Trade-Off Realities in HPGR vs. SAG Milling—A Practical Comparison of Tropicana and Gruyere Comminution Circuits

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Abstract

The uptake of HPGR technology in mineral processing has been accelerated by the drive for energy-efficient comminution solutions. A HPGR trade-off study is now part of the typical due diligence process when assessing the suitability of SAG milling circuits, particularly for large-scale, hard rock applications with moderate to high power cost.

The energy consumption savings are now reasonably well established for HPGR circuits, however the overall trade-off outcome in practice is less understood. To provide an operating benchmark, the authors undertook a collaborative review of the neighbouring Gruyere and Tropicana operations in Western Australia.

Construction of the Tropicana Gold Mine (Tropicana) commenced in November 2010, with first ore processed during July 2013. The comminution circuit is secondary crush, HPGR ball-milling now achieving 8.6-9.5 Mt/a. The Gruyere project construction commenced during 2017, with first ore processed in May 2019. The comminution circuit flowsheet is primary crush, SABC (SAG mill, ball mill and pebble crusher) treating about 8.5-9.0 Mt/a of fresh ore. Orway Mineral Consultants (OMC) has been involved with both projects from scoping-level study to current optimisation. This paper presents the energy efficiency and relative costs of both circuits, adjusted to provide a relative comparison of the two flowsheets.

Keywords

Circuit design, energy efficiency, SAG milling, HPGR grinding, cost comparison, trade-off economics.

Introduction

The Tropicana Gold Mine (Tropicana), a joint venture owned by AngloGold Ashanti Australia Limited (70% - JV manager) and Regis Resources Limited (30 %) is located on the western edge of the Great Victorian Desert in Western Australia. Gruyere Gold Mine, 170 km north-west of Tropicana, is operated by Gold Fields Ltd in a 50:50 joint venture with Gold Road Resources Ltd. The comminution circuits at both mines treat ore of comparable competency from the eastern border of the Yilgarn Craton. The former operation features a HPGR-ball milling circuit while the latter comprises a SABC milling circuit.

Both projects are now established operations, treating ore akin to the design competency point. This combination of attributes gave rise to the opportunity to conduct a comparison study using real operating data, to assess the actual performance of the two circuits. This paper summarises background information about the two projects including a brief geological description, major comminution equipment summary, block flow diagrams and comparison of design comminution parameters. The most comparable survey data from each circuit is used to assess the energy efficiency. The comminution circuit relative capital costs, operating costs, carbon emissions and stability are compared, highlighting significant points of difference and areas of interest.

Project Background

ORE CHARACTERISTICS

Both circuits were designed to treat 100% fresh ore. The design point used for equipment selection was the 85th percentile (15th percentile in the case of Axb) of the fresh ore samples for both projects. A summary of the design test work for each is presented in Table 1.

Table 1—Summary of Gruyere and Tropicana Design Ore Comminution Testwork Parameters

Parameter	Unit	Tropicana	Gruyere
Crushing Work Index	kWh/t	19.1	21.0
Bond Rod Work Index	kWh/t	21.5	22.0
Bond Ball Work Index	kWh/t	18.2	18.3
Abrasion Index	g	0.32	0.53
JKDW Axb		31.5	-
ta		0.32	0.3
SMC Axb		33.1	31.5
DWi	kWh/m^3	8.6	8.5
SG		2.82	2.69

For the purposed of this review, the most significant difference between the two projects is the abrasion index, which has an impact on the operating costs.

The location of both projects is shown in Figure 1.

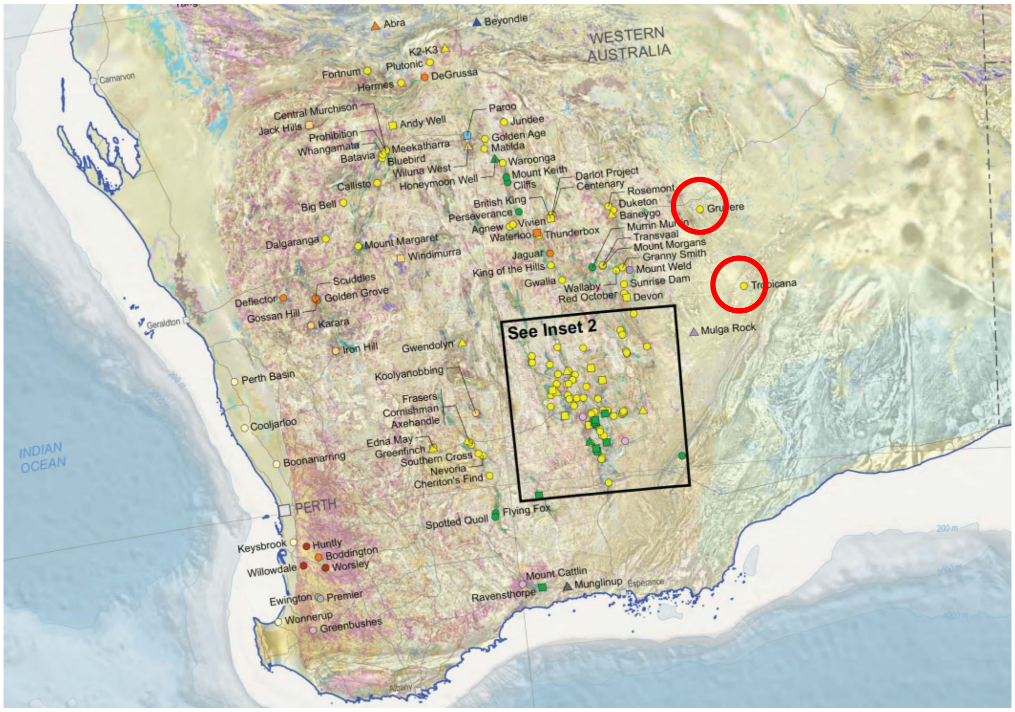

Figure 1—Location of Tropicana and Gruyere in Relation to Western Australian Gold Operations (Geoscience Australia, 2022)

PROCESS FLOW DESCRIPTION

Tropicana

The Tropicana comminution flowsheet has primary crushing followed by a coarse ore stockpile. Primary crushing is conducted in a single FLSmidth TSU 1400 x 2100 gyratory crusher, with 600 kW installed power. The crusher achieves a P_{80} of 150 mm-170 mm.

The coarse ore is reclaimed from the coarse ore stockpile via two reclaim apron feeders and conveyed to the secondary screen feed bins. The secondary screens are two parallel 3.0 m x 6.1 m double deck banana screens operating with a 90 mm top deck aperture and 45 mm bottom deck aperture. The oversize from both decks combine to feed the secondary cone crushers, while the -45 mm rock reports to the HPGR circuit. The secondary crushing stage comprises 2 x FLSmidth XL900 Raptor cone crushers, 600 kW each, which operate in closed circuit with the two secondary screens.

The secondary screen undersize reports to the HPGR feed bin, which has 540 t live capacity. A belt feeder, in combination with HPGR roll speed, is used to maintain choke feed conditions to the HPGR. A single Köppern Ø2.0 m x 1.85 m HPGR is used for the tertiary crushing stage. This is fitted with 2 x 2,200 kW variable speed motors. The HPGR operates in closed circuit with wet screens.

The design includes the ability to continuously cut a fraction from the HPGR discharge to create a HPGR fines emergency stockpile. A portion of the HPGR discharge is cut and dry screened at 4 mm, with minus 4mm material stockpiled and plus 4 mm material conveyed back to the HPGR discharge stream. The stockpiled fines (-4 mm) are reclaimed using a front-end loader (FEL), to either feed the wet screens (when the HPGR or secondary crushing plant is offline) or fed to a re-pulping system and pumped directly to the mill discharge sump when the wet screens are offline.

There are two parallel wet screens that classify the HPGR discharge. HPGR discharge reports to the wet screen feed bins, which have a combined live capacity of 1,328 t. Belt feeders reclaim from the HPGR bins and feed the screen pulping boxes, which de-agglomerate flake before reporting to the screens. The wet screens are 4.2 m W x 8.5 m L double deck banana screens which operate with 8 mm top deck and 4 mm bottom deck apertures. The combined screen oversize is combined with the secondary screen undersize and conveyed back to the HPGR feed bin. Included in the design is the ability to reject and stockpile wet screen oversize from the circuit if required.

The -4 mm wet screen undersize reports to the Ball Mill 1 discharge hopper along with the Ball Mill 1 discharge stream. This is pumped to a cyclone cluster for classification, which is fitted with 12 x GMAX26 hydrocyclones. The cyclone overflow exits the grinding circuit, reporting to the trash screens and leach feed thickener, while the cyclone underflow reports to Ball Mill 1. Ball Mill 1 is a Ø7.32 m x 13.12 m effective grinding length (EGL), overflow discharge mill operating in closed circuit. The Outotec ball mill is equipped with two 7.0 MW pinion drives (initially operated as variable speed via slip-energy-recovery (SER), now fixed speed). The final P_{80} target is 75 µm for the combined cyclone overflow.

A transfer stream is pumped from the Ball Mill 1 discharge hopper to the Ball Mill 2 discharge hopper. This material is pumped to a second cyclone cluster for classification, which is fitted with 10 x GMAX20 hydrocyclones. Cyclone overflow exits the grinding circuit and reports to the trash screens. Cyclone underflow gravitates to the Ø6.10 m x 9.05 m effective grinding length (EGL), overflow discharge ball mill for further size reduction. Ball Mill 2 is equipped with a 7.0 MW single pinion drive (fixed speed). Note that the drive is oversized to match Ball Mill 1; with maximum mill power draw of around 6.0 MW. The final P_{80} target is 75 µm for the combined cyclone overflow.

A block flow diagram of the Tropicana comminution circuit is shown in Figure 2, with Figure 3 showing an aerial view of the site.

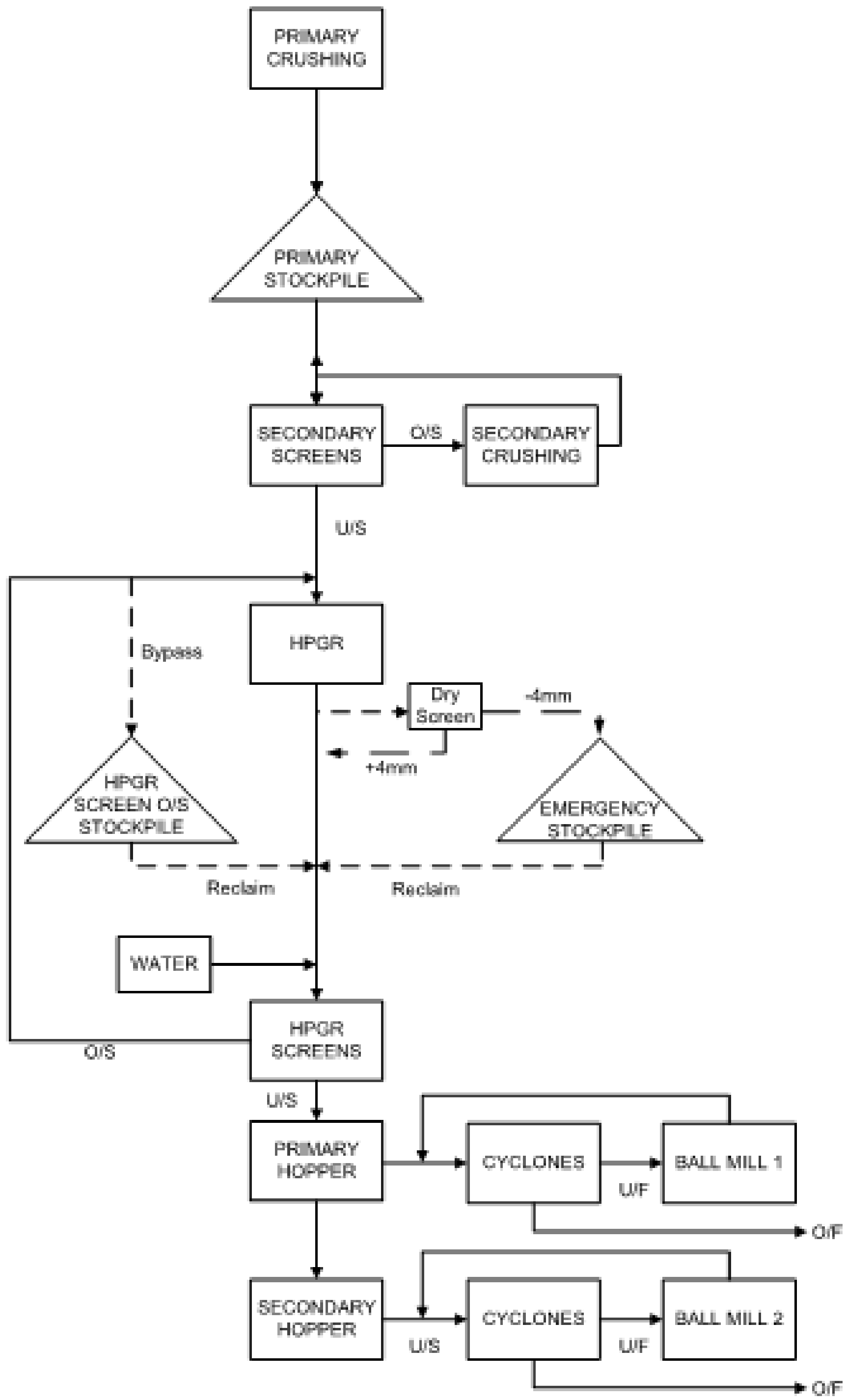

Figure 2—Tropicana Comminution Circuit Block Flow Diagram

Figure 3—Tropicana Comminution Circuit Layout

Gruyere

The Gruyere comminution flowsheet has primary crushing followed by a coarse ore stockpile. Primary crushing is conducted with an FLSmidth TSU 1400 x 2100 gyratory crusher, with 600 kW installed power. In practice, an F_{80} range of 100-110 mm is targeted and maintained at an 1,800 t/h average throughput. The coarse ore is reclaimed from the stockpile via three reclaim apron feeders and conveyed to the SAG mill.

The primary crushed feed is conveyed to the SAG mill feed chute. Lime is dosed to the SAG mill feed conveyor from two lime silos. The SAG mill is a single Outotec Ø 10.97 m x 5.79 m EGL (36' x 19') mill equipped with a 15 MW dual pinion drive (7.5 MW per drive). The SAG mill discharges over a single 3.6 m x 8.5 m vibrating screen fitted with 14 mm (8.5 mm originally) aperture screen panels. The screen oversize is conveyed to the pebble crusher storage bin. Pebbles are reclaimed from the bin via two belt feeders, each reporting to a pebble crusher. The pebble crushers are two parallel Metso HP4 cone crushers fitted with 315 kW drives. Crushed pebbles are returned to the SAG mill feed conveyor.

The SAG mill discharge screen undersize reports to the common mill discharge hopper, along with the ball mill discharge and dilution water. This is pumped to the cyclone cluster for classification, which is fitted with 12 x 650 mm hydrocyclones. The cyclone overflow exits the grinding circuit, reporting to the trash screens and leach feed thickener, while the cyclone underflow reports to the closed circuit Ø 7.92 m x 10.82 m EGL (26'x 35.4') overflow discharge ball mill for further size reduction. The FLSmidth ball mill is equipped with a 15 MW dual pinion drive (common 7.5 MW motors with SAG mill). There is the ability to bleed portion of the cyclone underflow to the SAG mill feed chute, if required. The final cyclone overflow P_{80} target is 125 µm.

Part of the cyclone feed is fed to the gravity circuit from the combined mill discharge hopper via a dedicated pump. A baffle in the mill discharge hopper is designed to segregate the SAG mill and ball mill discharge, with the gravity feed drawn from the ball mill side to assist in pre-concentration of the gravity feed. The gravity circuit comprises 2 x gravity screens and 4 x 48" Knelson centrifugal concentrators. Tailings from the gravity concentrators is combined with the gravity screen oversize and returned to the mill discharge hopper on the SAG mill discharge side of the baffle. The gravity concentrate reports to a Gekko intensive leach reactor, with pregnant solution reporting to the gold room, and washed leach residue returned to the mill discharge hopper. A block flow diagram of the Gruyere comminution circuit is shown in Figure 4, with Figure 5 showing the ariel overview of the site.

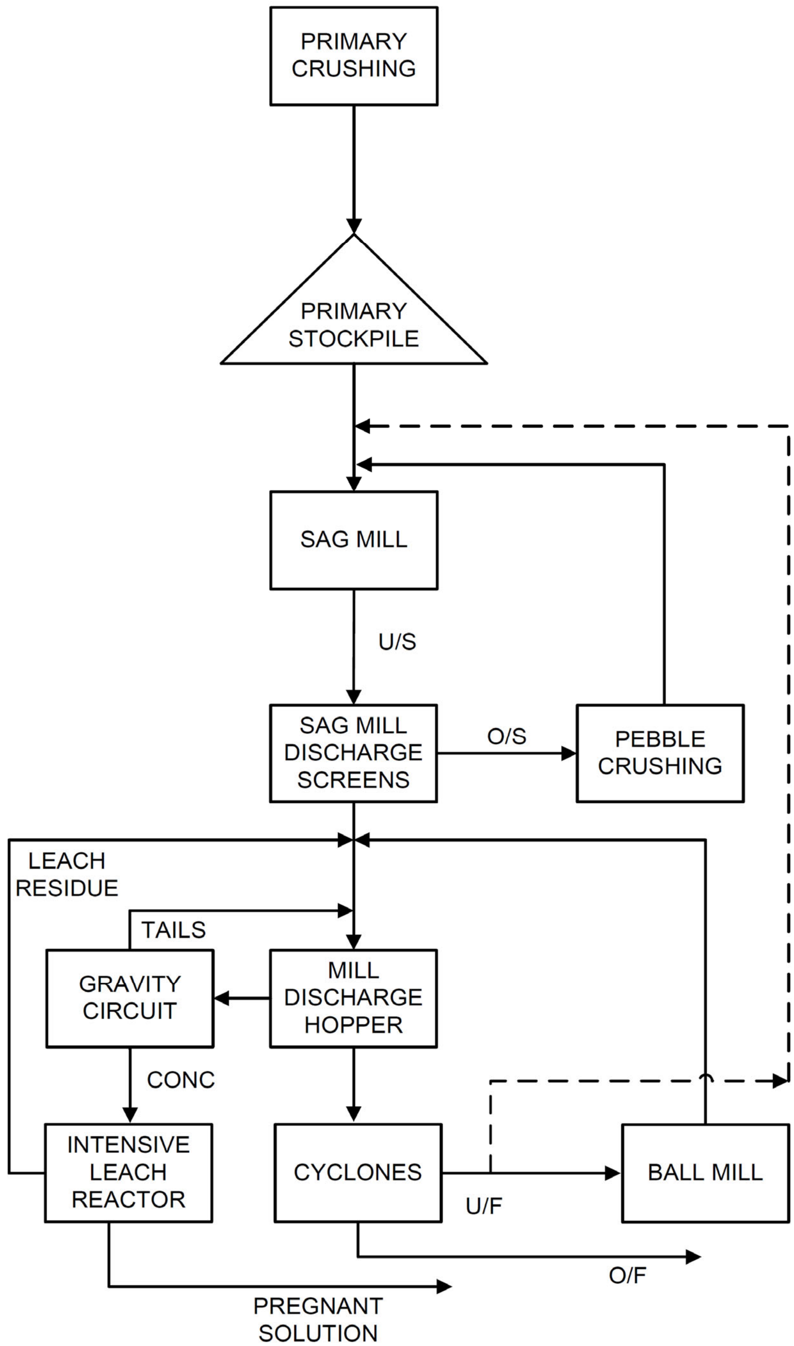

Figure 4—Gruyere Comminution Circuit Block Flow Diagram

Figure 5—Gruyere Comminution Circuit Layout

A summary of the major equipment of each comminution circuit is presented in Table 2.

Table 2—Major Comminution Equipment

Parameter	Unit	Tropicana	Gruyere
Primary Crusher			
Make		FLSmidth	FLSmidth
Model		TSU 1400 x 2100	TSU 1400 x 2100
Installed power	kW	600	600
Primary Stockpile	Dry tonnes, live	16,039	17,229
Secondary Crusher			
Make		FLSmidth	-
Model		XL Raptor900	-
Number installed		Two (duty/standby)	-
Installed power	kW	600	-
Secondary Feed Bins	Dry tonnes, live	200 per bin	-
Secondary Screens			
Type		DD Banana	-
W x L	m	3.0 x 6.1	-
Number Installed		Two (duty/standby)	-

Parameter	Unit	Tropicana	Gruyere
Pebble Crusher			
Make		-	Metso
Model		-	HP4
Number installed		-	Two
Installed power	kW	-	315
HPGR Feed Bin Size	Dry tonnes, live	540	-
HPGR			
Make		Koppern	-
Number installed		One	-
Roll Diameter		2.0	-
Roll Length		1.85	-
Installed Power	MW	4.4	-
Emergency Stockpile	Dry tonnes, live	30,000	-
HPGR Screens			
Type		DD Banana	-
W x L	m	4.2 x 8.5	-
Number Installed		Two	-
HPGR Screen Feed Bin Size	Dry tonnes, live	1,328 combined	-
Mill 1			
Type		Ball Mill	SAG Mill
Make		Outotec	Outotec
Inside shell diameter	m	7.32	10.97
Effective grinding length	m	13.14	5.79
Imperial measurements	ft x ft	24.0 x 43.0	36.0 x 18.9
Installed power	MW	14	15
Mill 2			
Type		Ball Mill	Ball Mill
Make		Outotec	FLSmidth
Inside shell diameter	m	6.10	7.93
Effective grinding length	m	9.05	10.82
Imperial measurements	ft x ft	20.0 x 29.7	26 x 35.4
Installed power	MW	7	15
Total Installed Power	**MW**	**27.20**	**31.23**

A significant difference in the overall circuit energy efficiency is driven by the installed conveyor power. A summary of the conveyor specifications is presented in Table 3.

Table 3—Conveyor Specifications

Conveyor ID	Description	Belt Width (mm)	Belt Length (m)	Belt Lift (m)	Motor (kW)
Gruyere					
CV001	Primary Crush Discharge	1,800	76	11.	110
CV002	Stockpile Feed	1,800	156	8	315
CV003	SAG Mill Feed	1,500	230	16	280
CV004	Pebble Transfer	600	16	0	45
CV005	Pebble Crusher Feed	600	138	18	55
CV006	Pebble Crusher Discharge 1	600	22	3	30
CV007	Pebble Crusher Discharge 2	600	22	3	30
CV008	Pebble Bypass Conveyor	750	32	0	30
	Total				**895**
Tropicana					
CV01	Primary Crush Discharge	1,600	210	40	500
CV02	Secondary Crusher Screen Feed	1,600	259	30	250
CV03	Secondary Crusher Feed	1,600	176	21	75
CV04	Secondary Crushed Transfer	1,600	71	5	30
CV05	HPGR Feed	1,600	162	28	250
CV06	HPGR Product	1,600	98	11	132
CV07	HPGR Scalp Screen Feed	1,600	205	35	355
CV08	Emergency Feed Transfer	600	63	8	7.5
CV09	HPGR Screen O/S Transfer	1,600	104	5	37
CV10	HPGR Screen O/S Stockpile	1,600	54	8	55
CV11	Reclaim Stacker	600	44	12	7.5
	Total				**1,699**

Current Operation

Tropicana was ramped up to design throughput within two months of HPGR commissioning (Kock, Siddall, Lovatt, Giddy & Di Trento, 2015). Gruyere commissioning and ramp-up started in May 2019, with nameplate capacity achieved in approximately 8 months, well within the expected McNulty schedule for a mature and well-developed technology (Radford, Foster, Putland & Lovatt, 2019). Both circuits were commissioned on oxide/transitional ore, which can mask the true ramp-up time, however this was problematic for the Tropicana flowsheet which typically cannot accommodate more than 20% of oxide in feed. This led to higher-than-design downtime due to materials handling issues, particularly around the wet screening circuit. These issues quickly resolved with the introduction of unweathered ore into the blend by the third month of production. This blend variation is an area of added complexity that can impact both flowsheets, however the SABC circuit can be much better adapted for processing extended periods of oxide with the correct liner design and charge operating setpoints.

The monthly processed tonnages for both the Tropicana and Gruyere circuits are shown for the 2019 to 2022 period in Figure 6.

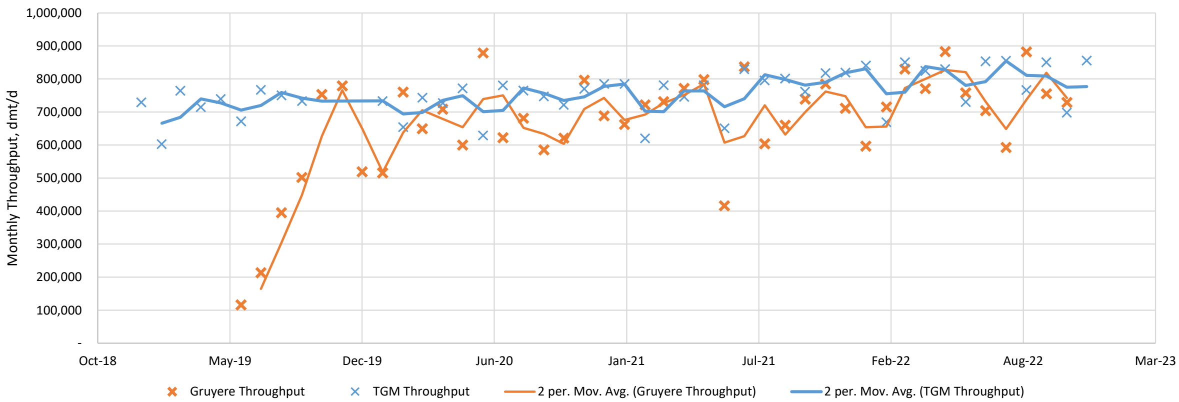

Figure 6—Circuit Monthly Throughput, 2019 to 2022

The Tropicana circuit, being in a more mature operation, demonstrates a more reliable performance and has engaged in continuous process and maintenance optimisation for a longer period. Both circuits exhibit cyclical throughput, in line with major maintenance activities such as relining and shutdowns (see Table 4 for details).

Table 4—Liner, Media & Roll Replacement Frequency (per annum per unit)

Description	Tropicana	Gruyere
Gyratory – Mantle	3	12
Gyratory – Concave	1	4
Secondary Crusher	12	-
Pebble Crusher	-	120
HPGR Rolls	1.0	-
SAG Mill Liners	-	3
Ball Mill Liners	0.7	0.8
SAG Mill Media, t	-	4,467
Ball Mill Media, t	4,902	5,307

A summary of average operating key performance indicators is presented in Table 5, with 2019 excluded to account for the ramp-up period. The auxiliary power consumption was determined was subtracting major equipment power consumption from the total power consumption by area of the plant.

Table 5—Key Operating Parameters Summary (Jan 2020—Dec 2022)

Parameter	Unit	Tropicana	Gruyere
Primary Crushing			
-Throughput	t/h	1,853	1,740
-Specific Energy	kWh/t	0.2	0.2
-Overall Utilisation	%	57.3	55.8
Secondary Crushing			
-Throughput	t/h	1,284	-
-Specific Energy	kWh/t	0.3	-
-Overall Utilisation	%	83.3	-
HPGR			
-Throughput	t/h	1,284	-
-Circulating Load	%	90	-
-Specific Pressing Force	kN/t	3.2	-
-Specific Energy	kWh/t	2.5	-
-Overall Utilisation	%	83.3*	-
Milling			
-Throughput	t/h	1,103	1,072
-Specific Energy	kWh/t	16.1	22.4
-Overall Utilisation	%	96.6	91.7
-Cyclone O/F P_{80}	µm	74	159
Auxiliary Equipment	kWh/t	3.8	2.0
Total Specific Energy	**kWh/t**	**22.9**	**24.6**

*HPGR circuit availability is 92.0%.

Both milling circuits are now exceeding design utilisation (91.3 %) and maintain comparable annual throughput rates (8.5 Mt/a). Tropicana targets a finer final product size than Gruyere. This is driven by differences in mineralogy that result in different grind-recovery curves and has been adjusted for in the energy efficiency comparison.

Short-Term Variability

The short-term variability in throughput is typically higher for SABC circuits than HPGR-ball mill circuits (Amelunxen, Mular, Vanderbeek, Hill & Herrera 2019). The Tropicana circuit typically exhibits a throughput and grind coefficient of variance (CoV) of only 2% when examining short-term data (Table 6). SABC circuits often have a throughput CoV of 5-15%, primarily due to the impact of variability in ore characteristics (Amelunxen et al, 2019). The CoV experienced can be exacerbated by the control philosophy implemented and the objectives the control system is programmed to achieve. The Gruyere circuit utilises an expert control system which varies the mill speed within a range to keep throughput more consistent while maximising throughput. This has resulted in a throughput CoV of about 5.8% for the Gruyere circuit. The importance of feed rate variability is generally less significant for the downstream leach circuit in Gruyere's case than more sensitive flotation circuits, where the improved stability should be considered in the trade-off study. In terms of stability, the HPGR-ball circuit is considered superior, allowing the circuit throughput rate to be controlled directly to a target grind size with minimal variability. This is driven by the variance in the finer grinding ore characteristics (Ball Work Index) alone.

The HPGR circuit has the ability to operate within a wider range of ore competency (Axb) with little operator intervention required and with minimal impact on process variability. At Tropicana, typically only a modest change in HPGR recirculating is experienced as ore hardness changes, with the operating pressure adjusted for greater changes in ore hardness. This is in contrasted to an SABC circuit, where the change in operation required is often greater than achievable with the SAG mill VSD alone. Comparable changes in ore characteristics often require a more tedious ball charge adjustment, increasing the propensity for reduced throughput rate. Additional benefit should be assigned to HPGR circuits in option studies where the ore variability is expected to be wide and changing frequently, particularly when the ore competency (Axb) doesn't trend with BWi. Only when the variance is such that impacts the material handling properties is the HPGR option disadvantaged (ability to handle blends high in sticky oxide ore).

Table 6—Variability in Typical 24-Hour Operating Period

Parameter	Unit	Tropicana		Gruyere	
		Average	**CoV**	**Average**	**CoV**
Throughput	t/h	1,174	1.0	1,296	5.8
Mill Power – Combined	kW	18,400	1.1	27,762	2.1
SAG Mill Weight	t	-	-	659	2.2
SAG Mill Speed, % of critical	%Nc	-	-	73.7	1.7
Milling Specific Energy Input	kWh/t	16.3	2.0	19.9	7.1
Grind P_{80}	µm	85	2.3	121	2.8

Figures 7 and 8 show the typical throughput rates and grind size for Tropicana and Gruyere respectively. It should be noted that the period used to assess short-term variability is a 24-hour period of high-frequency (1 minute) data, therefore does not line up exactly with the long-term annual averages reported in Table 5.

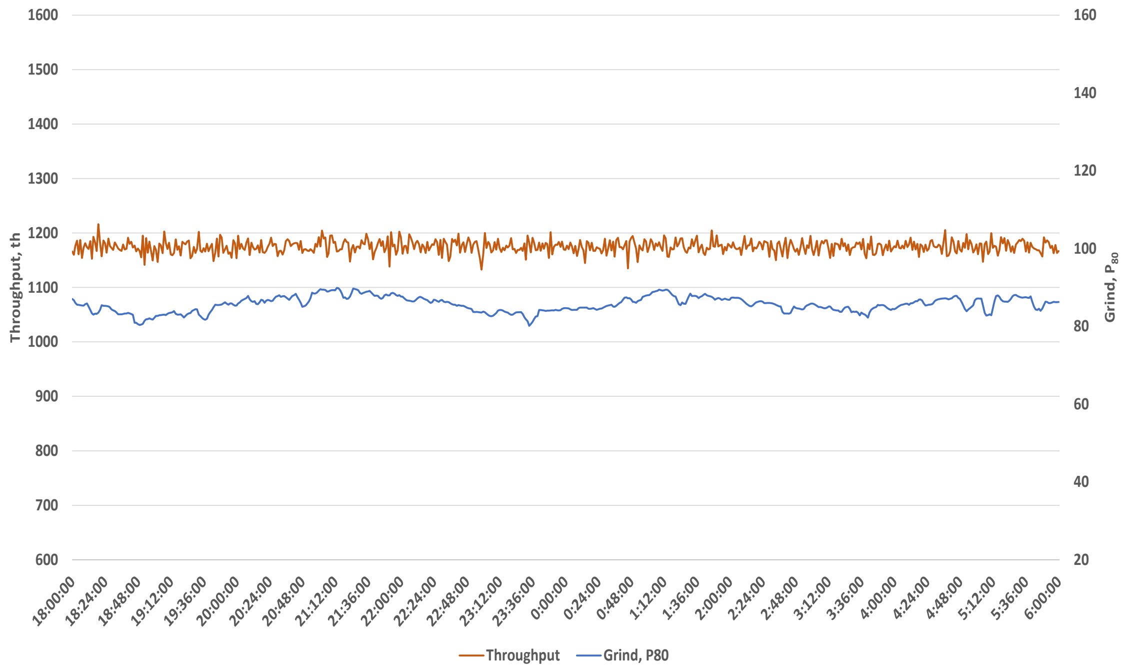

Figure 7—24-hour Throughput and Grind Trends for Tropicana

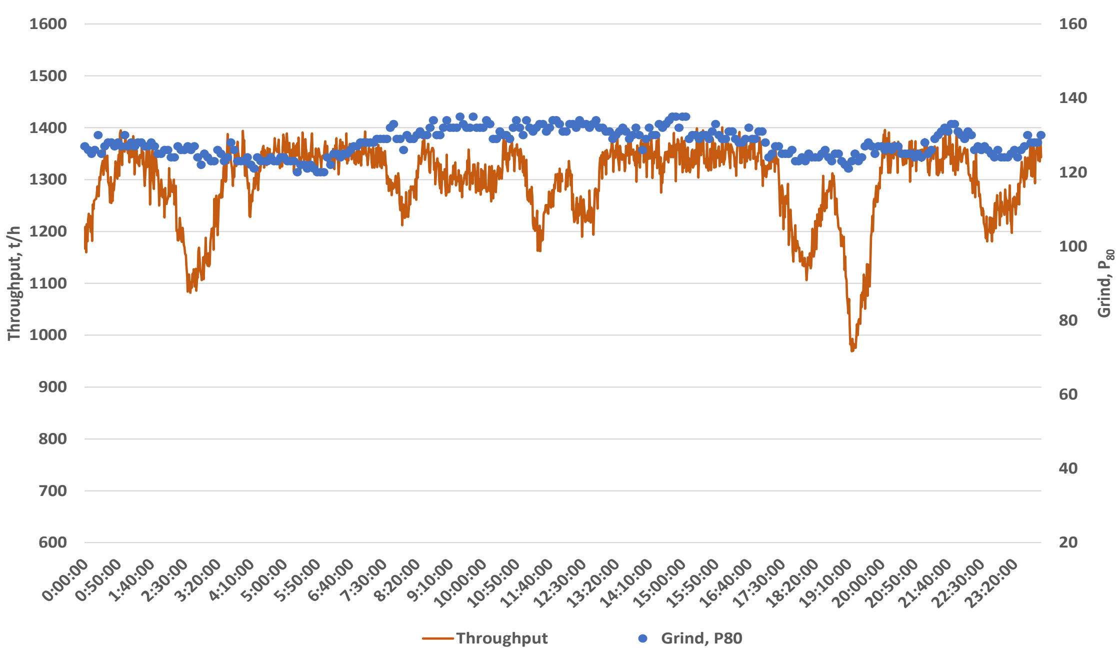

Figure 8—24-hour Throughput and Grind Trends for Gruyere

Energy Efficiency Comparison

Numerous comminution circuit surveys have been conducted at both operations across a range of ore types. For the purposes of this review, surveys with the most comparable ore properties, closest to the design point were selected. For Gruyere this was the most recent survey conducted in June 2022. For Tropicana, this was the first survey conducted in 2015, which was before the expansion and therefore only the original ball mill was operating.

The Gruyere survey aligned closest with the design ore characteristics for both projects, therefore the Tropicana data was adjusted via the following corrections to provide a relative comparison of specific energy:

- Grind size P_{80} was increased from 92 µm to 120 µm.
- The BWi was reduced by 1.5 kWh/t.
- Adjustment to the HPGR specific energy consumption for the harder Axb value, using OMC's HPGR model calibrated using survey data.

The correction was made to the ball mill energy consumption using the calibrated power model derived from the Bond method. A summary of survey data from each circuit treating comparable ore competency is presented in Table 7.

Table 7—Survey Data Summary

Criteria	**Units**	**Tropicana Sep 2015**	**Tropicana Adjusted**	**Gruyere Jun 2022**
BWi	kWh/t	**19.2**	**17.7**	**17.7**
Closing screen	µm	106	150	150
P_{80}	µm	79	114	114
Axb	-	**39.8**	**34.8**	**34.8**
ta	-	0.38	0.33	0.33
Throughput	t/h	883	883	1138
Grind, P_{80}	µm	92	120	120
Specific Energy Consumption*				
Primary Crusher	kWh/t	0.19	0.19	0.16
Secondary Crusher	kWh/t	0.32	0.32	-
HPGR	kWh/t	2.45	2.76	-
SAG Milling	kWh/t	-	-	11.3
Pebble Crusher	kWh/t	-	-	0.20
Ball Milling	kWh/t	15.0	11.7	11.2
Auxiliary Equipment	kWh/t	3.74	3.74	1.96
Total Circuit	**kWh/t**	21.7	18.7	24.8

*Excluding drive-train losses.

When standardised, the difference in total circuit energy consumption is 6.1 kWh/t, or 25 % less for the HPGR circuit when compared to the SABC circuit for the ore treated at the time of the respective surveys. The other notable difference is in the auxiliary equipment power consumption, with the HPGR option consuming more than double that of the SABC circuit.

For softer ore types, the total specific energy benefit of the HPGR circuit is less, as was seen during the commissioning phases when the circuits were treating oxide and transitional ores. This is in part due to the lower SAG milling energy and the little change in auxiliary power, which becomes a greater percentage of the overall circuit power for softer ores (Kock, et al., 2015).

One significant discrepancy regarding auxiliary power consumption was the cyclone recirculating load difference at the time of the surveys, with Gruyere operating at 247 % and Tropicana at 405%. Pumping the additional volume alone contributed 0.66 kWh/t of auxiliary equipment power consumption. This is in part driven by the flowsheet selection with the dilution of HPGR screen feed dictating the cyclone overflow density and the required number of operating cyclones. This water balance aspect of HPGR circuit selection can become an issue where coarser grinds are targeted, limiting the fineness of the HPGR screening aperture which in turn increases the overall circuit energy consumption.

Energy Efficiency Review

The efficiency of each circuit was compared by stage using the relative comparison SSE75 method (Powell, Evertsson, Mainza and Ballantyne, 2022). The output is presented in Figure 9.

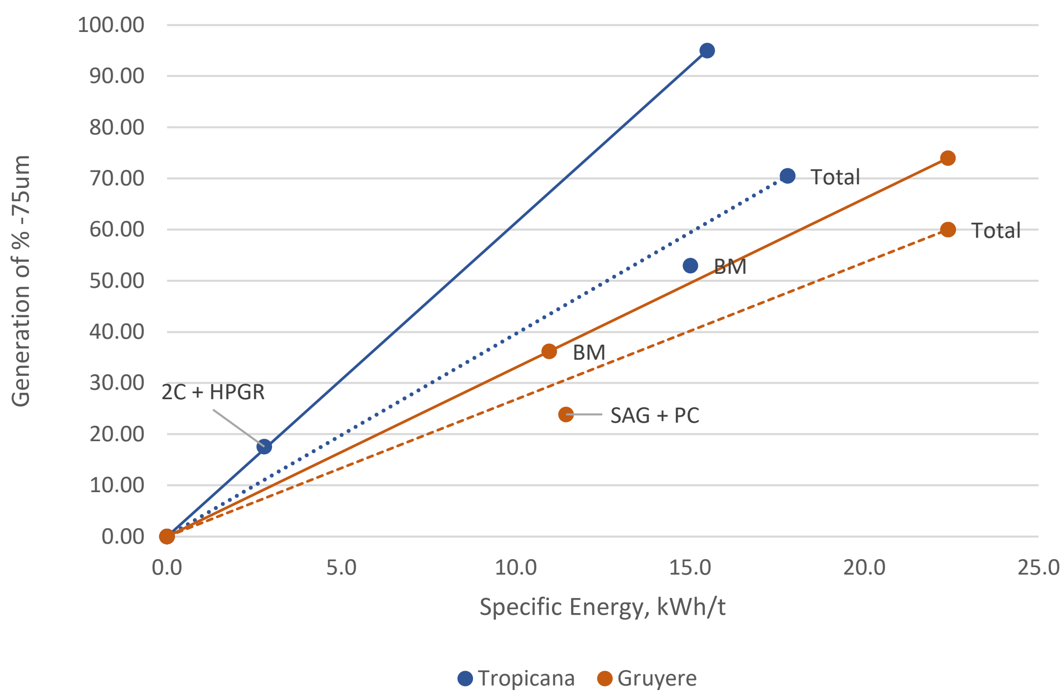

Figure 9—SSE75 Comparison by Stage

The SSE75 evaluation indicates that the ball mills are comparable in efficiency for the two circuit. The HPGR is the most efficient of the examined comminution stages, while the SAG mill is the least efficient. It is unlikely that the ball mill efficiency can be increased to match that of the HPGR, however the evaluation indicates that there may be opportunity to optimize the SAG mill performance. To explore this further, the actual vs predicted energy consumption of the grinding circuits is summarised in Table 8 using the Morrell method as prescribed by The Global Mining Standards Guidelines Group.

Table 8—Predicted and Measured Net Specific Energy of Grinding Circuit

Criteria	Units	Tropicana Adjusted	Gruyere Jun 2022
F_{80}	mm	30.0	83
P_{80}	µm	120	120
BWi	kWh/t	17.7	17.7
Mia		21.8	21.8
Mib		21.3	21.3
Mic		8.9	8.9
Mih		15.9	15.9
Measured	kWh/t	**14.5**	**22.5**
Morrell Predicted	kWh/t	15.1	19.9
Difference	%	4.0	-11.6

The Tropicana survey adjusted energy consumption was within 4% of predicted, indicating it operates within the expected efficiency range.

For Gruyere, the prediction is lower than actual measured for the milling circuit. This is consistent with OMC's method (Scinto, Festa & Putland 2015), which predicts 20.1 kWh/t. The detailed analysis suggests that the Gruyere SAG milling circuit is operating at lower than typical efficiency. It is suspected that liner and grate design (125-250 mm plate thickness and large lifters to target 6 month reline, pebble port blockages due to pulp lifter clash with grate) is contributing to this inefficiency, which is still being optimised at the time of writing. If the circuit efficiency is brought into line with typical SAG mill efficiency, then the difference between Tropicana and Gruyere circuits in total energy consumption would be 16.1% rather than the 25% shown in Table 7. This is more consistent with the 15% cited in other HPGR operating data reviews (Morrell, 2022).

HPGR Benefit Review

When designing the Tropicana circuit and conducting the trade-off study, there was uncertainty around the amount of HGPR benefit to apply in the ball mill selection. HPGR benefit is defined as weakening of the ball mill feed by action of the HPGR and represented by k_{hpgr} (Morrell, 2022). In the interest of understanding why the Tropicana circuit is more energy efficient than Gruyere and to provide addition benchmarking data for future HPGR trade-off studies, this section explores the Tropicana mill performance in more detail. To do this, four surveys have been considered and compared against predicted performance using a range of methods. The intent of this is to demonstrate whether the Tropicana ball mill(s) use less than predicted energy, which would indicate that a HPGR benefit is present and is contributing to the overall energy efficiency of the circuit. The full set of surveys from Tropicana are summarised in Table 9, including the actual vs theoretical energy consumption. The theoretical energy has been estimated using the Bond (1961b) method and Morrell (2022) method shown with the K_{hpgr} factor applied and without. OMC's typical approach is to use a modified Bond-Rowland method which only uses the oversize feed factor, however in this case, no factor is applicable.

Table 9—Tropicana Ball Mill Survey Data Summary

Criteria	Units	Survey 1	Survey 2	Survey 3	Survey 4	Average	Average Ex Survey 2
F_{80}	µm	**2,018**	**2,018**	**1,152**	**1,965**	**1,788**	
P_{80}	µm	93	79	75	70	79	
BWi	kWh/t	19.2	19.2	16.7	16.1	17.8	
BWi P_{80}		**79**	**79**	**78**	**73**	**77**	
Morrell Mib		26.5	27.5	23.7	23.0	25.2	
Mill Operating Speed	%Nc	83.6	76	83.6	76	-	
HPGR Pressing Force	N/mm^2	3.09	3.09	3.22	3.18	3.15	
Measured Specific Energy	kWh/t	15.2	13.2	14.7	16.2	14.8	
Morrell Predicted (no K_{hpgr})	kWh/t	15.8	17.6	14.1	15.7	15.8	
Morrell Predicted (+ K_{hpgr})	kWh/t	15.1	16.8	13.4	15.0	15.0	
Bond Predicted	kWh/t	15.7	17.3	14.4	15.6	15.8	
Predicted vs Actual Ratio							
Morrell Predicted no K_{hpgr}		0.96	0.75	1.04	1.03	0.95	1.01
Morrell Predicted + K_{hpgr}		1.01	0.78	1.09	1.08	0.99	1.06
Bond Predicted		0.97	0.76	1.02	1.04	0.95	1.01

The review indicates that when considering all the available survey data from Tropicana, K_{hpgr} is not consistently apparent. Survey 2 is an outlier when compared to the other three surveys. This survey was taken on the same day as Survey 1 however was only a partial survey collected around the ball mill cyclone streams. This meant that approximately 8 hours transpired between the collection of the fresh feed sample on which the comminution test work was conducted and the second survey. The fresh feed sample was taken immediately after the ball mill samples were collected in the other three surveys. Given these circumstances, there is more confidence around the representativity of both the comminution test work and HPGR screen undersize PSD in Surveys 1,3 and 4 than for Survey 2.

For Survey 2, it was assumed that the HPGR screen undersize PSD and comminution test work was the same as for Survey 1. It's worth noting that for the purposes of both Survey 1 and 2, a pre-blended stockpile was prepared on the ROM pad, which was reclaimed to the plant for the full duration of the aforementioned surveys, including running down of the coarse ore stockpile prior to the survey and waiting for the plant to reach stability on the new feed. Nevertheless, there is less confidence in the Survey 2 data. The purpose of Survey 2 was to incentivise a trial for operating at lower mill speed, as the longer-term operating data had for some time suggested that drawing high power at higher mill speed was not yielding any tangible benefits. In that respect, Survey 2 served its purpose, and a longer-term plant trial went on to demonstrate that operating at the lower speed did not impact throughput nor grind size, even though the mill power draw was reduced. None the less, the benefit was not repeated in Survey 4 with the ball mill operating at lower speed.

Several possible reasons for the difference in efficiency were advanced (Ballantyne, Di Trento, Lovatt & Putland 2015), however these were never confirmed. Since Survey 3, the mill SER has been de-commissioned and now the motors permanently run at synchronous speed, equating to 76%Nc for Ball Mill 1. Survey 3 was undertaken at 83.6 %Nc prior to the installation of the second ball mill. Survey 4 was at 76 %Nc and includes the second ball mill. These later surveys had comparable efficiency; however, several variables have been changed in the flowsheet and operating conditions across all four surveys. This includes changes in HPGR screen aperture, cyclone configuration and cyclone recirculating load which have the potential to impact circuit efficiency in several ways. The high efficiency of Survey 2 has not since been repeatable, casting further doubt around the reliability of that survey. If excluding this survey, both the Morrell method with no k_{hpgr} and Bond method provide good predictions for the energy requirement of the Tropicana ball mills. This is not to say that there is no HPGR weakening of feed occurring, however, to confirm the expected benefit of 3-7%, a better understanding of the interaction of other variables impacting efficiency is required to isolate HPGR benefit.

A key take-away from this review is that the HPGR circuit is still significantly more energy efficient regardless of any additional HPGR benefit to the ball milling stage, due to the HPGR's efficient size reduction to the ball mill feed size. As such, attempting to quantify HPGR benefit and making allowance for this in the study phase is not essential to realising the superior energy efficiency of the HPGR flowsheet, which should become apparent from the straight application of the uncorrected and proven estimation techniques.

CAPEX and OPEX Comparison

The capital considerations for each circuit are unique and on top of the inherent equipment differences, influenced by factors such as layout selection/optimisation, inflation, EPC vs. EPCM implementation and the timing within mining boom/bust cycles. Variations to these factors makes for a challenging apples-to-apples comparison.

While actual data has been utilised for comparison purposes, it is noted that significant normalisation and adjustment is required to overcome various factors such as orebody and circuit differences (i.e. target grind size), timeframe (i.e. Tropicana in 2014 vs Gruyere in 2019). Comparisons are made in terms of a HPGR-Ball Milling and SAG-Ball Milling circuit, rather than directly to Tropicana and Gruyere respectively.

The CAPEX data was provided by both companies, and addressed by the following methods:

- The capital costs were reduced to direct costs by excluding indirect, owners and contingency costs
- Direct costs were escalated to reflect 2022 dollars using the Chemical Engineering Plant Cost Index
- Direct costs were compared for the following areas:
  - Primary Crushing
  - Secondary Crushing
  - Stockpile & Reclaim
  - HPGR
  - SAG Mill & Pebble Crushing
  - Ball Mill(s) & Classification.

Analysis indicated that project-specific factors was normalised to a reasonable comparison of costs. Specifically, the following factors were addressed:

1. Gruyere's coarse grind target which reduces the comparative mill power required for a given throughput rate,
2. Gruyere took advantage of the availability of a new, unused ball mill,
3. Gruyere's development period is believed to have taken place during a relative lull in the Australian engineering market, leading to competitive equipment and execution pricing,

4. If Tropicana's initial design point was 8.6 Mt/a, a single ball mill (rather than parallel units) may have been adopted.

No correction has been made for Items 3 &4. It was possible to address Items 1 & 2 as follows:

- Tropicana ball mill requirements were reduced to reflect an equivalent grind size,
- The Gruyere ball mill costs were adjusted to reflect the impact of new equipment pricing.

When equalised, the Tropicana comminution circuit direct cost was assessed as 19.4 % higher than Gruyere. The relative plant area costs are presented in Table 10.

Table 10—Relative Comparative CAPEX (Direct Costs)

Area	Relative to Project		Relative to Gruyere	
	Tropicana	**Gruyere**	**Tropicana**	**Gruyere**
Primary Crushing	16	20	100	100
Secondary Crushing, Stockpile & Reclaim	32	13	283	100
HPGR/ SAG Mill & Pebble Crusher	18	36	61	100
Ball Mill & Classification	34	32	129	100
Total (%)	**100**	**100**	**119.4**	**100**

The difference is consistent with predictions made during the option studies, which estimated around 20 %. Note that any differences in ancillary facilities – such as total power generation capacity, maintenance workshops or storage facilities – were not considered.

Each company provided actual operating cost data for the 2022 calendar year. To complete a like-for-like comparison between the circuits, fundamental differences have been corrected. This included normalising:

- Specific grinding energy, with Tropicana adjusted to reflect Gruyere's P_{80} of 125 µm,
- Grinding media and liner consumption corrected to average derived ore abrasiveness,
- Unit costs for power generation and grinding media were normalised to arbitrary values; with a unit power cost of 0.20 A$/kWh and a grinding media cost of $2.19/tonne selected.

The normalised data indicated relative costs (in terms of %) against the key areas in Table 11.

Table 11—Relative OPEX Comparative

	Relative to Project		Relative to Gruyere	
	Tropicana	**Gruyere**	**Tropicana**	**Gruyere**
Power	**33.9**	**38.9**	**69.6**	**100**
Grinding Media	**9.6**	**18.1**	**42.3**	**100**
Process Labour	**12.2**	**11.1**	**87.5**	**100**
Maintenance Labour	**23.5**	**13.9**	**135.0**	**100**
Primary Crush	3.5	2.8		
Secondary Crush	7.2	-		
Pebble Crush	-	1.3		
HPGR	6.7	-		
SAG Milling	-	6.2		
Ball Milling	6.2	3.5		
Maintenance Consumables	20.9	18.1	92.3	100
Primary Crush	3.8	3.0		
Secondary Crush	6.4	-		
Pebble Crush	-	1.4		
HPGR	7.2	-		
SAG Milling	-	8.6		
Ball Milling	3.5	5.1		
Total (%)	**100**	**100**	**79.9**	**100**

The Tropicana circuit indicates a material operating cost saving, totalling 20.1% based on the comparative analysis. Key findings include:

- Significant reductions are observed in terms of power consumption and grinding media consumption.
- An increase is observed in allocated process & maintenance labour, however it is noted that labour has some operation-specific elements. Comparative departments may not have an exact match in terms of responsibilities, particularly a maintenance department which manages the process plant and other site infrastructure such as underground mining infrastructure,
- Maintenance consumables (primary, secondary, pebble crusher lines, HPGR ties, SAG & Ball mill liners) are a relatively low point of difference in percentage terms.

The difference in CO_2 generation for power generation and steel media for the equalised options is presented in Table 12. Power generation is estimated at 0.44 kg of CO_2/ kWh for natural gas (EIA, 2023). The total emission rate of 2.3 kg of CO_2/ kg of steel balls has been used (Morrell, 2022).

Table 12—Estimated CO_2 Emission Summary at Standardized Grind and Ore Properties

Description	Units per Year	Tropicana	Gruyere
Power Consumption	GWh	159.0	210.8
CO_2 from Electricity generation	kt	70.0	92.7
Steel Media Consumption	kt	5.27	10.71
CO_2 from steel media manufacture and delivery	kt	12.1	24.6
Total CO_2 Emission	**kt**	**82.1**	**117.3**

The HPGR circuit yields a 30% reduction in CO_2 emissions from the differences in power and media consumption.

Conclusions

Analysis of actual capital and operating cost data has provided an insight into the differences between HPGR-ball mill and SABC circuits. The CAPEX for a HPGR-ball mill circuit were assessed to be 19.4% higher than the SABC mill circuit for a similar scale.

Operating costs of a HPGR-ball mill circuit were assessed as 20.1% lower than a SABC circuit. The key contributors were power costs (valued at 20 c/kWh) and grinding media consumption (valued at 2.19/tonne). The reductions achieved in these two consumables more than offset the additional maintenance costs associated with the HPGR-ball circuit.

Additional benefits of the HPGR circuit include the superior process stability, typical of a tertiary crushing circuit when compared to the throughput and grind variation experienced for the SABC circuit. The comparison also demonstrates that the overall circuit availability of the HPGR-ball option can sustainably match that of the simpler SABC flowsheet, where appropriate considerations have been made for the surge capacity between the HPGR and ball mill. This is in part reflected in the higher CAPEX for the HPGR-Ball mill flowsheet; but is also a function of deliberate choices made during the design stages.

In some ways, review of the Tropicana circuit energy efficiency casts some doubt around the impact of HPGR feed-weakening. In this respect the data remains inconclusive, however the data does support the fact that the HPGR circuit is still notably more energy efficient, even where no additional HPGR correction is applied to the ball mill. This efficiency gain forms one (along with grinding media consumption) of the key factors for circuit selection in this case. Furthermore, the conventional Bond and Morrell modelling approaches have demonstrated to be reliable in predicting the energy requirement for the Tropicana ball mill.

For similar applications with moderate to highly competent ore, the HPGR-ball circuit is demonstrated to be a cost-effective solution, and a viable means of reducing comminution $C0_2$ emissions by 30 %. It is expected these benefits will be eroded in lower power cost jurisdictions, or if power generation relies on renewable sources. Nevertheless, the HPGR-Ball mill flowsheet still offers benefits in process stability for throughput and grind-sensitive applications. Conversely, the SAG mill option remains a compelling choice for capital-sensitive projects, situations where the cost of power is low, and operations where a significant range of weathered/binding-type ores are to be processed.

Given that Tropicana started operation with very high unit power cost from diesel generation, the selection seems well justified upon the review of the economics. Alternatively, with the lower gas-generated power cost from the outset, the higher design abrasion index and with the notably lower capital cost, it is also apparent why a project that was initially developed by a junior mining company would select the SABC circuit.

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