CAN WE SHIFT TO A NEW PARADIGM OF FLEXIBILITY IN MINING AND PROCESSING TO BUILD MINES POWERED EXCLUSIVELY BY THE VARIABLE INPUT OF RENEWABLES?

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ABSTRACT

An initiative to explore the viability of switching from the accepted business model of continuous operation under the exiting paradigm of a continuous, unconstrained supply of energy provides an alternative world view of how our essential minerals industry may lead global transformation in an energy-constrained world.

KEYWORDS

Constrained energy, Renewable Energy, Flexible processing, Mine viability, Mine planning

INTRODUCTION

The mining industry, as with the majority of heavy manufacture, is locked into a business model of continuous production that maximises rate of return on capital investment. This operating mode is dependent on a reliable, uninterrupted supply of electrical power, which in remote locations can be generated by gas or diesel generators. The shift away from fossil fuels to renewable sources of energy would be a desirable outcome for such locations, in fact potentially an imperative in light of the climate change targets. However, the grid-connected mine sites will also be dramatically affected by the shift to renewables energy production which are intrinsically variable, such as solar and wind. It is thus projected that night-time and low production periods will attract energy cost multipliers anywhere from 20 – 100 times on a regular basis. There may come a point where energy costs are so volatile that they outweigh the economics of continuous operation, requiring us to reconsider night-time operation in particular.

It is proposed that a viable alternative is to shift to flexible, variable intensity mining and processing that is synchronised with energy availability, so as to maximise the use of energy production while operating a profitable mine. Additionally, as a substantial energy user, the mine sites can potentially provide a source of energy balancing to an integrated user base such as a local area. The change requires a whole-of-system approach, integrating changes in the mining method, transport, storage, energy-hungry comminution and flotation recovery to enable variable and on-off production that does not compromise recovery. This is a roots-level shift, yet the technology readiness gaps may be small compared with the challenges of changing business models and operating patterns.

Under an initiative of OZ Minerals, a working group has explored a case study of an energy-constrained mine powered exclusively by solar generation and battery storage (OZ Minerals, 2022)

A fully-exploited underground satellite deposit of OZ Minerals' Prominent Hill mine offered known mineralised structure, variability, and recovery responses. Missing properties required for the novel processes involved were inferred from the processing data and mapped back into the orebody based on the measured ore properties (such as grade and competence).

The steeply-inclined structure of the deposit and high grade presented a suitable scenario for a study of mechanical extraction processes. It was fictitiously repositioned in a remote South Australian location to serve as the basis for the case study.

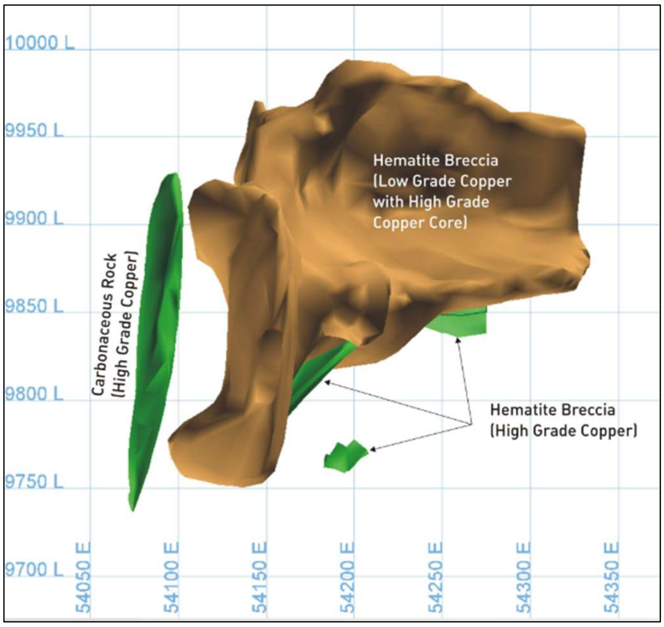

Figure 1 3D map of the orebody

The purpose of the study was to demonstrate that the value of flexibility could be determined in a mining value chain system context. Performance models were developed in collaboration with the challenge cohort partners, and the full mining chain simulated at a high level as a fully-coupled system. A systems approach was taken to capture the primary element in the study, illustrated by the flow diagram of Figure 2. Looking ahead to a time of greater volatility in energy supply, the team chose a highly constrained system of being powered solely by solar power.

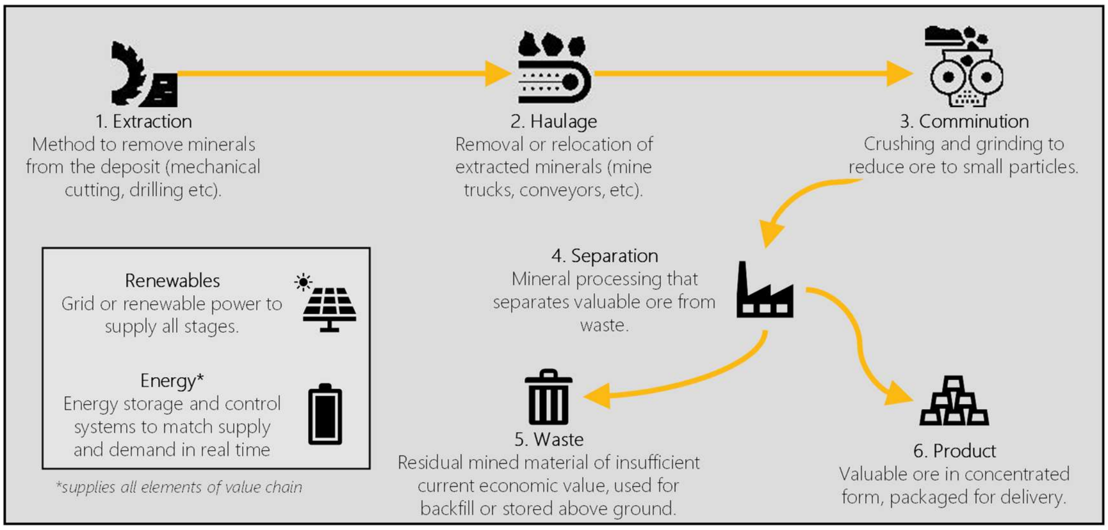

Figure 2 Elements of a value chain considered in the systems approach

RENEWABLE ENERGY

The traditional approach to mine site energy planning is to design the mine, calculate the levelized load then contract an energy service provider to deliver the required energy. The main decision for the mine planners seems to be what flavour of the 'Build, Own, Operate' set the mine should pursue. This practice was appropriate when the energy system could provide reliable, constantly available, cheap energy over the life of the mine. Now as we transition from fossil fuel to renewable energy, this approach becomes increasingly risky.

The coupled energy system

Energy touches everything we do, so if we change the energy system we will impact everything. Therefore, industry must adapt to the new energy reality, or pay someone else to adapt it for them. As the energy supply becomes variable, whether for an isolated or grid connected mine energy can no longer be left to others. A coupled energy/mine operations system is required.

The fundamental characteristics of renewable energy are variability, intermittency and correlation. These characteristics combine to erode the ability of the generation system to balance supply to demand. Of these three characteristics, variability is fairly predictable and fairly easy to handle. Intermittency means that we usually get less than we expect, but how much less is unknowable. The standard response is to overbuild generation and storage capacity.

The economic driving force of the three characteristics is correlation. Correlation means that renewables are either generating or not generating in unison. This supercharges intermittency because it means that supply switches between too much and none on a daily basis. For grid supplied mines, correlation leads to 'price separation' where the price jumps from a very low daytime price to an exorbitant evening price.

Contrary to common perception, isolated mines are not power supply limited. The power limit is economic because, due to correlation, the cost of a reliable constant renewable energy system rapidly enters diminishing returns. The alternative is to simply use renewables to reduce the cost and emissions of diesel fuel. This is tenable at present, but as the worldwide motor vehicle fleet electrifies, the cost of worldwide liquid fuel distribution will be increasingly borne by a reducing consumer base. Banking on uninterrupted supplies of cheap diesel introduces yet another risk to the energy/mine equation.

The solution to this growing list of energy challenges is to couple the energy system to the mine design at the planning stage, and then to run the energy system and mine as a closely coupled organisation. Throughout the mine life flow sheet and equipment selection needs to hold flexibility as a design objective to be co-optimised with energy and production. At the design stage the focus should be on addressing variability through flexibility, rather than addressing intermittency through overbuild. Addressing variability rather than intermittency solves both problems because the 'zero' points in variability demand either shutdown or minimised operations. Addressing intermittency then becomes a task of extending the minimum operating period.

The recommended process to embed flexibility at the design stage is as follows:

- Survey energy demand and flexibility at block level.
- Understand minimum operating and maximum rate for each sub system.
- Actively search for Process Storage.
- Prioritise flexibility: prioritise start, settle, ramp up/down, sleep, and off over absolute efficiency.
- If the energy profile is 'peaky' look for modularised units to allow for staged stepping-up of utilisation.
- Armed with this knowledge, engage energy providers and:
  Iterate generation/energy storage sets with operations sets to co-optimise the mine design.

The result will be a flexible, scalable, adaptable design, able to better adjust to uncertainties during energy transition and beyond. Flexibility will help deliver energy outcomes that will become increasingly necessary as the energy transition continues. However, that same flexibility will also produce a more resilient mine operation, able to respond to a range of challenges such as declining (or improving) market conditions, unexpected ore body variations and even political, social or workplace issues.

Supply

Australia has some of the best solar energy resource in the world with the highest radiation per square metre of any continent. For the case study the solar power system was based on a bifacial solar panel mounted to single axis trackers with centralised inverters to give an optimal yield per unit cost when compared to fixed tilt systems or monofacial solar panels. The system was modelled for energy yield using PVsyst software and an input weather data file from SolarGIS of a typical meteorological year for the location of the case study.

The output from the modelled system was then scaled to give an hourly energy output in kWh per kWp (kilowatt peak = nameplate capacity) of installed solar panels for a whole year. This data set was used in the wider system model and the installed capacity was able to be scaled up and down for multiple modelling runs. The modular basis for solar energy output was also reflected in the other parts of the overall model including the Battery Energy Storage System (BESS) and the mining fleet. The BESS was modelled with 1hr, 2hr and 4hr storage duration options with the energy capacity also scalable for multiple modelling runs. Assumptions were made to simplify the modelling with static energy flows and a constant round trip efficiency. Dynamics in the system will reduce the efficiency of the BESS to purely perform load shifting as the BESS may be required to provide other services to the system such as stability and spinning reserve. There may also be higher demand for reactive power at certain times depending on the load applied to the system.

An example of a PV system modelled based on relay daylight hours is provided in Figure 3. The load is an average 1 MW with 20% random variability for each timestep and 10% random variability day-to-day. The solar PV system is 4 MWp yielding 10 GWh over the year. The BESS is a 4 hour battery rated at 4 MW (i.e. 16 MWh capacity). Available PV output is shown in orange, note a significant cloud event during day of May 16 causes quick drop of power output. Black is battery state of charge, with PV having to provide operating load and recharge during daylight hours. Green is power load delivered by the battery, note that the periods where green does not overlap and orange does not exceed the blue (demand) are shortfalls in power supply – i.e. the process would have to be shut down or reduced by shedding some loads.

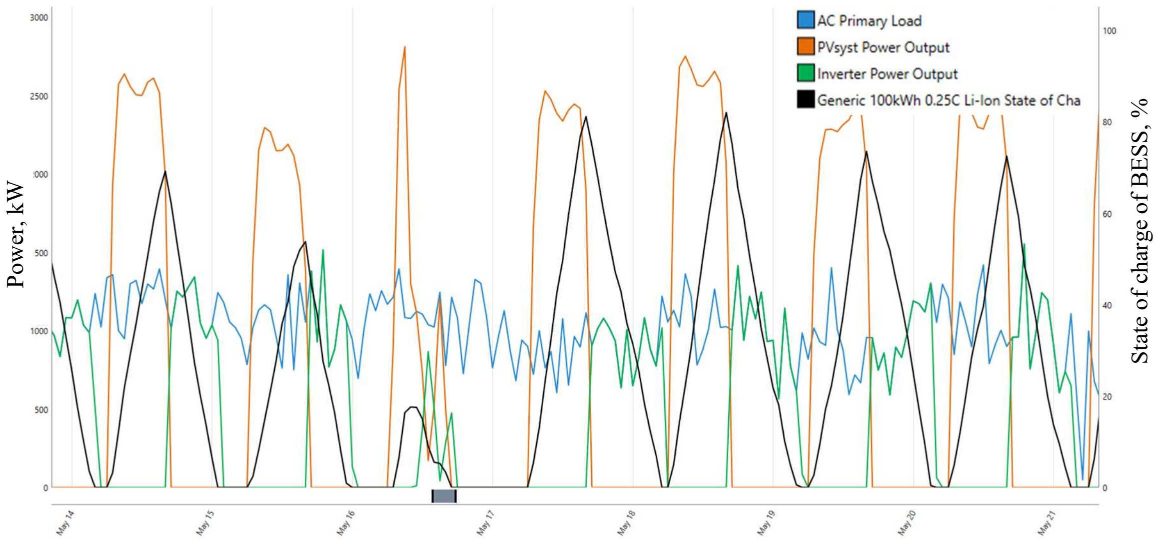

Figure 3 Plots of generation profiles versus a fixed target power consumption value

The simulation illustrates the issue of trying to operate off solar and battery alone, losing delivery even with 4 times the PV and 16 times the BESS of the nominal average power draw.

DISCONTINUOUS AND SCALABLE MINING

The mining concept developed was greatly influenced by the selection of winning proponents in the innovation challenge mounted by OZ Minerals for this project, who offered mechanical cutting methods. Less batch-cyclic and more electric in nature, with greater potential for automation, these mechanical methods may be more suitable for discontinuous operation than drill and blast extraction and could potentially reduce the need for ground support thanks to a smoother cut surface.

Horizontal Extraction

Komatsu's MC51 machine formed the basis of the extraction model for declines and drifts. In terms of mass and operation time, horizontal extraction is a small proportion of the total for all machines, enabling it to be modelled as a performance-based service over a series of annual campaigns.

Vertical precision extraction

Novamera's Sustainable Mining by Drilling (SMD) technology, based on pile-top drill rigs used in civil construction, formed the basis of the extraction models for columns below drifts. SMD is a reverse circulation drilling method with the capability to drill several hundred metres downwards. The technology uses machine vision, algorithms and AI to make rudimentary drilling equipment 'smart', able to precisely identify, navigate and extract high-value deposits (e.g., Li, Zn, Ni, Co & Ag, Au). In this concept study, the pile-top drill rig is utilized to represent the large diameter extraction tool to mine the lower columns in the underground mine design. In a practical underground application, the size of the conventional pile-top drill rig would have to be reduced or another type of large diameter drill would need to be employed. For columns above drifts, extraction was modelled based on raise bore machines. Raise bore mining has been utilized occasionally, for example at the McArthur River uranium mine in Saskatchewan, Canada (Hustrulid and Bullock, 2001).

Mine design

A novel underground mine topology, Modular Vertical Extraction (MVX), was developed that would allow extraction to proceed at a variable rate (constrained by available electric power), and on a variable number of fronts (constrained by available extraction machines) using the technologies proposed by challenge cohort partners. Although the feasibility of the concept has yet to be fully determined, for example in terms of geotechnical constraints or ventilation design, it has the advantage of being easy to simulate.

The MVX topology illustrated in Figure 4 comprises a vertically-separated pair of straight parallel arterial declines located one at and the other above the intersection of two planes derived from weighted least-squares models of spatial grade in the ore body. The gradient of these declines is thus determined by the ore body geometry, subject to gradient limits of the extraction machine. From these arterial declines numerous extraction drifts branch off horizontally, perpendicular to the arterial drifts, in alternating directions. Each extraction drift is the starting point for numerous extraction columns that extend vertically above and below it. The upper columns are extracted by raise boring machines and the lower columns are blind holes extracted by pile-top drill rigs, as used by Novamera Inc. for narrow-vein extraction from surface. The drifts are extracted by Komatsu Mining's MC51 mechanical cutting machine. For this project the drift dimensions were set to 5x5 m square section and the columns to 2.68 m diameter, giving two parallel rows of columns above and below each drift with perimeters that touch without overlap. As the product from column extraction is below 50 mm in size, reconfigurable modular conveyors are envisaged as the mechanism to transport ore from the base of extraction drifts to central ore haulage points.

The vertically-separated arterial declines and perpendicular extraction drifts create an interleaved, geometrically-regular structure. The alternating extraction drifts of the first arterial decline give rise to pillars between the extracted columns. The voided columns are backfilled with the processed tailings, addressing tailings disposal needs. The pillars can then be extracted from the conjugate drifts of the second decline. Because the arterial declines are driven through what may be thought of as the 'grade-weighted centroid' of the ore body, the MVX concept is essentially mining the resource from centre to periphery, enabling change of scale without change of architecture (hence use of the term topology).

In this study, decline and drift development was modelled as an annual campaign with a duration of several months. Aligning these campaigns with the seasonal solar maximum helped minimize the adverse impact of their power consumption on the rest of the system.

The MVX concept is a trade-off between precision of extraction and flexibility of operation. The geometrically regular structure creates the possibility for large and variable numbers of simultaneous extraction fronts but can incur significant dilution, depending on the structure of the ore body. The dilution is mitigated by (1) the potential for bulk-sorting of extracted material underground and dumping of gangue into voided columns below drifts, with paste fill, thus avoiding the cost of haulage to surface, (2) the potential for low activity cost enabled by renewable energy and automation, and (3) the opportunity to establish a grade profile by scanning a column's pilot hole before reaming, thus enabling longer-range look-ahead economic grade control and potentially even obviating some exploration drilling costs.

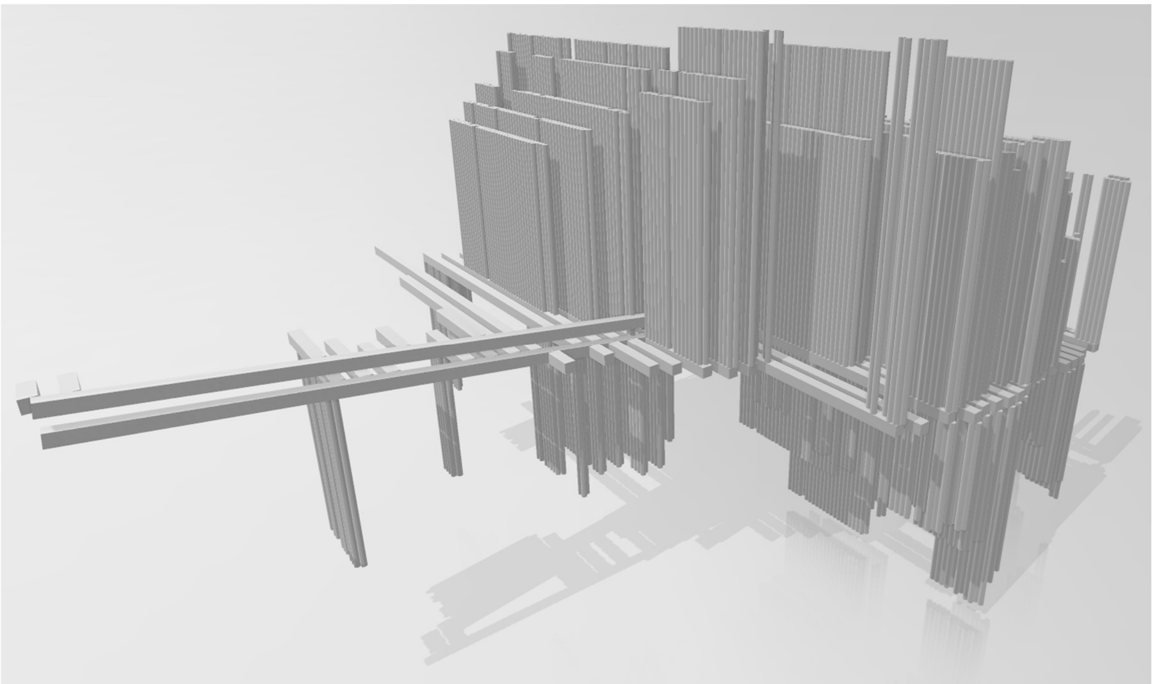

Figure 4 - Modular Vertical Extraction (MVX) Topology

An algorithm-driven mine plan

Previous approaches to mining flexibility have typically envisaged a small number of major decisions, for example the option to develop a second open pit (Ajak and Topal, 2015) or to switch between one mine plan and another (Cardin, Neufville and Kazakidis, 2008; Aeris, 2019). To model flexibility at the hourly resolution implied by the variability of solar energy however, it is impractical to develop *a priori* a suite of alternative mining plans. This is especially true for mechanical cutting, in which the advance rate of each machine (and to some extent the power consumption) depends heavily on its local rock properties that vary through the ore body. Therefore, an algorithm was developed for the MVX concept that allows the mine sequence to unfold in a path-dependent manner. The algorithm makes a decision for each increment of advance by each extraction machine, determined by the availability of electric power and the grade of the material to be extracted. Machines are dispatched to extract, to wait, to redeploy to a new column or drift, or to retire. The algorithm is modelled within a discrete event simulation that (1) respects constraints such as backfill cure time in adjacent columns and machine movement within drifts, (2) reconfigures a modular conveyor haulage network to account for extraction and in-situ waste dump routing, and (3) allows any number of extraction machines to participate at any point in the life of mine.

Algorithmic sequencing is the cornerstone of the flexibility of the MVX concept, because it allows extraction to be managed in agile fashion in a modular system, and because it allows scale adjustment by simply adding or subtracting extraction machines at any point in the simulated mine life. This points to a key aspect incorporated in the study, that of a flexible fleet size, being leased or contracted as required. Clearly this requires a degree of forward-planning compatible with equipment supply services and availability. This may be well suited to a cooperative eco-system of local mines that share these common resources.

MINERAL PROCESSING

The mineral processing and concentration aspect can be considered to commence with mining and can be in-situ, along the transport route or in the concentrator.

Gangue rejection early upgrade

The concept of rejecting a significant (10-30%) of rock prior to the energy-intensive process of comminution and expensive concentration processes is highly attractive. With new technologies offering higher resolution of differentiation between a wide range of minerals and gangue materials the doors open to gangue rejection being an essential tool in our armoury of addressing energy use in mineral recovery.

To maximise system value, early gangue rejection via ore-preconcentration has been investigated for inclusion within the circuit. Ore pre-concentration is a separation process to maximise the value of ore being process through the system, by selective removal of barren/ low grade material prior to expensive steps of comminution and flotation. In the context of a modular, renewable powered processing plant, the capacity of the process is a critical design point, thus maximising the valuable material and minimising the processing of barren material will enable optimised economics. Selection of the correct ore pre-concentration method is dependent on several ore specific factors, in combination with the overall process design and method, and based on the mineralogy, texture, other characteristics (i.e., density, deposit geometry and even mining method) of the ore body. For the example ore body used for this study, pre-concentration was deemed suitable to add value, in the form of early gangue rejection and its ability to flexibly respond to fluctuations in extraction throughputs.

As a system, the ore pre-concentration can be linked with the mining method, meaning when power is available, the extraction process takes place with the subsequent ore pre-concentration. The extraction method requires a somewhat high-power demand during operation, but with multiple unit operations, the specific throughput during peak power is maximised and subsequently scaled back during low power periods. The system can flexibly respond to these fluctuations due to buffering between mining and processing via a stockpile of high-grade material. As with most processing circuits, mining and processing are separated through a stockpile; however, the system employed here will have additional ability to determine a balance between mining and processing as the downstream processes do not require stable, continuous operation, a paradigm shift to current operations.

As the extraction for this process is utilising precision extraction and rock cutting, the presentation of the ore will have different characteristics to typical mining methods (i.e., drill and blast). The product is anticipated to have a finer top size along with the ability to mine higher grade areas whilst selectively leaving low grade material where appropriate, negating the need for certain ore pre-concentration circuits to include addition crushing or comminution units. Through these extraction methods, it is anticipated that ore will be extracted and presented with minimum sorting points, enabling the retention of grade domains as seen at the mining face, which will enable the ore-preconcentration device to effectively separate.

The in-principle amenability to sorting can be deduced from mineral structure, but physical samples are required to quantify the response, as the natural deportment and association of minerals after various stages of breakage cannot yet be modelled. The potential mass rejection and associated grade loss varies considerably across the orebody and even within localised areas as the mineral classes and associations vary. Without the test data available to the study, the outcomes cannot be meaningfully incorporated into the simulations. This led to a broad-brush simplification of reject mass and grade based off experience of similar ores. This allowed the waste to be rejected in-situ underground and returned to backfill without any further transport.

The precision extraction and rock cutting devices not only enable effective ore pre-concentration due to the reduced top size and continuous selective extraction, but also reduce the reduction ratio requirement for downstream comminution processes. Final grind size required (typically regrind size prior to cleaner stage flotation) for recovery circuits is a somewhat fixed parameter dependent on ore liberation characteristics and recovery processes, so reduction of ore size presented to the comminution circuit reduces the reduction ratio and comminution duty for the given circuit.

Shift the comminution paradigm

A significant consumer of energy in the mining process is comminution – breaking in-situ rock down to the particle sizes required to adequately expose the entrapped mineral for recovery. Comprehensive studies of Ballantyne and Powell (2014) indicate an average of 37% of total mining energy, representing 1-2% of world energy consumption. Additionally, the standard processes utilize steel grinding media that approximately doubles the energy and carbon footprint via embodied energy of the milling processes (Ballantyne 2019). In order to shift to viable processing powered by renewables, it is essential to slash this energy usage, or, as indicated earlier, the use of renewable energy has financial and environmental costs that are unacceptable. Although this is generally well understood, what is not generally appreciated is the challenge of variable operation. As noted in the energy generation section, renewables are intrinsically variable in production, yet the current comminution and recovery processes are dependent upon stable and continuous operation – dependent in turn upon continuous and stable energy supply. The limited operating range of rotary grinding mills, which are the workhorse of comminution, does not allow the power usage to be arbitrarily varied to match available power, as the mills rapidly grind out or overfill – leading to hours of unstable operation and variable product quality (grind size). This knocks on to the recovery process that suffers large losses to tailings as the feed size distribution from comminution fluctuates from too fine to too coarse.

Variable operation presents as much of a challenge as absolute power consumption. A key aspect is extended residence time, around 20 minutes per mill coupled with multi-stage grinding and recycles that lead to milling circuit superficial residence times of around 40 minutes. Surges with processing capacity circulate within the circuit for multiple residence times, with these surges being amplified in the recovery circuits, that have their own extended residence time and recycle streams. This points to the need for a comminution process with a short residence time, and that does not suffer a degradation in product quality as power use, and thus feedrate, is varied frequently and over a wide range. Such a device is under development, having progressed to pilot testing, and is used in this concept study. Measured performance is used, but the method is not yet open to publication. Specifically of relevance to this study, the equipment can provide:

- Dry processing
- A fixed product size from zero to maximum feedrate
- The rate of start-up or shutdown is less than a minute
- Residence time of the entire comminution process from run of mine feed to recovery product is in the order of a few minutes and has no recycles
- The primary product size distribution is steep, with a narrow size range – well suited to physical separation, ore sorting, and coarse flotation processes
- A secondary smaller product stream of fines extracted in the air stream is suited to separate recovery process of highly liberated fine particles
- Importantly for use of renewables, the process uses around 20% of current comminution energy to achieve equivalent recoveries.

These properties revolutionise the overall mineral recovery process, shifting comminution from a dominant to a minor energy consumer in the process, while opening the door to variable process throughput. Additionally, the coarser primary product allows for dewatering and alternative storage of the tailings from a wet recovery system (such as flotation), being well suited to back filling when blended with controlled portions of the fine product.

UPTAKE VIA ENGINEERING DESIGN

Conventional comminution and recovery circuits are not designed or engineered to enable flexible operation, limiting the applicability for these circuits to be wholly powered through renewable power sources. Comminution is a significant portion of both capital and operating costs for a mine site, resulting in maximising equipment uptime and specific throughput in order to minimise operational cost per ton of ore processed. A flexible processing plant design is configured with alternate design goals, which aims to support intermittent operation and have a modular design to enable construction and then operation at remote locations. Small, remote satellite ores are not economical under typical 'economy of scale' business models, instead requiring flexible and modular designs to enable attractive economic outcomes.

With a shift in the comminution paradigm by a device currently under development, outlined above, the focus on the processing circuit and its ability to respond to variable power and throughput then focusses on the recovery circuit supplementary to the comminution circuit. Typical mechanical flotation cells are designed with large residence times, 10 – 30 minutes, with considerable number of series units to recover valuable material, these design characteristics do not lend themselves to intermittent and start/stop operation. The use of Jameson cells (Jameson et al, 1988; Evans et al, 1995; Harbort et al, 2002; Harbort et al, 2004; Cowburn et al, 2005) has been investigated due to their operational attributes to enable flexibility and intermittent operation, whilst not requiring pressurised air for operation (simpler installation at remote sites). Critically, these cells are operated via pressurised slurry and high intensity mixing with entrained air to force particle-bubble contact resulting in residence times within the seconds, rather than minutes compared to mechanical cells. The particle-bubble contacts occur in the downcomer which allows the flotation cell to be much smaller than conventional mechanical cells. Optimum operation is achieved in these types of cells by operating at a fixed volumetric feed rate which is achieved by recycling a portion of the cell tailing (typically 30% - 40% during normal operation). When fresh feed is turned-on or ceased the cell can operate in a 100% recycle mode. This reduced residence time, size of cell and internal recycle of cell tailings enables this type of technology to better respond to fluctuations in the circuits throughput during operation whilst maintaining valuable mineral recovery. Metso Outotec provide an alternative cell called the Concorde cell™ (Jameson 2010) whereby the slurry and air are pressurised and the aerate slurry jet passes through a choke to force particle-bubble contacts at supersonic velocities. The marketing focus of this technology has been on fine and ultra-fine particle recovery so was not considered for this work. Additionally, the NovaCell technology (Jameson et al, 2019) has some similar operating characteristics as Jameson and Concorde cells. It utilises pressurised air to produce a high shear aeration zone in the downcomer for fines and ultra-fines recovery and uses a fluidised bed and collection cone within the froth zone to recover coarse particles. This collection of coarser particles than conventional mechanical cells enable the circuit to take advantage of the coarser and narrower size distribution produced in the primary grind product of the novel comminution process employed in this design. There are no current operating sites utilising the NovaCell technology so the study relied on the Jameson cell technology with over 380 installations globally.

On top of the critical unit operations enabling flexible operation, the circuit can be engineered to enable flexibility and support the overall processing circuit. This is achieved through the addition of modest supplementary stockpiles and fine ore buffer storage, which enables different rates between mining, milling and flotation as energy availability for the circuit varies. Critical to this design point is the comminution device's ability to efficiently mill to primary grind size required for the recovery circuit, which is fed to the recovery circuit via agitated tanks, providing some buffer between the circuits. The consistent primary grind combined with a buffer enables maximised valuable recovery via the use of Jameson, Concorde or Nova flotation cells.

TAILINGS

The majority of tailings are used to back-fill the active mine area as the extraction levels move across prior workings. The terminal velocity of a settling particle can be approximated by Stokes Law, with velocity proportional to the square of the radius. This means settling is much slower for smaller particle sizes. A coarser tailings particle size distribution, allowed by the comminution device noted above, is much easier to dewater and provides the increased recycling of process water and less costly dewatering in the case a tailings dam is not permitted, or thickened tailings for paste backfill is used. In the mine model used for this scalable and adaptable project, tailings were used to progressively back-fill the active mine area as the extraction levels moved across prior workings.

CIRCUIT

A high-level circuit is presented in Figure 5, which includes the roles of each of the contributing companies within the study.

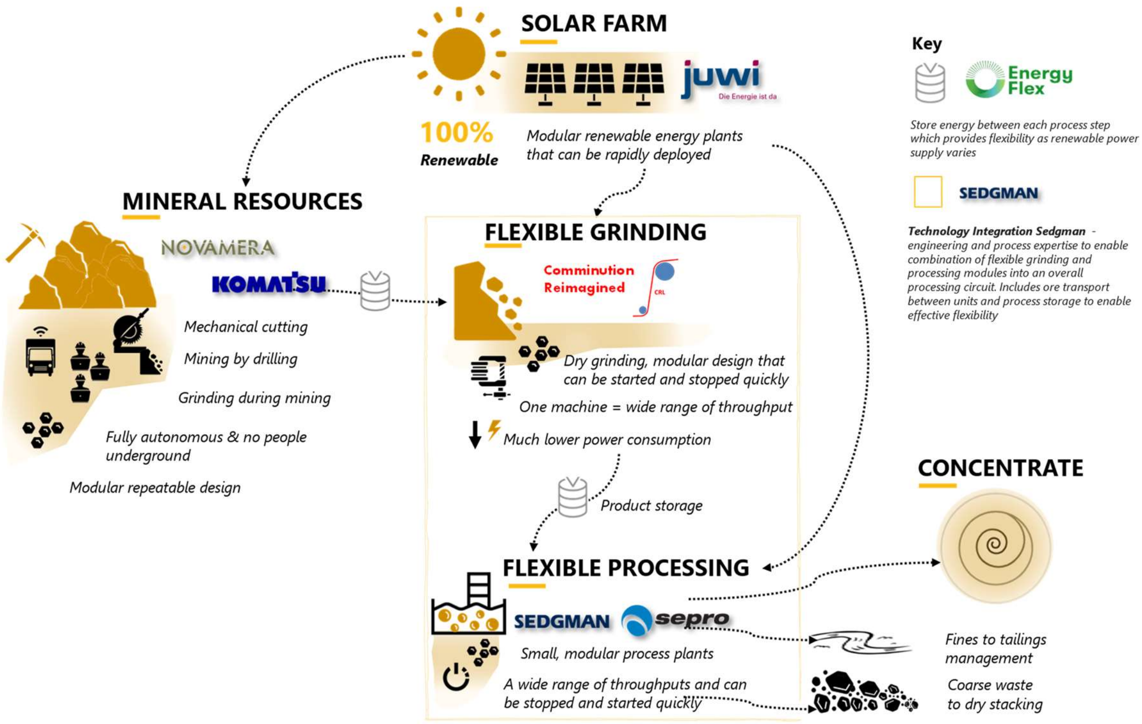

Figure 5 Mining and processing circuit diagram

A nominal plant capacity of 100 to 200 tph was targeted, with the value being an outcome of the simulated outcomes that varied the life of mine to fully mine out the viable ore resource. Process buffers are provided by a stockpile after the mine and a storage capacity of finely ground ore between the milling and separation stages. Other process storage options were reviewed such as gravitation potential energy and pumped process water storage, but did not indicate favourable economics relative to the high energy density of BESS.

SIMULATED CASE-STUDY OUTCOMES

The flexible value chain outlined above was modelled using MATLAB and Simulink, and applied to a satellite ore body of OZ Minerals' Prominent Hill mine, fictitiously repositioned in a remote location. The purpose of the simulation was to demonstrate that the value of flexibility could be determined in a mining value chain system context. Performance models were developed in collaboration with the challenge cohort partners and used in the simulation to relate equipment performance over time, including energy consumption, to material properties of blocks of ore in the deposit. An energy management algorithm was developed to manage loads across the system, with priority policies driven by stocks and flows to seek balance. The model was architected with a modular structure, enabling the size and configuration of the modelled system to be parameterized. The code was optimized for speed and parallel computing, to enable Monte Carlo simulations to be run economically; using a 128-core compute cluster in the cloud enabled a run rate of about 1000 mine life simulations per hour. The model included functions to track and report material flows and economic results over the life of mine, enabling net present value (NPV) and mine life to be calculated.

Initial parameter-sweep batch simulations considered the effect of varying the number of extraction machines and the size of the energy subsystem (in terms of number of modules of PV and BESS). As expected, with any two of the three parameters held constant, increasing the other generated diminishing returns for NPV and ultimately a peak value. The ultimate limiting factors for scale include congestion within the mine, which leaves machines stranded and unable to be redeployed, and mass flow rate limits for the underground conveyor segments. For most fleet sizes and PV capacities, the optimum storage capacity was found to be around 4 hours. In other words, NPV peaked when storage capacity (MWh) was around 4 times PV nameplate capacity (MW).

The simulation enabled operating patterns to be discerned for this optimal level of energy storage. The outputs are presented in three summary graphs plotted over hours of operation, representing around 20 days of sample data in each plot. The upper plot shows the units of mining fleet equipment usage of SMD cutting and raise bore (RB) mining, with this scenario having 6 available of each unit. The middle shows the power usage of the recovery section for milling and throughput in tph of the separation flotation units as a 'throttle' value representing the available capacity being used of the equipment up to the maximum (700 kW for milling and 120 tph for separation). The bottom plot tracks either the capacity of the stored product that is being used or the state of energy storage in the BESS – with a total storage capacity of 58 MWh in this simulated scenario.

Monte Carlo simulations of the system model were undertaken over an extensive number of scenarios, wherein a range of extraction and sorting operations were simulated to identify theoretically optimised operating conditions and parameters. Capacity at the extraction point was varied through the expansion or contraction of fleet size with an overlay of sorter reject grade, with these parameters resulting in variable mine life, throughputs, energy consumption and NPV. Sorting reject grade varied between 0.2% Cu to 0.7% Cu, resulting in mine life variations ±23% from the baseline as well as fluctuations in NPV as fleet sizes varied. The combination of novel extraction and ore pre-concentration also resulted in downstream processing benefits due to lower ore top size and range of feed grade.

The equipment utilisation patterns vary with the seasons, because of changes in daylight duration and intensity. Figure 6 shows a shoulder season period of spring or autumn of a little over two weeks, in which a clear diurnal operating pattern can be seen. The mining machine fleet (upper plot) is usually fully employed during the day and mostly idle at night. The mill and flotation plant (middle plot) follow a similar pattern. The mill throttle signal varies during the day according to the level of the ground product storage buffer (lower plot) that precedes the flotation stage. Occasionally there is sufficient energy for milling and flotation to continue overnight, but generally the BESS is fully discharged soon after sunset.

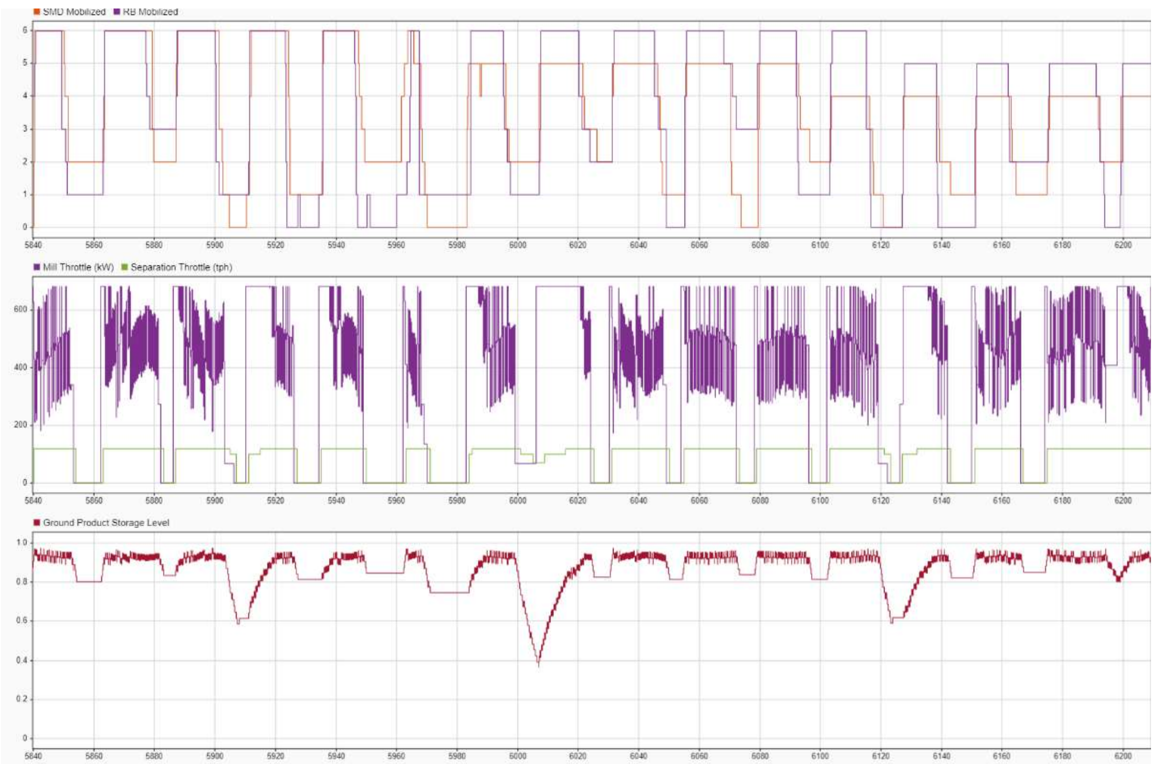

Figure 6 - Shoulder-season diurnal operating pattern

Figure 7 shows operating patterns in summer. The mining machines see shorter and fewer overnight pauses and the process plant runs continuously. There is a middle-of-day surplus of power, as indicated by the daily complete recharge of the energy storage (lower plot), which then has sufficient stored energy to power most of the mining activities through the night.

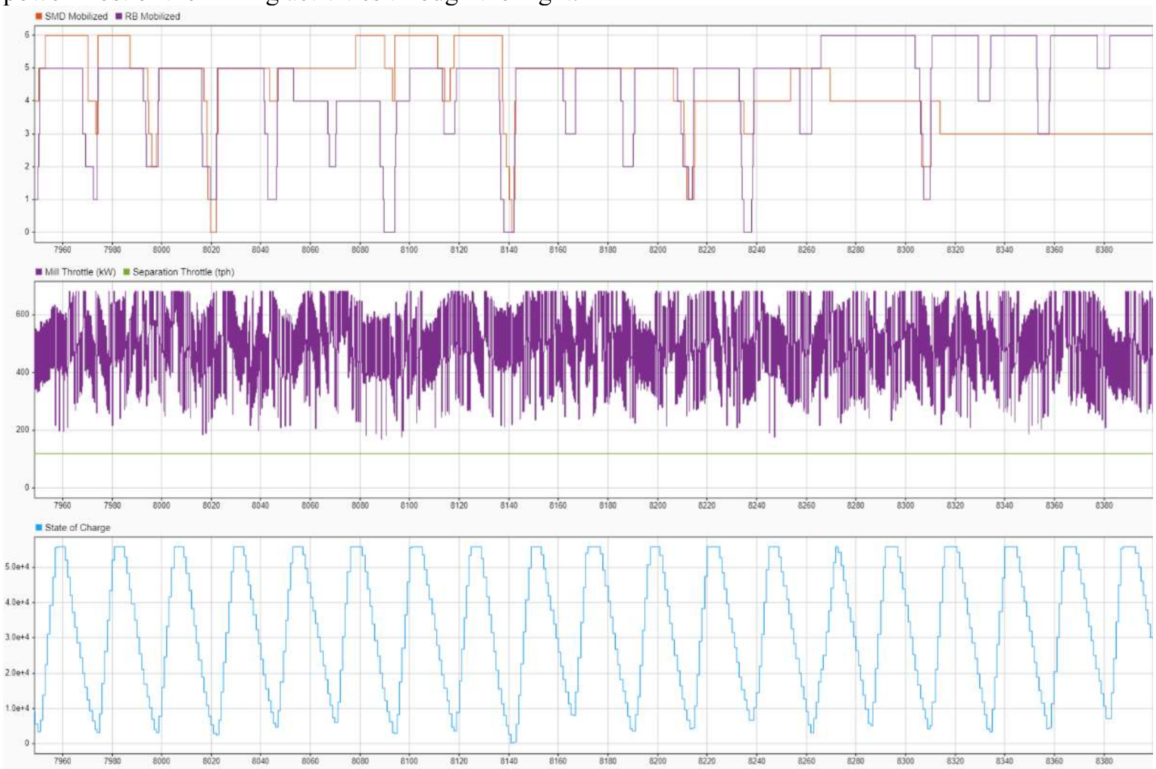

Figure 7 - summer operating pattern

In winter, when there is least solar energy available, a different pattern emerges (Figure 8). The mining fleet never reaches full mobilization, which leaves the process plant underfed on average because of the limited turndown ratio of flotation (this is especially true later in the mine life as grades decline and bulk sorting mass pull reduces). The process plant runs on a diurnal pattern that exhausts the stockpile, and then shuts down for 5-10 days until the stockpile is recharged to the threshold of resumed feed (this is a hysteresis characteristic included in the simulation). While the process plant is idle there is sufficient power to run most of the mining fleet continuously. Mining effort is first directed to the most valuable (in terms of financial return) parts of the orebody. As the higher grade ores are depleted the lower grade has a higher mass rejection from the ore sorting system, reducing the fraction of mass fed to the processing section relative to the mining section. This leads to increased pressure on mining as it struggles to keep up with the processing capacity. The multi-day cyclic behaviour is an emergent property of the complexity of the system, that would likely remain hidden without simulation; using simulation, the stockpile operating parameters could be optimized for various objectives relating to economics or operating pattern.

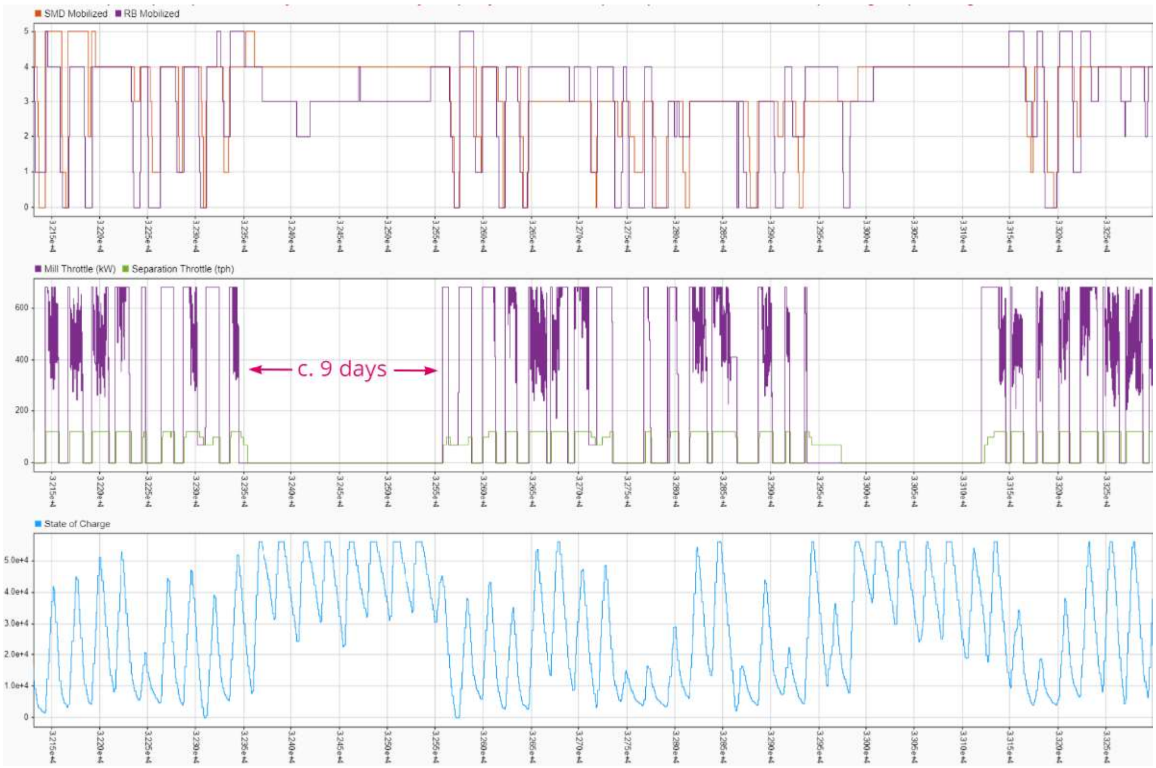

Figure 8 - winter operating pattern

With a scalable mine, there are a wide variety of financially viable operating plans, as expressed in Figure 9. There is a cluster of maximum NPV outcomes with different fleet sizes and power usage. The flexibility of the mine method and processing plant allow the mine plan to be continuously updated to seek the optimal outcome as metal price varies, the measured reserve varies as orebody resolution evolves over the mine life, energy availability and storage cost vary. This presents a far more robust solution than a long-term fixed plan come hell or high water.

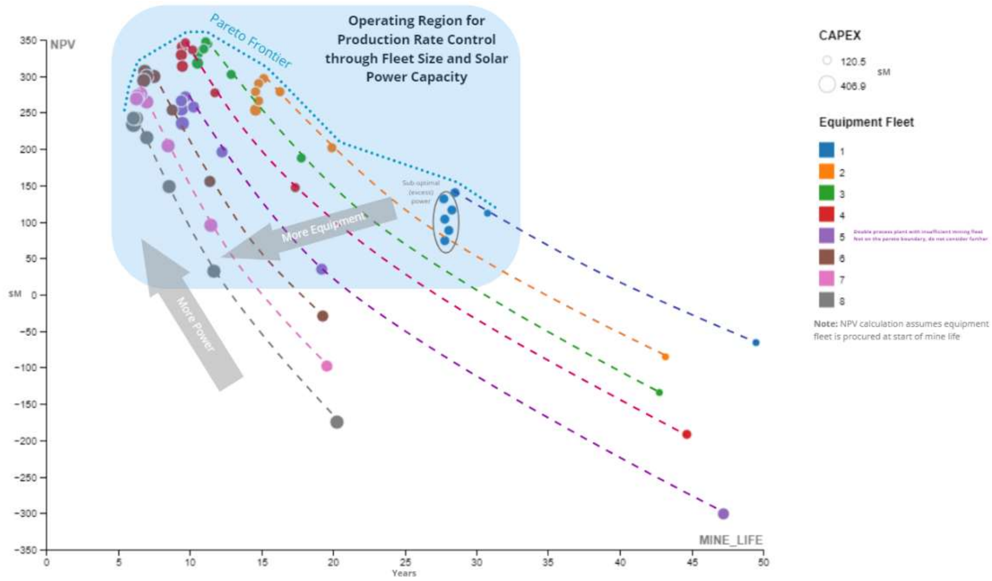

Figure 9 Effect of changing fleet size and power generation on NPV and life of mine

CONCLUSIONS

The constraint for solar as the only energy source with a BESS only being used to shift the curve of solar production gives rise to the specifically constrained outcome used in this study. Battery storage is one of the best energy storage methods, but is expensive in cost and mineral resources to manufacture, with alternatives such as hydrogen being both more expensive and having a low energy recovery (around 30%). A more balanced generation profile through the addition of other renewable resources such as wind energy would make for a smoother daily generation profile and could allow for systems with more optimal outcomes. However, it is unlikely to be economically viable to assume a business-as-usual model of continuous operation based exclusively on renewables and energy storage. There is a significant reduction, to as little as 50% of installed generating capacity and energy storage, if the demand requirement is reduced to 80%. Currently business may see this as a gap to be filled by diesel generators in remote sites, but as noted earlier, this will likely be off the table in years to come. The final 20% is a challenge for current pricing of batteries and other longer term storage devices in a business-as-usual scenario but with the addition of demand side management (i.e. the adaptable part of our study with the mining and processing equipment being ramped down when energy availability is low) this can become viable for a similar cost of energy. Hence, the wisdom of incorporating flexibility of mining and processing into our immediate future designs.

The results of the energy supply model showed that short-term flexibility of discontinuous operation was economically preferable as an alternative to increasing the capacity of energy storage. In other words, reducing the load at opportune timesteps reduced the requirement for a larger battery and made for a higher overall NPV when compared to the scenario with higher throughput but a more expensive, larger battery system.

It is clear that flexibility on the demand side of the electrical system delivered value to the system, thus to make the most use of any variable renewable energy resource it is beneficial for the energy consumers to be equally variable in energy demand. Advances are being made in mine processing equipment to allow for this greater flexibility of energy demand as discussed in this paper. In addition, as more mine fleet and equipment are electrified there will be more opportunities to shift load to different parts of the day to ensure the overall system can adapt to the available energy, for example charging electric haulage trucks at peak solar production periods.

A novel Modular Vertical Extraction MVX mining concept is proposed that suits underground mining and is built on the concept of a mine plan that can evolve over time, rather than being locked in years in advance. Algorithmic sequencing is the cornerstone of the MVX flexibility, because it allows extraction to be managed in agile fashion in a modular system, and because it allows scale adjustment by simply adding or subtracting extraction machines at any point in the simulated mine life. This points to a key aspect incorporated in the study, that of a flexible fleet size, being leased or contracted as required. Clearly this requires a degree of forward-planning compatible with equipment supply services and availability. This may be well suited to a cooperative eco-system of local mines that share these common resources.

The processing system uses a novel comminution device that is under development that intrinsically allows a continuum of throughput and energy usage from zero to maximum without any impact on product quality. This unlocks the flexible processing option that conventional milling processes prevent. The separation process is shifted to the emerging flotation technologies that allow coarser particle recovery and have short residence times that can match the variable comminution rates. A limited buffer capacity allows the flotation section to have extended operating time relative to the comminution circuit – allowing the mills to be switched off during low energy supply while continuing to produce mineral concentrate.

The study points to the massive value-add of incorporating flexible processing into a mine plan so as to fully utilise the variability of renewable energy sources. The extreme case of using solar energy as the only energy source demonstrated that the mine can be viable even under this unfavourable scenario. A challenging aspect for current business mind-set is that the equipment is not fully utilised, being idle when the system is energy constrained. This extends the mine life and pushes out the return on investment, however, it substantially reduces the cost of installed renewable energy and energy storage – which could equal the cost of developing the mine if not constrained!

The proposed mining method and associated algorithmic mine plan, open a completely new door on mine development. Based off a centre-point of well mapped and viable grade, the mine can be started with little further exploration. Extraction modules and modular processing units are added or removed as the mine size and mining rate evolve over life of mine and the process of mining and tracks the prospecting holes that can then be turned into the core of the raise bore process. This can potentially preclude the need for a known mine life and throughput rate based off many years of expensive exploration and the associated need for a massive up-front investment in a fixed processing plant - the size of which is coupled to the life of mine and thus mining rate. Smaller, more agile operations that can start up faster and evolve on the fly could open up many currently unviable resources, better match community aspirations and critical mineral supply imperatives, and be ideally suited to utilising renewable energy sources.

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