

During LME Week of 2023, Skarn held a seminar where we presented some high-level decarbonisation pathway scenarios for the copper mining industry. The conclusion was that under the current carbon price bracket of \$0-200/t CO₂e, the portion of operational emissions that could be abated at neutral to net positive return was less than 15% of total Business-as-Usual scenario (excluding any abatements achieved at that point of analysis). Unsurprisingly, much of the abatement with positive economics were transition to renewable electricity while mine fleet electrification and other alternatives were net negative projects.

It is widely believed in our industry that meaningful impact from mine fleet electrification will be possible beyond 2030. In the next 5 years, we expect to see companies review and restate where possible the decarbonisation targets that were set in the past five years. And as we inch toward 2030, there is more pressure to provide clearer and tangible guidance on how the Scope 1 emissions are to be addressed.

We wanted to revisit the decarbonisation economics of mine fleet electrification in this issue, specifically by collaborating with Whittle Consulting who are well established in the market for strategic mine plan optimisation using their proprietary Prober algorithm. The lift in financial performance from their [Enterprise Optimisation](#) methodology is well documented, but we wanted to understand how carbon is modelled and how carbon reductions are analysed within such a study.

The main question we wanted to address was – are there opportunities which are not reflected in Skarn's first pass analysis, which suggests that mine fleet electrification is not a commercially viable pathway for many operations?

The short answer is, sometimes yes, sometimes no. The “how” – is about making the most of what one has – reconfiguring the production schedule, addressing bottlenecks, to make the disadvantageous economics work for you. To quote: “At worst, it isn't as bad as you think. At best, it will be net neutral or even marginally positive.”

We would like to thank Mike Sinden at Costmine Intelligence and Philip Bangerter at Whittle Consulting for their collaboration on this insight.

1

What is the current cost structure?

Capex of electric mine equipment carries a premium of 60-100% to diesel equivalents. Consumption of diesel accounts for 23% of open pit mine costs, 43% labour and the balance from consumables.

2

First order substitution: how bad is it?

Preliminary analysis suggests that under the current carbon price range of \$0-200/t CO₂e, the portion of operational emissions that could be abated by 2040 at neutral to net positive return is less than 15% of total Business-as-Usual scenario.

3

What second order opportunities are overlooked?

"Optimisation can often enhance and at worst will heavily mitigate the negative impacts to NPV that emissions reduction activity brings. It's never as bad as you first thought."

4

Case studies: Nordic Iron Ore and Dundee Precious Metals

In the re-optimisation process to consider decarbonisation projects, it is sometimes possible to take a small hit in the financials for meaningful reduction in emissions, either on an absolute or intensity basis. For almost all of Whittle's clients, GHG emissions have factored into the decision-making process in the past three years.

5

Appendix: How does mine plan optimisation work?

Mine plan optimisation is an iterative process involving algorithms to determine what part of the ore deposit to extract and process (**where**), at what time (**when**), and using what method and equipment (**how**).

To set the scene, we interviewed Costmine Intelligence who have proprietary primary data on capex and opex for the mining industry. According to their latest dataset, the cost of battery electric vehicles is at a premium of 60-100% to their diesel-equivalents.

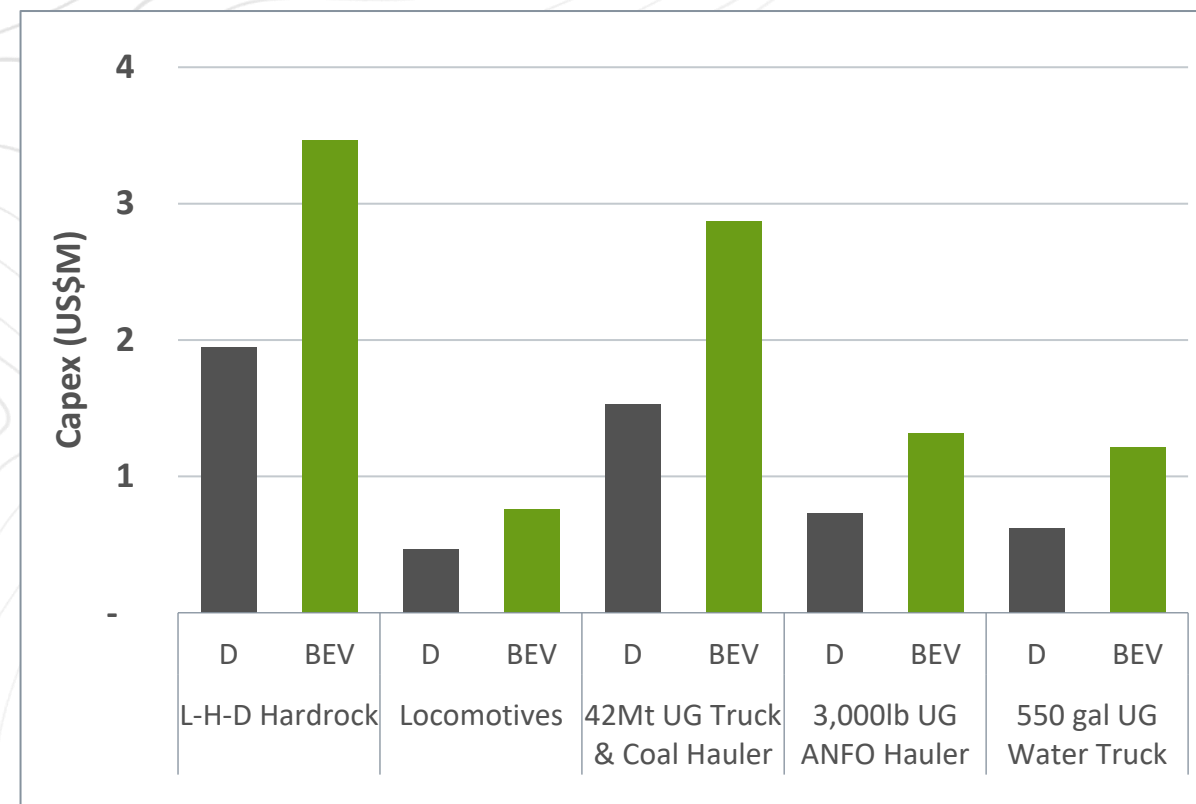
This is excluding supporting infrastructure, which may include varying degrees of automation, trolley assists and substations, charging stations and battery swaps.

It is also worth noting that capex and opex for most mine equipment has consistently increased year after year. The major producers are currently in partnerships with leading OEMs to pilot prototypes of a battery electric haul trucks at open pit mines, with plans to transition to electric fleet from 2030 onwards. It is widely understood that the order books are full for the first generation of commercially available electric mine fleet, which suggests that the premium over conventional trucks may persist due to high demand.

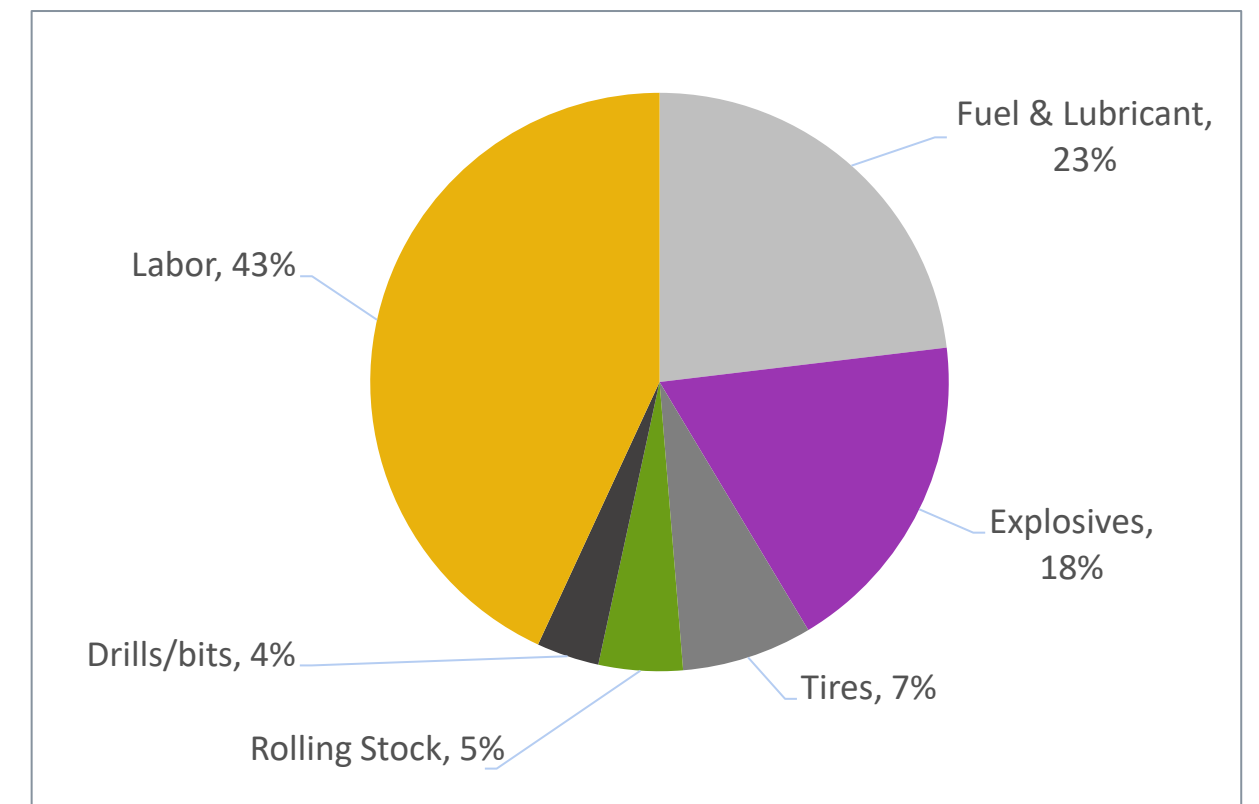
It is important to understand this not just from the financial perspective but the knock on impacts the change in mine fleet will have. How frequently the fleet needs to be charged, and the speed at which they are able to operate relative to the diesel equivalent will change fleet availability and mining schedule.

It is worth noting that diesel accounts for c. 23% of open pit mine costs on average, where potential savings are possible to offset the increased cost of electric equipment depending on the purchase agreement for electricity. A larger contribution to opex is labour at 43%, which we explore on the next page.

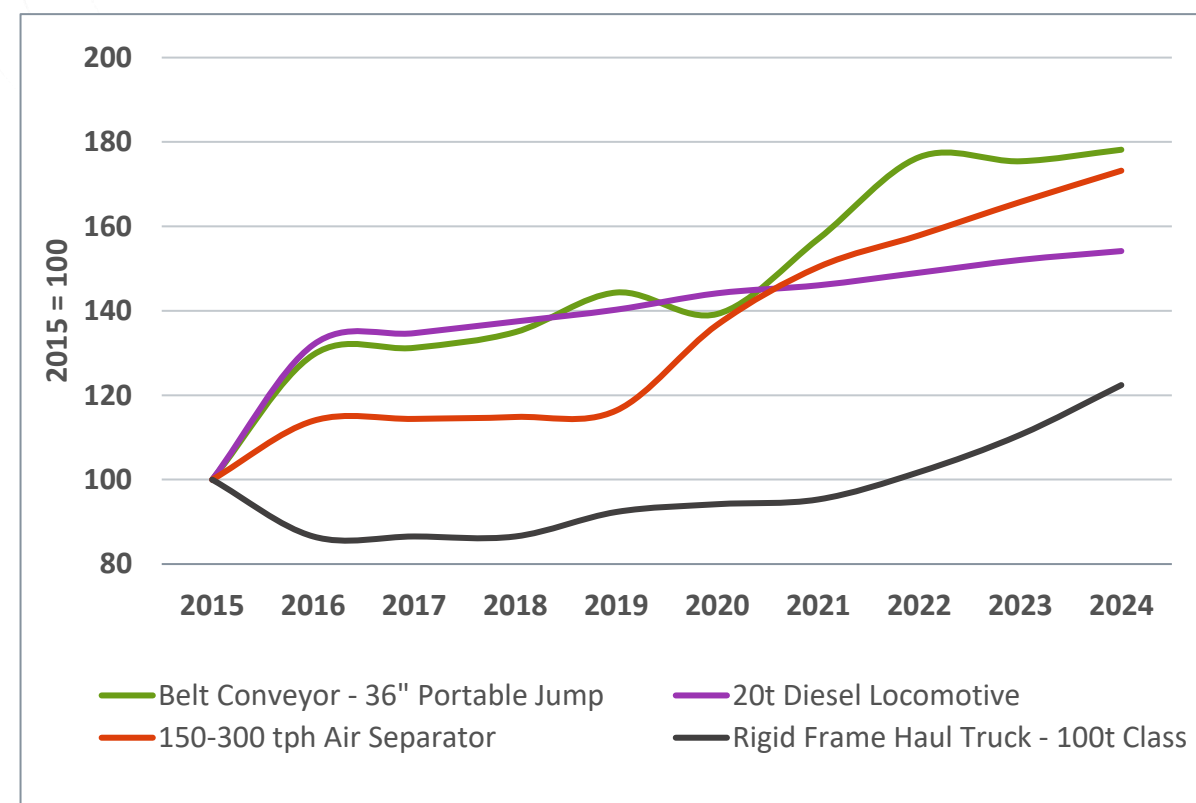
Diesel (D) and Battery Electric (BEV) Capex for Select Equipment



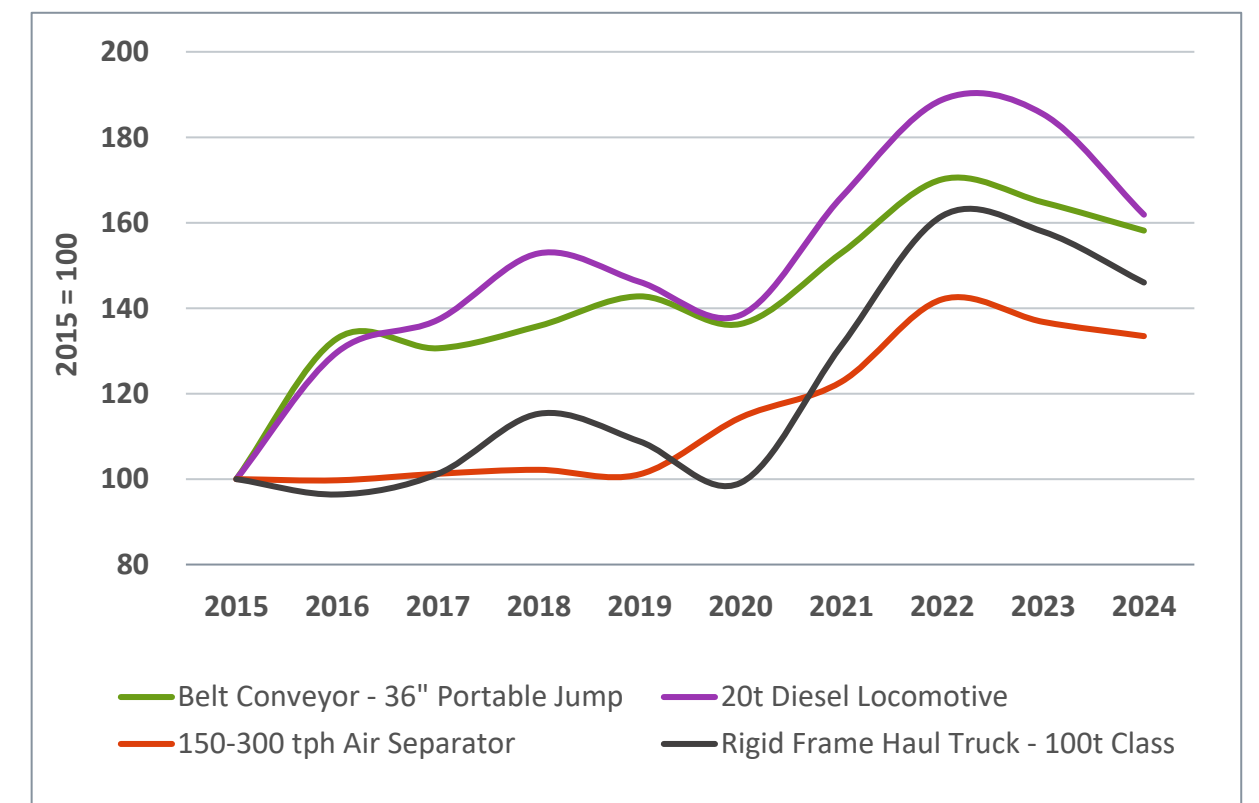
Surface Mine Opex Breakdown



Inflation of Mine Equipment Capex – Select Items, Indexed



Inflation of Mine Equipment Opex – Select Items, Indexed



US mining labour rates have steadily increased at 2.2% per year until 2018, but have more sharply, at risen 6.0% per year since. The inflation in wages is most notable for the skilled wages category.

Costmine Intelligence notes this trend begins prior to COVID, suggesting a general shortage of labour even in the face of challenging global economy.

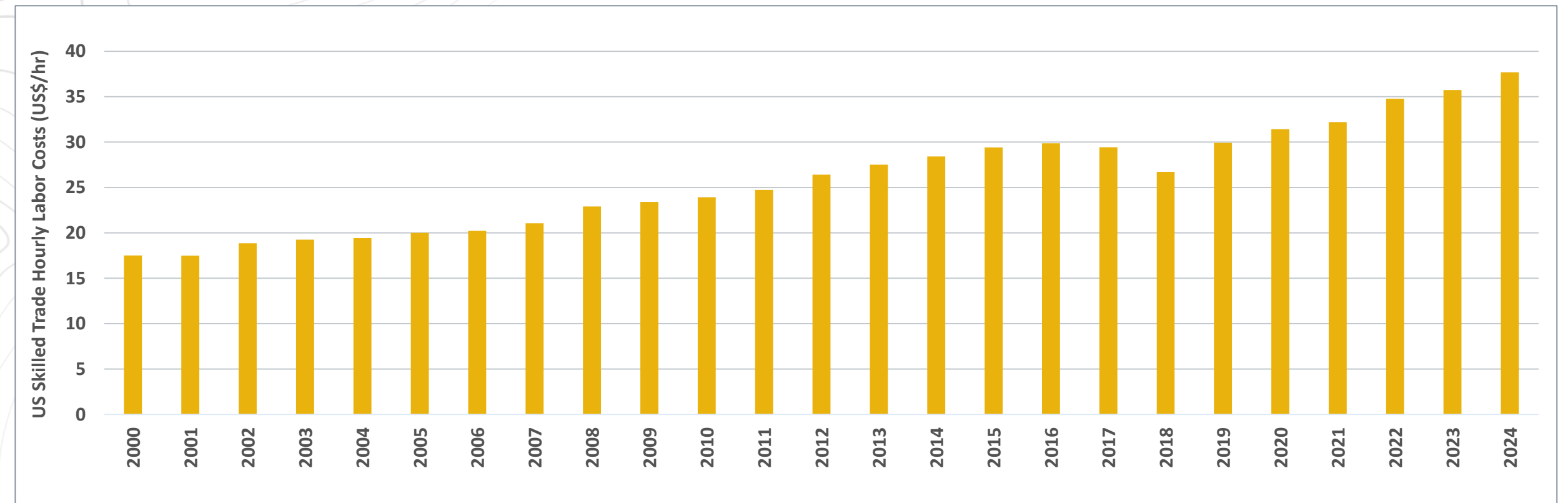
In this context, the growing adoption of automated mine fleet makes sense. Some producers have noted it is an important 'bridging' technology for transition to a fully electric mine, whilst also presumably delivering some gains in optimisation and cost savings.

Maintenance and servicing of electrical equipment and associated infrastructure will potentially require a labour force with additional skillsets to what is currently available in the industry.

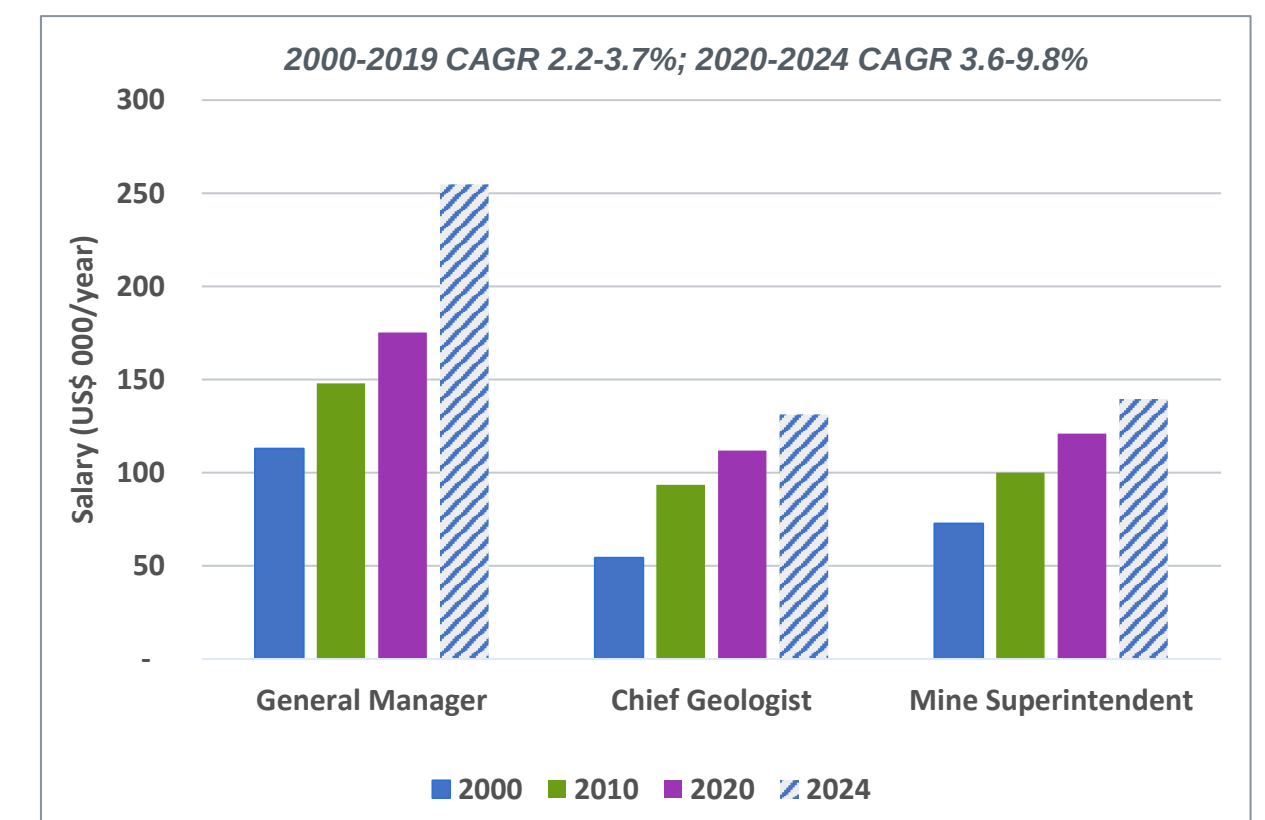
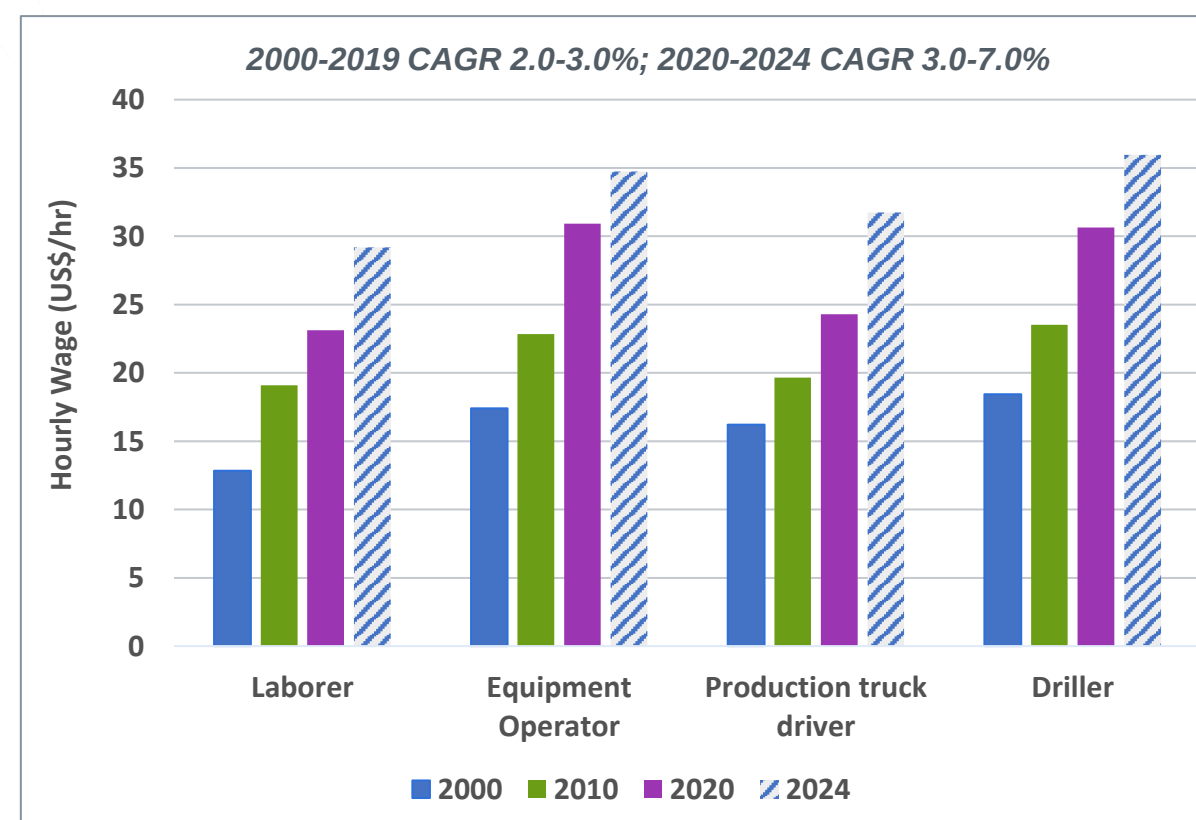
In short, transitioning a diesel-based mine fleet to be fully electric is a task that faces much uncertainty over future pricing and availability; additionally, changes in operating parameters of electric fleet will require for mine plans to change, and in most cases be re-optimised to extract the most value from the mine.

We discuss some of these nuances in later slides, but first we showcase Skarn's first pass analysis of what the financial implications would for existing mine plans if the equipment is switched out with all other parameters staying constant.

Inflation for the 'skilled wage' category was steady at 2.2% p.a. from 2000 to 2018, but has risen to 6.0% p.a. since



Wage inflation for labour varies, but weighted to the higher end



As discussed in an earlier slide, electric mine equipment carry a significant premium of 60-100% to its diesel equivalent. A linear way to assess the impact of mine fleet electrification is to switch out the existing fleet with electric equivalents and associated infrastructure assuming the mine plan remains unchanged. According to Whittle Consulting, the re-costing of this is a **first-order** impact only.

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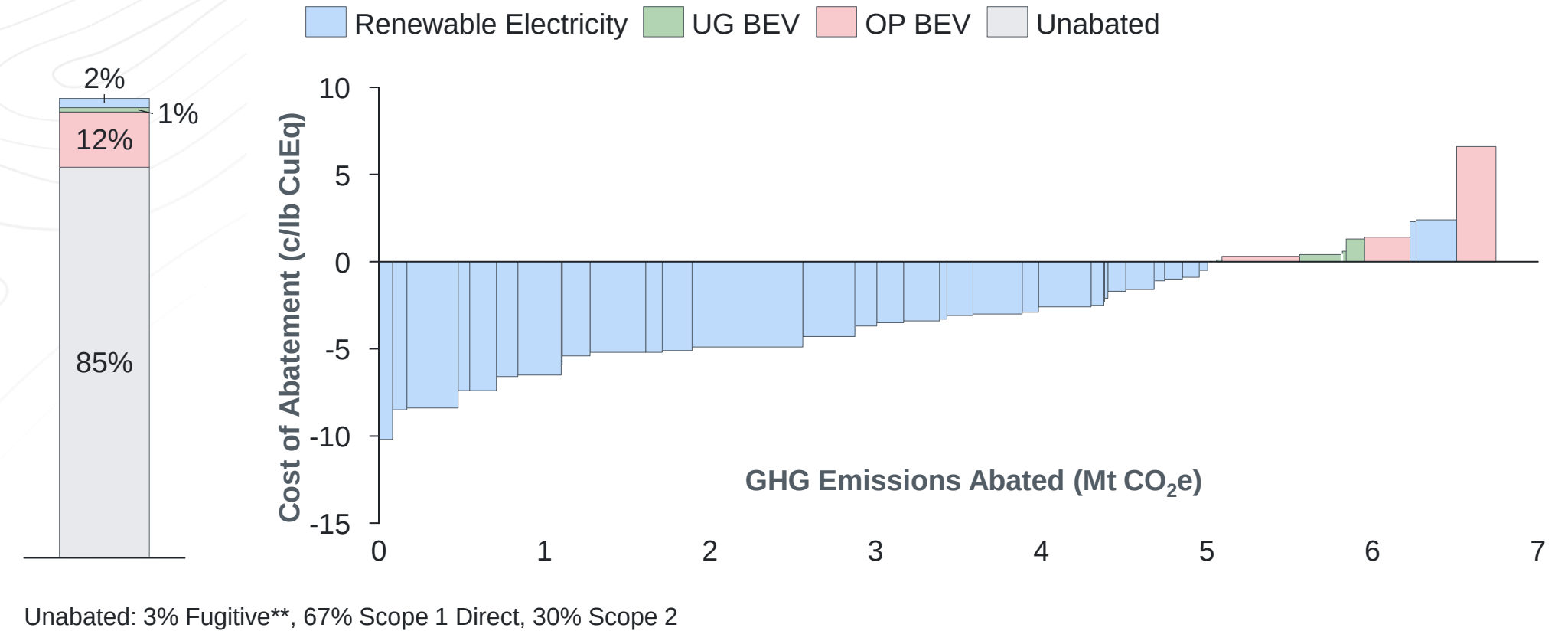
Unsurprisingly, much of the abatement with positive economics were transition to renewable electricity while mine fleet electrification and other alternatives were net negative projects. **We caveat that these results are highly sensitive to assumptions on carbon tax, diesel and electricity prices. These curves represent weighted average values only and vary significantly from asset to asset.**

In reality, it should be an iterative process where any changes in cost structure (or commodity prices, for that matter) result in a re-optimisation not only of mine plan and ore reserves but of other bottlenecks in the full processing chain including concentrators.

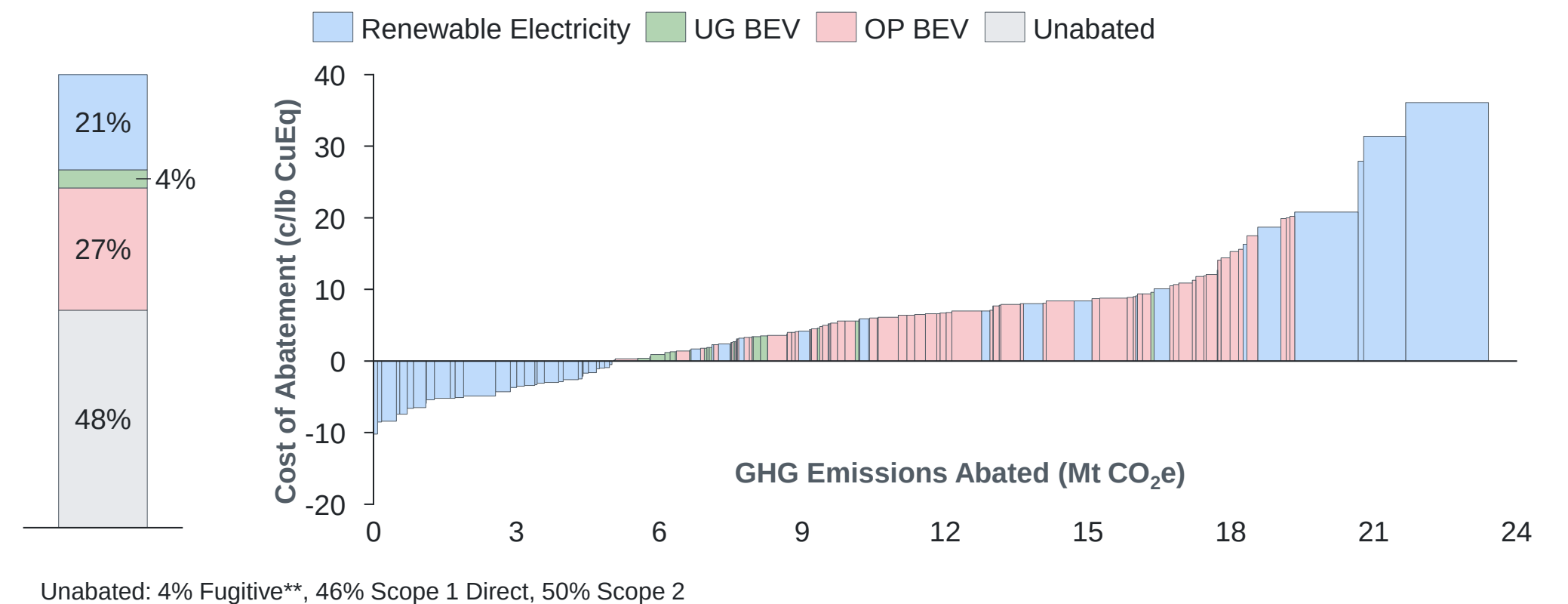
For example, introducing new equipment such as in-pit crushing and conveying, or trolley assist lines along the steepest portion of the haul route, will change the haul distances and the speed at which the distances are covered, and the number of fleet required. These changes in turn affect cut-off grades, in turn changing the shape of the ore reserves and therefore the production schedule.

According to Whittle Consulting these second order impacts are often overlooked; re-optimising the production plan can improve NPV of the mine plan and offset higher costs, sometimes even yielding a net positive or net neutral result depending on the asset.

2040 Abatement Scenario: Optimising Financials



2040 Abatement Scenario: Optimising Abatement



The basic tenet of mine plan optimisation is that any change in cost structure or commodity prices will result in a change in the mine plan. Optimisation typically involves a software to determine cut-off grade and schedule around which process plants are designed. Leading producers often have an in-house model to manage this process.

Whittle's methodology incorporates the system as a whole (block model, mine, plant, logistics) and unifies information that traditionally resides in multiple models. Prior case studies have shown that optimisation at worst will reduce an impact. Where there is premium to pay on opex, the optimiser will reduce the impact of that. Most especially it is important to consider the trade-off of capex and opex, as they are treated entirely differently in optimisation models.

This is particularly important now; the global movement to decarbonise has placed non-economic pressures on companies to reduce emissions. While many consider internal shadow carbon prices of \$50-200/t CO₂e, Whittle confirms Skarn's preliminary analysis that these levels have minimal impact to financials and is not a main 'driver' of the optimisation outcomes.

Given the premium on electric fleet equipment, the savings come predominantly from lower consumption of diesel, lower electricity prices from renewable sources and gains from reconfiguring the pit design and the production schedule. Whittle also confirms that current clients are considering swap out of ICEs to electric fleet from 2030 and beyond assuming equipment availability.

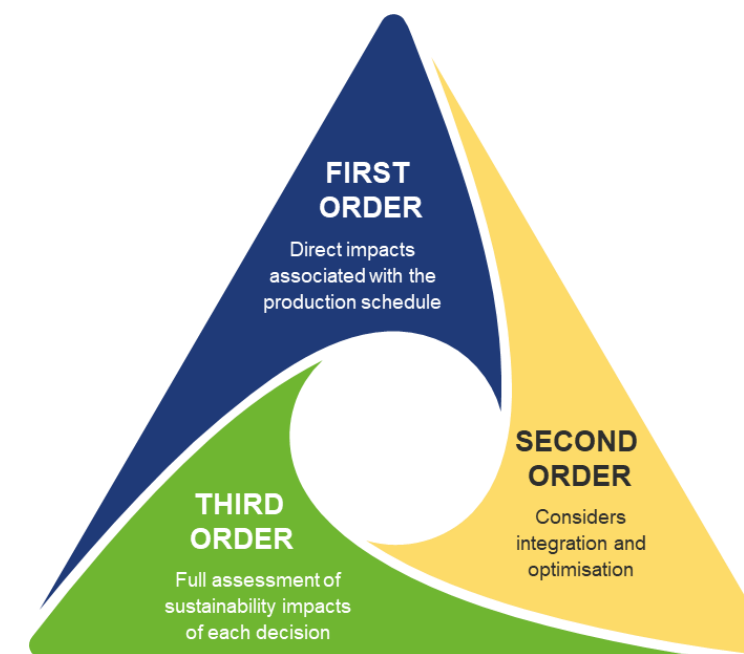
Capex or opex?

In the optimiser, cost to mine and process a block of ore does not have a capital cost attached to it. This is considered separately as part of the NPV calculations with iterations between opex and capex to derive the scenarios. Therefore, whether a cost is considered opex or capex can have a big impact on the results.

Examples include cost of electricity, and contract mining services – which is incurred on a levelised-cost basis rather than on a cash flow basis if the power generation unit or mine equipment is directly owned and operated.

If planners change the mix of fleet or the mix of off-grid renewables then this has a direct (usually positive) effect on the optimisation, often leading to cut-off changes and an expanded orebody.

"Optimisation can often enhance and at worst will heavily mitigate the negative impacts to NPV that emissions reduction activity brings. It's never as bad as you first thought."



Strategic Planning can be applied at the first, second and third-order (Bangerter & Pan, 2023):

- **First-order** effects concern assembling capital and operating costs and calculating a net-present-cost for these. Financial impacts can be compared across options or scenarios, as required.
- **Second-order** effects concern the orebody as an integrated whole and its optimization.
- **Third-order** effects are concerned with environmental and community value or impact and an evolving full assessment of sustainability impacts of each choice between options.

Renewable Electricity: Most remote sites with diesel generation benefit from installation of renewable electricity, with optimisation yielding a positive second-order benefit.

In-Pit Crush and Convey: There is a threshold on the incline of the conveyor belts, with viability dependent on the depth of the mine. This solution lends itself to laterally expansive mines, for example open-cast iron ore operations.

Trolley Assists: This is viable for pits with long fixed routes that do not move over time, but difficult for a pit (e.g. conical) which expands across all dimensions over time. This makes it cheaper to install and maintain supporting infrastructure with productivity gains from higher speeds potentially offsetting the incremental costs. It is also an option for satellite deposits if the connecting haul route from the pits to the processing plant is fixed.

Battery Electrics: The two comparative options are to operate a smaller fleet with battery swaps, or a larger fleet which take time out to charge from a station. Addition of trolley assist provides dynamic charging. The choices between three options are not clear cut and difficult to generalise. These scenarios are often considered in the next 5-10 years as mine fleet are naturally replaced with operation of mixed fleet for 1 to 2 years. Whichever of these scenarios is considered, the key drivers become the effects on (a) pit slope angles and (b) cut-policies - we must do the work to find out the best option.

Ultimately, carbon reduction is a third-order idea, or outside pressure brought to bear. The first-order effects can be daunting, but Whittle Consulting's point is that the second-order effects may reduce or eliminate much of the downside.

In the re-optimisation process to consider decarbonisation projects, it is sometimes possible to **take a small hit in the financials for meaningful reduction in emissions, either on an absolute or intensity basis**. For almost all of Whittle's clients, GHG emissions have factored into the decision-making process in the past three years.

Other third order values Whittle has worked with include noise and dust reduction, operational windows (e.g. cannot blast at night, or only at certain depths), and obligation to employ a certain size of labour force. The latter can be an important consideration for automation projects depending on location.

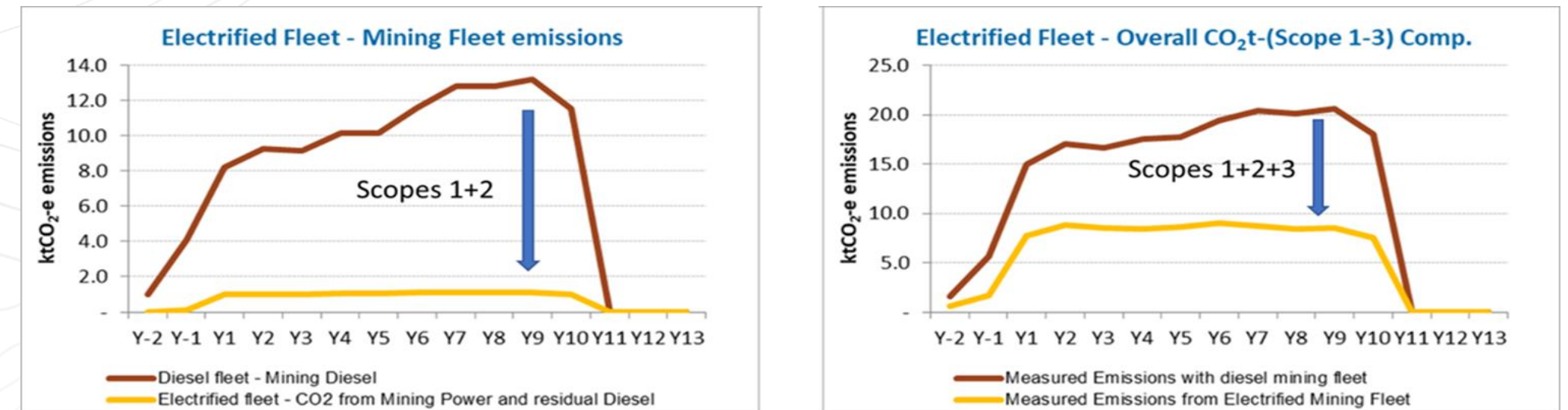
Whittle has also observed a lot of traction around water in the past 18 months, with operations working to new government rulings and regulations around water usage for regions with high levels of water stress, and water treatment for regions with high levels of flooding.

Recently, **Nordic Iron Ore (NIO)** revisited their pre-feasibility level 2019 strategic planning which now includes both a new carbon model and a decarbonisation strategy that includes fleet electrification for their project Blötberget (Hamerslag, 2022). The charts to the top-right compares the total estimated emissions for the originally planned diesel-powered fleet and the substantial reductions afforded by electrification in a low-carbon grid (Sweden).

Dundee Precious Metals (DPM) have used their integrated strategic planning study at Chelopech, judging improvements to long-range forecasts (LRF) and hence integrating climate decision-making into capital allocation decisions and transport of concentrates (Nolte, 2022). Assessing the carbon footprint vs. the NPV of the operation became a key feature of the study. It found that:

- Scope 1 and 2 emissions are insensitive to LOM scenarios meaning maximisation of NPV does not increase absolute carbon emissions, but that,
- Incorporating scope 3 emissions into the modelling presented some decision challenges in terms of 'up-stream' and 'down-stream' transport and processing assumptions because Scope 3 emissions are sensitive to the LOM scenario selected (including alternative destinations other than DPM's Tsumeb smelter).

Nordic Iron Ore: Electrification of Underground Mine Fleet

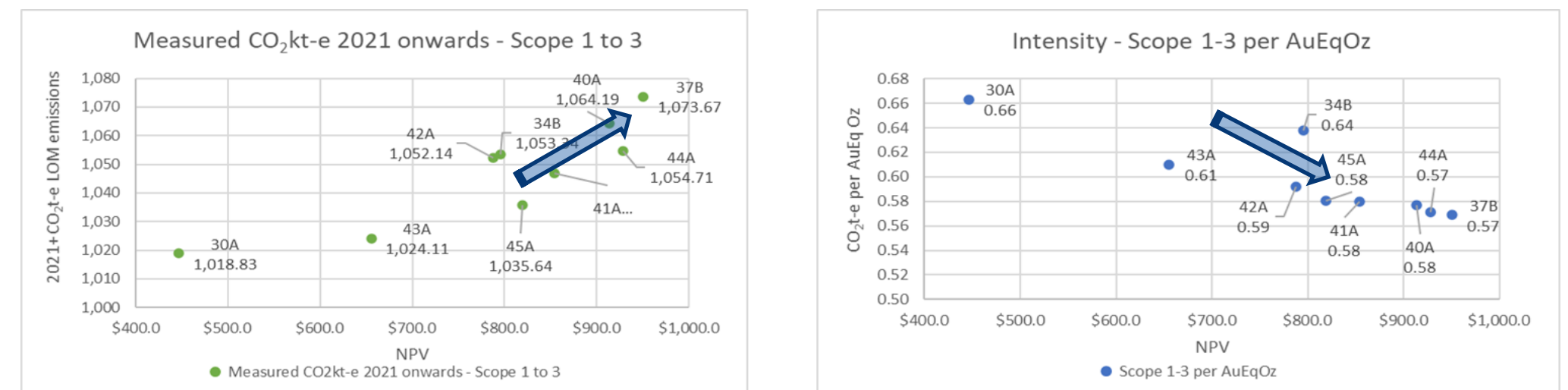


Key Summary

- Modelling of carbon inventories and intensities should form a part of the LOM planning cycle
- Planning scenarios can be compared for their carbon footprint
- Knowledge of carbon inventories and intensities can inform decision-making beyond traditional financial metrics
- Schedule and pit optimisation has natural effect on carbon inventories in a dynamic way
- Any examination of decarbonisation initiatives/technologies must consider the effect on the definition of the ore body - e.g. mine design, cut-off grades, grind sizes, product specs etc

Dundee Precious Metals: Downstream Processing Pathways for Chelopech

For Scope 1,2,3 inventories, CO₂ tracks upwards with NPV, but Intensity trends downwards



Where, When and How

Mine plan optimisation is an iterative process involving algorithms to determine what part of the ore deposit to extract and process (**where**), at what time (**when**), and using what method and equipment (**how**). Typically, many scenarios are run to optimise for financials (e.g. NPV) as well as to manage risk (e.g. VaR or Value at Risk, the maximum (worst) loss possible over a target time horizon at a given level of confidence).

The Lerchs-Grossman algorithm first applied in 1965 to solve for the most economic shape of a mine; methodologies and approaches have evolved since to include other algorithms such as Bienstock-Zuckerberg (BZ) which was introduced in 2009 to speed up and solve for scheduling problems in the area of mixed-integer linear programming (MILP).

Software algorithms available today allows dynamic iterations to be run at much faster speeds, making it possible to evaluate a multitude of scenarios and parameters over a relatively short timeframe that was possible even a decade ago.

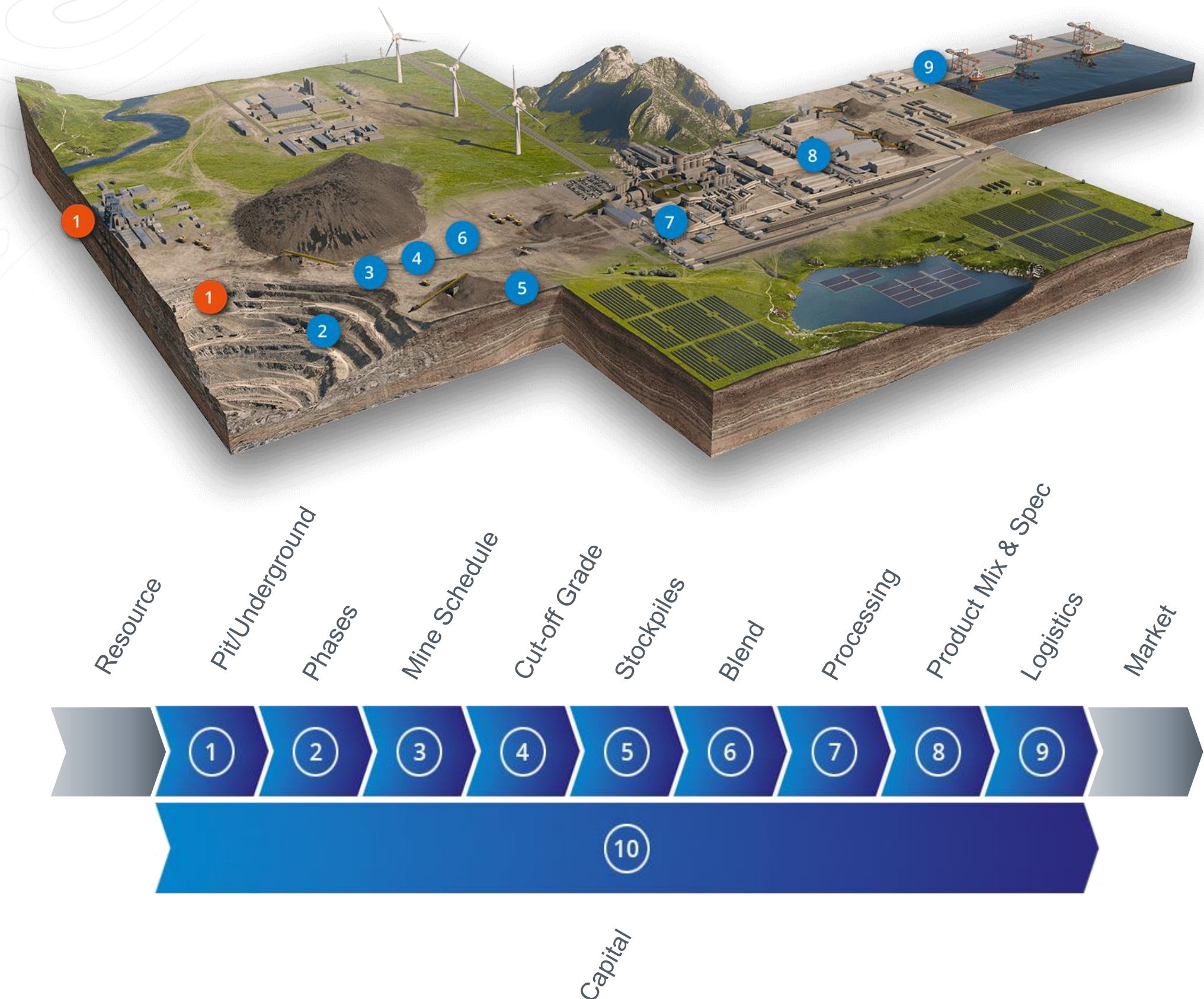
Who is leading this space?

Current thought leaders on this topic include Whittle Consulting (Enterprise Optimisation and Prober), Dassault Systèmes (GEOVIA), Comet Strategy and others who differ in their approaches but ultimately seek to integrate the different stages of an operation from the mine to placing the saleable product in the market to deliver a plan that creates the most value for a given asset.

Whittle's Enterprise Optimisation Model

The Enterprise Optimisation (EO) methodology maximises the life of mine value of mining and mineral processing assets (NPV). The technique involves simultaneous optimisation of the entire mining value chain from the mineral resource through to the end product market. EO employs Theory of Constraints (TOC) and Activity Based Costing (ABC) as economic principles coupled to the ten mechanisms, or steps, of Integrated Strategic Planning using the company's proprietary Prober® software.

The role of the Prober-user is to describe the mining system mathematically and then let the optimiser produce the best mining and processing schedule. This is an advance on using traditional schedulers and then pushing the schedule through processing steps and financial models.

The Ten Steps of a Whittle Enterprise Optimisation Model

Afum ([2017](#)) A review of models and algorithms for strategic mining options optimization

Bangerter & Pan ([2023](#)) Dynamic Influences of Optimisation on Emissions – Extended Abstract

Bangerter & Pan ([2023](#)) Dynamic Influences of Optimisation on Emissions – Presentation

Barlow ([2024](#)) The evolution of mine planning: is optimal the best we can do?

Davies ([2024](#)) The Role of Strategic Mine Planning in Decarbonising the Mining Industry

Hamerslag, R. (2022) Nordic Iron Ore AB. Liam Forum. Toronto: Brock University.

Nolte, M. (2022) Holistic Approaches, Integrated Strategic Planning & Sustainable Resource Development. Liam Forum. Toronto: Brock University.

Whittle ([2010](#)) Enterprise Optimisation

Whittle ([2023](#)). Activity Based Costing (ABC) and Theory of Constraints (TOC).

Whittle and Burks ([2010](#)) Simultaneous mining and mineral processing enterprise optimization for the platinum industry

Whittle, Stanger and Hanson ([2007](#)) Optimising Project Value and Robustness