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Improving Energy Efficiency and Reducing Carbon Footprint at the FMR Greenfields Mill Operation

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ABSTRACT

Comminution is energy intensive and a major contributor to the carbon footprint of the resources sector. Morrell (2022) estimated that the global installed motor capacity of ball mills is approximately 67.6 billion kWh - 58% of the total estimated annual global comminution electricity consumption. More than a century ago, in 1914 (Van Winkle, 1918), it was well demonstrated that Marcy open-ended grate discharge ball mills are more energy efficient compared to Hardinge overflow ball mills. However, overflow mills have become dominant due to the inability of trunnion-based grate-pulp lifter discharge ball mills to reproduce the expected performance of open-ended grate discharge mills because of internal material transport issues.

The invention of the dual chamber pulp lifter, energy efficient pulp lifter (EEPL), which eliminates the internal material transport issues, namely flow-back and carry-over, and hence ensures efficient grinding conditions, thus allows the trunnion-based grate-pulp lifter ball mills to operate like open-ended grate discharge ball mills. This has generated research interest to understand and demonstrate the century old proven benefits of open-ended grate discharge mills.

Comprehensive laboratory and pilot mill studies undertaken at the University of Utah have once again demonstrated the significant energy savings of open-ended grate discharge mills compared to overflow mills, which have led to successful industrial installations.

This paper summarises the results from three implementations between 2015 and 2022, at copper, magnetite, and gold milling operations. This paper further discusses the energy savings and other benefits observed at the most recent (2022) implementation at FMR Greenfields Mill Operation in Australia. All three operations have demonstrated energy savings of over 25%, in addition to an increase in throughput.

After successful conversion of one out of three overflow mills (one primary and two secondary mills), specifically secondary Mill#2, at the Greenfields Mill Operation in March 2022, the plant is operating with one primary mill and one secondary mill instead of two secondary mills; demonstrating the ability of one grate discharge mill to do the work of two overflow mills, in addition to saving 510 kWh of motor power and decreasing grinding media consumption by 19.7%. Electrical energy savings alone remove 2268 tonnes of CO_2 emissions per annum (22% of the operations emission) besides reducing 244 tonnes of CO_2 emissions per annum due to reduction in media consumption.

In the next phase of the project, FMR Greenfields Mill Operation will review the upgrade of the primary Mill#3 from an overflow mill to an EEMS discharge system based on the results of the Mill#2 grate conversion. This is expected to further increase power savings by ~300 kWh, decrease the total carbon footprint by 3869 tonnes (35.2% of total), and provide circuit flexibility when toll treating different ore types.

INTRODUCTION

The most energy efficient breakage system would be one where particles leave the energy field as soon as they become of product size, so that the energy is used to break coarser particles. In

1. NET revenue is referring to the total dollar value minus all the expenses. All the economics in this section are referring to NET values, all expenditures are not included in this report.

tumbling mills, free falling or tumbling rocks and balls transfer the energy to break particles and a special discharge arrangement is required to facilitate the internal material transport of product sized particles out of the breakage field. The efficiency of product removal depends on the design of the discharge mechanism.

In its Technical Brochure No 101, The Mines and Miners Supply Company USA (1942), reported that the quest for an efficient discharge mechanism started as early as 1912 when Mr. Frank Marcy stated that ‘rapid change of mill content is necessary for high efficiency’. However, overflow mills are preferred due to their simplicity of design and operation, where it has been a well-accepted practice to increase the circulating load to attain rapid material displacement in mill contents and avoid over grinding.

Literature on overflow and grate discharge mechanism

The first true comparative tests between overflow and grate discharge mechanisms in ball mills were carried out in 1914, when the Marcy open-ended ball mills (Figure 1) were successfully tested against Hardinge’s conical overflow ball mills at Inspiration Consolidated Copper Concentrator (Van Winkle, 1918). The comparative tests conducted over 3 months at Inspiration have amply demonstrated the advantages of open-ended grate discharge mills when compared to overflow mills in terms of lower energy consumption per tonne and significantly higher productivity of up to 35%.

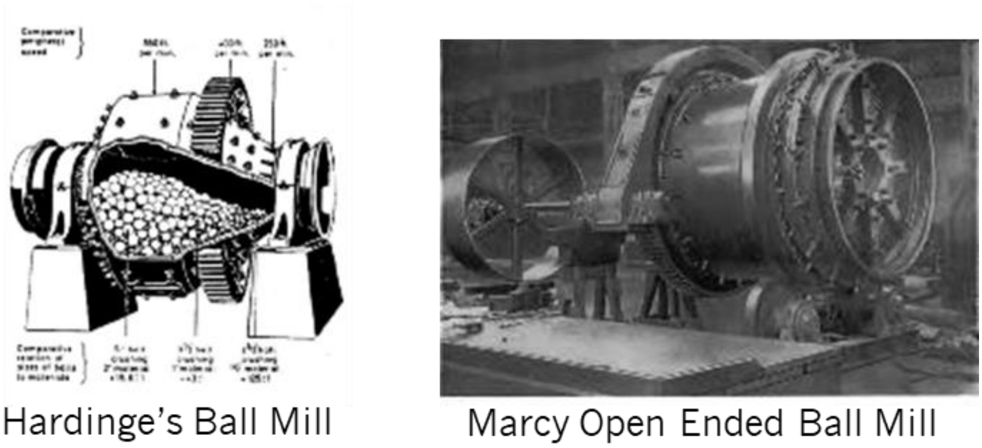


Figure 1: Hardinge and Marcy open ended ball mills.

Increase in mill diameter to more than 3m and, many mechanical and operational challenges with open-ended or grate-only mills, led to the development of the modern grate discharge mill design, consisting of a grate and pan or pulp lifter as shown in Figure 2. The two conventional pan lifter designs – radial and curved or spiral type, were developed in the 1930s and have since been predominantly used in autogenous grinding (AG), semi-autogenous grinding (SAG) and Ball mills.

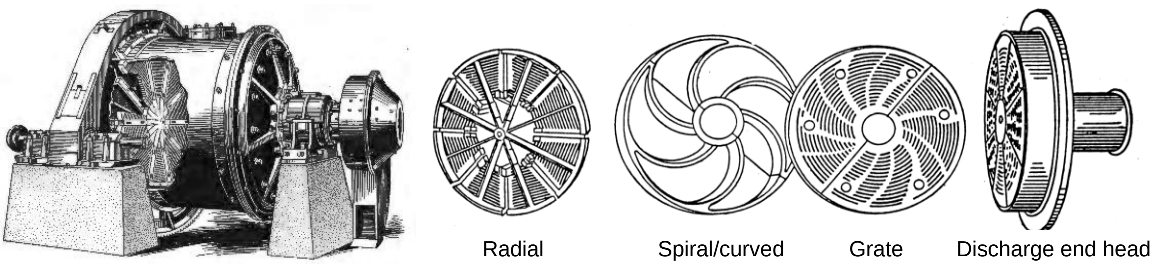


Figure 2: Grate discharge ball mill and different discharge systems. (Taggart, 1940).

Although the addition of pulp lifters on top of the grates facilitated the use of simpler trunnion support, the arrangement did not produce similar improvements in throughput and energy savings as observed in open-ended grate mills. The high cost of maintenance could not be justified compared to overflow mills; hence ball mills have moved predominantly to the overflow design. McIver and Makni (2022) have recently summarised the performance comparisons of grate ball mills verses overflow ball mills and mentioned that a grate discharge has never been reported to have had a negative effect on milling efficiency, and grate discharge provides ball milling efficiency greater than an overflow discharge.

The poor performance of grate discharge mills with radial pulp lifters is attributed to the presence of excessive slurry and curved or spiral pulp lifters were tried as alternative, but the problem could not be eliminated (Mokken et al, 1975). Subsequently, Rowland & Kjos, (1975) reported that if there is an excessive amount of slurry, i.e. more than the volume of voids in the grinding media, it affects grinding efficiency. Morrell and Kojovic, (1996) observed a reduction in power draw of SAG mills operating with a slurry pool and mentioned that it adversely affects the mill grinding capacity. Songfack and Rajamani (1999) reported that the main bottleneck in trying to improve the efficiency of current grinding circuits is the lack of understanding of the mechanism of material transport in grinding mills. Unfortunately, there was no published data, either to substantiate the previous claims or to understand what relationship exists between the load carrying capacity of pulp lifters and mill performance, until late 1990.

Material transport through mills and development of Energy Efficient Pulp Lifters (EEPL)

Extensive research carried out by Latchireddi S (1996, 2002, 2003a, 2003b) on grate discharge mills with different designs of grate and pulp lifters, radial and curved, has identified the inherent process issues as **flow-back** and **carry-over** of slurry, resulting in a large slurry pool inside the grinding chamber as illustrated in Figure 3.

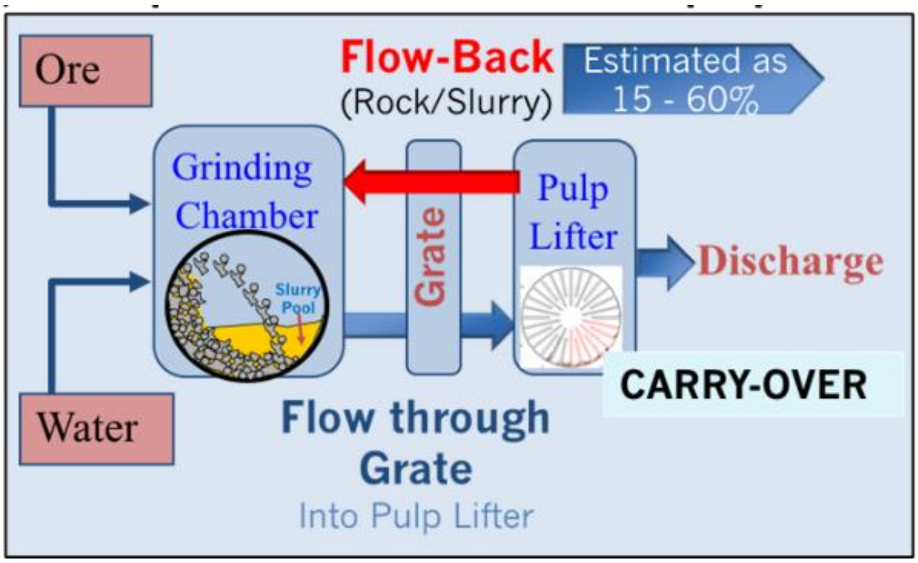


Figure 3: Material transport in mills with radial or curved pulp lifters (Latchireddi S, 1996, 2002).

To overcome these inherent issues, Latchireddi S and Latchireddi R (2016) developed a novel pulp lifter design called EEPL which is more advanced and efficient compared to its predecessors. The EEPL designs eliminates flow-back and carry-over and allows mills to operate as open-ended grate discharge mills (Figure 4). EEPL designs have been successfully operating at several AG/SAG mill operations around the world, and consistently delivering significant energy savings and increases in productivity.

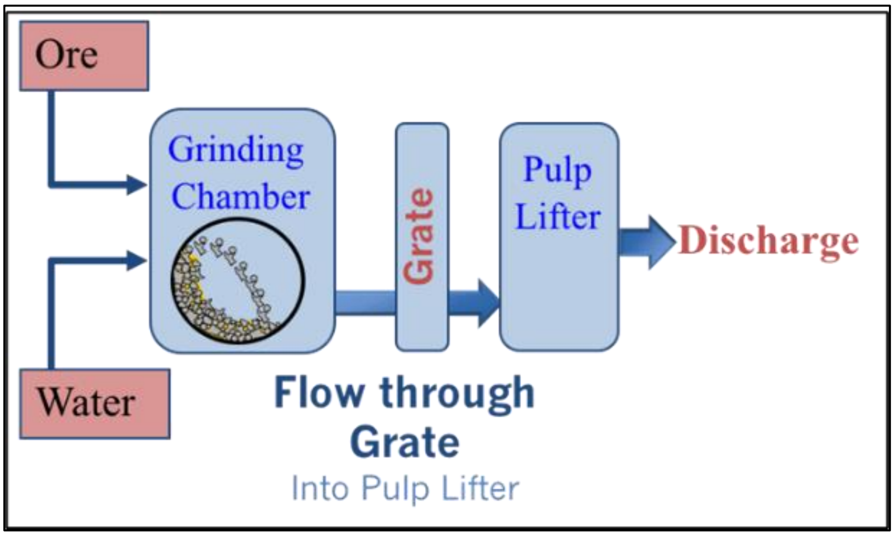


Figure 4: Material transport with EEPL in mills (Latchireddi S and Latchireddi R 2016).

Research at University of Utah

Successful operation of EEPL in AG/SAG mills prompted studies to apply the same design to ball mills to eliminate the large body of slurry and ensure efficient grinding conditions. To understand the process advantages of grate discharge ball mills compared to overflow mills, extensive experimental investigations were carried out in a pilot mill (Figure 5) at the University of Utah by Prof Rajamani and team (Latchireddi R et al, 2015 and Latchireddi R, 2017) during 2011-2017, which was equipped with load cells and a torque sensor.

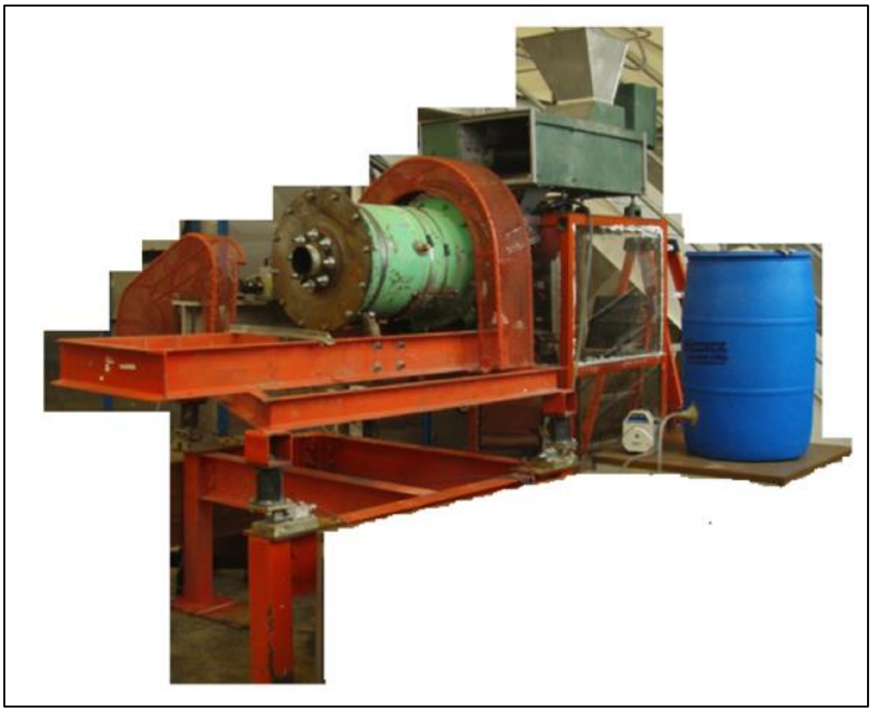


Figure 5: The pilot ball mill with interchangeable discharge end (overflow and grate discharge).

The findings of this research are summarised as follows:

- The grate discharge mill demonstrated a lower energy requirement of ~40% to achieve the same product size when compared to overflow mills.
- A significantly lower particle residence time in the grate discharge mill, compared to the overflow mill, implied a quicker and more efficient transport of product-size particles, thus providing potential for breakage of new particles.
- The higher particle residence time in the overflow mill suggested inefficient material transport, with particles spending more time in the mill.
- Variation of product size with respect to mill speed and percent solids concludes that grate mills can be effectively used to vary product size using both control variables.
- In an open-ended grate mill, slurry volume is effectively 100% of charge void space, thereby allowing all particles to pass through the cascading media before exiting the mill, which leads to efficient breakage of particles.
- The slurry pool in overflow mills is estimated to be 270% to 300% of the charge void space, where a significant proportion of the grinding energy is utilised against buoyancy and drag forces and not directly for comminution.
- The excessive slurry pooling in overflow mills promotes movement of slurry over the ball mass, resulting in short circuiting of some of the feed to the discharge, causing inefficient comminution.

Industrial application of research findings

Application 1

The first application of the research findings was carried out at Sandfire Resources' Degrussa Copper operation, whose grinding circuit was designed as a SAG and ball (SAB) circuit, with the SAG mill in closed circuit with primary cyclones, and pebbles circulating to the SAG mill feed, to produce particles P_{80} 180 µm going forward to an overflow ball mill (but supplied with a grate discharge option). The ball mill is in closed circuit with cyclones to produce particles P_{80} 45 µm. The grinding circuit operated as expected until the mill feed shifted to more competent ore in 2013, which limited throughput and resulted in high pebble circulation and production of a large proportion of ultra fine particles (-10 µm) that adversely affected flotation performance.

To overcome these issues, several conventional techniques were implemented but with limited success. EEMS were then engaged to develop a holistic model and identified poor material transport and inefficient charge motion as the critical issues. In 2015, Sandfire successfully implemented the EEMS modified design of SAG shell liners to generate optimal charge motion and the patented EEMS energy efficient pulp lifter (EEPL) to overcome the material transport issues in both the SAG mill and ball mill, in addition to replacing the SAG circuit cyclones with a 2 mm aperture vibrating screen and adding a pebble crusher as shown in Figure 6. The operational data of the EEPL discharge system compared with the design data of ball mill in overflow configuration are presented in Table 1 (Knoblauch et al. 2015).

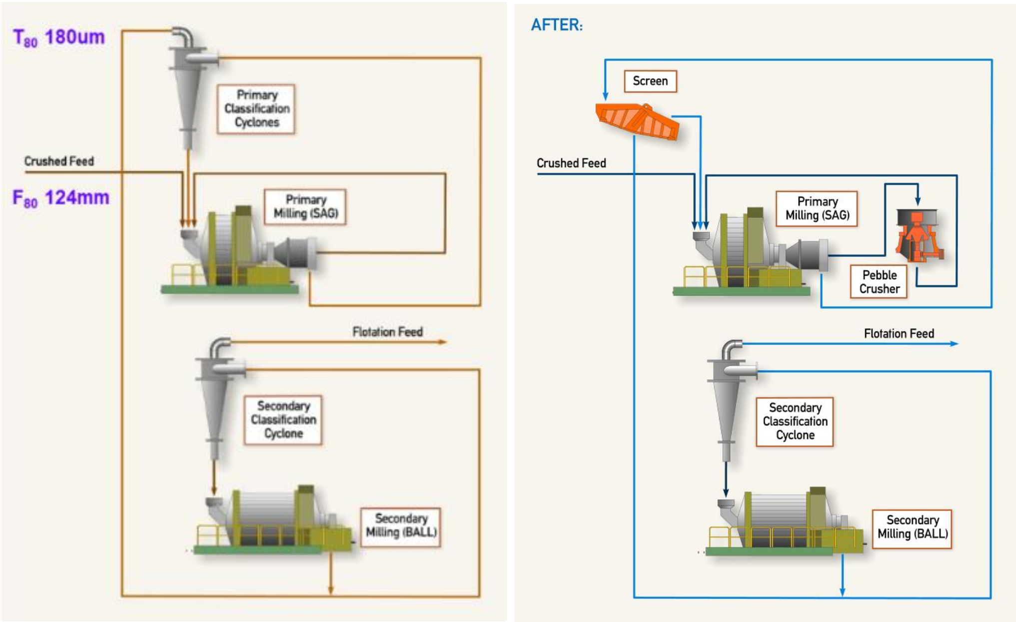


Figure 6: Degrussa grinding circuit before and after modification.

Table 1: Operational results of ball mill at Sandfire Resources Degrussa operation.

Parameter	**Overflow (design)**	**Grate-EEPL (after)**	**Benefit against Overflow**
Mill Size	4.7 m x 7.5 m 2800 kW	4.7 m x 7.2 m 2800 kW	
Ball Charge, % volume	28	16	-42.8%
Throughput, t/h	187	236	+26.2%
Feed Size, F_{80}	180 µm with cyclones	1300 µm with 2 mm Screen	
Product Size, P_{80}	45 µm	45 µm	
Power draw, kW	2321	1690	-27.2%
Specific Energy, kWh/t	12.4	7.2	-42.2%

A summary of the observations includes:

- an observed 42.2% energy saving, confirming the pilot mill test results of 40% energy savings with open-ended grate discharge compared to overflow mills.
- the EEPL discharge system appeared to allow an overflow ball mill to operate like an open-ended grate discharge mill.
- a grate mill is capable of handling coarser feed to produce the same product size.
- at the Degrussa ball mill, 40% of motor power remains available to achieve more throughput and finer grind, so a second ball mill was not required for future expansion to process 287tph.

Application 2

Iron pipe manufacturer Jindal Saw, identified an opportunity at its magnetite ore processing plant where ore is processed in parallel ball mills before beneficiation in rougher wet magnetic separators in closed circuit with cyclones to produce a final product of P_{80} 74 µm. A schematic process flow diagram of one line of four parallel lines in Plant B is shown in Figure 7.

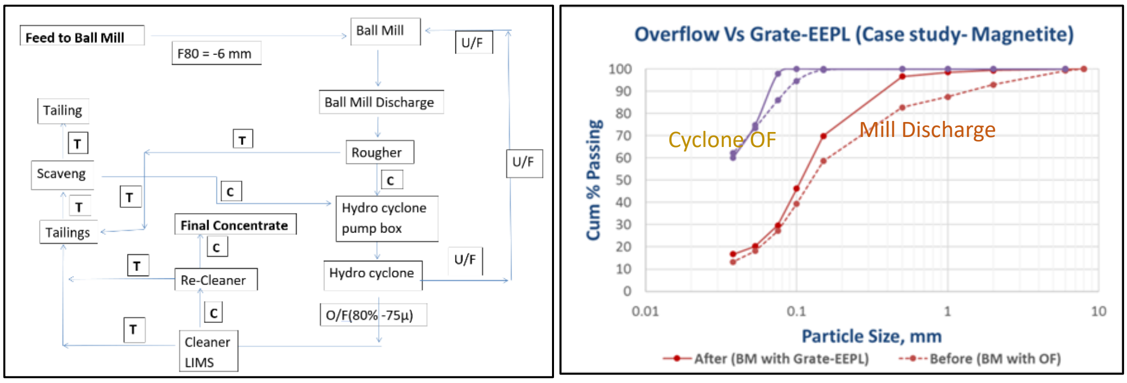


Figure 7: a) Jindal Saw grinding circuit flow diagram and b) Size distribution of mill discharge and cyclone overflow.

Line-6 of the four (lines 5, 6, 7 and 8) was first selected to convert from overflow to grate discharge by installing the patented EEPL discharge system with the primary objective of saving energy. A comprehensive grinding survey of Line-6 was carried out, followed by holistic modelling to predict the performance of a grate mill with the EEPL discharge system. Modelling estimated energy savings of around 30% as well as an increase in throughput by 10-20%. All mill internals, shell, and discharge liners were modified to suit the grate discharge process. The Line-6 ball mill was commissioned in July 2019 and Table 2 summarises the mill performance before and after installation.

Table 2: Operational results of ball mill at Jindal Saw operation.

Parameter	**Overflow (before)**	**Grate-EEPL (after)**	**Benefit against Overflow**
Mill Size	4.57 m x 8.08 m 2800 kW	4.57 m x 7.7 m 2800 kW	
Ball Charge, %vol	28	14	-50%
Throughput, t/h	128	159	+24%
Feed Size, F_{80}	3520 µm	3520 µm	
Product Size, P_{80}	74.0 µm	74.2 µm	
Power draw, kW	2214	1490	-32.6%
Specific Energy, kWh/t	17.3	9.4	-45.6%

Consistent energy savings have once again proven the research findings and ability of the patented EEPL discharge technology to operate ball mills as open-ended grate discharge mills.

A summary of the observations is as follows:

- Consistent energy saving of >45%.
- A 24% increase in ball mill throughput.

Considering the consistent energy savings and higher throughput, two more mills (Line-5 and Line-7) have been converted to grate discharge with EEPL technology.

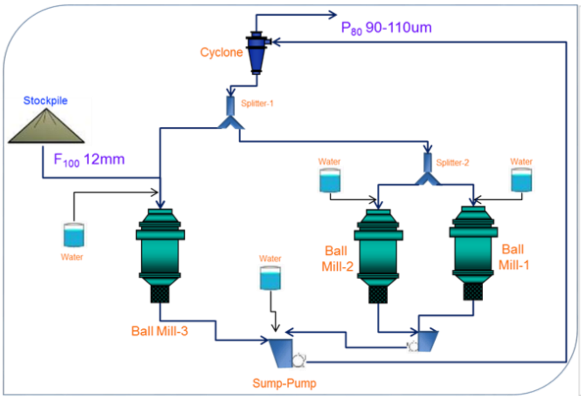
The advantage of an increase in throughput while reducing energy (kWh/t) has significant ramifications for the industry; no longer will mill constrained operations need to sacrifice throughput, the primary grind, and recovery, and operations that are ore-supply-limited can reduce their energy costs and carbon emissions.

FMR GREENFIELDS MILL OPERATION

Background

The FMR Greenfields Mill Operation located near Coolgardie was founded in 1892, when gold was discovered in the area known as Fly Flat by prospectors Arthur Bayley and William Ford. Gold exploration and processing continued to occur sporadically at the Greenfields site until the Greenfields Processing Site was constructed in 1987 by Coolgardie Gold NL to process ore from the Baileys Underground Mine with a nameplate capacity of 250,000 t/y, with the 500 kW ball mill being the sole mill. In 1994 throughput was doubled to 500 000 t/y with the installation of the 875 kW ball mill and a third upgrade to 900 000 t/y occurred in 2008 by adding the 1325 kW ball mill.

During the majority of toll milling campaigns the Greenfields Mill Operation treated low to moderate grade ores which meant that the plant had sufficient downstream capacity to handle an increased throughput rate. This was where the opportunity was identified to potentially improve the grinding efficiency and throughput and therefore increase the revenue generated through toll milling. Alternate options were discussed as to how to utilise the efficiency gains, including maintaining the existing throughput rate and grinding finer to increase recovery on certain ores, and maintaining the existing grind and increasing throughput. A decision was taken to turn off the 500 kW ball mill to realise significant maintenance and operational cost savings.



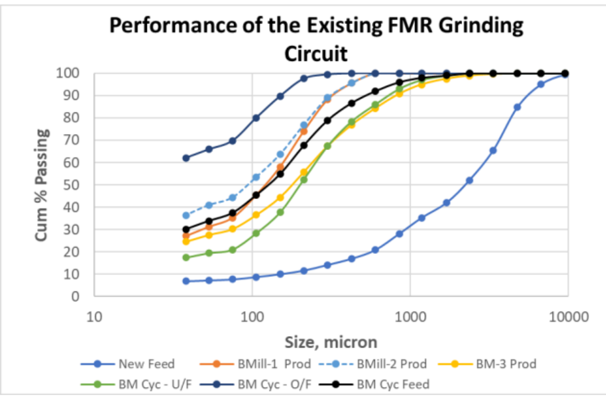


Figure 8: a) Greenfields Mill Operation grinding circuit flow diagram and b) Grinding survey size distribution data.

The FMR grinding circuit at the Greenfields Mill Operation was treating about 2 800 dry tonnes per day using 3 overflow balls mills – 1325 kW (Mill#1 - 3.8 x 6m), 875 kW (Mill#2 - 3.32 x 5.18m) and 500 kW (Mill#1 - 2.7 x 4.8m), all in one closed circuit with new feed of F_{80} 6-10 mm going into the Mill#3 (Figure 8). The Bond work indices (BWi) and product size varies with the ore treated in the toll treatment facility.

FMR Greenfields Mill Operation reached out to EEMS Australia with the objective of improving the grinding efficiency of the toll treatment facility to increase the plant throughput. An initial plant visit and grinding survey was carried out in October 2019 and the results were sent to EEMS for analysis and modelling in January 2020. Following is a summary of the data analysis, EEMS's holistic modelling results and the plant operating results.

EEMS modelling and simulation results with EEPL technology

EEMS carried out holistic modelling of the FMR Greenfields Mill Operation grinding circuit using the design, process, and operational data provided along with the particle size distribution (PSD) and percent solids data from grinding surveys.

The major issue in each existing overflow ball mill was the presence of a large slurry pool well above discharge trunnion level, which:

- Absorbs a significant amount of grinding energy.
- Exerts buoyancy force on media, thus reducing grinding efficiency.
- Reduces probability of particle breakage as illustrated in the Discrete Element Modelling (DEM) charge motion and transport simulations (Figure 9).

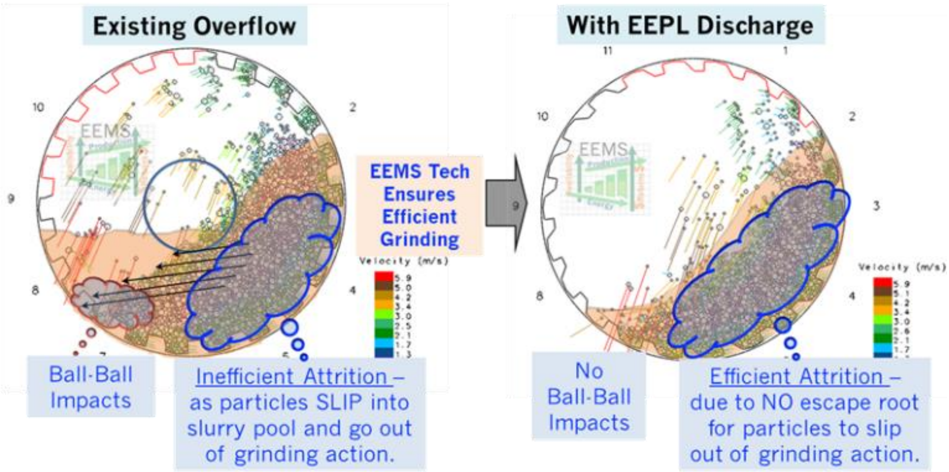


Figure 9: Charge motion in Mill#2 a) with overflow and b) with grate-EEPL discharge.

The EEMS design, consisting of optimised patented EEPL discharge system and shell liners, eliminates all material transport issues and ensures efficient grinding conditions for particle breakage by:

- providing a smooth cascading motion with efficient attrition without the excess slurry, which results in efficient grinding while ensuring all particles pass through the grinding media.
- ensuring optimal grinding conditions to significantly improve particle breakage rates and allow efficient material transport.
- producing a steeper particle size distribution which then improves classification efficiency and reduces the circulating load.

EEMS holistic modelling results and recommendations

The holistic modelling for FMR Greenfields Mill Operation grinding circuit converting Mill#2 from overflow to grate-EEPL discharge, together with a chart showing the comparison of Mill#2 discharge PSD, are given in Figure 10.

Parameter	Units	Survey 4Oct 2019	Simulation (Mill2 with EEPL + Mill3 in OF mode)
Bond Wi (Coarse)	kWh/t	16	16
Feed Size, F_{80}	micron	4318	4318
New Feed	TPH	120	120
Cyc U/f to Ball Mill-1	TPH	52	0
Cyc U/f to Ball Mill-2	TPH	46	94
Cyc U/f to Ball Mill-3	TPH	204	198
Ball Load (Mill-1)	Vol%	33	0
Ball Load (Mill-2_EEPS)	Vol%	36	25
Ball Load (Mill-3_OF)	Vol%	31	31
Mill-1 Power (Motor 500KW)	kW	414	0
Mill-2 Power (Motor 875KW)	kW	708	632
Mill-3 Power (Motor 1325KW)	kW	1203	1203
Total Power	kW	2325	1835
# of Cyclones		5	5
Cycone o/f, P_{80}	micron	106	91
Specific Energy (SE)	kWh/t	19.38	15.29
Operating Work Index	kWh/t	23.65	17.06
Energy saving, % w.r.t. Existing			21.1
Capacity increase, % w.r.t. Existing			0.0
Reduction in Ball Load, % w.r.t. Existing			44%

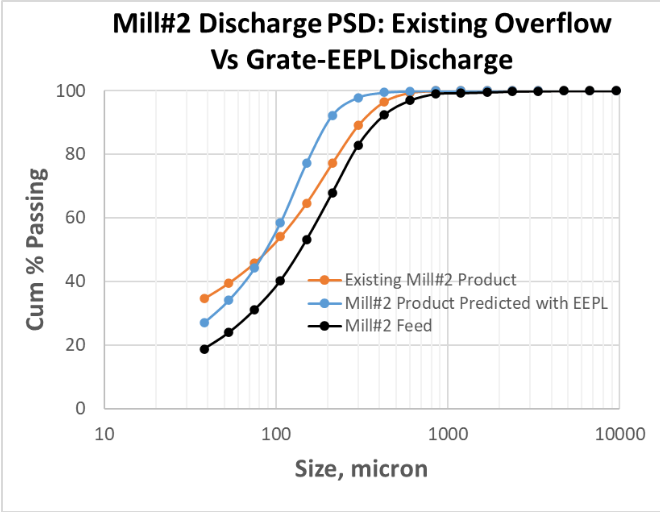


Figure 10: a) Modelling and simulation results and b) comparison of Mill#2 product PSD.

The key benefit of converting Mill#2 from overflow to grate discharge with EEPL technology is that the FMR Greenfields Mill Operation grinding circuit will have surplus capacity to utilise as and when required. Important process advantages noted from the installation are as follows:

- capacity to allow Mill#1 to be completely bypassed and reduce operational costs.
- Mill#2 will be able to do the work of both Mill#1 and Mill#2 as overflow mills, demonstrating the ability of the grate-EEPL system to double the grinding capacity for the same product size, while saving 70 kWh of motor power, and observing a 31% reduction in ball charge in Mill#2.
- reduction in plant specific energy to 15.29 kWh/t (from 19.38 kWh/t), leading to a 21.1% decrease in plant energy requirements.
- improved breakage of +150 µm particles, as all particles must trickle through the tumbling grinding media.
- relatively lower fines generation, as the finer particles discharge faster than the coarse particles and present for classification.

The following stagewise recommendations were given to FMR for implementation to realise the stated benefits.

Stage-1: Convert Mill#2 to grate-discharge with EEPL technology and completely bypass Mill#1, reducing energy requirements by 21.1% as well as saving power, operating, maintenance, and media consumption costs associated with Mill#1.

Stage-2: Convert Mill#3 to grate-discharge with EEPL technology to increase total energy savings to 36% and increase grinding capacity.

Stage-3: Upgrade classification circuit to handle the extra grinding capacity created.

Implementation of Stage 1-converting Mil#2 from overflow to EEPL grate discharge system

The custom designed EEPL discharge pulp lifters and grates were made of chrome-moly steel while the shell and feed head liners were made of rubber. Conversion of Mill#2 from overflow to grate-EEPL discharge occurred in April 2022.

After installation, the circuit started in the pre-installation configuration with all three mills in operation. Shortly after start-up the feed to Mill#1 was gradually diverted to Mill#2 while observing the Mill#2 product size and adjusting the ball charge as required. Mill#2 ball charge volume started at 15% and gradually increased to 21% until Mill#1 was completely bypassed. The proportion of cyclone underflow was also increased towards Mill#2, however no quantitative estimation was done. Mill#2 discharge end with grate-EEPL system is shown in Figure 11 together with the grates after 3 and 4 months of operation.

Figure 11: a) Mill#2 with grate-EEPL discharge end and b) worn steel grates after 3 months c) worn rubber grates after 4 months.

While the rubber liners have worn at the expected wear rate, taking into consideration the increased mill productivity, higher wear rates were observed on the steel grates. This prompted steel grates to be replaced with rubber grates, which improved grate life. Alternative designs are being considered to further improve the life of grates. Pegging of both steel and rubber grates has not been an issue.

Pre and post grinding survey data

Grinding surveys were carried out before and after installation of EEPL grate discharge system in Mill#2 to assess the performance of the overall comminution circuit with details given in Figure 12.

Parameter	Units	PRE (Mill1+Mill2+Mill3 in OF mode)	POST (Mill2 with EEPL + Mill3 in OF mode)
Bond Wi (Coarse)	kWh/t	17.2	17.2
Feed Size, F_{80}	micron	8053	7318
New Feed	TPH	150	150
Cyc U/f to Ball Mill-1	TPH	62	0
Cyc U/f to Ball Mill-2	TPH	60	122
Cyc U/f to Ball Mill-3	TPH	256	256
Ball Load (Mill-1)	Vol%	33	0
Ball Load (Mill-2_EEPS)	Vol%	36	21
Ball Load (Mill-3_OF)	Vol%	31	31
Mill-1 Power (Motor 500KW)	kW	414	0
Mill-2 Power (Motor 875KW)	kW	708	583
Mill-3 Power (Motor 1325KW)	kW	1203	1208
Total Power	kW	2325	1791
# of Cyclones		6	5
Cycone o/f, P_{80}	micron	136	132
Specific Energy (SE)	kWh/t	15.50	11.94
Operating Work Index	kWh/t	20.78	15.85
Energy saving, % w.r.t. Existing			23.0
Capacity increase, % w.r.t. Existing			0.0
Reduction in Ball Load, % w.r.t. Existing			47%

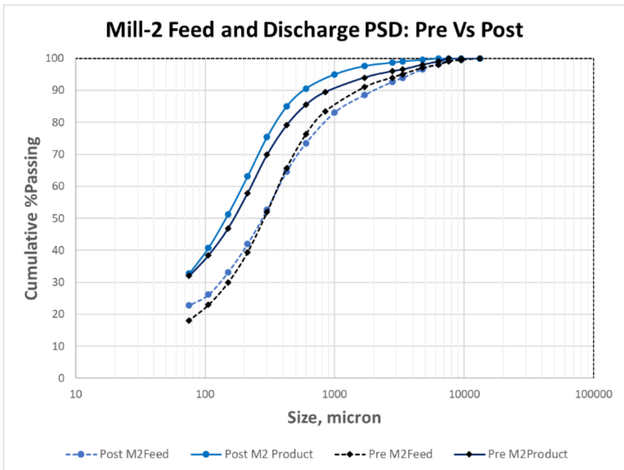


Figure 12: a) Pre and post survey data b) Pre and post comparison of Mill#2 feed and product PSD.

Comparing the pre and post grinding survey data shown in Figure 12, the following observations were made:

- Savings of 534 kWh of motor power from secondary grinding mills (Mill#1 and Mill#2) has decreased the plant specific energy from 15.50kWh/t to 11.94kWh/t – a reduction by 23%.
- Although mill feed and product size from the pre and post grinding surveys of 2022 (Figure 11) are significantly different to the 2019 survey (Figure 10), the observed plant energy savings (23%) matched well with the predicted energy savings (21.1%), which illustrates the predictive capability of the EEMS holistic modelling approach.

- The PSD of Mill#2 product post installation shows higher breakage of coarser particles as predicted in the simulation (Figure 10), which indicates a fundamental advantage where particles cannot bypass the tumbling media, (unlike in overflow ball mills due to presence of a large slurry pool) which increases particle breakage rates.

Pre and post operational data

The daily operational data of pre (January 2021 to March 2022) and post (April 2022 to Apr2023) conversion of Mill#2 from overflow to EEPL grate discharge system has been compared to evaluate the performance of FMR Greenfields grinding circuit.

Comparison of plant throughput:

Operational results since April 2022 have amply proven that the conversion of the overflow ball mill to a true open-ended grate mill using EEPL technology enables a significant increase in mill capacity for the same grind size. In addition to doubling Mill#2 capacity, diverting a higher proportion of cyclone underflow towards Mill#2 has also helped increase plant capacity by 10% from 0.935 Mt/y using Mill#1+Mill#2+Mill#3 to 1.025 Mt/y using Mill#2+Mill#3 (Figure 13).

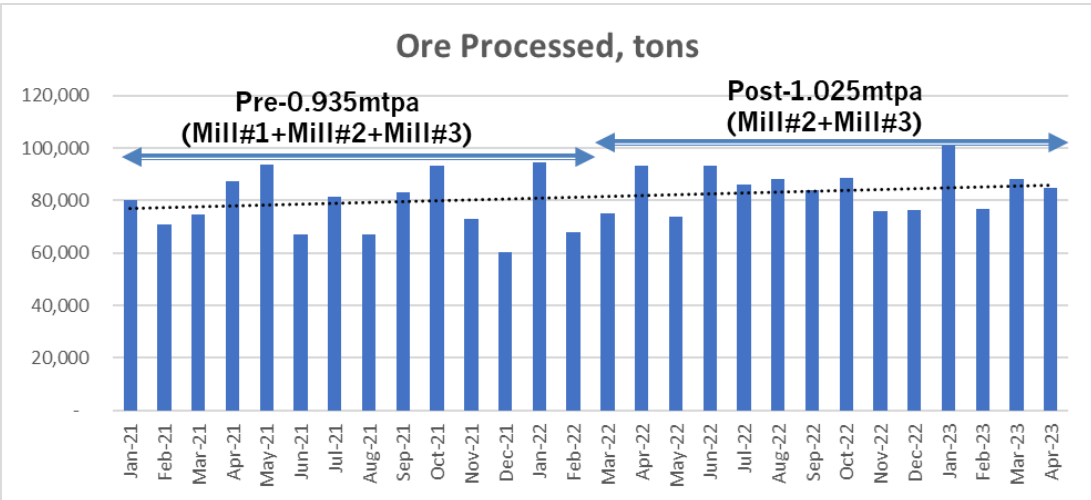


Figure 13: Pre and post comparison of plant throughput.

Comparison of plant power consumption:

Pre and post data of daily plant power draw and daily plant specific energy are plotted in Figure 14 which clearly shows the power savings since implementation of the grate-EEPL system in Mill#2 with plant power draw decreased from 2315 kWh to 1805 kWh – a saving of 510 kWh on average since April 2022, which reduced the plant specific energy by 22% from 19.07 kWh/t to 14.44 kWh/t while doing the same or more grinding without Mill#1.

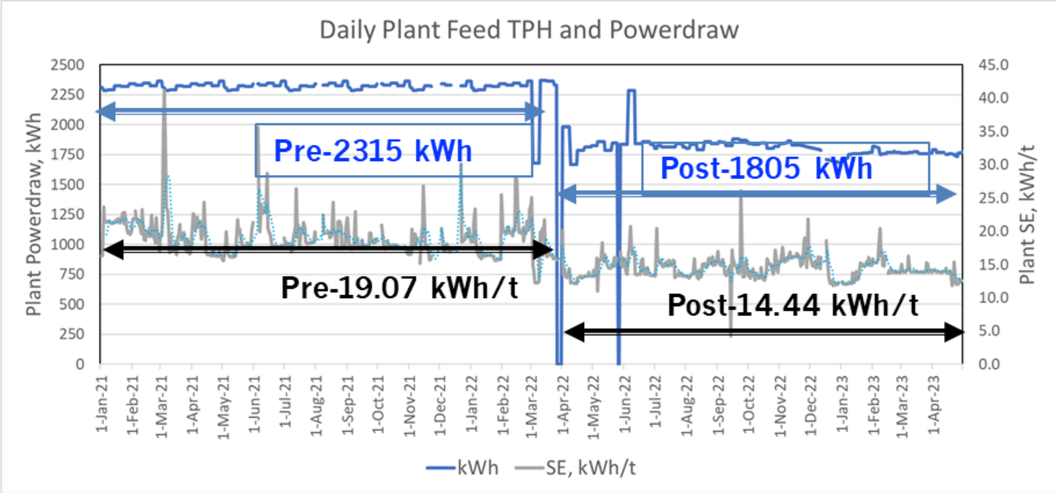


Figure 14: Pre and post comparison of plant power draw and plant specific comminution energy.

Comparison of feed and product size:

Effective utilisation of ball action and quick migration and removal of the finished product enables grinding of particles with high energy efficiency, and this too can grind coarser particles, which is evident from Figure 15, where the daily plant data of feed (F_{80}) and product (P_{80}) size are plotted for pre and post operating conditions. It is visible from Figure 15 that the product size gradually increases with increase in feed size before conversion, whereas finer product is generated after conversion of Mill#2 to grate-EEPL discharge.

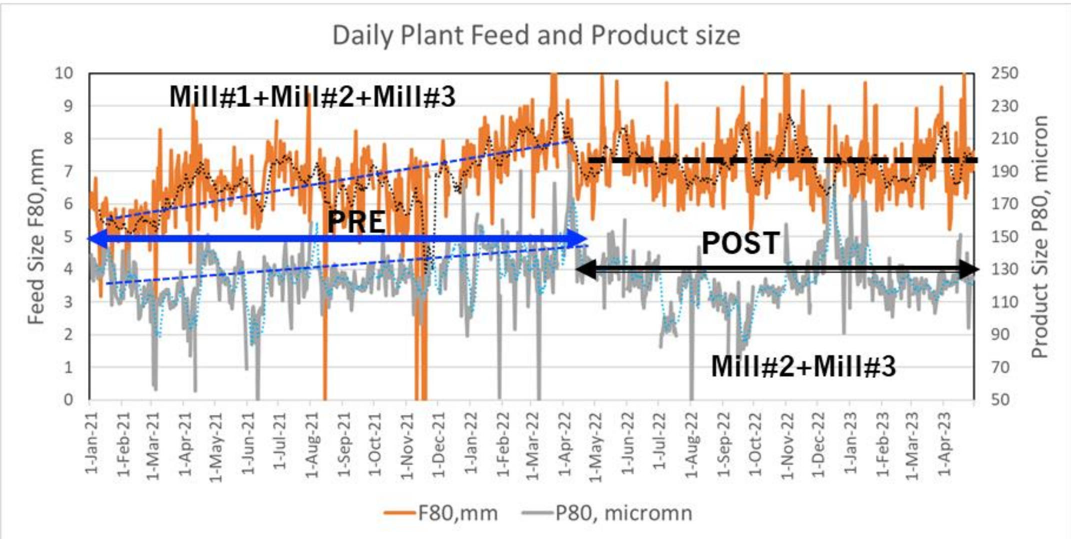


Figure 15: Pre and Post comparison of plant feed and product sizes.

Comparison of ball wear:

The plant media consumed in 12 months before conversion of Mill#2 was 875 t to process 0.935 Mt of ore, while used 769 t of media and processed 1.025 Mt of ore. In contrast to the general concern of higher ball wear and ball breakage, media wear decreased from 936 g/t to 751 g/t (a 19.7% reduction) as shown in Figure 15, while processing more tonnes. Lowering the media consumption also leads to a reduction in carbon footprint by 2.3 kg CO_2 per kg of steel ball consumption (Morrell 2022), and it is estimated to further reduce CO_2 emissions by 397 t/y to process 0.935 Mt/y of ore in post operational scenario. Similar observations were made at Jindal Saw and Degrussa, where hi-chrome media is used.

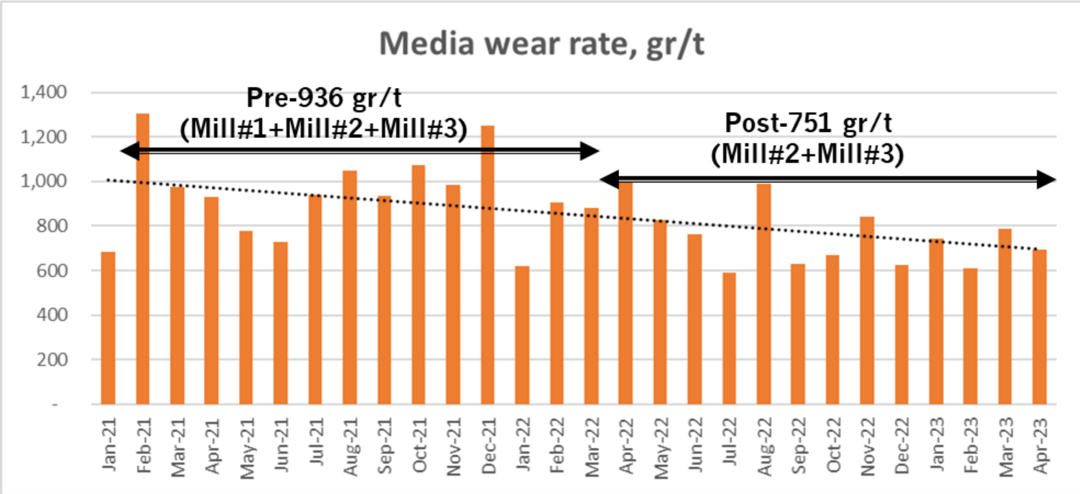


Figure 16: Pre and post comparison of media consumption.

ENERGY EFFICIENCY AND CARBON FOOTPRINT

A major contributor to the carbon footprint of the mining industry is comminution and the pressure to significantly improve comminution energy efficiency is intense. Morrell (2022) recently estimated the annual electricity consumption of AG/SAG and ball mills as 116.5 billion kWh (TWh) with 48.9 billion kWh being consumed in AG/SAG mill circuits and 67.6 billion kWh in ball mill circuits. Considering a global emissions rate of 0.556 kg CO_2/kWh of electricity generated and a total of 2.3 kg CO_2 emitted per kg of steel ball consumption, Morrell (2022) estimated the total annual CO_2 emissions from AG/SAG and ball mills as summarised in Table 3 including the potential reduction in CO_2 emissions of the mining industry using High Pressure Grinding Rolls (HPGR) technology.

Table 3: Estimated global CO_2 emissions from AG/SAG-ball mill circuits and potential savings using HPGR-ball mill technology (Morrell 2022).

Estimated Global Data	Units - per year	AG/SAG-Ball Mill
Electricity consumption	TWh	116.5
CO_2 from electricity generation	Mt	64.8
Steel ball consumption	Mt	6.5
CO_2 from steel ball manufacture	Mt	15.0
Total CO_2 emissions	Mt	79.8

Consistent operation of ball mills over the last few years after converting from overflow to open-ended grate discharge with EEPL technology has demonstrated a significant increase in energy efficiency with a considerable reduction in specific energy consumption, as predicted and observed in both laboratory and pilot scale tests carried out at the University of Utah (Latchireddi R, 2017).

CO_2 emissions are estimated using the specific energy (kWh/t) values and the throughput operated after converting an overflow mill to a grate discharge using EEPL technology for each of the case studies and summarised in Table 4.

Table 4: Estimated CO_2 emissions from case studies based on specific energy consumption and absolute power savings from converting overflow to grate discharge with EEPL Technology.

Based on Specific Energy (SE) consumption	Copper (Degrussa)		Magnetite (JSW)		Gold (FMR)	
	Before (Overflow)	After (EEPL)**	Before (Overflow)	After (EEPL)**	Before (Mill#1+Mill#2)	After (Mill#2-EEPL)**
# of Mills	1	1	3	3	2	1
Bwi, kWh/t	14.3	14.3	15.5	15.5	17.4	17.4
Ball Load, Vol%	33	18	32	16	36	21
Throughput, TPH	187	236	128	159	122	122
Motor Power, kW	2800	2800	2800	2800	1300	825
Power Draw, kWh	2321	1690	2214	1492	1122	612
Sp Eneregy, kWh/t	12.412	7.161	17.297	9.384	9.221	5.016
%Energy Savings wrt Overflow		**42.3**	-	**45.7**	-	**45.6**
Tonnes of CO2 Emmisions wrt specific energy@tph**	13,029	7,517	12,233	6,636	5,004	2,722
Reduction in CO2 Emmisions, tonnes/yr		5,512		5,596		2,282
%Reduction in Carbon Footprint		**42.3**		**45.7**		**45.6**
** throughput attained with EEMS is taken for estimation of CO2 emmisions						
Based on absolute power savings	**Copper (Degrussa)**		**Magnetite (JSW)**		**Gold (FMR)**	
	Before (Overflow)	After (EEPL)	Before (Overflow)	After (EEPL)	Before (Mill#1+Mill#2+ Mill#3)	After (Mill#2-EEPL+ Mill#3)
Power Draw, kWh	2321	1690	2214	1492	2315	1805
Tonnes of CO2 Emmisions per Year from Electricity	10,324	7,517	9,848	6,636	10,297	8,029
Reduction in CO2 Emmisions, tonnes/yr		2,807	-	3,211	-	2,268
%Reduction in Carbon Footprint		**27.2**	-	**32.6**	-	**22.0**

An example of estimating CO_2 emissions for the FMR (Gold) case is provided following:

Reduction of CO_2 emissions based on the specific energy:

- Base case in overflow = 122 tph x 9.221 kWh/t x 8000 hr x 0.556 kg)/1000 = 5004 t CO_2 per annum.
- With EEMS = (122 tph x 5.123 kWh/t x 8000 hr x 0.556 kg)/1000 = 2780 t CO_2 per annum.

Reduction of CO_2 emissions based on the absolute power savings:

- Absolute motor power savings per hour = 2315-1805 = 510 kWh
- Reduction in CO_2 emissions per annum= 510kWhx 8000 hr x 0.556 kg) /1000 = 2,268 t

Considering the absolute motor power savings realised at each of the operations, without considering the increased throughput, the estimated annual reduction in carbon footprint in tonnes of CO_2 emissions are given in Table 4, which shows an average of 27.3% reduction in carbon footprint. This illustrates that the global carbon footprint from ball mills can be reduced to the tune of 10.26 Mt of CO_2 emissions per year from a total of 37.58 Mt (58% of 64.8 Mt) of CO_2 emissions generated from global power consumption of ball Mills.

CONCLUSIONS

Successful operation of numerous ball mills installed at copper, iron, and gold operations, after converting overflow ball mills to open-ended grate mills using EEPL discharge technology, has illustrated the benefits observed early in the twentieth century when the Marcy open-ended grate discharge mill was compared against Hardinge's conical overflow mill at Inspiration Hills Copper Mine (Van Winkle, 1918).

Since successful conversion of one secondary overflow mill at the Greenfields Mill Operation in March 2022, the plant has been operating with one primary mill and one secondary mill and not needing to utilise a second secondary mill, demonstrating the magnitude of attaining high throughput in open-ended grate discharge mills compared to overflow mills.

Following comparison of one-year of post-operational data with one year of pre-operational data, the following observations were made:

- a reduction of 510 kWh in electricity consumption, which reduced specific energy of the secondary grinding circuit by 45.6% and overall plant specific energy by 22%
- saving of 510 kWh (4.08 million kWh per annum) electrical energy reduces a total of 2268 t of CO_2 emissions per annum.
- a decrease in grinding media consumption by 19.7% that further reduces the CO_2 emissions by 397 t/y for processing 0.935 Mt/y.
- increased plant capacity by 10% from 0.935 Mt/y to 1.025 Mt/y
- a sharper product size distribution with coarser feed product
- an ability to use percent solids to control product size.

FMR Greenfields Mill Operation is considering the upgrade of the primary Mill#3 from an overflow to an EEPL discharge system based on the results of the Mill#2. This is expected to save more energy, further reduce the operations carbon footprint, and provide circuit flexibility when toll treating different ore types.

Converting overflow ball mills to open-ended grate mills using EEPL discharge technology can result in:

- improved revenue by increased throughput with a lower carbon footprint
- direct power savings with real reductions in carbon emissions
- direct media cost savings
- no requirement to sacrifice the primary grind (and recovery) in mill-limited operations.

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