Evaluating Long-Term Co-Product Mineral Supply and Exploration Interdependencies using the Pemmss Model

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ABSTRACT

Demand for many specialty mineral and metal commodities is rapidly increasing due to their use in advanced alloys, renewable energy systems and as part of other technologies required to decarbonise the global economy. Many of these specialty, often 'critical', commodities are produced in only small quantities as a co- or by-product of bulk commodity supply. In these cases they will typically represent only a minor contributor to the revenue realised from a mineral processing, smelting or refining operation. As a result of this, mineral exploration and the development of mining, smelting and refining operations capable of producing specialty co-product commodities is often driven by the demand and market conditions for bulk commodities. Despite the increasingly broad recognition of these supply dependencies, we still have a limited understanding of how the supply of one commodity influences the supply potential of others over the long-term. Existing scenario models for mineral supply typically only consider commodities on an individual basis, with relatively few attempts to develop integrated scenario models that are capable of considering complex supply interdependencies between commodities. With that in mind, the Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model was developed to enable mine-by-mine, deposit-by-deposit modelling of long-term co-product supply and exploration dynamics. This paper provides a brief summary of the PEMMSS model and an example of model outputs. Alongside this, a roadmap for application of the PEMMSS model is presented that includes four main stages: (1) Model development (completed). (2) Scenarios for individual base metal commodities. (3) Integrated scenarios for co-product metal commodities. (4) Adding environmental extensions (life cycle inventories, greenhouse gas emissions, water consumption, land-use impacts). Application of the PEMMSS model will allow us to better understand interdependent systems of mineral and metal co-production and the implications for long-term sustainable development. We anticipate that this will provide improved understanding of the technology, investment and policy interventions that will be required to avoid structural material supply bottlenecks during the sustainability and decarbonisation transition.

KEYWORDS

Scenario, co-production, mineral supply, prospective material flow analysis, MFA

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1. INTRODUCTION

The influence of mineral co-production on the long-term feasibility of technology rollout and sustainability transitions is still poorly understand. Many minor, specialty commodities are produced as co-products or by-products from production systems for major commodities. Due to this, the long-term supply potential of these specialty commodities can be heavily dependent on the production rates of major commodities and the economics of their extraction. These co-production dynamics are poorly captured by existing long-term scenario modelling for mineral supply and demand. Quite often, existing approaches to scenario modelling will consider each commodity in isolation. Also, while long-term demand side scenarios (i.e. 30+ years) might be sophisticated in their approach by considering sector and service based demand estimates, the supply side of the equation is often modelled in a highly aggregated way, often with a black box placed entirely around primary mineral and material supply chains and no consideration given to important industry dynamics such as mineral exploration. Due to this, it can be difficult to translate the outputs of many long-term supply-demand models for metals into clear implications for the mineral exploration, mining and mineral processing sectors.

The scenario modelling that does include detail on the supply side is typically only conducted for shorter time horizons (e.g. 10-20 years), where there is more certainty regarding potential development outcomes and the supply capacity of individual mineral projects. These short term assessments provide information that aligns with the immediate needs for most industry planning and investment decisions. However, they may provide limited understanding of industry dynamics that are required to evaluate the feasibility of different sustainable development trajectories over the very long-term (e.g. 50+ years).

Large-scale deployment of infrastructure, renewable energy and battery technologies is likely to lead to a sustained increase in demand for major metal commodities such as copper and nickel, as well as many specialty metal commodities such as cobalt, indium, germanium and tellurium. There are persistent concerns regarding the ability for supply to meet demand for some of these metals, and so new modelling approaches are required that can evaluate the range of potential outcomes and the uncertainty associated with mineral exploration, mine development and mineral/metal co-product supply dynamics required to meet this demand over the long-term.

2. DESCRIPTION OF THE PEMMSS MODEL

The Primary Exploration, Mining and Metal Supply Scenario (PEMMSS) model was developed to enable analysis of the long-term outcomes and implications of co-product mineral supply (Northey et al. 2022; under review). The PEMMSS model includes a number of key innovations not present in existing scenario modelling approaches. This includes: mine-by-mine, deposit-by-deposit modelling of mineral extraction and recovery; incorporation of exploration uncertainties through deposit type and regionally specific resource grade and tonnage probability distributions; mining and co-product recovery cost models; regional development delays and time periods; and, mine throughput to resource size relationships (e.g. Taylor's Rule). This differs substantially from most existing models for long-term mineral supply or resource scarcity, which usually utilise top-down, heavily aggregated modelling approaches that can't leverage the full detail and richness of emerging mineral deposit and mine production datasets. Incorporating this detail results in a modelling approach capable of answering key industry and minerals policy questions that could only be addressed superficially by previous approaches. The model is designed to be driven by primary demand scenarios derived from broader scenario models that consider material flows in society and socio-economic metabolism. This will enable the outputs of long-term material cycle modelling for sustainable development and decarbonisation pathways to be translated into a more discrete understanding of how these may impact,

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influence and shape the mineral sector.

Figure 1 provides an overview of the key components of the PEMMSS model. The model is designed to balance primary (i.e. mined) demand for commodities with supply from mineral operations. Primary demand is an exogenous input to the PEMMSS model, which can be obtained from the outputs of broader socio-economic material flow models – such as the ODYM-RECC model (Pauliuk et al., 2020). The demand for each commodity is converted into demand for mined commodities by accounting for assumed recovery efficiencies in intermediate processing steps (e.g. smelting, refining, etc.) that may exist between the commodity market and individual mine and mineral processing operations. Following this, the production from individual mines are ordered based on their relative net value, and short-falls in demand can trigger development of deposits into active mines. Greenfield exploration is incorporated in two ways – either by defining background rates of deposit discovery or by having this be triggered as a response to meet unmet commodity demand. Generated deposits are randomly assigned to regions and deposit types based on probability weightings, which can dictate parameters such as their required development periods, value/cost models, production capacity and recovery functions, as well as the probability distributions used to stochastically assign resource ore tonnages and grades. Brownfield exploration can be modelled through factors governing the addition of new units of resource at each deposit and mine overtime. These additional units of brownfield ore can be defined to be marginally lower grade than the existing resource to simulate grade dilution or incorporation of marginal ores into the resource overtime. The model can also be figured to model competition between developed and undeveloped deposits, so if a particularly rich deposit was discovered it could lead to supply from less valuable mines being halted (effectively simulating mines in care and maintenance). The outputs of the model include rich scenarios and statistics on potential (or required) rates of deposit discovery, mine development and closure, commodity production across regions and deposit type classifications, commodity recovery rates and losses, ore grades, and the ability to balance supply and demand for co-product commodities. A full description of the model is provided by Northey et al. (under review) and an open-source Python implementation of the model is available (Northey et al., 2022).

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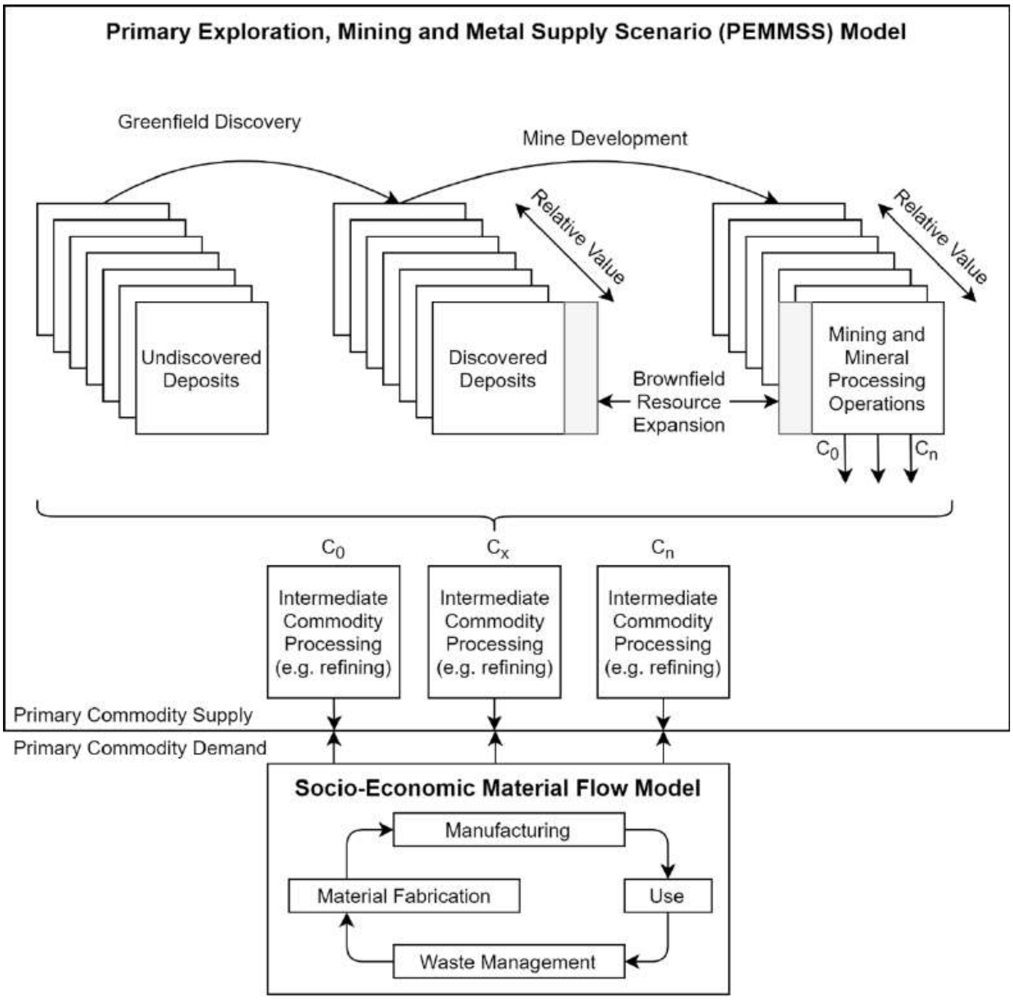

Figure 1 – Key components of the PEMMSS model and interface with primary commodity demand scenarios from socio-economic material flow models

3. EXAMPLE FOR A 4-COMMODITY SYSTEM

Initial analysis using this model is revealing that uncertainty in mineral exploration and mine development outcomes translates into significant uncertainty in the supply potential of co-product minerals over the long-term. Figure 1 shows an example of the initial outputs of this modelling approach for a hypothetical four co-product commodity system. In this case the supply of commodities 'A' and 'B' must always meet demand over the time period. However, supply potential for commodities 'C' and 'D' is highly variable and dependent upon the specific deposit types and mining operations being developed for commodities 'A' and 'B', which have differing co-product ore grades and recovery potentials. These results also show how the differing demand scenarios for commodity 'A' and 'B' directly translate into altered supply potential for commodities 'C' and 'D', although this is less pronounced for commodity 'D'. This modelling approach can also be used to develop a more nuanced understanding of future mineral supply, such as improved understanding of required investment magnitudes and timing required to meet long-term mineral demand. Or to understand how policies that would alter development periods between deposit discovery and production change how aggressive we have to be with greenfield exploration and deposit discovery in the near-term to be able to meet long-term demand. For instance, Figure 2 shows the rate of additional deposits that need to be

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discovered and the number of operating mines that would be required overtime to meeting demands for commodity ‘A’ and ‘B’. This type of understanding may be useful for understanding the magnitude of investment in greenfield exploration or new mining projects that will be required to meet different sustainable development scenarios.

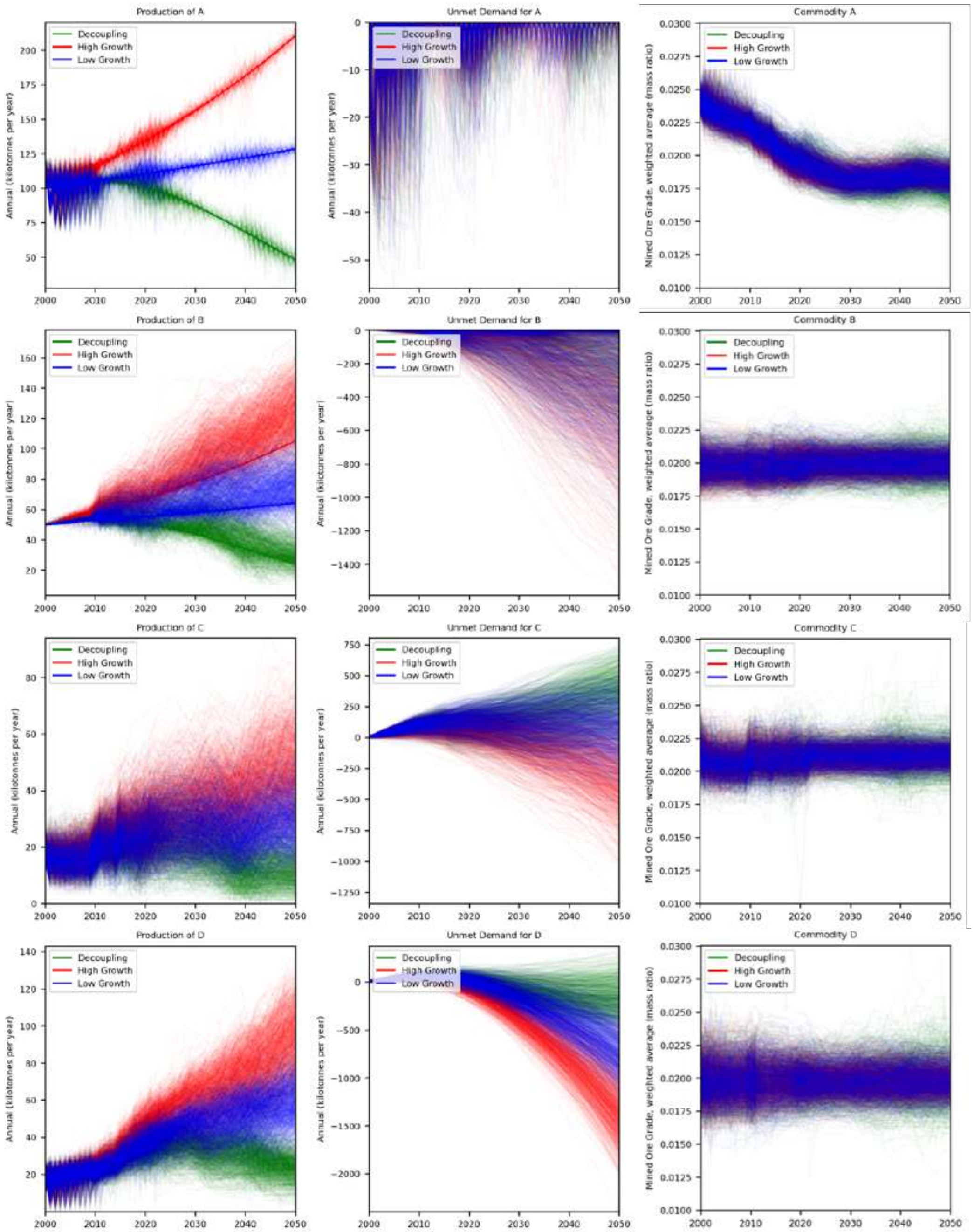

Figure 1 – Total primary commodity supply, unmet demand and average mined ore grades for a 4 hypothetical co-product commodity system (A, B, C & D), where demand for A and B must always be met. Results for three demand scenarios are shown, with 1000 iterations of the model run (reproduced from Northey et al., under review). The range of results for each scenario is primarily due to differing deposit discovery and mine development outcomes for each model run.

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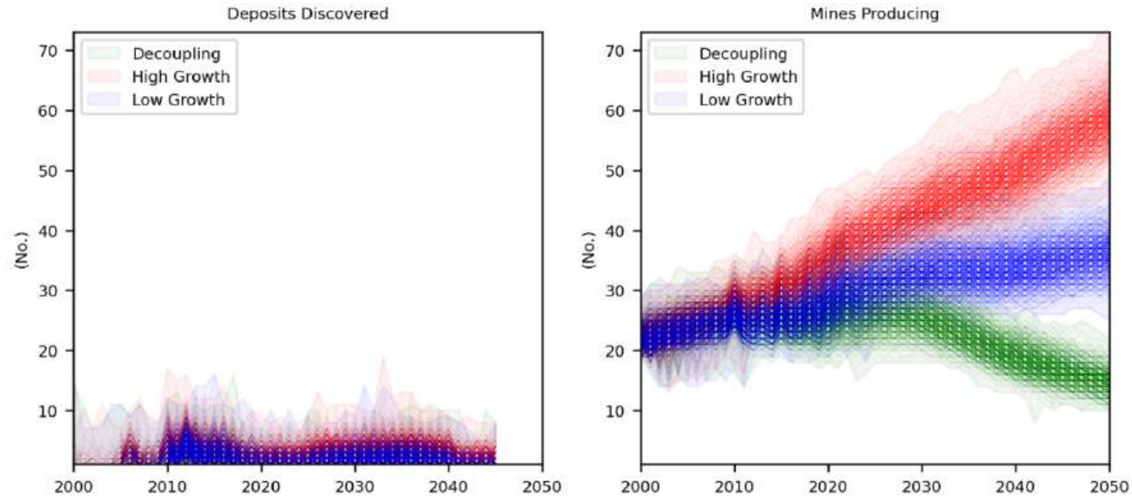

Figure 2 – Deposit discoveries and mines producing for a hypothetical 4 co-product commodity system. Results for three demand scenarios are shown, with 1000 iterations of the model run (reproduced from Northey et al., under review).

4. ROADMAP FOR MODEL APPLICATION

A roadmap for the development and application of the PEMMSS model is presented in Figure 3. Stage 1 has been completed and stages 2-4 are currently in progress, with some common tasks across these being undertaken simultaneously. This roadmap is expected to be completed in the next several years.

COMPLETED	IN PROGRESS		
STAGE 1 **PEMMSS Model Development**	**STAGE 2** **Scenarios for Individual Base Metal Commodities** - Cu - Ni - Pb - Zn	**STAGE 3** **Integrated Scenarios for Co-Product Metal Commodities** - Cu-Ni-Co - Zn-Pb-In-Ge - Cu-Mo	**STAGE 4** **Adding Environmental Extensions** - Life Cycle Inventories - Greenhouse gas emissions - Water consumption - Land-use impacts

Figure 3 – Development and application roadmap for the PEMMSS model

Stage 1 represents the development of the PEMMSS model. Initial conceptualisation, design, programming and testing of the model took place iteratively over an extended period from February 2018 to August 2022. The development process was initially supported by a UA-DAAD Australia-Germany Collaboration Grant that facilitated researcher exchanges between Monash University and the University of Freiburg. Development from 2019 onwards was supported by the University of Technology Sydney as part of a Chancellor's Postdoctoral Research Fellowship project.

During Stage 2, the PEMMSS model is being used to develop a series of scenarios for individual base metal commodities (Cu, Ni, Pb and Zn). This involves calibrating the PEMMSS model using mineral resource and

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production datasets for base metal commodities and linking this to external primary commodity demand scenarios that align with the *shared socio-economic pathways* (SSP), which are a defined set of socio-economic pathways used for long-term policy development and climate change modelling. The results of stage 2 will be a set of exploration, mining and metal supply scenarios for each commodity and SSP.

Stage 3 builds on the outcomes of stage 2 by incorporating commodity co-production into the exploration and supply scenarios derived for each SSP. Scenarios are being developed for commodity groups of relevance for future battery production (e.g. Cu-Ni-Co) and infrastructure and renewables deployment (e.g. Zn-Pb-Cu-In-Ge) to better understand co-product supply chain dynamics required to decarbonise the global economy.

Stage 4 considers the addition of environmental extensions to the PEMMSS model. Integration of life cycle inventory modelling at the mine scale will enable regionalized scenarios for the greenhouse gas emissions, water consumption and land-use impacts of mining to be considered. This is intended to leverage the recently developed spatially-explicit life cycle impact characterization models for water and land-use impacts, which are increasingly being used in product environmental life cycle assessment studies but have seen limited application to date as part of scenario assessments of the mining industry. Scenarios developed at these lower levels of aggregation are important, as prior research has identified that assessing the impacts of mining's water use at national levels of aggregation may lead to highly uncertain and potentially misleading results – compared to similar assessments done on a watershed basis (Northey et al., 2018).

4. CONCLUSIONS

The PEMMSS model has been designed to fill in the black box for primary metal production that is often seen in global material flow scenario modelling frameworks. Through linking the PEMMSS model to these broader modelling frameworks, the PEMMSS model will enable material flow scenarios for decarbonisation and sustainable development trajectories to be translated into the structural implications for mineral exploration, mining and the primary metal production industries. Further extension of the PEMMSS model to consider environmental burdens associated with metal supply will also provide an avenue understanding the complex sustainability trade-offs associated with material. We believe these applications of the PEMMSS model may facilitate improved foresight regarding the required investment, technology and policy interventions in primary mineral and metal supply chains that will be required to overcome sustainable development challenges facing society.

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