THE ROLE OF MODULAR AND FLEXIBLE MINERAL PROCESSING IN A MORE SUSTAINABILE WORLD

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Abstract

There are two key themes that will accelerate the attraction of flexible and modular processing over the next decade. These are the commitment to low emissions mining, including electrification and renewable-energy use, and the exhaustion of large higher-grade deposits, with satellite deposits becoming the next targets for new mines or mine extensions. Smaller satellite deposits do not lend themselves to the economy of scale considerations that drive current large mining strategies. Instead, targeting higher grade small deposits economically may be better served by relocatable equipment and flexible fleets. In addition, flexible equipment able to manage energy supply disruption may also become attractive as both grid and on-site fossil fuel power generation is disrupted and energy storage costs for high reliability 24/7 renewable power based operation remain high in many regions. The authors are involved in an industry collaboration project that seeks to simulate the value of this flexibility - the 'Scalable and Adaptable Mining Challenge', within the Think and Act Differently (TAD) incubator, powered by OZ Minerals. Complementary to the work of the challenge cohort, this paper explores how alternate emerging milling technologies and minerals processing design can support a more flexible mine. Alternate comminution and flotation circuit technologies and configurations are compared which focus on flexible applications. The paper aims to give additional considerations for shifting power use towards renewables and daytime use as well as design for intermittency, including solar-powered remote pumping, compressed air services, and milled ore storage.

Keywords

Modular minerals processing, variable processing, renewable energy, flexible energy demand

1. The drivers towards flexible and modular processing

1.1 Growing NetZero commitments

Members of the ICMM account for about a third of the global metals and mining industry. In 2021 ICMM member companies published a commitment to a goal for net zero Scope 1 and 2 greenhouse gas (GHG) emissions by 2050 or sooner (ICMM Climate Change Position Statement, Oct 2021). Many companies also have ambitious 2030 emissions reductions goals. To achieve these targets, we will see a significant shift away from fossil fuels and towards electrification based on renewable generation and energy storage solutions. In order to manage demand for renewable generated power, whilst moderating the cost of energy storage, flexible mine demand-side energy usage management may play a part in achieving these goals.

1.2 Future mineral resources constraints

As more economically attractive mines, in terms of resource volume, grade and location have been mined initially, grades for key minerals, including copper and gold, are declining. Copper mines currently operating have an average grade of 0.50% whilst those under development have an average grade of 0.45% (Data source: S&P Capital IQ Pro platform by S&P Global Market Intelligence Sept 2022). As grades decline, the energy required for processing ores is increasing, as more gangue needs to be milled and treated for the same volume of metal produced (Calvo et al, 2016). In addition, with larger economic mines being already under production, there is an increase in satellite deposits being considered for future production.

At the same time, demand for copper is increasing, with the World Energy Investment 2022 report indicating a significant increase in projected demand above current production rates for copper to meet climate pledge scenario and net zero emissions targets by 2050. This demand is likely to drive production from deposits previously considered uneconomic, due to lower grade or smaller resource volume.

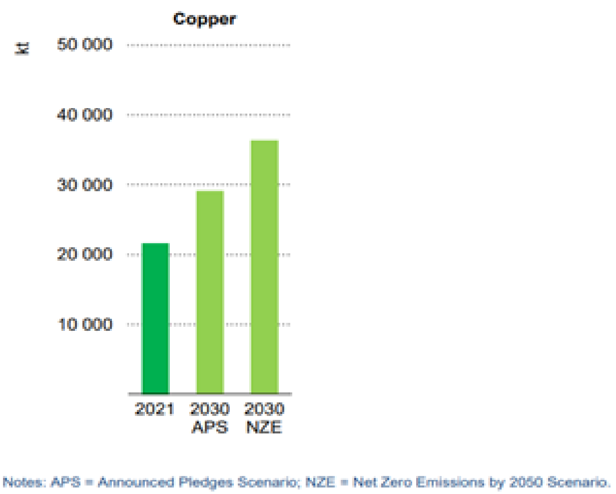

Figure 1 – Production in 2021 and projected demand in 2030 in climate-driven scenarios (World Energy Investment 2022 Report)

1.3 Economic uncertainty and energy supply risks

A recent study on the underlying factors for mining company generation of shareholder returns, was based on a review of over 100 Canadian mining companies from 2003-2016 (Gillis, 2021). It was found that over this period, 90% of studied companies reported a mineral asset impairment, and on average companies wrote off 40% of a mines value when declaring an impairment. The largest category was impairments related to declines in metal prices, followed by ore grade, and ore access. This work highlights the difficulty with capital intensive mining projects, where uncertainty in predicting grade and ore access can significantly impact shareholder returns.

Cost overruns in large construction projects is the subject of many studies. In mining construction, a 2015 study by Export Development Canada reviewed capital cost overruns in mining, and indicated an average of 37% cost overrun for the 78 projects studied. (Lwin, 2017). Flyvbjerg in the November Harvard Business Review (Nov-Dec 2021) argued that modular (repeatable) designs with quick iterations can reduce cost overrun risk. Where a project must be 100% complete to commence production, the risk of delay and overrun can be high, and arguably even more so in an increasingly volatile global supply market. Risks from both a capital overrun, and mineral asset impairment perspective mean that a more modular and scalable approach to mine development may support improved shareholder returns, with less risk of stranded assets where commodity price or grade and access issues impact mine viability.

Operating costs for energy are also a key consideration for project economics. Figure 2 outlines the percent of total cash cost taken up by energy (fuel and electricity) for Australian copper mines. In particular for mines with higher energy costs, increased volatility causing higher energy contract prices may mean significant increases in total cash costs. Both fuel and electricity are included here due to the trend of increasing electrification across mines to reduce GHG emissions.

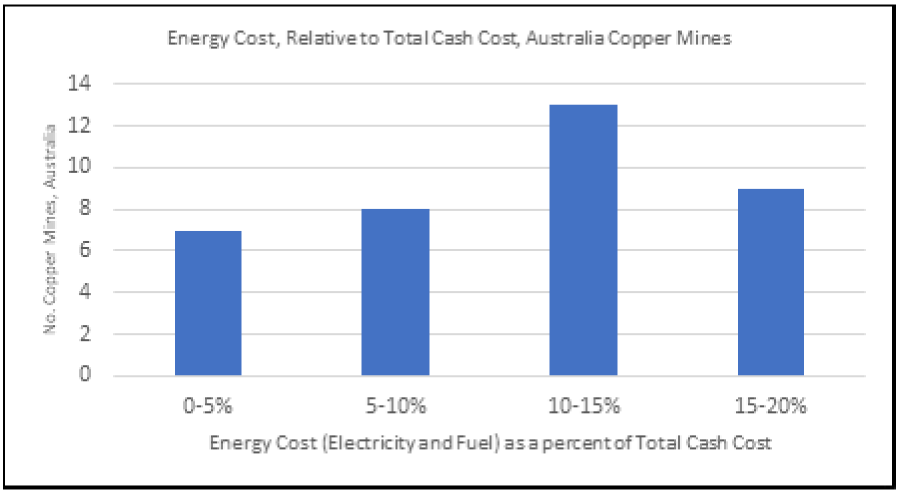

Figure 2 – Energy cost (electricity and fuel) as a percent of total cash cost for Australian copper mines (Data source: S&P Capital IQ Pro platform by S&P Global Market Intelligence, retrieved 9 Sept 2022)

The Australian Energy Market Operator (AEMO) Quarterly Energy Dynamics Report for Q2 2022 provides an insight to the growing volatility in the Australian Energy market. Interestingly, the State of the Energy Market Report, 2021 predicted that low futures contract prices from 2021 were expected to continue into 2022. In the 2022 second quarter, there were unprecedented average wholesale spot prices in the National Electricity Market (NEM) and eastern Australian gas markets. For example, the AEMO report notes the quarterly average NEM spot price of $264 per megawatt-hour (MWh) was more than triple Q2 2021's average of $85/MWh. During the quarter there were price capping events and a period of suspended spot electricity markets. Key underlying factors included:

- High international prices for traded gas and thermal coal reduced availability of coal-fired generation due to scheduled and unscheduled down time
- Physical fuel supply and hydrological constraints for a number for thermal and hydro generators

The report also indicated that volatile prices are also impacted by:

- Demand due to temperature changes (of key consideration as average temperature and temperature variability may be increasing)
- Changeable solar and wind power supply due to weather and seasonal variability
- Transmission constraints limiting transfers of power between regions.

The fundamental characteristics of renewable energy are variability, intermittency, and correlation. The standard response to both variability and intermittency is to overbuild generation and storage capacity, but this increases the effect of correlation. Correlation means that renewables are either all generating or not generating in unison. This supercharges intermittency because it means that supply switches between too much and none daily. Therefore, correlation leads to 'price separation' where the price jumps from a very low daytime price to an exorbitant evening price. A record number of negative spot prices occurred in 2021 with nearly two-thirds occurring in South Australia and Victoria. These states have the highest penetration of wind and solar energy. AEMO powers were used for the first time in March 2021 to instruct network operators to back off rooftop solar generation, forcing them to draw power from the grid (State of the Energy Market Report, 2021).

The price point required to return capital for energy storage will depend on a number of factors. However, the required extent of overbuild will mean significant price separation between peak and low demand times. The 'Net Zero Australia' project estimates up to 100GW of BES capability may be needed by 2050 for a number of scenarios tested (NetZero Australia, Interim Results 2022). Set against a projected approximate 40GW of load, this equates to 2.5 times overbuild factor. A flat price in a volatile system will be high, as a significant amount of overgeneration and storage as well as expensive variable supply is required. Electricity customers will need to manage volatility themselves or be charged by providers to manage the volatility.

Predictions of future increased temperatures and extreme weather events, and volatile global energy markets indicate the real risk of higher and more volatile energy pricing on mine development projects. At the same time, the GHG emissions reductions focus is likely to shift more energy use at mines towards electricity and away from diesel. This will put pressure on the pace of supply of both new generation and transmission infrastructure for these mines. Supply of copper and battery minerals during this period of global energy transition is likely to be constrained. Michaux (2021) estimates 189 years of 2019 copper production will be required to produce one generation of technology required to phase out fossil fuels globally.

P. Horschhorn et al (2022) outlines how natural gas currently plays a key role in setting prices in wholesale energy markets. They argue that the future of the grids, pricing and stability are dependent on the dominant firming technologies as the grids include increasingly more variable renewable power production. Grid firming technologies include zero emissions gas-fired generation, flexible demand, and energy storage technologies. From both a reliability and cost perspective, the increased volatility, uncertainty in firming capacity, and looming materials constraint issues for growth of generation, storage and transmission infrastructure points to the potential benefit of energy supply resilient systems design. Indeed, flexibility in energy demand can play a key part in a high-renewable penetration energy grid, whether at a regional or micro-grid level.

Options for mine sites to reduce risk exposure to energy markets include on-site storage and generation capacity, as well as demand side flexibility. In 2022, an OZ Minerals Think and Act Differently innovation challenge white paper was published on "Scalable and Adaptable Mining" (hereafter, TAD S&A Study). It included simulation of various scalable mine configurations in a fully electric solar and battery powered small resource scenario. In optimising the amount of energy storage for this configuration the simulation of peak net present value (NPV) did not coincide with 24/7 continuous operation. The authors found that beyond a nominal storage of four hours, the model indicated that discontinuous operation may provide a better solution to variable energy supply than additional storage.

2. How flexible and modular processing can support an adaptable and lower footprint mine

A flexible processing plant solution with modular construction can support mines in remote locations where skilled local workforce availability for construction and operation are a challenge. Smaller deposits and satellite deposits do not lend themselves to the economy of scale considerations that drive current large mining strategies. Relocatable processing and mining infrastructure and fleets can allow extraction from satellite deposits that cannot economically support a fixed solution with dedicated assets. These relocatable processing facilities may be front-end ore pre-concentration facilities which function to reduce the mass required for transportation to a fixed asset. In addition, larger projects may benefit from the flexibility provided to adapt to changes in the mine plan, with less sunk costs than fixed plants.

By considering the value chain as a system subject to inevitable disruption, there is significant value in flexibility, for example through starting an operation at small scale, enabling early cash flow, and ramping production up or down as required. The modular and flexible model is particularly suitable for small higher-grade deposits with a greater degree of variability. From an environmental footprint perspective, a relocatable modular facility provides a pathway to a lower cost and more rapid rehabilitation of processing facility footprint. The facility may also have lower embedded carbon emissions per feed tonne for mines with a shorter mine life, by re-use of the facility on other mine sites.

The ability to adjust fleet scale and processing scale and relocate between deposits can also be viewed as a paradigm shift for community engagement. A fixed long-term mine plan is difficult to adjust based on shifting demands from local stakeholders. The owner of a mine that can manage disruption and can retain value from sunk capital by relocating equipment to adjacent deposits, is better able to respond to needs of local stakeholders, whilst managing shareholder returns. A processing facility designed for discontinuous operation provides optionality to balance production with operating energy costs, and de-risk operations from the impact of intermittency in power supply.

3. Comminution and minerals processing design considerations for increased flexibility

The following sections outline considerations within some key areas of processing facility design than can be considered to improve flexibility to manage commodity price and resource understanding variability, as well as energy supply and cost volatility. These include modular facility design, comminution technology for reduced energy and intermittent operation, flotation circuit considerations, and services design for reduced peak power use.

3.1 Modular Facilities

Modular processing facilities are not a new concept. The capacity of such facilities is constrained by the size of equipment able to fit within transportation envelopes. Throughputs for base and precious metal processing plants range from small movable facilities at around 20tph to larger 100tph modular plants. Installation timeframes of modular facilities is significantly reduced from standard stick or pancake build construction. An example of this is a 550tph modular bulk commodity processing facility in Queensland (post development of train load out facilities). For the first facility built, modules were lifted into place within eight days. This approach reduces site manhours and associated safety risk exposure, including work at heights, and allowed faster time to initial production. Staged expansion also allowed improvements to design when the processing facility was later duplicated.

Figure 3 – Example of Sedgman modular construction

Ore pre-concentration is an attractive concept to couple with modular and flexible mineral processing plant design. In this context, pre-concentration is defined as the selective removal of barren or low-grade material prior to the expensive steps of comminution and flotation, usually at a coarse particle size. Removal of waste early by size, density or automatic ore sorting (separating on the basis of mineralogy, elemental composition or texture) has the advantage of reducing downstream energy and water demand, and scale of equipment, which allows designers to consider more options for modularity and flexibility. This becomes ever more important as projects target lower grade ores due to the demand for a higher up-grade ratio to achieve a fixed concentrate grade target.

Comminution considerations for modular installations focus around civil and mechanical considerations of the units, with many typical comminution devices not being suited to modular designs. SAG and ball mills require significant civil works and foundations, which limit their applicability to modular processing plant design. To enable modular circuits to operate, the comminution circuit design and selected comminution unit is critical as most circuits will be throughput constrained by the comminution circuit. With typical unit operations not being applicable for modular design and flexible operation, an opportunity for novel comminution devices arises to try and address key issues within the modular circuit design. In theory, an ideal comminution technology would be able to meet the following issues:

- Simple mechanical design, limited civil and ancillary structures
- Reduced comminution device size and weight
- Performance in terms of energy and downstream recovery
- Ability to operate in remote locations – low power, flexible operation, relocatable.

3.2 Options for reducing comminution demand power

It is well understood that comminution machines are the largest single equipment contributing to a mines overall power consumption, with most comminution circuits utilising tumbling mills in the form of SAG and ball mills. Comminution is required to enable liberation of the valuable material within an ore, which allows downstream separation processes to then recover these valuables. In their current form comminution circuits have little to no ability for flexible processing due to the significant size, foundation requirements, operating cost and residence times within the circuit. In most current circuits, variation of operating conditions results in a compromised product being sent downstream to the recovery circuit, which in turn can reduce recovery rates of valuable minerals.

Flexible processing circuits with the ability to respond to variable renewable power input will require a fundamental change to current comminution circuits. Requirements would include the comminution process having the ability to rapidly start-up and shutdown, all whilst producing a consistent product for downstream recovery circuits. Reduction in the specific energy requirements is also a key driver for comminution suited to renewable power sources.

A number of novel technologies are emerging into the market with the aims to address the comminution energy requirement. Some of these technologies are mature and established within the market, such as High Pressure Grinding Rolls (HPGR) and Vertical Roller Mills (VRM), which are capable of up to 30% reduction in comminution energy for the given duty of the machine. Other novel devices which include the EDS Multi-Shaft Mill, and the VeRo-Liberator are at a smaller scale and use high speed impacts to comminute incoming ore, with initial results suggesting significant reductions in comminution energy.

A novel precision comminution device which is currently at pilot capacity aims to address not only the specific energy requirements of comminution, but also the high residence time and recycle requirements for comminution devices. The properties of this mill enable a shift from current paradigms due to reduced comminution specific energy and the rapid ability to start-up and shutdown. Critically, the mill can maintain a constant product size over a variable feed rate, which will enable maximum recovery in downstream processing.

Due to the breakage mechanism within the HPGR, VRM, EDS and VeRo these technologies in most applications require recycle streams via classification. Classification and recycle streams result in higher residence time per unit operation, with extended start-up and shutdown time frames before a consistent recycle stream and stable operation is established. These technologies are therefore less suited for use in flexible process design powered through variable renewable energy sources. Table 1 summarises at a high level some considerations for flexible operation for a number of common and emerging comminution devices.

Table 1 - Qualitative comparison between current and future circuit configurations regarding flexibility

	SAG/ Ball Circuit	**HPGR/ Ball Circuit**	**VRM**	**High speed comminution (VeRo, Multi-Shaft Mill)**	**Novel precision comminution device**
Energy consumption	Baseline	~30% reduction	~30% - 50% reduction	~30% - 50% reduction at pilot scale	~80% reduction at pilot scale
Start-up/ shutdown time	>1 hour, prone to circuit instability and varied product	>1 hour, prone to circuit instability and varied product	~0.5 hours start-up/ ~5 minutes shutdown	~ 5 minutes	~ 5 minutes
Flexible operation	± 10% possible but likely inconsistent product to recovery circuit	± 10% possible but likely inconsistent product to recovery circuit	60% - 100% capacity with consistent product size	0% - 100% capacity range, some control over product size	0% - 100% capacity range with consistent product size
Ability to respond to variable power supply	No	No	Within capacity bounds	Yes	Yes
Downstream processes required	Recovery circuit	Recovery circuit	Recovery circuit	Additional comminution + recovery circuit	Recovery circuit
Rapidly choose product size according to feed type	No	No	No	No, dependent on additional comminution	Yes, < 1 minute
Amenable to modular construction	No	No	Somewhat	Yes	Yes

3.3 Configuration of flotation processing circuits to support intermittency

Mechanical flotation cell arrangements (forced-air or air-induced) are designed with operating volumes to support a target residence time. This equipment isn't suitable for modular designs due to size, electrical power demand and foundation requirements. The residence time in these cells is often 15 – 30 minutes, or more in polymetallic concentrators, which does not enable start/stop flexibility. The reason for this is due to the probability of particle-bubble interactions in a mixed slurry being low. Ensuring a sufficient number of these interactions occur means that large volumes of slurry need to be contained within the equipment to achieve a satisfactory result.

Jameson, Concorde and Nova cells have similar operating concepts and appear more suited to intermittent operations. Jameson cells were considered during the TAD S&A Study, as they are the most mature of this range, and account for over 380 installations. Operators are slowly embracing this technology into base and precious metals operations. The operation of Jameson cells is explained in detail elsewhere, but a basic overview is warranted here. Pressurised slurry enters the downcomer through a nozzle at high velocity. The jet entrains air in the headspace inside the downcomer and as the jet contacts the slurry surface it causes the entrained air to shear into fine bubbles. High intensity mixing inside the downcomer forces particle-bubble contact therefore results in residence times of only a few seconds. Slurry and collected particles exit the downcomer into the tank where particle laden bubbles are separated from the pulp.

As part of the TAD S&A Study, milled ore storage was explored to serve as a pseudo energy storage solution during periods of low energy availability. The simulated milled ore storage solution (at <200 mm) allowed the mill energy use to be decoupled from the flotation circuit energy demand. The model included agitated tanks to allow for wet fine ore storage for up to 12 hours capacity. The simulation utilised this storage to maximise production in an energy constrained environment. The simulation of intermittent use of a flotation circuit required modelling of recovery losses during startup and shutdowns. Functions used to model recovery losses as a percentage of steady-state recovery were developed based on operating experience. These algorithms are presented graphically in Figure 4 for both start-ups and shutdowns, and show that Jameson and similar cells are much more amenable to intermittent processing.

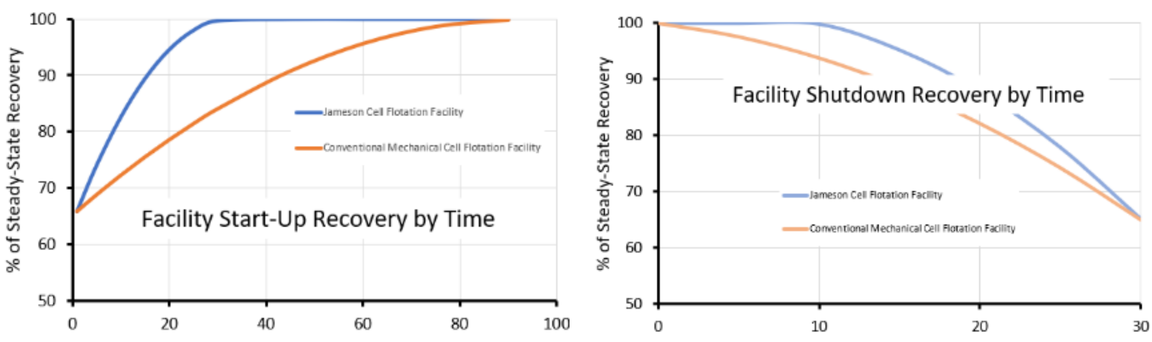

Figure 4 – Recovery as a percent of steady state during start-up and shutdown for Jameson cell vs conventional cell from author experience

For the simulation, the processing plant function was configured to run with minimum settings for ore availability and operation timeframes (four hours). Reliant on solar power and battery storage, optimum NPV was found to occur at less than 24/7 operation, as the cost of off-grid storage to achieve full operation in periods of low power production is very high. In summer, the simulation indicated long periods of continuous process plant operation, with the battery storage rarely discharging fully. In winter, activity was generally on a daily cycle with battery storage used to prolong process plant operation by drawing on crushed ore storage, with occasional overnight continuity of operation. Whilst further simulation of systems and economics is planned, the initial model indicates the flexibility that a processing configuration capable of discontinuous operation provides in an energy-constrained environment.

3.4 Jameson cell and Isamill™ power demand and footprint

For the TAD S&A Study, for a nominal 100tph feed rate, the initial sizing of equipment has shown that two Jameson Cells can replace five mechanical rougher cells and three Jameson Cells can replace an entire mechanical cleaning circuit design comprising five cleaner 1 cells, three cleaner 1 scavenger cells and five cleaner 2 cells.

The above approach has the potential to reduce the cleaner flotation circuit footprint by more than 30%. A major operating cost advantage of using Jameson Cells in place of conventional mechanical cells is reduced power requirements. Each cell needs only a feed pump, with no requirements for agitators or blowers. Comparing flowsheets of Jameson cells to mechanical (forced air) cells, savings of up to 54% reduction in power demand can be realised. In addition, a feature of this flowsheet is that there is no requirement for any cleaner flotation stream to be recycled back to the regrind mill if the regrind mill produces a product size of P98/P80 < 2.5, such as a Isamill™. Minimal recycle streams again supports faster process plant start-up and shutdown times.

3.5 Plant services options to reduce peak power demand and emissions

Whilst services have a much smaller demand than milling, adjustment to services design can be an option to both reduce peak demand and maximise use during high periods of power availability from renewable sources and reduce associated GHG. Whilst tradeoff between increased capital cost vs energy cost and GHG emissions reduction must be undertaken on a site-specific basis, the following services can be considered for intermittent operation design:

- For grid-connected remote raw and return water pumping and bore field pumping, oversizing allows for more intermittent operation. Power can be used during higher availability and lower cost periods and reduce demand at peak and higher cost periods.
- Remote raw and return water pumping and bore field pumping - where not connected to the site energy grid, oversized storage and pumping facilities with solar or hybrid energy supply can allow more operation during the day and reduce operational greenhouse gas emissions.
- Compressed air services may also be oversized to allow for intermittency to reduce peak loading and maximise renewables use.

Conclusion

Challenges to mine profitability relating to volatility in commodity prices, energy supply and price, and grade decline seem to be increasing. In addition, mineral impairments related to ore grade, and ore access are not uncommon. To manage these risks, miners may consider mining and processing designs that provide flexibility and resilience in the face of these challenges.

Processing facility design criteria can be considered to improve flexibility. These include modular facility design, ore pre-concentration, comminution technology for reduced energy and intermittent operation, flotation and regrind circuit considerations, and services design for reduced peak power use. Equipment manufacturers and processing circuit designers may find competitive advantage in a low-carbon economy by offering designs with lower power use and increased flexibility with regards to intermittent operation.

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