Making electrified underground mining a reality

Lessons from the Cosmos Electrification Study

A global mine electrification **collaboration**

Who's behind this study?

About IGO

IGO is an ASX 100-listed company focused on creating a better planet for future generations by discovering, developing and delivering products critical to a clean energy future. Through upstream mining and downstream processing assets, IGO is enabling future-facing technologies including the electrification of transport, energy storage and renewable energy generation.

About Perenti

Perenti is an ASX-listed, diversified mining services group with over 35 years' experience in surface and underground mining. With more than 11,000 employees, Perenti's focus is on safety and creating a better working and operating environment for mining companies. Helping customers accelerate decarbonisation strategies is a special focus in preparation for the future of mining.

About ABB

ABB is a technology leader in electrification and automation, enabling a more sustainable and resource-efficient future. The company's solutions connect engineering know-how and software to optimise how things are manufactured, moved, powered and operated. Building on more than 140 years of excellence, ABB's 105,000 employees are committed to driving innovations that accelerate industrial transformation.

Perenti and ABB have established a collaboration combining Perenti's mining expertise and technical capability with ABB's electrical and technological expertise. The collaboration offers services supporting net zero emissions targets and electrification of operations for pilot, brownfield and greenfield mining customer projects.

The findings presented in this white paper relate specifically to the Cosmos mine and should be considered in that context. Any mine or mining project considering converting to a battery electric fleet should carefully consider the applicability of these findings in relation to the specific circumstances of its own mine (including but not limited to mine depth, geometry, material movement method (shaft or decline haulage), expected mine life, and production rate).

Underground Battery Charging / Swap Located At AngloGold Ashanti's Sunrise Dam Operation

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Executive summary

In pursuit of delivering its commitment to achieving net zero emissions from direct operations by 2035, IGO's pre-feasibility level Cosmos Nickel Operation (Cosmos) Underground Electrification: Phase 2 Study (the "Study") aimed to determine the viability of battery electric vehicles (BEVs) as an alternative to a diesel fleet, in an existing underground mine.

The Study was conducted by IGO, who engaged Perenti and ABB working in close collaboration to understand the technical feasibility, cost and operational implications of implementing a BEV fleet underground.

Leveraging the three companies' combined electrification knowledge and underground mine operations expertise, the Study is one of the first to comprehensively detail the requirements for underground mine electrification and diesel fleet transition.

The Study's results demonstrate that transitioning to an all-electric fleet at Cosmos is technically feasible and not cost prohibitive. Accordingly, if not for commodity headwinds, IGO was committed to further studies to explore an all-electric fleet at Cosmos. While each mine is different, the findings have substantial value for IGO and the industry more broadly.

This paper captures key aspects of the evolving mine electrification knowledge base, explores the Study's findings, and considers the implications for the broader mining industry when evaluating the conversion of underground mining fleets from diesel to BEV.

Key findings

1. Based on Original Equipment Manufacturer (OEM) provided assumptions, BEV fleet offerings matching the productivity of the existing Cosmos diesel mobile fleet are available to the Australian market.
2. The estimated cost to electrify the Cosmos underground fleet was not prohibitive over the envisaged life of mine, even based on conservative productivity and cost assumptions.
3. The total power consumption of a fully electrified fleet was calculated to be less than that of the equivalent diesel operation, due to substantial power savings in mine cooling and ventilation.

The encouraging results of the Study reinforce the importance of BEV trials in Australia and globally. Further study by the industry is encouraged to fully realise the potential of fleet electrification.

The Cosmos Mine - Image Courtesy IGO

Introduction

Why electrify?

Facing mounting societal pressure for cleaner operations and stricter regulations aimed at curbing greenhouse gas emissions, the mining industry is actively seeking ways to decarbonise. IGO is committed to achieving a target of net zero emissions from direct operations by 2035. As part of its roadmap towards achieving this goal, IGO has identified several projects to progressively decarbonise and electrify its power generation, mining and processing operations and other operational activities. Converting from a diesel to an electrified underground mining fleet is a key step in the journey towards net zero.

In addition to supporting decarbonisation, electrification supports compliance with increasingly stringent work health and safety (WHS) and occupational hygiene regulations by enabling significant improvements to worker wellbeing. An electric fleet eliminates exhaust and diesel particulate matter during underground operations, reduces vibration levels experienced by operators, and decreases noise impacts on personnel. These benefits are expected to outweigh the potential risks presented by using BEV fleets, so long as those risks are appropriately mitigated. This presents a strong imperative beyond decarbonisation alone for implementing an electric mining fleet.

Mobile fleet electrification may also result in productivity improvements and targeted capital savings. This stems from two key factors. Firstly, the higher tramming speeds and increased breakout force of electric load haul dump (LHD) loaders and trucks (compared to their diesel equivalents) may directly translate to increased production output. Secondly, eliminating diesel emissions and reducing heat generation (electric vs diesel motors produce less waste heat) through electrification can (depending on circumstances) reduce the ventilation and cooling infrastructure required underground, indirectly reducing capital demands.

The challenge – fleet electrification of an existing underground mine

Electric mining equipment has been used underground for many years, ranging from electric rail systems to trolley-assist haulage trucks and tethered electric loaders. These electric technologies are often capital intensive and inflexible, and as such have limited and specific applications in underground metalliferous mining.

BEVs combine the advantages of electric equipment with the mobility and flexibility of diesel equipment. However, battery technology has only recently advanced to meet the high instantaneous duty requirements of mobile mining equipment. Despite these advances, battery capacity still currently imposes range limitations on battery-operated haulage vehicles, presenting challenges for mines reliant on long incline truck hauls.

The full value potential and optimal utilisation of BEVs will remain uncertain until they have been adopted at scale. Accordingly, IGO recognised that this Study required the expertise and resources of similarly innovative companies like Perenti and ABB who are also focused on decarbonisation and mine electrification.

While several companies have studied or even implemented partial fleet electrification, IGO, Perenti and ABB believe the Study is one of the first to explore how to convert from a diesel fleet to a fully battery electric fleet in an underground metalliferous mine.

A holistic view of electrification was taken for the Study, in part to address common questions surrounding fleet electrification, including:

- What machinery and technology is currently (or will soon be) available in market?
- How should a mine be designed to suit a battery electric fleet?
- What are the operating philosophies and productivities of this new fleet?
- What infrastructure and power reticulation will be required?
- What are the capital and operating costs?
- What are the risks in transitioning from a diesel to a BEV fleet?

Why Cosmos?

The Cosmos Nickel Operation (Cosmos) is located 30 km north of Leinster in Western Australia. The project is 100% owned by IGO Limited (IGO), with underground mining services provided by Barminco (an underground mining contracting arm of Perenti).

The mine includes historical workings completed prior to 2012. The underground mine was reopened in early 2019, and at the commencement of the Study in mid-2023 the site was in a project development phase. Cosmos was planned to mine and process up to 1.1 Mtpa of nickel ore over approximately 10 years, utilising shaft hoisting from mid-2024.

Cosmos was a promising candidate for full underground mine electrification, due to the use of a 1,000 m deep hoisting shaft to move ore and waste to the surface. This limited the length of truck haulage routes to distances compatible with the current battery technology in underground mining equipment.

In principle, mines stand to save operational costs and offset additional capital requirements by electrifying their fleets as soon as practicable. Accordingly, an aspirational target of 2025 to fully electrify the Cosmos underground fleet was agreed upon for the Study.

In parallel with the Study, a detailed review of Cosmos was conducted in the second half of 2023. This review identified increases in capital and operating costs and a reduction in expected mine life, in parallel with a significant deterioration in nickel prices. With the economics of Cosmos impacted, in January 2024 the decision was made to place Cosmos into care and maintenance. This decision was made independently of the results of the Study, and does not affect the Study's positive underlying findings on the feasibility of transitioning to a fully electric underground mining fleet.

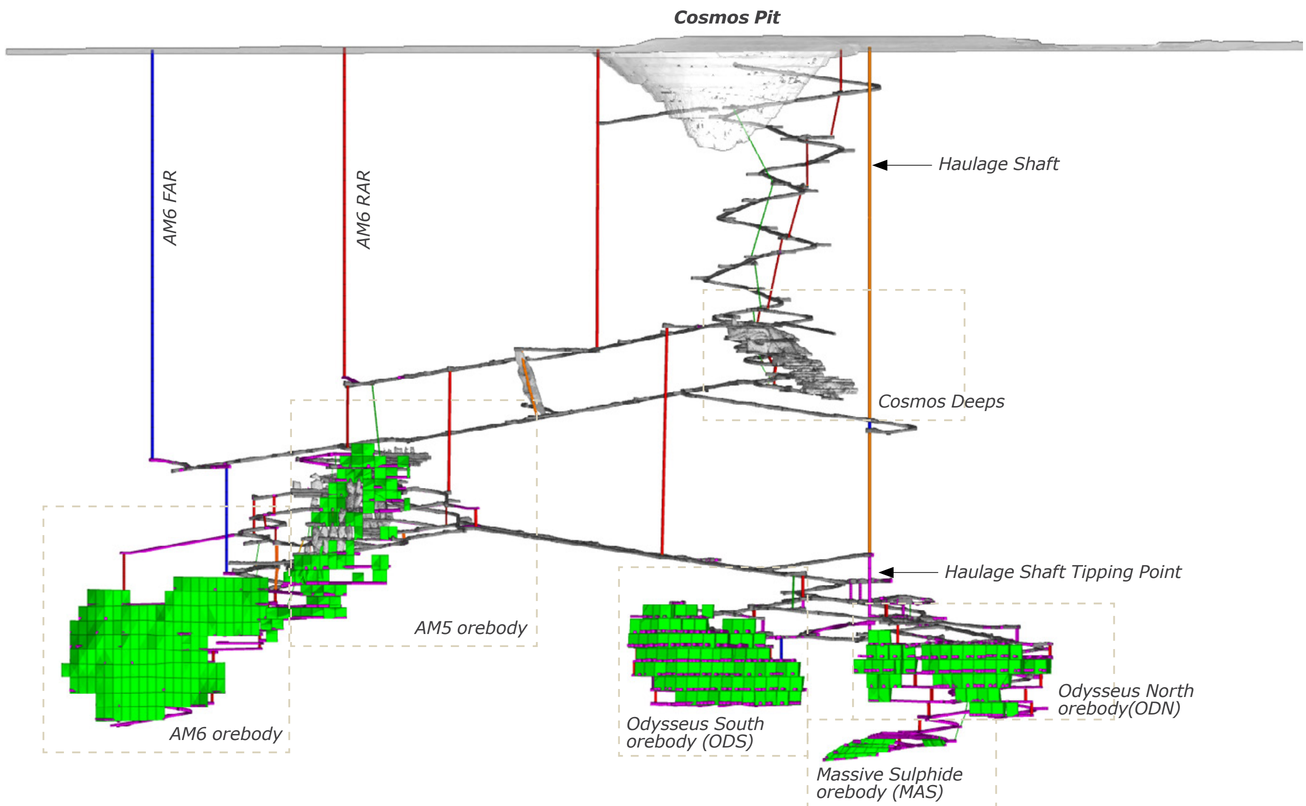

***Figure 1** – Section View Showing Cosmos Infrastructure And Planned Mining*

Addressing the problem of electrifying a diesel mine

While it is generally accepted that fleet electrification will produce meaningful environmental, social and governance (ESG) and WHS benefits, to date there has been little detailed guidance on how to practically implement a fully BEV fleet in an already operating underground mine.

The technical process of completing an electrification study is different to undertaking a pre-feasibility study for a mine with a standard diesel fleet and requires new thinking and re-evaluation of commonly accepted mining practices for diesel equipment.

The three key focus points of the Study were:

- Can a BEV mining fleet replace an existing diesel fleet and maintain the required productivities?
- What cost delta would be associated with the transition to 'and operation of' this all-electric fleet?
- How long would it take and what would be required to transition an operating mine from fully diesel to fully BEV without impacting operations?

Challenges to overcome

- **Availability of fleet operating information** – a lack of industry experience and data on BEV machines.
- **Capital hurdles** – including the high initial cost of BEVs and charging infrastructure.
- **Location-specific external operating costs** – including power costs, fuel prices and subsidies.
- **Mine design** – some layouts are more favourable for BEV truck haulage; deep decline-centric haulage designs are currently not favourable.
- **Infrastructure requirements** – installing or upgrading electrical infrastructure can be complex and costly, especially in the limited space of an underground mine.
- **Lack of location-specific regulation** – regulation has generally not kept pace with changes in technology, necessitating reliance on a burgeoning set of global guidelines instead.
- **Rapidly changing technology** – fast-evolving battery chemistry and equipment render it difficult to evaluate future options and make capital decisions.
- **Skills and training** – because the industry is still new, the skills to operate, maintain and design BEV equipment need to be developed.

BEV Longhole Drill At The IGO Nova Operation

Considerations when using batteries

Battery safety

While BEVs may reduce or eliminate many risks to underground workers from diesel vehicles, they also introduce new hazards inherent to using batteries, including:

- thermal run-away leading to fire or explosion
- fume generation during a fire
- rupture causing toxic or flammable liquid / gas release
- electric shock risk
- manual handling risks
- burns due to heat.

While the mining industry has typically focused on battery chemistry in discussions on battery safety, IGO, Perenti and ABB believe it is time to move beyond this with battery chemistry being just one aspect of a wider holistic battery safety discussion.

The Study considered BEVs using four different battery chemistries: Lithium Iron Phosphate (LiFePO4) / (LFP), Sodium Nickel Chloride (SoNick), Lithium Titanium Oxide (LTO) and Lithium Nickel Manganese Cobalt (NMC). Each of these chemistries are expected to be safe for use in underground mining BEVs provided that the batteries are:

- sourced from reputable Original Equipment Manufacturers (OEMs)
- used as prescribed by OEMs
- subject to appropriate monitoring and controls via a battery management system (BMS).

As with all aspects of safety in the mining industry, managing battery safety in underground mines will require a comprehensive approach. The commercial electric vehicle industry offers relevant insights, where its regulations, standards and best practices identify battery chemistry as only one of many important considerations in managing battery safety (see Figure 2 below).

Best practices to managing battery safety within the underground mining context are expected to develop rapidly as electrified mining fleets become increasingly common. However, the unique challenges and risks inherent in underground mining will always mean that applying any proposed approach to managing battery safety underground requires, at a minimum, a comprehensive assessment of site-specific risks. Continued investment and investigation by industry in this area is recommended.

Battery charging

While the general electric grid support and power supply network in an underground mine is alternating current (AC), power in a vehicle battery is stored as direct current (DC). A number of battery charging options are available:

- **Onboard charging** uses a 3 phase 1000V mine power outlet and requires a conversion from AC power to DC power onboard the vehicle. Completing this conversion onboard the vehicle usually limits the size of the charger and this slows down the charging process compared to other methods.
- **Off-board charging** uses a charging station to convert the AC power supply to DC power before it is introduced to the vehicle. This results in faster charging than onboard charging but requires substantial additional infrastructure.
- **Battery swapping** entails swapping out a depleted battery for a new, fully charged battery to preserve operating time. The depleted battery is recharged by an off-board charger in a dedicated charging bay and cycled back into use once recharged, usually resulting in minimal machine downtime.

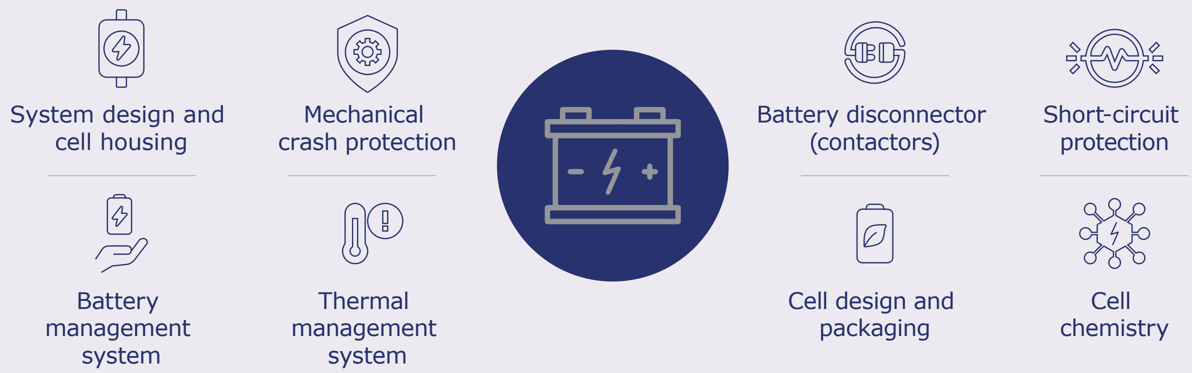

Figure 2 *– Components of Battery Safety (Not Just Battery Chemistry)*

Finding a solution for fleet electrification

IGO, Perenti and ABB set out to clearly detail how to transition the Cosmos underground mining fleet from fully diesel to a fully battery electric fleet. As part of this process, several questions common to every mine were considered:

- **What machinery and technology is currently (or will soon be) available in the market?**
- **How should a mine be designed to suit a battery electric fleet?**
- **What are the operating philosophies and productivities of this new fleet?**
- **What infrastructure and power reticulation will be required?**
- **What are the capital and operating costs?**
- **What are the risks of transitioning to a BEV fleet?**

Machine availability and fleet selection

The order lead times for BEVs currently exceed those of diesel equivalents. However, this disparity is expected to narrow as BEV uptake increases and OEM BEV production increases accordingly.

While there are BEV models available across the entire range of mining fleet, not all categories are well developed or advanced.

Heavy vehicles such as trucks and loaders are particularly capital intensive (relative to the same size diesel machines), in large part due to their currently expensive batteries. There are fewer OEM / model choices for this class of BEV in sizes that are comparable to standard operating fleet in Australia (60 t trucks and 20 t loaders). There is currently limited access to in-mine operating data for battery electric heavy vehicles.

Ancillary vehicles have been available as BEV options in similar sizes and with similar capabilities to their diesel equivalents for longer than heavy vehicles. Additionally, more performance data is available for battery ancillary vehicles.

Light vehicles (LVs) currently have the most choice of available BEV models, with both diesel-conversions and dedicated, designed-for-purpose BEVs available; however, most of these vehicles are still being trialled and are yet to be proven in the harsh underground operating environment.

For the Study, a market scan was conducted to identify available BEV models capable of achieving similar productivity and work output to the existing Cosmos diesel fleet. In line with the Study's key goal of an expeditious full Cosmos BEV conversion, only OEMs and BEV models that were in production or nearing production readiness for Australia were considered.

Fleet evaluation criteria

Each BEV model considered by the Study was evaluated against criteria including:

- fleet matching – compatibility between models (e.g. loader-truck pairs)
- charging method – onboard, off-board and / or battery swap method
- operating data confidence – based on trials / usage
- level of OEM support – will vary between regions / locations
- operating and maintenance skill set – existing and required skills
- productivity
- battery specifications – size, range and chemistry
- operating limitations – e.g. ambient temperature
- safety – including battery chemistry and battery management systems
- capital expenditure (CAPEX)
- operating expenditure (OPEX)
- operator ergonomics
- mine matching – suitability for existing mine dimensions / excavations
- lead time
- task suitability / practicality
- technology maturity.

Key Study findings for machine availability and fleet selection

Underground diesel haulage fleets in Australia typically consist of 65 t haulage trucks and a combination of 17 t and 21 t loaders. At the time of the Study, only Sandvik had a 65 t BEV truck available, which was undergoing field testing in Western Australia and was expected to be available commercially in 2025. A BEV 21 t loader was not yet available from any OEM; however, both Sandvik and Epiroc had 18 t BEV loaders commercially available. The Study concluded that the Sandvik 65 t truck and 18 t loader were suitable for Cosmos due to size, fleet matching and battery swap methodology.

All ancillary equipment units required for underground operations at Cosmos are available in BEV format from established OEMs such as Normet and MacLean (barring a grader, which is only available from MacLean). The Study determined that all these options were suitable to replace the equivalent diesel ancillary vehicles at Cosmos.

The BEV light vehicle market is rapidly expanding, with a mix of Toyota Landcruiser conversions and custom-built BEV light vehicles available. The Study determined that a mix of light vehicles matched to specific tasks would be most cost effective for Cosmos given the variance in cost, battery capacity, ruggedness and suitability for different tasks between currently available BEV light vehicles.

BEV Longhole Drill At The IGO Nova Operation

Mine design considerations

Fleet selection is naturally one of the first considerations when planning a move to battery electrification. In many ways, decisions made about fleet are similar regardless of whether it is diesel or electric (i.e. what is available in the market, can it do the job, and does it fit in the mining ecosystem?). The real pioneering work for fleet battery electrification is in determining how the new fleet will operate inside the mine, and how the mine can best be designed to maximise the value derived from the new equipment.

In the case of Cosmos, the existing mine development was not able to be significantly altered due to the timing of the proposed BEV transition (over 90% of the development would be completed before the 2025 target transition to BEV). Consequently, the mine design component of the Study focused primarily on mine ventilation, battery management and charging infrastructure. However, high level analysis completed as part of the Study showed that for greenfield operations, the switch to a BEV fleet offers considerable scope to re-think and test some traditional mining paradigms, with potential for steeper declines to take advantage of faster and more powerful haulage trucks, and smaller development profiles due to reduced secondary ventilation volumes.

Ventilation

The selection of an electric fleet for a greenfield mine is expected to result in significant reductions in primary airflow and cooling compared to that required for a diesel fleet. This is principally the result of the removal of the diesel dilution requirement and reduced heat generation by electric equipment (electric motors are 80-90% efficient in converting electrical to kinetic energy, whereas diesel engines are 30-40% efficient).

When the Study commenced in 2023, the ventilation circuit for the existing orebodies at Cosmos had already been well established, with some additional future infrastructure required to extend the ventilation circuit to the AM5 and AM6 orebodies. The Study used the most recent ventilation study work and VentSim model (incorporating the AM5 and AM6 orebodies) as the basis for the diesel fleet scenario, with appropriate changes made to the VentSim model to estimate the ventilation and cooling requirements for the electric fleet scenario. Modelling of re-entry times with various sizes of secondary fans was also undertaken.

Key Study findings on ventilation

- Savings to primary airflow volume enabled by converting to a BEV fleet were modest and constrained by two factors. Firstly, the bulk of the Cosmos ventilation network and infrastructure had already been established to support a diesel fleet. Secondly, a BEV transition still required sufficient ventilation to accommodate diesel equipment during the transition period. Accordingly, only a small reduction (7%) in the primary airflow volume was achievable.
- Significant reductions in cooling requirements were achieved, with bulk air cooling plant capacity reduced from 6 MW_{BAC} to 4.5 MW_{BAC}, and cooling only being required for two months of the year instead of five.
- While the diesel case required the purchase of two new primary fans, the BEV case enabled two existing primary fans to be re-purposed with a fan overhaul and motor upgrade. The feasibility, cost and timeframe for this was to be confirmed in the next stage of study.
- Ventilation modelling showed that the reduced airflow requirements of the BEV case enabled the adoption of smaller, 45 kW auxiliary fans for secondary ventilation, compared to the 55 kW fans required for the diesel case. Modelling of blast fume clearance times indicated that re-entry times would only be slightly impacted (an increase of two minutes and five minutes for development and production blasts respectively) by the adoption of the smaller fans. For a greenfield site, the smaller auxiliary fans would enable CAPEX and OPEX savings. However, in the case of Cosmos, sufficient 55 kW fans were already installed and operating, so the decision was made not to replace them with the smaller 45 kW fans.

Battery management and charge bay design

Battery capacity imposes constraints on the range over which BEVs can operate on a single charge (refer to Figure 3). Consequently, underground workshops and battery maintenance facilities are recommended to limit the requirement for tramming BEVs to surface (particularly in the case of deeper mines). Consideration must also be given to the implications of an increased prevalence of supporting electrical infrastructure in the mine. Additional preventative and breakdown maintenance of these electrical facilities should be expected, along with associated safety systems such as fire suppression. Additional electrical personnel may be required.

Selecting suitable charging locations (both underground and on surface) is critical for successful BEV integration. Charging locations must be considered both individually for each class of equipment, and as an integrated network able to service multiple units. Some key considerations for selecting charging locations are:

- the maximum tramming distances of machines (loaded and unloaded) (shown in Figure 3 below)
- the ability of different units to charge in-cycle or out-of-cycle
- the ability to utilise opportunistic charging locations to minimise unproductive time.

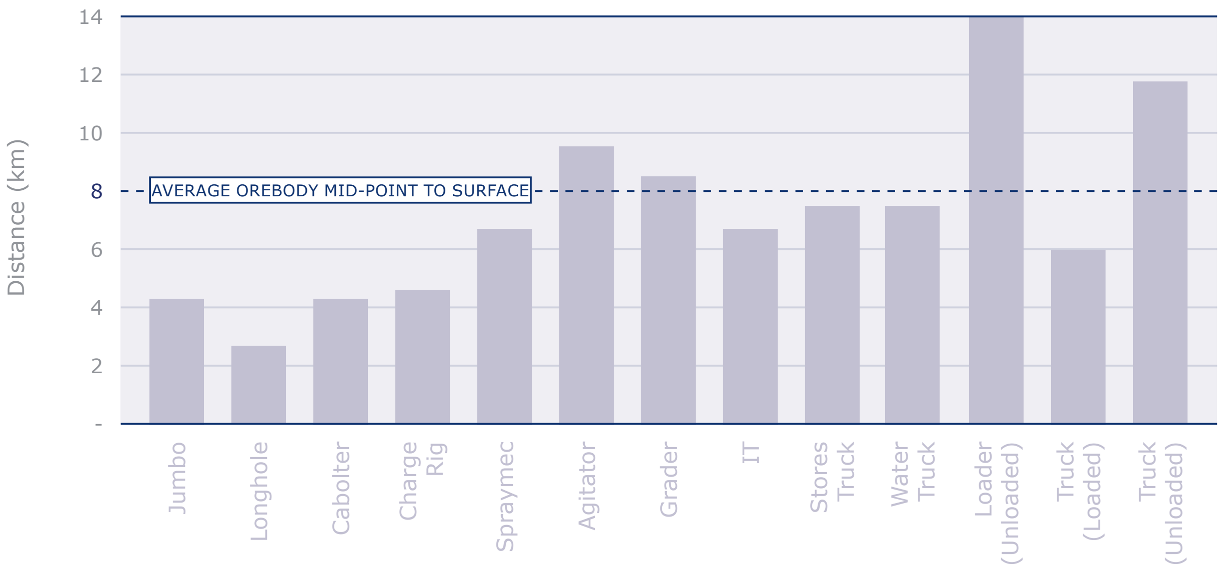

***Figure 3** – Estimated Tramming Range for a +14% Gradient*

Key Study findings on mine design and battery management

- Due to the inability of most units to tram to the surface on one battery charge, an underground workshop was designed to enable underground vehicle maintenance and servicing.
- Charging locations, charger types (i.e. 1000V jumbo box, CCS2 DC charger) and charger sizes were strategically distributed across various surface and underground locations in highly trafficked areas (including workshops, crib hubs and consumables stores) to ensure efficient access to chargers and to enable opportunistic charging for high use vehicles, in turn minimising unproductive time. Detailed operational design and traffic management plans for these high use areas would be required in the next study phase.
- To enable all vehicles to tram to surface, a mid-decline charging station was planned, which incorporates a battery swapping location for the heavy haulage fleet, a 1000V jumbo box for drills, and a CCS2 charger for ancillary fleet and light vehicles.
- Modelling indicated minimal unproductive time for out-of-cycle charging of ancillary fleet and light vehicles. Battery swapping methods were proposed for the heavy load and haul fleet.
- A whole of mine charging schedule was created, which allowed the required number of chargers to be optimised. Charger numbers and locations were selected to minimise unproductive time (when tramming to charging locations or charging), while also optimising charger numbers to avoid unnecessary capital spend.

Operating philosophy and productivity

BEV operational performance is a critical consideration when contemplating a transition to a battery electric mining fleet. Keeping a fully battery electric fleet charged is inherently more complex than traditional diesel fleet refuelling. Accordingly, an understanding of battery swapping and battery charging is central to operating a productive electric fleet in the underground environment.

The Study demonstrated that with careful consideration, charging a BEV fleet at Cosmos could be accomplished with minimal disruption to operations.

For example, heavy fleet such as trucks and loaders have high capacity batteries which may require long charging periods. Consequently, these units utilise battery swapping (rather than onboard charging) in order to minimise standing time due to charging. Therefore, locating truck battery swap bays on or close to haulage routes will minimise unnecessary tramming and limit unproductive time.

Loader battery swap bay locations were determined by analysing the volume and location of material movements throughout the LOM schedule. To balance the number (and hence cost) of battery swap locations against the requirement to minimise tramming to and from battery swap locations, the Study proposed to progressively relocate battery swap bays positioned within the orebodies to follow the deepening mining front.

Additional proposed permanent swap bays were positioned close to permanent infrastructure (workshop / crib hub and mid-decline). Ancillary fleet and light vehicle charging will occur during operation (ie. while plugged in and operating at the face), during scheduled breaks (crib time and shift change), and opportunistically (e.g. during loading of consumables onto the vehicle).

Trucking fleet productivity and operating philosophy

Modelling of BEV truck productivity for each of the five orebodies at Cosmos was completed, to confirm that the selected BEV trucking fleet (2 x 65 t trucks) could meet or exceed the scheduled annual tonne-kilometres (tkm) in the LOM plan. The modelling also enabled analysis of expected truck battery usage.

Key Study findings on truck productivity and operating philosophy

- The Study proposed that from mid-2024, all ore and waste at Cosmos will be trucked to the shaft for hoisting to surface. This enables a dedicated truck battery swap bay to be located near the workshop, in close proximity to the sizer tipping area (refer to Figure 1). While truck battery swap locations would ideally be located near the base of a downhill haul (to enable maximum use of power regeneration for battery charging), the geometry of the Cosmos orebodies was not suitable for this option.
- Trucks at Cosmos will typically be required to swap to a fresh battery after every 3 to 5 haul cycles, resulting in between 3 to 5 battery swaps being required per shift. The battery swap time was estimated to be ~8-10 minutes per swap.
- To limit safety hazards or damage caused by spillage from the truck tub, truck batteries should only be swapped when trucks are unloaded.
- Modelling demonstrated that 2 x 65 t BEV trucks were able to achieve the required life of mine (LOM) haulage schedule at Cosmos, successfully replacing 2 x 60 t diesel trucks.
- The geometry of the AM5 orebody enables significant downhill loaded truck haulage. In turn, this provides sufficient regenerative battery charging to eliminate the need for external charging. However, the truck batteries still need to be swapped out regularly to enable them to cool and avoid damaging the battery cells.
- Battery recharging times should be dynamically adjusted (ie. charged more quickly or more slowly) to match the trucking cycle. To enable power smoothing and extend the life of the truck batteries, they should be charged as slowly as possible while still ensuring they are ready when required for the next battery swap.

Loading fleet productivity and operating philosophy

The operating philosophy of the loading fleet significantly impacts the economics of an electric mine. Excessive time spent tramming to / from a battery swap location, or swapping batteries, will have a material effect on overall loader productivity.

The Study considered the following options for managing loader battery swaps and battery recharging:

Single, fixed (over LOM) location for battery swapping by all loaders (similar to a fuel bay)	**Multiple, semi-permanent locations for battery swapping**	**Deliver a charged battery from recharging bay directly to the loader at the workplace** (eg. via a heavy-lift IT)
☑ single set-up of power infrastructure	☑ reduced unproductive loader time, CAPEX spread out over longer period	☑ minimal time lost during battery swap
☒ loss of productivity while loader trams to battery swap / recharging location	☒ higher total LOM set-up costs	☒ additional CAPEX / OPEX, increased traffic in the mine, reliance on the battery being delivered at the required time

Modelling of loader productivity was completed for each orebody, based on typical level layouts. This modelling aimed to estimate loader productivities for each mining area, assess the number of units required, and confirm that the required LOM material movement was achievable with BEV machines.

The modelling was supplemented with 'day-in-the-life-of' (DILO) modelling to investigate in-shift operating scenarios for development and production loaders in greater detail. The DILO modelling calculated the power draw for individual tasks performed by each loader, with the tasks subsequently aggregated to show the profile of the loader battery state of charge throughout a typical shift (refer to Figure 5).

Key Study findings on loader productivity and operating philosophy

- Multiple, semi-permanent loader charge bays (refer to Figure 4) were selected to minimise unproductive loader time and reduce mine traffic congestion. Most of the loader battery swap stations could remain fixed across the LOM, with one station relocating at key times to match the progression of the deepening mining front. Charging bays in the orebodies were recommended to be located at intervals of around 2 to 3 levels. Additionally, permanent battery swap bays were recommended to be positioned near the workshop and crib hub, and at the mid-decline recharging location.
- Modelling indicated that the loaders would typically need to swap batteries 2 to 3 times per shift.
- While it is believed that the increased speed of BEV loaders should enable increased instantaneous and overall productivity (compared to diesel loaders), there is currently a lack of field data to support these assertions. Consequently, the Study adopted conservative productivity assumptions, resulting in the estimated loader fleet size increasing from 3 units for the diesel scenario to 4 units for the BEV scenario. However, it is expected that more detailed modelling in the next study phase, combined with future field trial data, could enable the estimated BEV loader fleet size to be reduced to match that of the diesel fleet.

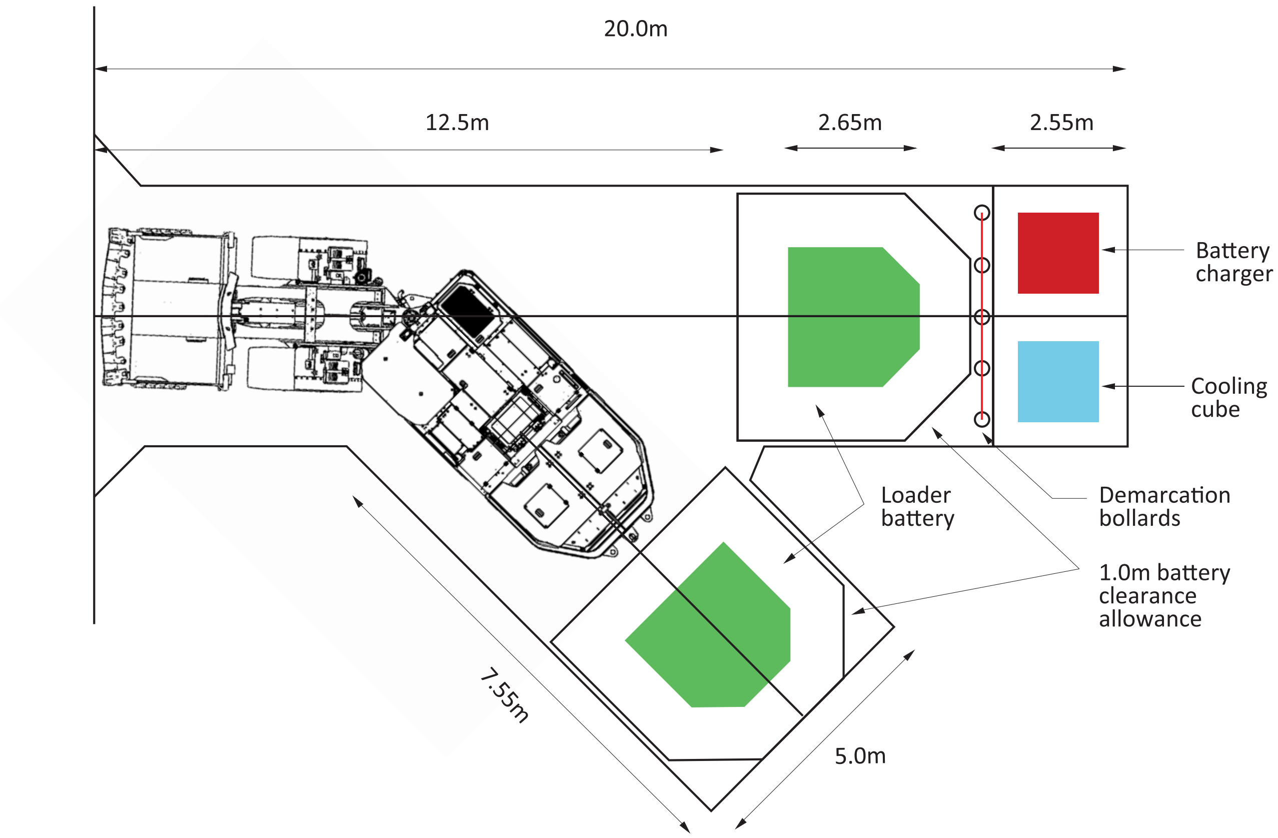

***Figure 4** – Loader Battery Swap / Charging Design*

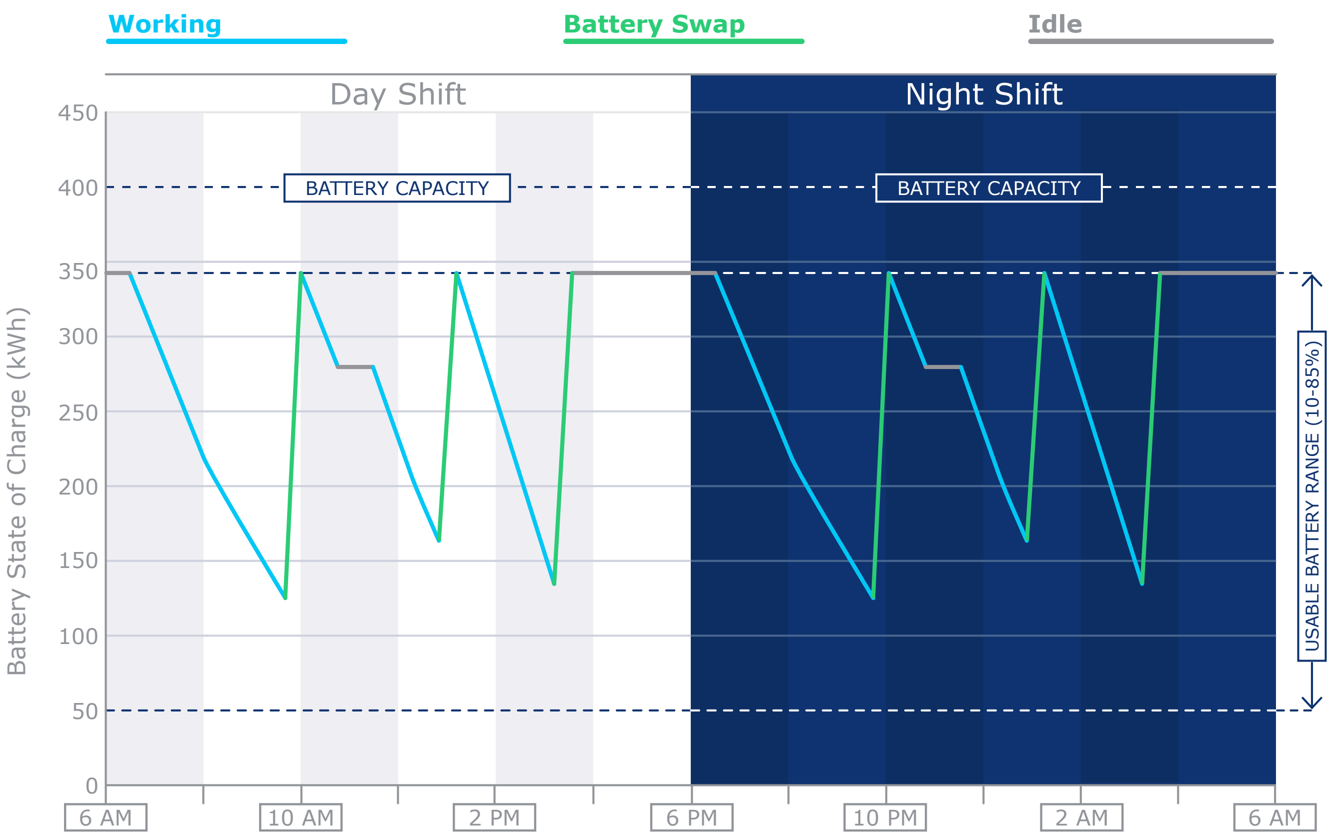

***Figure 5** – Example DILO Modelling for a Development Loader*

Ancillary equipment operating philosophy

Ancillary and light vehicles are not able to swap batteries and must be 'plugged in' to charge. To minimise unproductive charging time, the Study recommended adopting opportunistic charging for these units, such as recharging at shift change and crib times, while operating at the face, and while loading consumables onto vehicles.

Drills plug in to the 1000 V power system while they operate, enabling battery charging while they are working. The Study modelling indicates that this generally provides sufficient recharging to enable tramming between work areas; hence, these units should not require additional charging time (other than mid-decline charging when tramming to surface).

The Study further concluded that:

- Shotcrete sprayers, agitator trucks and charge-up rigs primarily charge while plugged in and working at the face, with supplementary charging opportunities available at crib time and shift change, and while loading consumables. Service trucks and light vehicles primarily charge at crib time and shift change, with some opportunistic charging during the shift (e.g. while loading consumables).
- Given that integrated tool carriers (ITs), graders and water trucks cannot plug in to charge while working, these units require more frequent dedicated charging slots (and unproductive time) throughout the shift.

Light vehicle operating philosophy

LVs are operated by a wide range of users for a varied range of applications and duties. Correspondingly, a wide range of BEV LVs are available, offering a range of body types, batteries (with differing chemistry and capacity), and prices.

The Study identified and separated the typical duties of LVs used underground into four distinct classes (refer to Table 1). Each class requires a different operating and battery charging philosophy. Additionally, each class may require a different model of LV to match the required application and provide the required battery capacity.

The Study used the classes to determine:

- the number of BEV LVs required for each vehicle class
- the number and location of chargers required
- charging priority when multiple vehicles require access to charging facilities simultaneously.

The Study determined that the Cosmos BEV LV fleet would include a mixed fleet of several different models, to best match the requirements of each duty type at the lowest cost.

It further determined that:

- LVs could undertake charging at crib time, shift change, and opportunistically while parked up during the shift (e.g. at the workshop or service crew store).
- High duty vehicles (e.g. charge-up and nipper LVs) could remain underground to charge at the crib room and workshop over shift change.
- Selected lower-duty LVs could be used for 'personnel-runs' to surface at the start and end of shift, and would recharge on surface.

Table 1 - *Light Vehicle Duty Types*

Vehicle Class	Vehicle Usage / Duty	Opportunity for Undertaking Charging	Typical Roles / Functions	Peak Hour Charging Priority	Charger Type
A	High	Low	Charge Up, Service and Paste Crew, Nipper	High	Fast
B	High	High	Shift Boss, Fitter, Auto-electrician, Survey	Low	Fast
C	Low	High	Foreman, HSE, Engineering, Geology	Low	Regular
D	Low	Low	Drillers Vehicle, Personnel-Run Vehicles	Medium	Fast

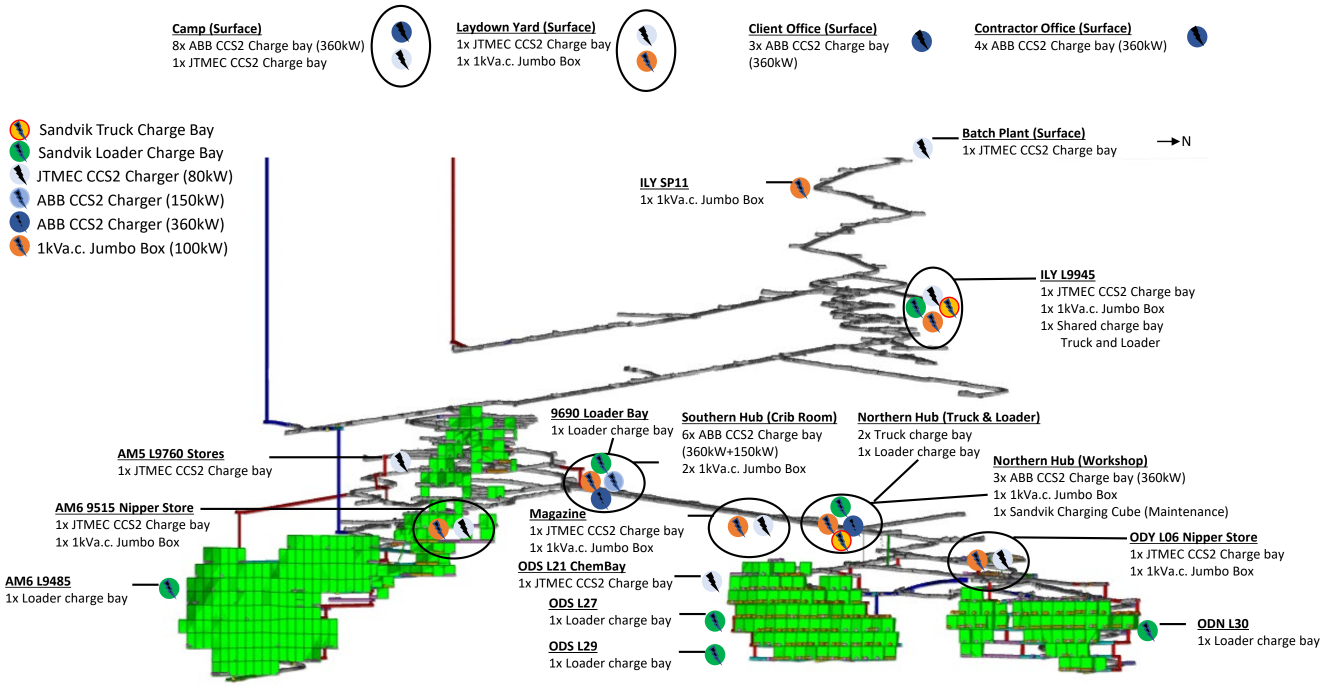

Figure 6 *– Cosmos Underground Charging Locations*

Key Study findings on BEV fleet numbers

The Study determined that all units in the Cosmos diesel fleet could be replaced by BEV models. Except for loaders and ITs, the estimated BEV fleet numbers matched those of the diesel fleet.

The Study modelling indicated that one additional loader would be required for the BEV fleet scenario (increasing from 3 diesel units to 4 BEV units). As discussed previously, this increase is primarily due to conservative productivity assumptions which may be able to be revised as more trial data becomes available.

The estimated number of ITs required increased from 5 diesel units to 6 BEV units. This was primarily due to these vehicles' high battery usage (particularly when travelling up gradient), relatively frequent charging requirements and inability to charge while working. Additional BEV IT capacity was also required to deliver bulk explosives directly to the production charge-up vehicle, in order to avoid the need for battery-draining trips to the underground magazine.

Productivity and battery life specifications have yet to be validated in field trials, and it is hoped that further field trials and more detailed productivity modelling in a future phase of study would allow a reduction of the BEV fleet numbers to match those of the diesel fleet.

Zero Automotive BEV Landcruiser Conversion

Electrical infrastructure and power system analysis

Infrastructure and power reticulation

When evaluating the conversion from a diesel fleet to a BEV fleet for a brownfield project, it is essential to understand the existing power system environment. This provides a starting point from which to determine the power system additions, upgrades and modifications required to support a BEV fleet.

The net changes to the overall power requirements resulting from a BEV transition comprise the increased power required to recharge the fleet batteries minus any reduction in power demand resulting from reduced ventilation and cooling demand.

The power consumed by each individual electric vehicle is determined by analysing:

- haulage route
- payload size
- battery capacity
- upper and lower limits of usable battery capacity
- charge cycles
- distance to charging bays
- the number of cycles per shift.

An understanding of the power requirements for each unit enables the cumulative power requirement for the fleet to be determined. In turn, this is followed by an assessment of:

- the number of charging stations required to service the BEV fleet
- the size of each station (in kWh)
- the location of the stations throughout the mine.

Figure 7 indicates the cyclical nature of design for an electric mine. Electrifying equipment introduces an additional layer of complexity to the typical mine planning process for a diesel mine, due to the interdependencies between the number and location of charging stations, the productivity of BEV units, and the power consumed by the fleet. If the results at any stage in the planning cycle are unsatisfactory, then design revisions must be made and the stage re-evaluated.

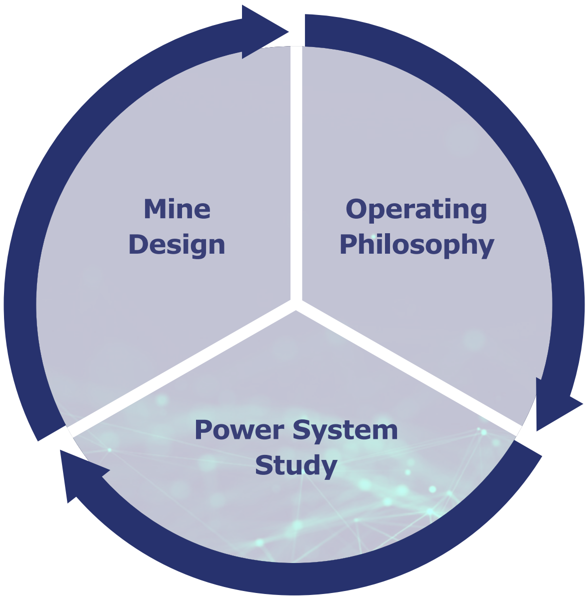

***Figure 7** – Iterative Process of Mine Design, Operating Philosophy and Power System Studies*

Power system analysis

The Study power system analysis aimed to determine how much additional power, and power infrastructure, was required to support a BEV fleet at Cosmos. The power system analysis assessed three criteria:

1. **Maximum demand** – This is instrumental in determining the necessary power generation capacity. It accounts for specific load factors of individual consumers, as well as the coincidence factor (which acknowledges that not all loads will operate simultaneously).
2. **Design power** – This aids in sizing components including substations, transformers, motor control centres and cables, and ensures alignment with the power system's requirements.
3. **Average power** – This incorporates load and utilisation factors to represent the plant's average loading, and directly correlates with overall energy consumption.

All three criteria are essential to understanding whether the existing power system can provide enough power over the course of long-term operation and handle instantaneous requirements in a maximum demand scenario, or whether power system additions, upgrades and modifications are required.

Key Study findings on power system analysis

For an all-electric Cosmos mine at full operation (ie. including all surface operations and the hoisting shaft, in addition to the mine ventilation and fleet recharging requirements), the power system analysis indicated:

- **27.5 MW maximum demand** (with a coincidence factor of 0.8)
- **31.4 MW design power** (cumulative peak demand without a coincidence factor)
- **24.3 MW average power.**

While the Study estimated power demand on an annualised basis, in practice the power consumed by the BEV fleet will vary from shift to shift. Detailed modelling of power demand at a more granular level would form part of the analysis in the next stage of study to enable power system optimisation and to refine the estimate of average power.

The Study determined that this demand could be met with the current generation and supply system, with the surface power infrastructure requiring only minor upgrades to one existing supply cable.

The Study identified that the underground power system required additional transformers, sub-stations and cabling, particularly in areas hosting multiple chargers such as the crib hub and workshop. Additional distribution infrastructure within the production areas was generally not required, as the existing distribution network installed for mine development was sufficient.

Annualised power usage

Annualised power usage was modelled for each type of BEV unit operating at Cosmos. While the modelled annual electricity consumption for loaders and trucks varied between periods (based on tonnes moved and tkm hauled), annualised power consumption for each of the other vehicle types was assumed to be relatively constant.

A load list was developed by determining all of the loads on the underground power system, with analysis of their load factor and utilisation. The major power demand differences between the BEV and diesel fleet scenarios at Cosmos related to the power for primary ventilation, cooling, and for the underground mobile fleet. The load list was used to develop an annual power estimate. Figure 8 below shows the difference in annual underground power required in FY28 for both a BEV and a diesel fleet scenario.

Despite the increased power required to directly run the BEV fleet, the annual underground power consumption (excluding hoisting shaft) for the BEV fleet scenario was less than for a diesel fleet scenario, primarily due to the significant reduction in cooling requirements.

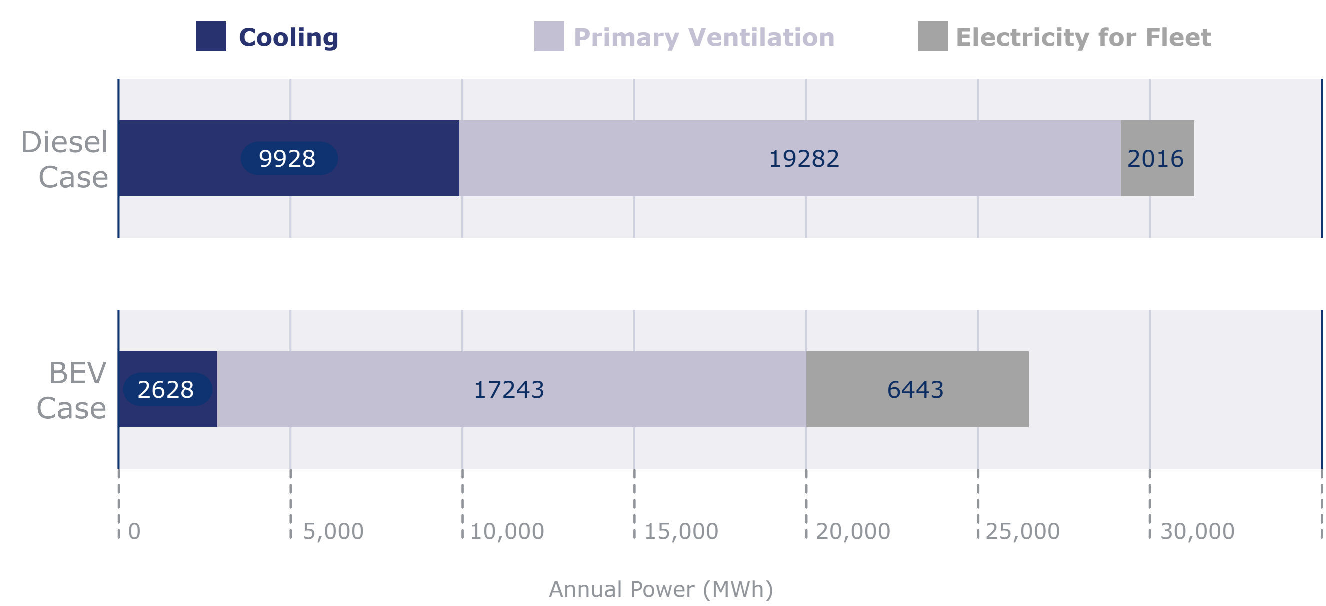

Figure 8 *– FY28 Difference in Power Consumption for Diesel and BEV Cases*

Cost modelling

Mining fleet electrification requires a shift in financial mindset towards longer term value creation. The capital associated with procuring and implementing a BEV fleet is currently higher than that for a diesel fleet. However, BEV fleets offer significant operating cost savings to be realised over the life of a typical project. These savings are expected to grow as battery technology matures, economies of scale increase and the use of fossil fuels becomes more regulated and restrictive.

The increasing demands on the mining industry necessitate looking beyond the immediate financials when building the business case for electrification, and considering the broader value of the ESG and WHS benefits that electrification provides. While these intangible benefits are more difficult to quantify and value, they nonetheless add to the previously compelling reasons for making the switch to an electric fleet.

Cosmos cost model

The Study did not attempt to estimate the total cost of mining; instead, it focused on the components of the capital and operating costs which resulted in a direct cost difference for the diesel versus the BEV fleet. Correspondingly, the cost model was used to estimate the Net Present Cost (NPC) (ie. cost delta) of undertaking fleet electrification, rather than the more commonly used Net Present Value (NPV) metric.

The Study cost model was based on contractor mining, and considered several factors specific to a BEV environment including monthly equipment costs (based on contractor-owned BEV fleet), BEV productivities, maintenance savings, and Battery-as-a-Service (BaaS) OPEX costs.

Costs were calculated to a PFS degree of accuracy (+/- 25%). Where operational data inputs impacted estimated BEV costs, conservative assumptions were used due to lack of operational field data. For example, anticipated higher machine availabilities, maintenance savings and increased asset life for a BEV fleet are expected to at least partially offset these units' additional capital costs (compared to a diesel fleet). However, conservative inputs were adopted during cost modelling because these assumptions have not yet been proven through extended operations.

Capital costs and savings

By premising the Study on contractor mining, the initial capital cost of the machines was able to be treated as an operating cost to IGO over the life of mine.

Consequently, the largest capital cost associated with the transition to a BEV fleet at Cosmos was for the excavation and fit-out of the underground charging infrastructure (including the purchase of charging equipment). The primary capital savings related to downsizing of the cooling system and re-purposing (rather than purchasing new) primary ventilation equipment.

Operating costs and savings

The Study built up operating cost estimates for a BEV fleet similarly to regular contract mining rates. These include:

- capital purchase of BEV fleet (using RRP provided by OEMs)
- maintenance parts and labour (including conservative estimates of expected savings due to BEVs being easier to maintain than diesel)
- BaaS for loaders and trucks (equating to 35% of the total cost of ownership for loaders and trucks).

Ongoing operating costs associated with the maintenance of the charging infrastructure were also modelled.

The main operating cost savings attributable to a BEV fleet were from reduced primary ventilation and cooling requirements. The model also included operating cost savings for the BEV fleet relating to the cost of carbon, based on IGO's internal carbon price (attributable to lower total power consumption for the BEV scenario, and the use of electricity rather than diesel to power the mining fleet).

While the Study was premised on diesel power generation, IGO also studied options for installing majority renewables power generation at Cosmos, which would result in greater carbon savings.

Key Study findings on BEV cost

The results of the cost model were very encouraging. Overall, the net present cost of transitioning Cosmos to a BEV fleet was an additional 6% compared to the diesel base case. This cost differential could be expected to be quickly closed in the event of either rising diesel prices, an increased internal carbon price, or with a decrease in battery and BEV prices. Each of these events is considered to be plausible in the foreseeable future.

The most significant cost difference between the two cases was the direct cost associated with purchasing, operating and maintaining the BEV fleet. This was largely offset by cost savings related to decreased primary ventilation and cooling requirements for the BEV fleet. Mine development for the workshop and charging bays, as well as the chargers required for ancillary and lift vehicles, made up the remaining cost differential (Figure 9).

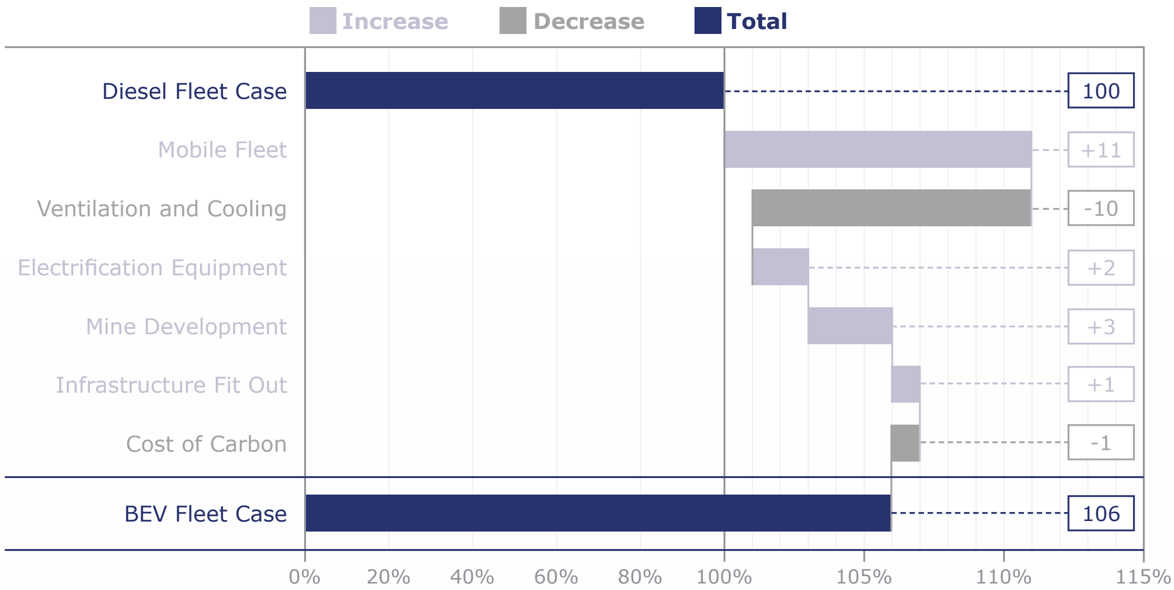

***Figure 9** – Waterfall Chart of Discounted Cost*

Battery Electric Truck Swapping A Battery At AngloGold Ashanti's Sunrise Dam Operation

Risk assessment and BEV transition

The risk assessment process for the Study considered two categories of risks: risks related to the Study itself (inputs, processes and outcomes), and risks related to the BEV transition / implementation process. A number of these identified risks are outlined below:

BEV study risks

- Battery / machine performance – lack of real-world data to validate OEM claims.
- Battery fire – adequacy of planning for emergency response.
- Regulatory regimes – potential for future changes.
- Power supply – ensuring sufficiently wide study battery limits to confirm adequacy of supply.
- Charging infrastructure – sub-optimal location or under-estimation of number required.
- Project development – impact on brownfield operation mining schedules.

BEV transition / implementation risks

- Electrical safety – increased exposure to electrical hazards.
- Long machine lead times – reliability of delivery timeframes.
- Ramp-up period – potential for underestimation of the duration of the diesel-BEV fleet overlap/ transition phase.
- Communications infrastructure – adequacy of underground Wifi/5G networks.
- Workforce training – new skillsets required and growing demand for skilled personnel.
- Impact to current operations – potential for disruption during installation and commissioning.

Key Study findings on risk assessment

- The risk assessment process was critical for identifying areas / items requiring additional work in the next planned phase of study.
- The risk analysis also highlighted areas of operational risk and lack of current data that need to be further understood or validated through field trials and further engagement with OEMs.
- It was necessary to balance the speed of the transition to a BEV fleet with the need to maintain production levels during the transition. Adequate resourcing will be critical to ensure this transition period can be planned and executed with minimal impact to existing operations.

Planning for the transition to an electric mine

The Study targeted a 2-year transition period to achieve full fleet electrification. Three major priorities were considered when developing a transition schedule:

- **Workforce recruitment, training and skills transfer** – As more BEV machinery comes onsite, the training and familiarisation time for similar machines should decrease.
- **Machine availability and lead time** – The items with the longest lead times governed the project critical path and dictated the timing for procurement and commissioning of other BEV units.
- **Construction / installation and commissioning of underground and surface infrastructure** – Commissioning of the load and haul fleet cannot begin until the underground workshop is complete, rendering excavation and fit-out of the workshop a schedule critical path item. The crib hubs were also prioritised, due to their importance as a locus for charging of LVs and ancillary fleet.

Key Study findings on the Cosmos BEV transition plan

The transition plan showed that the aim of converting to a fully BEV fleet at Cosmos in 2025 was not practically achievable in that timeframe. Based on the lead and delivery time estimates provided by OEMs, multiple pieces of BEV equipment would not arrive on site, let alone be commissioned, prior to the end of 2025. The Sandvik LH518iB loader has the longest lead time of all machinery and equipment selected, making it a schedule critical path item. Critically, the majority of the production fleet would not arrive on site for commissioning until the very end of 2025 or early in 2026. Ancillary equipment such as the grader and both agitators, would not arrive until 2026.

What's next?

The Study found that, within the accuracy of a pre-feasibility level of study, the conversion of the Cosmos mining fleet from diesel to battery electric was technically feasible, and not cost prohibitive. The results of the Study were sufficiently encouraging to warrant proceeding to a more detailed feasibility level of study. As the Cosmos mine is now moving into care and maintenance, the next study will not proceed in its originally envisaged form. However, the learnings of the completed Study have substantial value for IGO and for the broader mining industry.

It is vitally important that BEV trials and adoption of BEV units continue within the Australian underground mining environment in order to achieve the industry's vision of a decarbonised future. Obtaining real life experience and familiarity with necessary changes to operating and maintenance practices for BEVs compared to diesel machines, as well as validating OEM supplied operating data, will help to build confidence in the viability of a fully battery electric underground metalliferous mine.

Replacing a diesel underground mining fleet with a battery electric fleet is now technically feasible and will increasingly be a key technological enabler for mining companies to achieve their decarbonisation goals. The financial impact or benefit derived from fleet electrification will depend on the specific mine characteristics but is likely to continue to improve as battery capacity improves and economies of scale in BEV manufacturing take effect.

IGO, Perenti and ABB hope that this white paper will assist mining companies which are considering battery electric vehicles for their underground mines.

The Study identified that the following areas require further study to realise the full potential of battery electrification, and to optimise the underground electric mine for commercial benefit:

- Detailed modelling and simulation of battery electric loading and hauling equipment on an annual, monthly and daily basis.
- Detailed modelling and simulation of battery electric ancillary equipment on an annual, monthly and daily basis.
- Detailed modelling and simulation of underground power demand and supply, on an annual, monthly and daily basis.
- Scenario analysis of cost model and business case drivers to determine the optimal level of fleet electrification (% BEV penetration). For example, does it make sense to transition from diesel to BEV for some units but not others? This will be an important consideration for decline haulage mines where BEV technology imposes practical limitations.
- Determine the network and communication infrastructure, as well as the digital systems, required to support the effective monitoring and control of battery electric vehicles, batteries, chargers and other electrical infrastructure. To achieve productive, safe and energy efficient operations, all digital systems and platform must be seamlessly connected at a platform level to manage and optimise these critical assets.
- Identify the fleet management systems to be used for monitoring vehicle batteries and directing vehicles to undertake out-of-cycle charging.
- Identify the energy management systems to be used for managing charging system prioritisation, truck and loader battery recharging rates, and smoothing of power loads.
- Consider what level of automation is a logical consequence of battery electric equipment and digital mines.
- Detail the strategy for battery management, including battery end life usage and disposal (especially at the scale generated by mining fleets).
- Current Battery as a Service (BaaS) operating costs are substantial. The various battery ownership models need to be explored in more detail to make an informed and cost-effective choice.
- Non-battery electrification options that were excluded from consideration in this Study (due to the 2025 target date) should be considered further.
- Validate BEV performance (in particular heavy haulage vehicles) against OEM claims. Both miners and OEMs are eager for this information, making industry collaboration crucial to expediting this knowledge.

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Making electrified underground mining a reality

Lessons from the Cosmos Electrification Study

A global mine electrification **collaboration**