHG emissions.

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REGRIND TECHNOLOGIES

Ball mills are the most common and versatile type of grinding mill. They are remarkable in that they can operate over a very wide range of conditions and geometries. At product sizes finer than 80%

passing 75 µm, the efficiency of ball mill grinding rapidly decreases. Although ball mills can still be found in the regrind circuits in several mineral processing plants, their energy consumption is high, and size reduction efficiency is low.

Alternative, energy-efficient regrind technology is stirred milling. In contrast to tumbling mills where motion is imparted to the charge via the rotation of the mill shell, motion in stirred mills is imparted to the charge by the movement of an internal stirrer while the shell remains stationary. Table 1 presents a comparison of design features of various regrind technologies. The high-speed horizontal stirred mill (IsaMill) was not considered for the present study due the expected similarity to the results of high-speed vertical stirred mill (VRM or HIG mill).

Table 1 Regrind technology comparison

		Ball Mill	**Vertimill/Tower mill**	**VRM / HIG mill**	**IsaMill**
Manufacturer		Various	Metso/Eirich	Metso/STM	Glencore
Description	Orientation	Horizontal	Vertical	Vertical	Horizontal
	Circuit Config.	Closed	Closed	Open	Open
	Impeller shape	n/a	Screw	Disc	Disc
	Shell	Lifter/liner	Smooth	Smooth	Smooth
	Speed	Low	Low	High	High
Impeller tip speed (m/s)		4 - 5	<3	6 – 13	19 - 23
Power Intensity (kW/m^3)		55 -65	20 – 40	150 – 300	300 - 1000
Typical size range (µm)	Feed (F_{80})	300 - 70	300 – 70	300 – 20	300 - 70
	Product (P_{80})	>30	20 – 40	8 – 75	<10
Media size (mm)		20 - 50	12 - 20	1 – 15	1 - 5
Media material		Steel	Steel	Ceramic	Ceramic

GRINDING MEDIA FOR REGRIND CIRCUITS

Grinding media is a key consumable in regrind processes in tumbling and stirred mills. The grinding media cost and consumption in a regrind circuit typically have a significant impact on operating costs and are the greater contributor to indirect emissions. The grinding media consumption can vary widely depending on factors such as the feed material, target grind size and the equipment technology. The selection of grinding media material is also driven by the application, with the main common types being:

- Steel balls: most widely used grinding media. They are available in various diameters and hardness levels to suit different grinding applications. Low-alloy steel, high-carbon steel, and stainless steel are some of the variations used based on the specific needs of the process.
- Ceramic beads: such as alumina, zirconia, and silicon carbide, are known for their high wear resistance and chemical inertness. They are often used in industries where contamination from the grinding media itself is a concern, such as in the pharmaceutical or food industries. Ceramic media is also used by the mining industry, particularly in stirred mills that produce very fine products.

CARBON EMISSION INTENSITY OF STEEL AND CERAMIC

According to Boylston (2021), the manufacturing of steel media necessitates substantial energy inputs for the extraction and refining of iron ore, as well as the subsequent steel smelting and shaping processes. Recent assessments provided by the World Steel Council (2022) have shown that emissions can fluctuate based on the steelmaking processes with the carbon emission intensity associated with blast furnace being much higher than direct reduction. The CO_2 emissions associated with the production of steel between 2012 and 2021 are shown in Figure 1, indicating an average of 1.84 tonnes of CO_2 per tonne of steel.

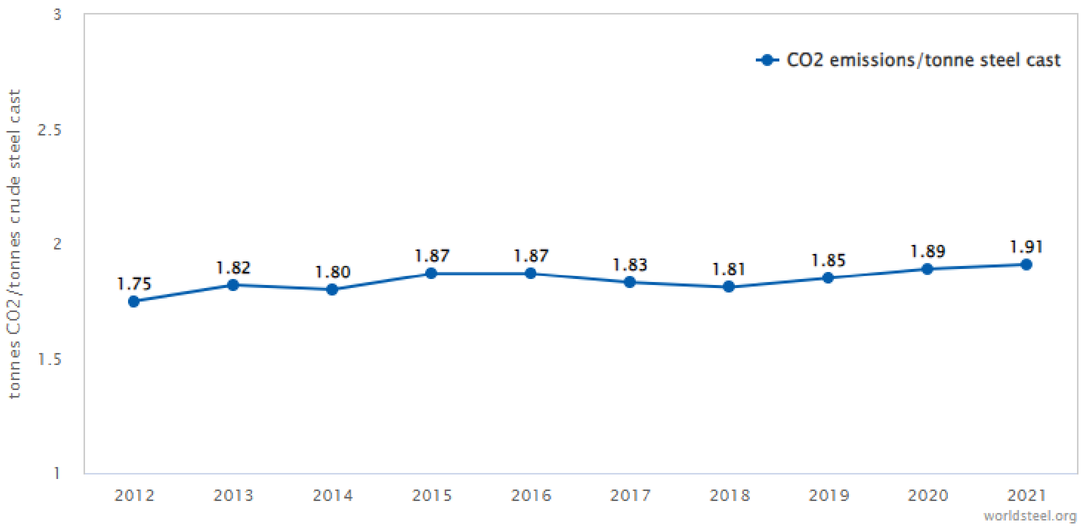

Figure 1 Steel CO_2 emissions intensity (World Steel Council, 2022)

The ball metallurgy also plays a significant role in the CO_2 emissions required to produce steel media consumption (Ballantyne, 2019). While casting requires more energy than forging media, it can use recycled scrap steel, which can result in lower overall emissions.

High-quality ceramic raw materials are chosen for the manufacturing of ceramic media, based on factors such as size, density and wear resistance. Ceramic media is produced through a manufacturing process that involves material preparation, pelletizing (or any other shaping process) and sintering. Emissions associated with the production of ceramics can vary in a wide range. According to the Building Services Research and Information Association (BSRIA) guide (Hammond and Jones, 2011), the average CO_2 emissions associated with production of ceramic is 0.66 tonnes of CO_2 per tonne of ceramic; however, can be as high as 1.51 tonnes of CO_2 per tonne of ceramic depending on the application.

Limited data related to production of grinding media specifically is available in the public domain and figures above are related to construction materials. A more detailed analysis of the natural gas and electricity required to produce ceramic media, indicate a CO_2 emission intensity of approximately 1.0 tonne of CO_2 per tonne of ceramic media, which is almost half the specific emissions associated with steel media production.

CARBON EMISSION INTENSITY OF GRINDING MEDIA TRANSPORTATION

In addition to the emissions attributed to the manufacturing process of grinding media, additional emissions arise from the transportation of the grinding media to the operational site. Depending on the distance between the manufacturing point and the utilization location and the transportation mode, the transportation-related emissions can assume an important magnitude given the weight and volume of steel media. For example, emission factors associated with diesel trucks and trains are 116 and 14 g of CO_2/(t km), respectively (US EPA, 2022).

TRADE-OFF STUDY

A regrind trade-off study for the expansion of a gold processing plant was conducted, evaluating the merits of rougher flotation concentrate regrind flowsheets featuring ball mill, low and high-speed stirred mills. The existing regrind milling circuit grinds the rougher flotation concentrate to a size appropriate for processing by cyanide leaching. A regrind ball mill operates in closed circuit with the regrind cyclone, with the overflow reporting to the continuous leaching circuit. A new regrind circuit was considered for the regrind circuit expansion and the existing ball mill would be decommissioned.

The assessment focused on the development of GHG emission inventory for each regrind technology focusing on the major contributors in the operation of regrind circuits, i.e. power consumption and consumables (grinding media, and mill liners).

Project Background

The new regrind circuit was designed to process 31 t/h of the rougher flotation concentrate. Regrind testwork using a stirred mill was conducted and provided the signature plots used to estimate the specific energy to regrind the concentrate in stirred mills. It was assumed that low- and high-speed stirred mills would deliver the same energy efficiency. The design criteria outlined in **Error! Reference source not found.** 2 were used to model and size the regrind mills.

Table 2 Regrind mill design criteria

	Unit	Base Case
Hourly throughput	t/h	31
Regrind circuit feed size (F_{80})	µm	150
Regrind circuit product (P_{80})	µm	25
Regrind specific energy, ball mill	kWh/t	41.5
Regrind specific energy, stirred mill	kWh/t	33.2
Abrasion index, average, regrind circuit feed	g	0.06

GHG Emissions Inventory

The GHG emissions were classified following the United States Environmental Protection Agency (EPA) guidance, which includes the following scopes:

- Scope 1 emissions are direct GHG emissions from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion). Scope 1 emissions were not considered in this paper as they would be similar for all regrind technologies, within the accuracy of the data available.
- Scope 2 emissions are indirect GHG emissions associated with power consumption. These are expected to differ across the technologies considered in this paper due to the higher energy efficiency of stirred milling in regrind duties.
- Scope 3 emissions are associated with activities from assets not owned or controlled by the organization, but that the organization indirectly impacts in its value chain.
    - Scope 3 emissions in operations relate principally to grinding media and mill liner consumption and transportation. Steel and ceramic consumption differs significantly across the options considered.
    - Scope 3 emissions in construction relate principally to concrete and steel usage. Scope 3 construction emissions were not considered in this paper as they would be significantly lower than the emissions in operation of regrind circuits.

The main input parameters to quantify GHG emissions are listed in Table 3. The GHG emission intensity of Canada's electricity grid (project location) was measured by the Canada Energy Regulator (CER) for the year of 2020.

Table 3 Main input parameters to quantify GHG emissions

	Unit	Value
Electrical energy	kg CO_2/kWh	0.11
Steel (media)	kg CO_2/kg	1.84
Ceramic (media)	kg CO_2/kg	1.00
Transportation by diesel trucks	t CO_2/100 km/truck	0.116
Truck capacity	t/truck	40
Transportation distance	km	1,000

Table 4 presents the yearly energy and media consumption as determined for each regrind technology. Media consumption (wear rate) is expressed as grams of media per kWh, and is typically associated with the media material, shape, size, milling technology. For the purpose of the analysis, the media consumption was benchmarked against current operation at site for the ball mill case, while the Vertimill and the VRM/HIG mill wear rates were estimated by vendors.

Table 4 Energy and grinding media consumption

	Unit	Ball Mill	Vertimill	VRM / HIG mill
Regrind mill circuit power	GWh/y	10.22	8.34	8.,34
Regrind mill power	kW	1,269	1,035	1,035
Media consumption	kg/kWh	0.033	0.020	0.010
Media consumption	t/y	339.5	166.8	83.4

Table 5 presents the yearly carbon emissions inventory, related to Scope 2 and Scope 3 (operation), of each regrind technology under evaluation.

Table 5 GHG emissions inventory

	Unit	Ball Mill	Vertimill	VRM / HIG mill
Electrical energy (Scope 2)	t CO_2/y	1,125	918	918
Media consumption (Scope 3)	t CO_2/y	625.2	307.0	83.5
Media transportation (Scope 3)	t CO_2/y	9.9	4.8	2.4
Total Scope 2 and Scope 3 (operation) emissions	t CO_2/y	1,760	1,229	1,005

The results of the GHG emissions inventory reveal a significant disparity in the total operation emissions across the evaluated regrind technologies. The ball mill exhibits the highest GHG emissions from electrical energy consumption, attributed to its reduced energy efficiency in fine grinding applications. This inefficiency translates into accentuating the associated Scope 2 emissions related to media consumption and transportation.

In contrast, the Vertimill and VRM/HIG mill demonstrate comparatively lower emissions from electrical energy consumption, as their energy efficiency was assumed to be the same. The Vertimill media consumption indicates a lower value than that for the ball mill (likely associated with the modes of breakage within the mill), which resulted in a significant reduction in emissions associated with media consumption and transportation. The VRM/HIG mill exhibit further reduced media consumption rates. Of particular significance is the influence of media material on emissions, with ceramic media emerging as a standout choice in the pursuit of reduced environmental impact.

CONCLUSION

In summary, this study expands upon the framework proposed by Ballantyne et al. (2023) for incorporating GHG emissions into the economic evaluation of comminution circuits, extending its application to regrind technologies. Stirred milling, known for its improved energy efficiency at very fine grinds compared to ball mills, is a widely adopted method for regrinding duties. This study highlights the influence of energy and grinding media-related indirect emissions (production and transportation) on the overall GHG emissions inventory of regrind circuits:

- Electrical energy consumption (Scope 2) is the greatest contributor to GHG emissions in a regrind circuit, independent of the technology
    - increasing the use of renewable energy sources is key to reduce emissions associated with energy consumption.
- GHG emissions associated with media consumption and transportation (Scope 3) decrease when stirred milling technologies are considered instead of ball mills

  - the emissions associated with media transportation using diesel trucks (distance of 1,000 km) is not significant compared to the energy required to produce media.
- Reductions in Scope 3 GHG emissions are realized when ceramic media are used, due to the lower embodied energy
  - the use of recycled steel to produce cast media has the potential to reduce the difference in emissions between steel and ceramic media.

By incorporating the GHG emissions considerations, this study presented a comprehensive assessment of the indirect emissions associated with the operation of the regrind circuits considering three regrind technologies. A robust GHG emission inventory comparison was provided, which allows integrating sustainability metrics into the evaluation of regrind technologies.

REFERENCES

Ballantyne G (2019) '*Quantifying the additional energy consumed by ancillary equipment and embodied in grinding media in comminution circuits*'. SAG 2019 Conference, Vancouver, Canada.

Ballantyne G, Pyle M, Foggiatto B, Martin K and Lane G (2023) '*The Impact of Greenhouse Gas Emission Costs on the "True Economics" in Comminution Trade-Off Studies*'. SAG 2023 Conference, Vancouver, Canada.

Boylston A / Metso (2021) '*Boosting energy efficiency for comminution solutions*', 10 August 2023, https://www.metso.com/insights/blog/mining-and-metals/boosting-energy-efficiency-for-comminution-solutions/

Canada Energy Regulator (2023) *Energy Production*, 10 August 2023, https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html#:~:text=The%20greenhouse%20gas%20intensity%20of,e%2FkWh)%20in%202020

Daniel M, Lane G and McLean E. (2010) '*Efficiency, economics, energy and emissions – Emerging criteria for comminution circuit decision making*', XXV International Mineral Processing Congress (IMPC) 2010 Proceedings / Brisbane, QLD, Australia / 6 - 10 September 2010.

Hammond G and Jones C (2011) Embodied Carbon – The inventory of carbon and energy (ICE). Image Data Ltd, England.

Lane G., Ballantyne, G. and Foggiatto B (2023) 'Ausenco: Innovations in comminution', *AusIMM Webinar series*, 10 August 2023, https://www.ausimm.com/videos/community-event/ausenco-innovations-in-comminution/

World Steel Council (2022) '*Our performance: Sustainability Indicators*', 10 August 2023, https://worldsteel.org/steel-topics/sustainability/sustainability-indicators/

United States Environmental Protection Agency (2022) '*GHG Inventory Development Process and Guidance*', 10 August 2023, https://www.epa.gov/climateleadership/ghg-inventory-development-process-and-guidance